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Culvert Repair Practices Manual

Volume I

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FOREWORD

The *Culvert Repair Practices Manual* was designed to supplement the *Culvert Inspection Manual* developed by the Federal Highway Administration in 1986. The *Culvert Repair Practices Manual* provides a compendium of rehabilitation techniques to be used when inspections show the need to repair a culvert. Volume I consists of the text. Volume II presents Appendixes.

Culverts, like pavements, are generally classified into two groups: rigid and flexible. Concrete is typically used in rigid culverts; steel and aluminum are primary materials that comprise flexible systems. The *Culvert Repair Practices Manual* provides resource information on all culvert types, the materials used in their fabrication, and the construction methods used in their placement. It outlines the causes of common deterioration problems and methods for maintenance and repair. It also includes guidance for deciding whether a culvert should be repaired or replaced.

This manual is designed for a broad audience. Recognizing that some states assign responsibility of culvert repair to maintenance departments while others assign it to bridge sections or other departments, the authors have designed the manual for all design, construction, and maintenance staff who are involved in the construction of culverts. Those responsible for the design and engineering of new culverts may also find the information useful.

Charles J. Nemmers
Director, Office of Engineering and
Highway Operations Research and Development

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16. Abstract

All culverts with openings of more than 20 ft, measured parallel to the roadway, must be inspected on a two-year cycle in accordance with the National Bridge Inspection Standards (NBIS). Many highway agencies also inspect smaller culverts on the same cycle. The NBIS, and prudent engineering, requires that culverts that are structurally weak or hydraulically inadequate be inspected on a more frequent cycle.

This manual has been developed to provide guidance to highway agencies on procedures that may be used to repair a wide variety of types of problems that beset metal and concrete culverts of all types. Many of the procedures are also applicable to the repair of timber and stone masonry culverts. Procedures are also presented on ways to improve the inlet and outlet ends of culverts as well as the streambed channels leading to and from them.

Information presented in this manual has been compiled from numerous contacts with representatives of the culvert industry as well as many highway agencies through the United States and Canada.

This is a two-volume report. Volume I consists of the text. Volume II presents Appendixes.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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GLOSSARY OF TERMS

Abrasion: Wearing or grinding away of material by water laden with sand, gravel, or stones.

Acidic: Substances with a pH less than 7.0 which may react with or corrode certain metals. Soils or water may be acidic and react with metal culverts.

Aggradation: General and progressive raising of the streambed by deposition of sediment.

Aggressive Environment: A soil-stream environment where corrosion-abrasion deterioration is highly destructive to culvert life.

Alkaline: Substances having a pH greater than 7.0. Such substances are caustic or able to corrode or dissolve materials. Mineral salts found in arid soils are alkaline.

Allowable Headwater: Difference in elevation between the flowline of the culvert and the lowest point at which the water surface upstream would either flood the roadway or jeopardize property.

Anode: A metallic surface on which oxidation occurs, giving up electrons with metal ions going into solution or forming an insoluble compound of the metal.

Autogeneous Healing: A process where small cracks are healed by exposure to moisture, forming calcium carbonate crystals that accumulate along the crack edges, inter-twining and building until the crack is filled.

Backfill: The material used to refill the trench or the embankment placed over the top of the bedding and culvert.

Backwater: The water upstream from an obstruction in which the free surface is elevated above the normal water surface profile.

Bedding: The soil used to support the load on the pipe. For rigid pipe, the bedding distributes the load over the foundation. It does the same thing for flexible pipe except that it is not as important a design factor.

Bed Load: Sediment that is transported in a stream by rolling, sliding, or skipping along the bed or very close to it; considered to be within the bed layer.

Bituminous (Coating): Of or containing bitumen, as asphalt or tar.

Box Section: A concrete or corrugated pipe with a rectangular or nearly rectangular cross section.

Buckling: Failure by an inelastic change in alignment (usually as a result of compression)

Buried Pipe: A structure that incorporates both the properties of the pipe and the properties of the soil surrounding the pipe.

Buoyancy: The upward force exerted by a fluid on a body in it; the tendency to float an empty pipe (by exterior hydraulic pressure).

Capacity: Maximum flow rate that a channel, conduit, or structure is hydraulically capable of carrying. The units are usually CFS or GPM.

Cathode: A surface that accepts electrons and does not corrode.

Cathodic Protection: A means of preventing metal from eroding. This is done by making the metal a cathode through the use of impressed direct current or by attaching a sacrificial anode.

Cavitation: A phenomenon associated with the vaporization of a flowing liquid at high velocities in a zone of low pressure, wherein cavities filled with liquid (vapor bubbles) alternately develop and collapse; surface pitting of a culvert may result.

Cement Mortar Lining: Cement mortar grout centrifugally applied to the interior of existing culverts. Grout is applied after cleaning the existing pipe to protect the pipe and maintain capacity.

CFS: Rate of flow in cubic feet per second.

Chlorides: Binary chemical compounds containing chlorine which can corrode concrete reinforcing steel.

Cladding: Aluminum culvert sheet sandwich with aluminum magnesium - manganese alloy 3004 between two layers of aluminum - zinc alloy 7072 cladding for corrosion protection.

Class: The grade or quality of pipe.

Coating: Any material used to protect the integrity of the structural elements of a pipe from the environment and add service life to the culvert.

Compaction: The process by which a sufficient amount of energy is applied to soil to achieve a specific density.

Conductivity: A measure of the corrosive potential of soils which is expressed in milli-mhos per centimeter. It is the reciprocal of resistivity.

Conductor: A metallic connection (in drainage facilities, usually the pipe itself) that permits electrical current flow by completing the circuit.

Conduit: Usually a pipe, designed to flow according to open channel equations.

Corrosion: Deterioration or dissolution of a material by chemical or electrochemical reaction with its environment.

Cover: The depth of backfill over the top of the pipe.

Crack: A fissure in an installed precast concrete culvert.

Critical Depth: Critical depth is the depth at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry, there is only one critical depth.

Critical Flow: That flow in open channels or conduits at which the energy content of the fluid is at a minimum.

Crown: The crown is the inside top of the culvert.

Culvert: A culvert is defined as the following: A structure that is usually designed hydraulically to take advantage of submergence to increase hydraulic capacity; a structure used to convey surface runoff through embankment; a structure, as distinguished from bridges, that is usually covered with embankment and is composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert; and a structure that is 20 feet or less in centerline length between extreme ends of openings for multiple.

Debris: Any material including floating woody materials and other trash, suspended sediment, or bed load, moved by a flowing stream.

Deflection: Change in the original or specified inside diameter of pipe.

Degradation: General progressive lowering of the stream channel by erosion.

Discharge (Q): Flow from a culvert, sewer, or channel in cubic feet per second (CFS).

Drainage: Interception and removal of ground water or surface water by artificial or natural means.

Drop Inlet: A type of inlet structure which conveys the water from a higher elevation to a lower outlet elevation smoothly without a free fall at the discharge.

Durability:	Ability to withstand corrosion and abrasion over time or service life.
Electrolyte:	Moisture or a liquid carrying ionic current between two metal surfaces, the anode and the cathode.
Embankment:	A bank of earth, rock or material constructed above the natural ground surface over a culvert.
End Section:	A concrete or steel appurtenance attached to the end of a culvert for the purpose of hydraulic efficiency and anchorage.
Energy Dissipator:	Device to decrease hydraulic energy placed in ditches or culvert outfalls to reduce streambed scour.
Energy Gradient:	The increase or decrease in total energy of flow with respect to distance along the channel.
Energy Grade Line:	The line which represents the total energy gradient along the channel. It is established by adding together the potential energy expressed as the water surface elevation referenced to a datum and the kinetic energy (usually expressed as velocity head) at points along the streambed or channel floor.
Erosion (Culvert):	Wearing or grinding away of culvert material by water laden with sand, gravel, or stones; generally referred to as abrasion.
Erosion (Stream):	Wearing away of the streambed by flowing water.
Female End of Pipe (bell, socket, groove, modified groove):	That portion of the end of the pipe, regardless of its shape, size, or dimensions, which overlaps a portion of the end of the adjoining pipe.
Fish Passage:	Ability of native trout and anadromous fish to pass through bridge and culvert structures.
Flexible Pipe:	A pipe with relatively little resistance to bending. As the load increases, the vertical diameter decreases and the horizontal diameter increases, which is resisted by the soil around the pipe.

Flood Frequency:	The number of years, on the average, within which a given discharge will be equaled or exceeded.
Flow Line:	A line formed by the inverts of pipe.
Foundation:	The in place material beneath the pipe.
Free Outlet:	A free outlet has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering of the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.
Galvanizing:	Application of a thin layer of zinc to steel by hot-dipping.
Gauge:	Thickness of sheet metal used in corrugated metal pipe.
GPM:	Gallons per minute.
Grade:	The longitudinal slope of the channel as a ratio of the drop in elevation to the distance.
Gradient:	See grade.
Groundwater:	Water contained in the subsoil which is free to move either vertically or horizontally.
Hairline Cracks:	Very small cracks that form in the surface of the concrete pipe due to tension caused by loading.
Holidays:	Defect in protective coating on metal surface.
Haunches:	The outside areas of a pipe between the spring line and the bottom of the pipe.
Head (Static):	The heights of water above any plane or point of reference.
Headloss:	The loss of energy reported in feet of head.
Headwall:	A concrete structure placed at the inlet and outlet of a culvert to protect the embankment slopes, anchor the culvert, and prevent undercutting.

Headwater: The distance between the flowline elevation at the inlet of a culvert and the water surface at the inlet.

Hydraulics: The mechanics of fluids, primarily water.

Hydraulic Gradeline: An imaginary line, representing the total energy and paralleling the free water surface if the flow were at atmospheric pressure.

Hydraulic Jump: An abrupt rise in the water surface in the direction of flow when the type of flow changes from supercritical to subcritical.

Hydraulic Radius: The cross-sectional area of flow divided by the length of that part of its periphery in contact with its containing conduit; the ratio of area to wetted perimeter.

Hydrology: The science of water related to its properties and distribution in the atmosphere, on the land surface, and beneath the surface of the land.

Improved Inlet: An improved inlet has an entrance geometry that decreases the flow constriction at the inlet and thus increases the capacity of culverts. These inlets are referred to as either side- or slope-tapered (walls or bottom tapered).

Impingement: Suspended solid particles or gas bubbles in water striking the surface or turbulence alone breaking down the protective layer of a metal or concrete surface.

Insertion Renewal: General term for relining or sliplining.

Inversion Lining: Process of inverting pliable tube into existing pipe with hydrostatic or air pressure to reline existing pipe. The liner is forced against the existing pipe and bonded with thermosetting resins to provide structural strength and improved smoothness.

Invert: The invert is the flowline of the culvert (inside bottom). of the transverse cross section of a pipe.

Joint: A connection between two pipe sections made either with or without the use of additional parts.

Link Pipe Lining: Method of pulling a short, folded pipe line segment to the damaged point in an existing pipe and jacking the segment into place.

Long Span Culverts: Culverts that are designed on structural aspects rather than hydraulic considerations. Usually constructed of structural plate which exceed defined sizes for pipes, pipe arches, or arches or may be special shapes that involve a long radius of curvature in the crown or side plates.

Male End of Pipe (Spigot, Tongue, Modified Tongue): That portion of the end of the pipe, regardless of its shape or dimensions, which is overlapped by a portion of the end of the adjoining pipe.

Manning's Equation: An equation for the empirical relationship used to calculate the barrel friction loss in culvert design.

Metal Corrosion: An electrical process involving an electrolyte (moisture), an anode (the metallic surface where oxidation occurs), a cathode (the metallic surface that accepts electrons and does not corrode), and a conductor (the metal pipe itself).

Minor Head Losses: Head lost through transitions such as entrances, outlets, obstructions, and bends.

Normal Flow: Normal flow occurs in a channel reach when the discharge, velocity and depth of flow do not change throughout the reach. The water surface profile and channel bottom slope will be parallel. This type of flow will exist in a culvert operating on a steep slope provided the culvert is sufficiently long.

O-Ring Gasket: A solid gasket of circular cross section. Used in joint connections.

Outfall: In hydraulics, the discharge end of drains or sewers. Also referred to as outlet.

Outlet: See Outfall.

Oxidation-Reduction potential: Used as a primary indicator of anaerobic bacterial corrosion which occurs in wet, poorly drained soils at the soil-metal interface. Iron in aerated water in the presence of sulfate-reducing bacteria corrodes at an accelerated rate. Also known as the "redox potential."

Perforation: Complete penetration of metal culvert that generally occurs in the invert.

pH Value: The log of the reciprocal of the hydrogen ion concentration of a solution. A pH value of 7.0 is neutral; values of less than 7.0 are acid; values of more than 7.0 are alkaline.

Pipe: A tube or conduit.

Pipe Diameter: The inside diameter of a pipe.

Piping: A process of subsurface erosion in which surface runoff flows along the outside of a culvert and with sufficient hydraulic gradient erodes and carries away soil around or beneath the culvert.

Polyethylene Pipe: Plastic pipe manufactured from polymerized ethylene in corrugated or smooth configurations of various dimensions.

Polymer Coating: Protective coatings of plastic polymer resins with other materials.

Ponding: Water back up in a channel or ditch as the result of a culvert of inadequate capacity or design to permit the water to flow unrestricted.

Prestressed Concrete: Concrete that is continually under a compressive stress that is created when the steel reinforcing bars, wires, or cables are held in a stretched condition during placing of the plastic concrete and until the concrete has hardened. The pull on the reinforcing steel is then released providing additional strength.

Reinforced Concrete Pipe: A concrete pipe designed with reinforcement as a composite structure.

Rigid Pipe: A pipe with a high resistance to bending

Rip Rap: Rough stone of various sizes placed compactly or irregularly to prevent scour by water or debris.

Roughness Coefficient (n): A factor in the Kutter, Manning, and other flow formulas representing the effect of channel (or conduit) roughness upon energy losses in flowing water. It is based on either hydraulic test results or calculated using theoretical relationships.

Resistivity (Soil): An electrical measurement in ohm-cm, which is one of the factors for estimating the corrosivity of a given soil to metals.

Runoff: That part of precipitation carried off from the area upon which it falls.

Sacrificial Coating: A coating over the base material to provide protection to the base material. Examples include galvanizing on steel and cladding on aluminum.

Sacrificial Thickness: Additional pipe thickness provided for extra service life of the culvert in an aggressive environment.

Scour (Outlet): Degradation of the channel at the culvert outlet as a result of erosive velocities.

Seepage: The escape of water through the soil, or water flowing from a fairly large area of soil instead of from one spot, as in the case of a spring.

Shotcrete Lining: Application of pneumatically applied cement plaster or concrete to an in place structure to increase structural strength and improve the surface smoothness.

Skew (Skew Angle): The acute angle formed by the intersection of the line normal to the centerline of the road with the centerline of a culvert or other structure.

Slabbing: Radial tension failure of concrete pipe resulting from the tendency of curved reinforcing steel or cage to straighten out under load. It is characterized by large slabs of concrete "peeling" away from the sides of the pipe.

Slide: Movement of a part of the earth (embankment) under the force of gravity.

Sliplining: The process of placing a smaller diameter pipe in a larger diameter existing pipe to improve the culvert structure and repair leaks. The annular space between the pipes is usually filled with grout.

Slope: Steep slope occurs where the critical depth is greater than the normal depth. Mild slope occurs where critical depth is less than normal depth.

Spelter: Zinc slabs or plates.

Spalling (Culvert): The separation of surface concrete due to fractures in the concrete parallel or slightly inclined to the surface of the concrete.

Springline: The points on the internal surface of the transverse cross section of a pipe intersected by the line of maximum horizontal dimension; or in box sections, the mid-height of the internal vertical wall.

Structural Plate: Plates of structural steel used to fabricate large culvert structures such as arches or boxes.

Submerged Inlet: A submerged inlet occurs where the headwater is greater than 1.2D.

Submerged Outlet: A submerged outlet occurs where the tailwater elevation is higher than the crown of the culvert.

Sulfates: Chemical compounds containing SO found in alkaline soils that cause concrete deterioration.

Suspended Load: Sediment that is supported by the upward components of the turbulent currents in a stream.

Tailwater Depth: The depth of water just downstream from a structure.

Velocity Head: For water moving at a given velocity, the equivalent head through which it would have to fall by gravity to acquire the same velocity.

Wall (Concrete Pipe): The structural element composed of concrete or concrete and reinforcing steel between the inside and outside of a concrete pipe.

Watercourse: A channel in which a flow of water occurs, either continuously or intermittently, with some degree of regularity.

Watershed: Region or area contributing to the supply of a stream or lake, drainage area, drainage basin, or catchment area.

Weir: A man made barrier in an open channel over which water flows. It is used to measure the quantity of flow.

Wetted Perimeter: The length of the wetted contact between the water and the containing conduit measured at right angles to the conduit.

CHAPTER 1. INTRODUCTION

There are hundreds of thousands of culverts under the highways of America, many over 50 years old. Culverts do not receive much attention, primarily because they are generally hidden from view from the traveling public. Occasionally, however, an incident occurs that serves as a reminder that the failure of a culvert can have serious consequences.

One of the most serious accidents occurred in 1983 in Antwerp, Ohio. As reported in the *Engineering News Record*[(1)], five persons died and four were injured when their cars plunged into a shallow ravine after a corrugated steel culvert collapsed under a county road. Four cars drove into the creek about a half hour after the failure, which occurred at 9:30 p.m. The culvert spanned 30 feet and had a rise of 15 feet. It was topped by 8 or 9 feet of fill and an asphalt pavement. As gradual settlement occurred, rock and asphalt had been added. The pavement was thinnest over the arch. Figure 1.1 shows the collapsed culvert, with the guardrail still in place overhead, after the vehicles had been removed. The culvert, which was ten years old, had been inspected the year before.

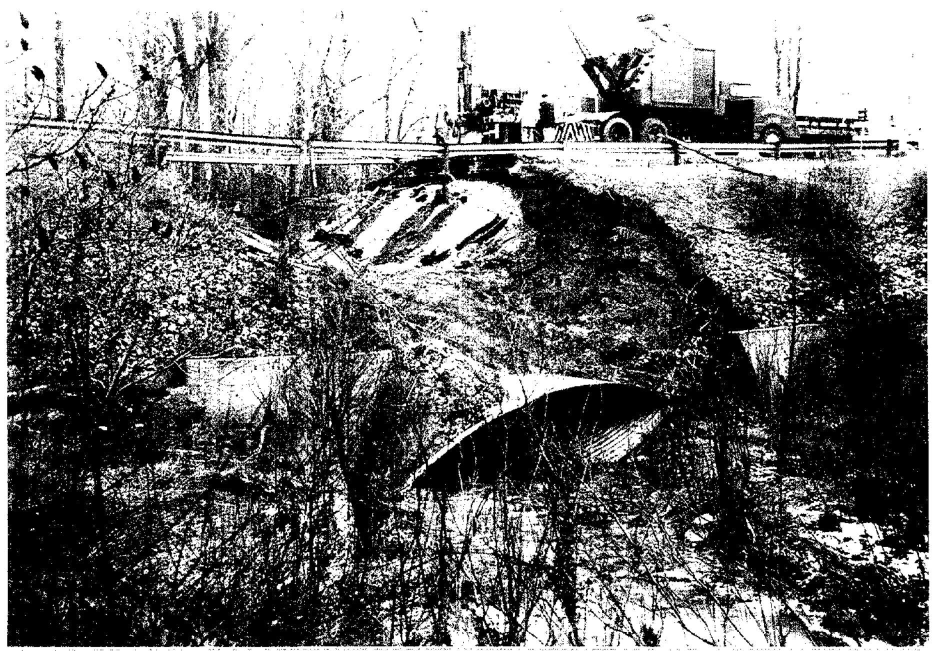


Figure 1.1 Culvert failures may be both hazardous and costly.

Over the past twenty years, most of the larger highway culverts, with openings measuring over 20 feet, have been inspected at least every two years. These inspections, which were on a wide variety of culvert types and materials, revealed numerous types of problems. The inspections have not only documented the problems but rated the culverts with regard to their serviceability and structural safety.

Although inspection reports document problems, the reports do not indicate or stipulate the type(s) of repairs that should be undertaken. Neither do they provide guidance on how the work should be done nor provide a rationale for selecting the best or most cost-effective alternative for complete repair, restoration, or replacement of the culvert.

One of the problems associated with repair, rehabilitation, and replacement of culverts is that the work frequently is approached strictly as a maintenance problem without consideration of the underlying structural or hydraulic conditions from which the deterioration originates. Moreover, there has never been enough money to maintain culverts properly and, over the years, the overall condition of culverts in the highway system has steadily worsened.

Traditionally, maintenance and repair of culverts has been handled on a "brush fire" basis, where only the most critical problems are given attention, and very few records have been kept on (1) the condition of the culvert, (2) the type of repair work that was done and its cost, and (3) the effectiveness of the repair work. Although there is considerable information available on the design and construction of new culverts of many materials, there is little information in the literature on how to repair culvert problems and even less on how to rehabilitate, strengthen, or retrofit upgrade culverts. There are essentially no criteria for selecting the most cost-effective alternative for the work that should be done.

SCOPE

This chapter provides an overview of the manual and the problem of culvert repair. It includes the purpose, objectives, and organization of information presented in the manual, as well as a synopsis of the characteristics and problems associated with culverts. The need for economical methods of repair and replacement is also highlighted.

PURPOSE OF THE MANUAL

The primary purpose of this manual is to provide information, guidelines, and alternatives for the cost-effective repair of culverts. It provides an overview of current practices for maintenance, repair, rehabilitation, retrofit upgrading, and replacement of highway culverts. It gives detailed information on appropriate related procedures. It supplies guidelines for selecting the most cost-effective procedures for resolving current problems to provide increased serviceability and life expectancy of culverts.

Objectives

The objective of this manual is to provide information that will assist users in doing the following tasks:

- Recognize the causes of problems and how to determine solutions.
- Conduct routine inspection and maintenance to minimize progressive deterioration of culverts.
- Select procedures to repair the individual components of culverts with various types of distress.
- Select procedures to rehabilitate culverts to their original functional condition.
- Select procedures to strengthen or retrofit upgrade culverts to correct design and/or construction deficiencies and to improve serviceability and functionality.
- Select procedures to replace deteriorated or functionally obsolete culverts.
- Use guidelines and criteria for selecting the most cost-effective procedure(s) for addressing current problems to provide increased serviceability and life expectancy of culverts.

Audience

This manual is intended to be of assistance to highway agency maintenance personnel and hydraulic and structural engineers who are responsible for decisions regarding maintenance, repair, rehabilitation, retrofit upgrading, and replacing highway culverts.

Organization

This manual is organized into seven chapters:

- Chapter 1 provides an introduction to this manual and an overview of the types of culvert problems that are addressed in more detail in subsequent sections of this manual.

- Chapter 2 reviews basic concepts and descriptions of culvert components.

- Chapter 3 provides an overview of the various types of problems associated with culverts.

- Chapter 4 provides general guidelines and information on culvert maintenance procedures.

- Chapter 5 presents guidelines and information on specific procedures for repair, rehabilitation, and retrofit improvement of the ends and appurtenances of culverts.

- Chapter 6 offers guidelines and information on procedures for the repair, rehabilitation, and retrofit improvement of culvert barrels.

- Chapter 7 provides information on the alternatives for replacement of culverts and presents general criteria that may be used for selecting the best alternative for the necessary work.

OVERVIEW OF THE PROBLEM

There are thousands of culverts in the highway system that are in various states of deterioration, ranging from relatively minor serviceability problems to serious functional and safety problems that impair the usefulness of the culvert or overlying roadway. Highway agency personnel are faced with the question of deciding whether to repair, rehabilitate, retrofit, or replace these culverts and how to do so with available funds. Experience of various departments has shown that it is often economically feasible to restore or upgrade culverts, and procedures have been developed for doing such work. In order for agency personnel to decide which repair procedures are most appropriate, it is necessary that they have a basic understanding of culvert design, construction, and maintenance and, more pertinent, how to evaluate causes and solutions to the problems.

Culvert Structures

Culverts are primarily structures that carry surface and stream water under highway pavements. However, the same types of structures are also used to facilitate highway undercrossings by animals, people, and a limited number and size of vehicles.

Definition - Although the primary function of culverts is to carry water, the definition of culverts is based on the span length of the structure in the roadway direction. According to the Federal Highway Administration's National Bridge Inspection Standards,"... structures over 20 feet in span parallel to the roadway are usually called bridges; and structures less than 20 feet in span are called culverts even though they support traffic loads directly."[2,3,4]

The American Association of State Highway and Transportation Officials' (AASHTO) *Model Drainage Manual*[5] defines a culvert as follows:

- A structure which is usually designed hydraulically to take advantage of submergence to increase hydraulic capacity.
- A structure used to convey surface runoff through embankments.
- A structure, as distinguished from bridges, which is usually covered with embankment and is composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert.
- A structure which is 20 feet or less in centerline length between extreme ends of openings for multiple boxes.

This manual addresses the repair, rehabilitation, retrofit improvement, and replacement of this class of hydraulic structures.

Basic Characteristics - The structural and hydraulic design of culverts is substantially different from that of bridges, as are the construction, maintenance, repair, and replacement procedures. A few of the more significant characteristics of water-carrying culverts are:

- Hydraulic - Culverts are usually designed to operate at peak flows with a submerged inlet to improve hydraulic efficiency. The culvert constricts the flow of the stream and may cause ponding at the upstream or inlet end. The resulting rise in elevation of the water surface produces a head at the inlet that increases the hydraulic capacity of the culvert. The effects of ponding and flow on appurtenant structures, embankments, and abutting properties are important considerations in the design of culverts.
- Structural - Culverts are buried in soil and are designed to support the dead load of soil over the culvert as well as live loads of traffic. Either the live load

or the dead load may be the most significant load element, depending on the type of culvert, type and thickness of cover, and amount of live load. However, live loads on culverts are generally not as significant as the dead load unless the cover is shallow. Box culverts with shallow cover are examples of the type of installation where live loads are important.

In most culvert designs, the soil or embankment material surrounding the culvert plays an important structural role. Lateral soil pressures enhance the culvert's ability to support vertical loads. The stability of the surrounding soil is important to the structural performance of most culverts.

- Maintenance - Because culverts usually constrict flow, there is an increased potential for waterway blockage by debris and sediment, especially for culverts subject to seasonal flow. Multiple barrel culverts are particularly susceptible to debris accumulation. Scour caused by high outlet velocity or turbulence at the inlet end is of concern. As a result of these factors, routine maintenance for culverts primarily involves the removal of obstructions and the repair of erosion and scour. Other defects from weathering, loads, and age will occur and require routine maintenance.

- Traffic Safety - A significant safety feature of many culverts, as compared to bridges, is the elimination of a constriction in the roadway. Culverts can be extended so that the standard roadway cross section can be carried over the culvert to provide a vehicle recovery area. However, when the ends are located near traffic lanes or adjacent to shoulders, guardrails may be required to protect the traffic. Differential icing, which occurs when water on the road surface over the culvert freezes before water on the roadway approaches, is sometimes a problem with large culverts with shallow cover.

- Construction - One of the most significant factors is that culverts are constructed in and through the roadway embankment, and vehicle loads are carried by the combined strengths of the culvert and the surrounding embankment. The trench width, bedding, compaction, and amount of fill over the culvert are important factors that influence the ability of the culvert to carry the design loads. Thus, the construction techniques and quality control of workmanship are critical to the ultimate serviceability and life expectancy of culverts.

- Durability - Durability of materials is a significant problem in culverts and other drainage structures. In hostile environments, corrosion and abrasion can cause deterioration of all commonly available culvert materials. Many types of serviceability problems may occur because of scour of streambeds and erosion of embankments adjacent to the culverts.

- Inspection - Highway bridges and culverts with a span length greater than 20 feet must be inspected at least every two years. There is no mandated criteria for the length of time between inspections for culverts that are less than 20 feet in roadway span. However, it is recognized that culverts may be routinely inspected and that problems are reported on an as-noticed basis.

Types of culverts - Although there is a very wide range of styles and designs of culverts in service, all culverts may be classified into two basic types: rigid and flexible. This classification is based on the primary difference in the manner in which structural loads are carried by the culvert and the interrelationship between the culvert structure and the surrounding soil. Rigid culverts are designed to resist bending moment; flexible culverts are not.

Culverts are also often described by their shape, which may be circular, arch, elliptical, or box. The box shape may be made more torsionally rigid by adding internal web walls between the top and bottom surfaces. Culverts may also be made with multiple barrels for additional flow capacity. Most modern culverts are made from either corrugated metal, or reinforced concrete. Concrete culverts may be of either precast or cast-in-place construction, which may be post-tensioned in the field. These materials may be used to construct most of the mentioned structural shapes.

General Problems With Culverts

There is a wide variety of types of problems that occur with culverts. The problems may be classified by serviceability and strength-related criteria. Listed below are general types of culvert problems:

Serviceability-related problems

- Scour and erosion of streambed and embankments;
- Inadequate flow capacity;
- Corrosion and abrasion of metal culverts;
- Abrasion and deterioration of concrete and masonry culverts;

- Sedimentation and blockage by debris;
- Separation and/or dropoff of sections of modular culverts; and
- Inadequate length.

Strength-related problems

- Cracking of rigid culverts;
- Undermining and loss of structural support;
- Loss of the invert of culverts due to corrosion or abrasion;
- Over-deflection and shape deformation of flexible culverts; and
- Stress cracking of plastic culverts.

Need for Economical Methods of Repair & Replacement

Although many local agencies may have procedures for their repair, many culverts are allowed to deteriorate until they are no longer serviceable or until they become unsafe. Then, most often, they are replaced rather than repaired or rehabilitated.

Many culverts are reaching the end of their design life. In many cases, these culverts have been constructed under high fill or are under roadways that carry high volumes of traffic. Replacement of these culverts require significant construction costs as well as cause severe disruption to traffic. These circumstances require that viable methods of repair and rehabilitation be found.

This manual is an attempt to provide a compendium of the procedures that are being used by different agencies for the repair, rehabilitation, or retrofit upgrade of these structures.

REFERENCES

1. *Engineering News-Record*, McGraw-Hill Inc., New York, New York, January 27, 1983.

2. *National Bridge Inspection Standards, Code of Federal Regulations, Title 23-Part 650.* (enacted in about 1969).

3. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, Report No. FHWA-ED-89-044 (OMB No. 215-0501), Federal Highway Administration, Office of Engineering, Bridge Division, Washington, D.C., December 1988.

4. *Bridge Inspector's Training Manual 70*, USDOT, Federal Highway Administration, Washington, DC, 1979. (Updated manual, "Manual 90", will be printed in 1992.

5. *AASHTO Model Drainage Manual*, American Association of State Highway and Transportation Officials, Washington, D. C., 1991.

CHAPTER 2. PRINCIPLES OF CULVERT STRUCTURES

SCOPE

This chapter presents a summary of general information on the principles of culverts. The purpose is to provide key background information for personnel responsible for the repair of culverts. It is important for maintenance personnel to understand these principles because it assists in recognizing the basic causes of problems. Also, it aids in the process of evaluating what to do about the problems as well as designing and constructing the repair.

GENERAL

A wide variety of culvert structures are currently in use as stream crossings, underpasses, and other highway and railroad applications. Although modern culverts are made primarily from reinforced concrete, corrugated metal, and, more recently, solid-wall, profile-wall, and reinforced plastic, some culverts constructed with stone masonry, terra cotta, or timber still exist. The emphasis of this chapter and the manual is on modern culvert construction.

Engineering Considerations

The primary purpose of culverts in the highway system is to carry surface, stream, and river water under highway pavements. In order to design a highway culvert, an analysis of the site is performed to determine hydraulic, structural and durability requirements. Consideration is given to requirements and potential problems associated with construction, maintenance, traffic safety and environmental aspects. The selection of the type, shape, and length of culverts and their appurtenances will depend upon many factors including the following types of analysis.

Hydrology - Hydrology is the science that deals with the occurrence and distribution of waters on the earth. In culvert design, it is the process of determining how much flow the culvert should be designed to carry.

a. Hydrologic cycle - This is the name given to the cycle of water in the atmosphere falling to the ground, running off to rivers, lakes, and the ocean and then evaporating back to the atmosphere.

b. Peak flow - Peak flow refers to the maximum amount of water that will arrive at, and flow past, a particular point of land. The peak flow is a major factor in the culvert design process. This value will depend upon many topographic, geological, and environmental factors, including those listed below. For design purposes, peak flow is generally determined on the basis of the maximum storm that may be encountered in some period of time, for example 25, 50, or 100 years. Additional design information is available from AASHTO.[1,2] State drainage manuals generally prescribe the design flood recurrence interval for various culvert applications.

Together, the factors listed below influence the amount of runoff and the amount of time required for water to flow to the point of concern from the most remote part of the drainage area.

- The size, shape, and slope of the drainage area, as illustrated in figure 2.1.

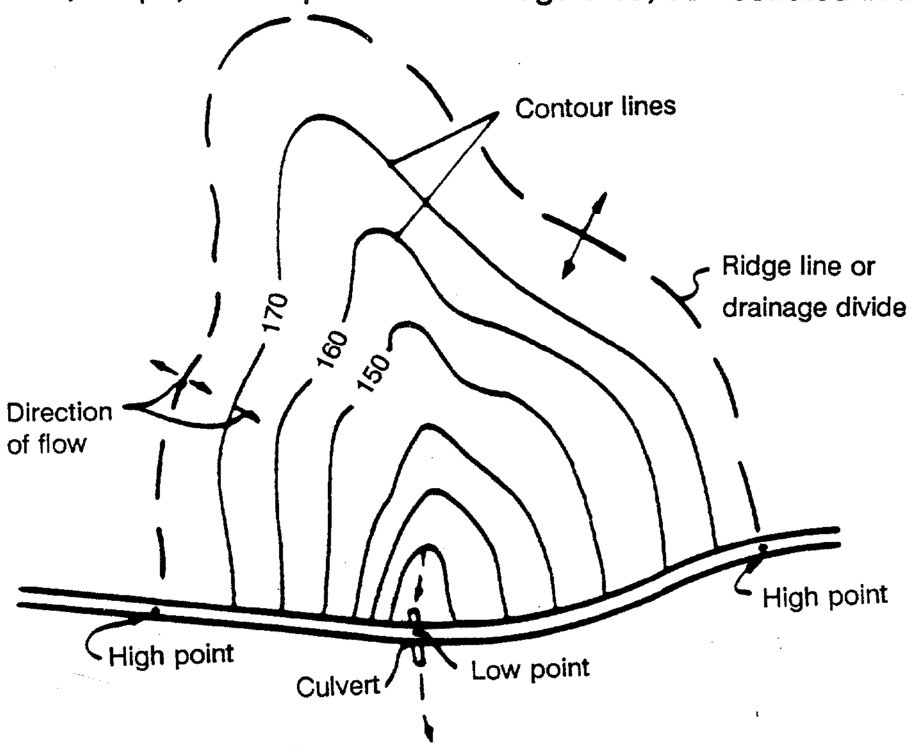


Figure 2.1. Drainage area served by a culvert. [3]

- The rainfall intensity, storm duration, and rainfall distribution within the drainage area;
- Type of land use (open ground, paved, wooded, etc.);
- The type of soil and its degree of saturation or imperviousness;
- Type of precipitation (snow, snow melt, rain) and ambient temperature; and
- Existing flow if a stream is present.

Hydraulics - Design of the culvert, including selection of the shape, size, and length of the culvert, is a complicated process that involves consideration and analysis of many factors that influence how much water may be carried through the culvert. Although inspectors and maintenance personnel should be aware of the various factors, these analyses should be undertaken by an experienced hydraulics engineer.

The factors that affect capacity of a culvert include: headwater depth, tailwater depth, inlet geometry, the slope of the culvert barrel, and the roughness of the culvert barrel. These factors are illustrated in figure 2.2. The various combinations of the factors affecting flow can be grouped into two types of conditions in culverts: inlet control and outlet control.

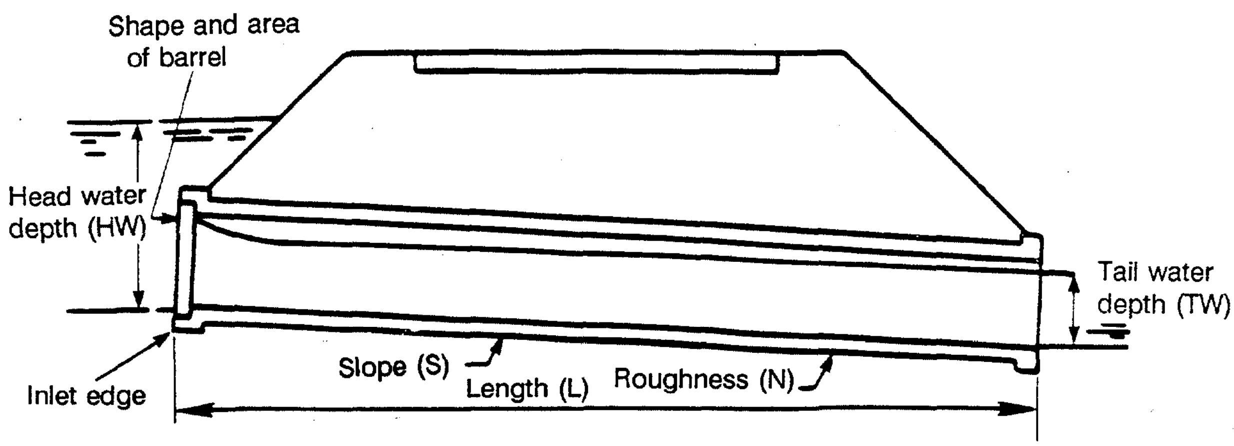


Figure 2.2. Factors affecting culvert discharge.[4]

a. Inlet control - Under inlet control, the capacity of the culvert is controlled at the entrance of the culvert by headwater depth, cross-sectional area, barrel shape, and the configuration of the inlet edge. Inlet control governs the capacity as long as water can flow out of the culvert faster than it can enter the culvert. Typical culvert sections under inlet control are shown in figure 2.3.

Most culverts, except those in flat terrain, are designed to operate under inlet control during peak flows. Since the entrance characteristics govern, minor modifications at the culvert inlet can significantly affect hydraulic capacity. For example, change in the approach alignment of the stream may reduce capacity, while improvement in the inlet edge configuration, or addition of properly designed headwalls and wingwalls may increase the capacity.

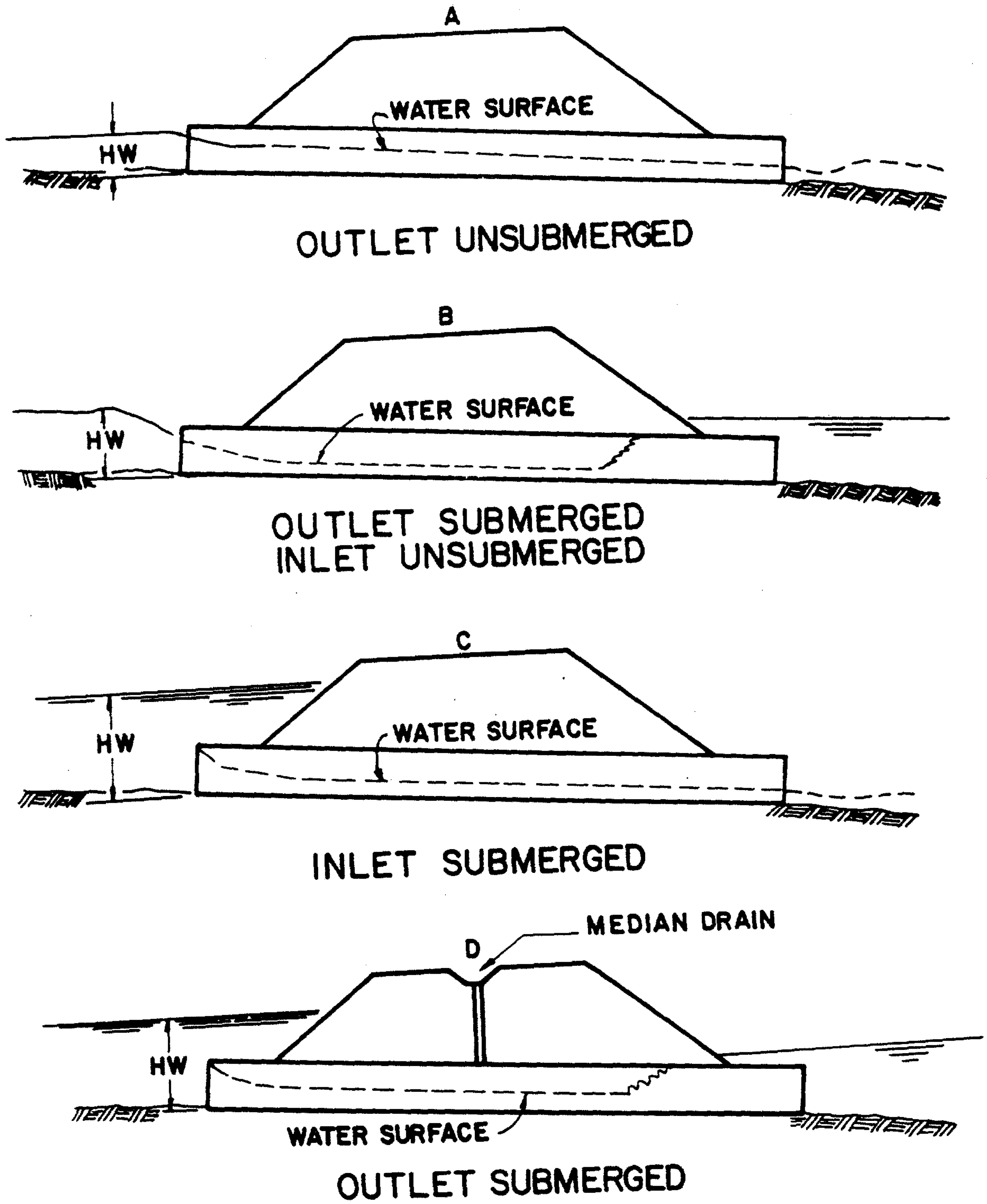


Figure 2.3. Typical culvert section under inlet control.[11]

For inlet control designs, the culvert designer must balance the design peak flow to the culvert location against the allowable depth and spread of backwater. Consideration must also be given to possible changes in land use, which will also influence runoff rates.

b. Outlet control - Under outlet control, water can enter the culvert faster than it can flow through the culvert. The discharge is influenced by the same factors as inlet control plus the tailwater depth and barrel characteristics (slope, length, and roughness). Culverts operating with outlet control usually lie on flat slopes or have high tailwater. When culverts are operating under outlet control, changes in barrel characteristics or tailwater depth may affect capacity. Examples of culverts operating under outlet control are shown in figure 2.4.

c. Special hydraulic conditions - The inlet and outlet of culverts may require protection to withstand the hydraulic forces exerted during peak flows. Inlet ends of flexible pipe culverts that are not adequately protected or anchored may be subject to entrance failures due to buoyant forces. The outlet may require energy dissipators to control erosion and scour and to protect downstream properties. High outlet velocities may cause scour and undermining of the endwall, wingwalls, and the culvert barrel. This erosion can cause end-section drop-off in rigid sectional pipe culverts.

Seeping along the outside of the culvert barrel may remove supporting material. This problem is referred to as "piping" since it creates a hollow void, similar to a pipe. Although piping frequently starts by scour at the inlet end, around or under the entrance features, it may occur because of scour of the embankment above the culvert. Piping can also occur because of water seepage through open joints. Control of piping may require the use of watertight joints and anti-seep collars.

Structural - Structural design of a culvert must be done to ensure that the culvert is strong enough to resist the loads that will be imposed upon it. The strength of a culvert depends on the strength of the materials that are used and the shape of the culvert barrel. For example, a circular shape carries and resists loads differently than a box shape.

a. Loads -In addition to fulfilling their hydraulic functions, culverts must also support the weight of the embankment or fill covering the culvert and loads on the roadway. There are two general types of loads that must be carried by culverts: dead loads and live loads. The amount of both dead and live load that is actually exerted on a culvert depends upon whether it is a rigid or flexible material, the type of material surrounding the culvert, the degree of compaction of the material, and whether special types of structural members are built around the culvert to resist and distribute soil pressures.

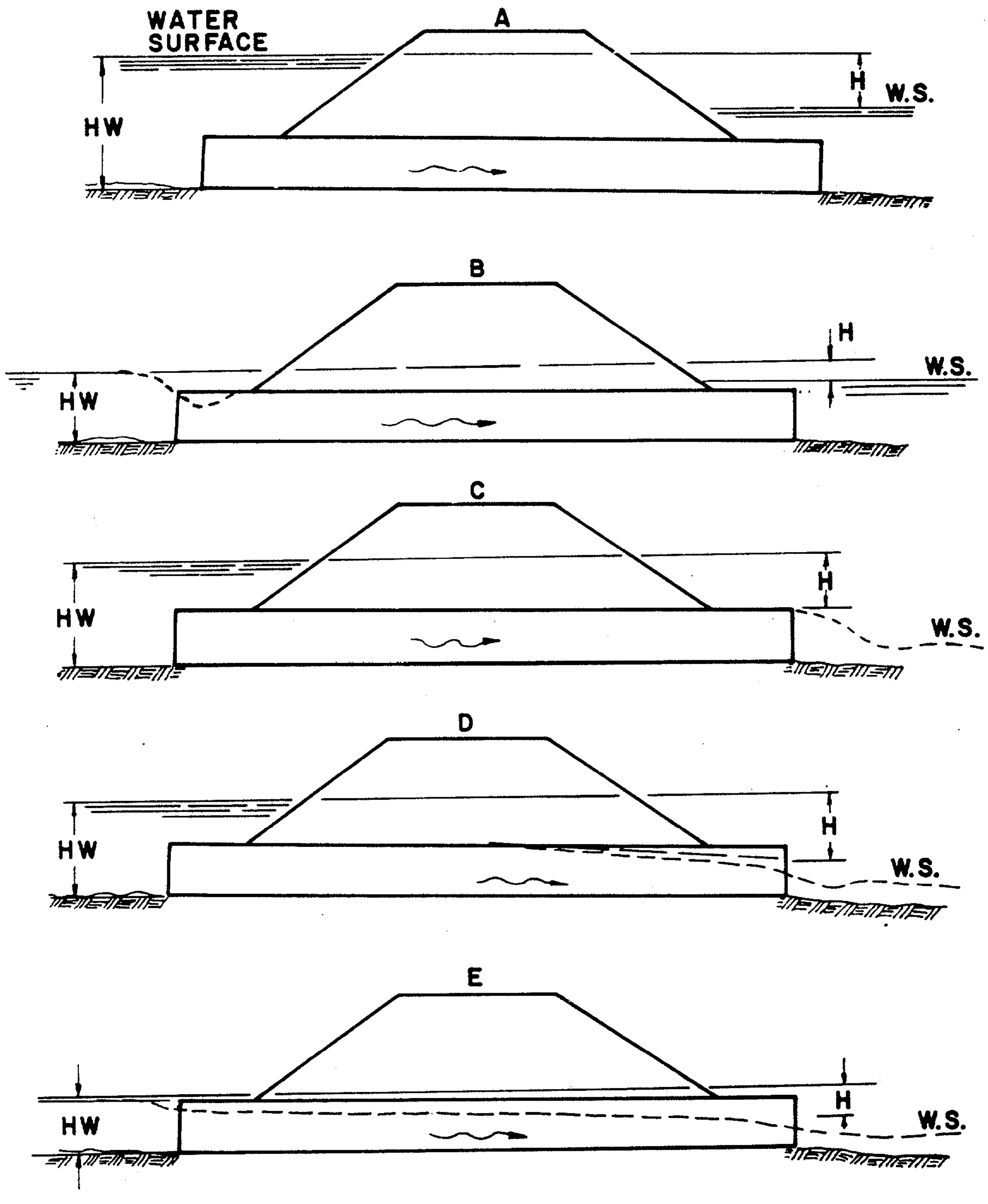


Figure 2.4. Typical culvert section under outlet control.[11]

Dead loads on a culvert include the earth load or weight of the soil over the culvert and any added surcharge loads such as buildings or additional earth fill placed over or adjacent to the culvert alignment. If the actual weight of earth is not known, 120 pounds per cubic foot is generally assumed.

The live loads on a culvert include the loads and forces that act upon the culvert due to vehicular or pedestrian traffic plus an impact factor. The highway wheel loads generally used for analysis are shown in figure 2.5. Actual loads for specific cases are assigned by the designer. The effect of live loads decreases as the height

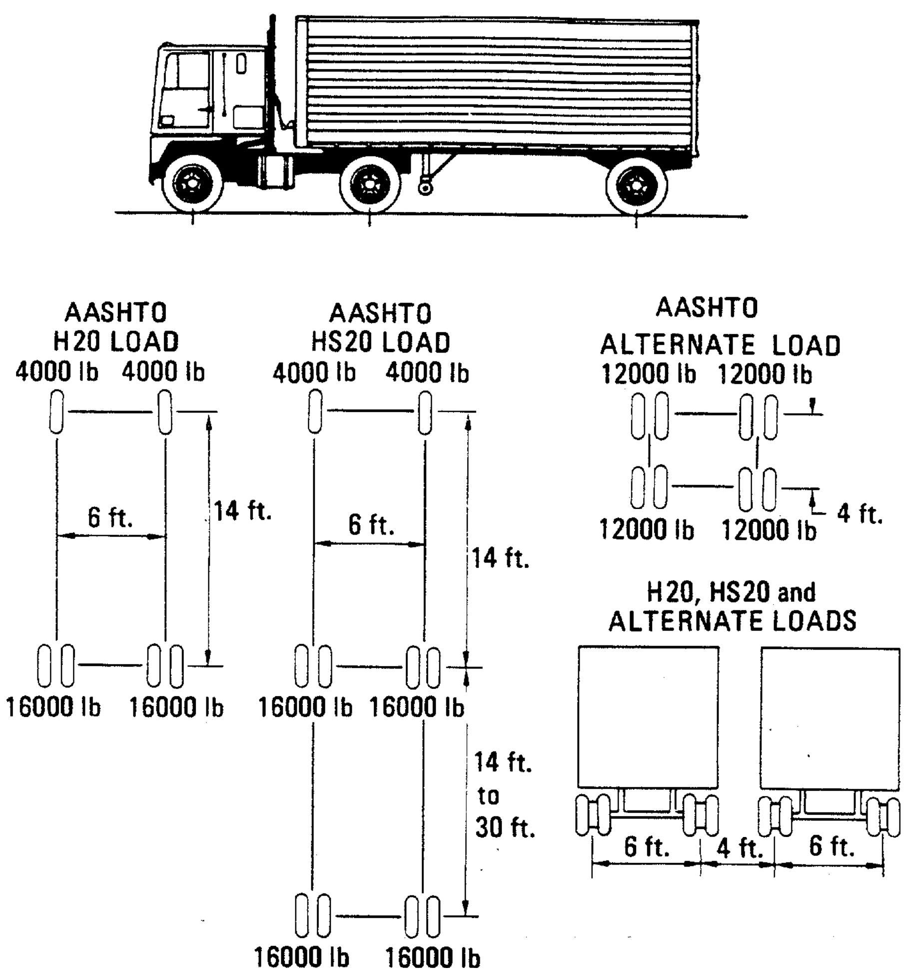


Figure 2.5. AASHTO live load spacing for highway structures.[4]

of cover over the culvert increases. When the cover is more than two feet, concentrated loads may be considered as being spread uniformly over a square with sides 1.75 times the depth of cover. This concept is illustrated in figures 2.6 and 2.7.

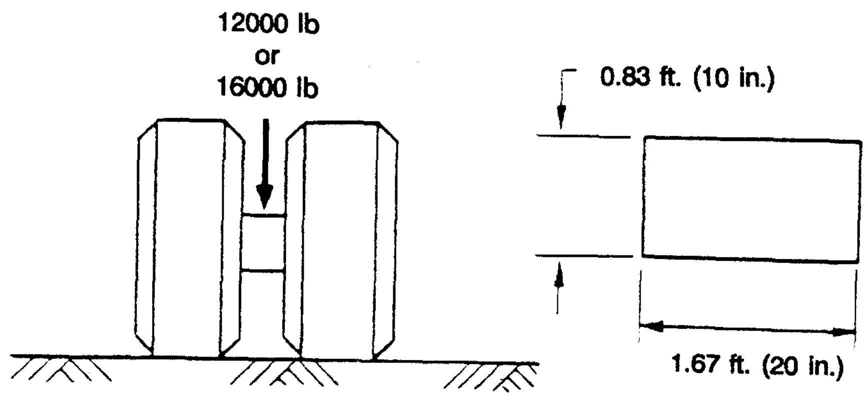


Figure 2.6. Surface contact area for single dual wheel.[2]

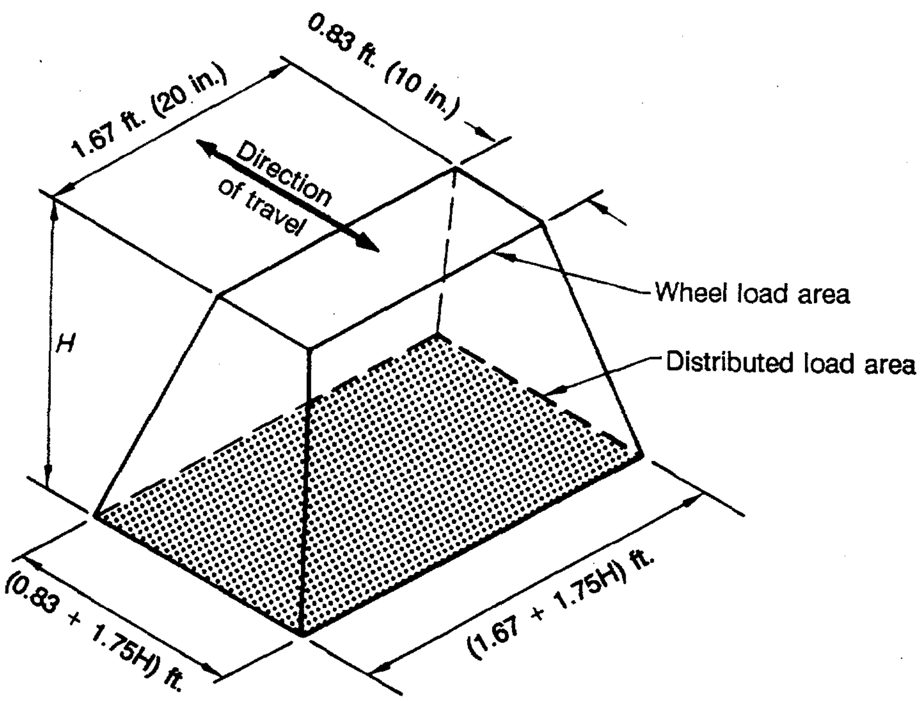
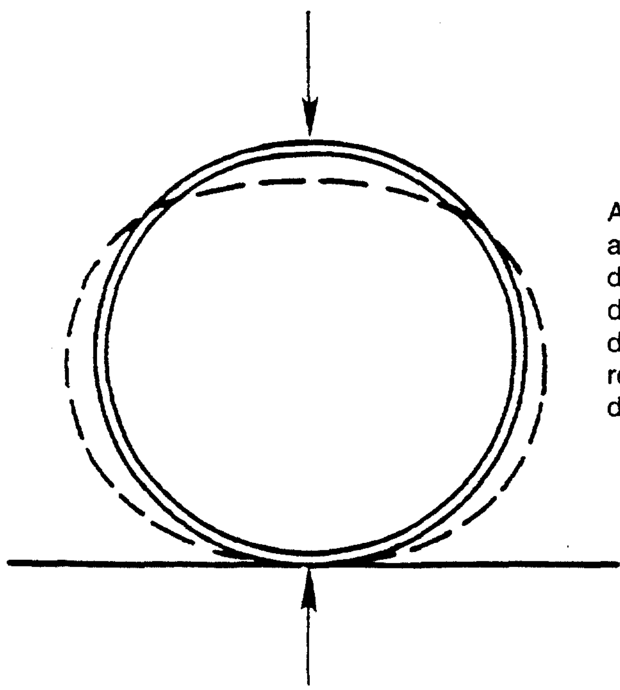


Figure 2.7. Distribution of live load (single dual wheel) for depth of cover H.[4]

b. Flexible culvert behavior - A flexible culvert is a composite structure made up of the culvert barrel and the surrounding soil. The barrel and the soil are both vital elements to the structural performance of the culvert.

Flexible pipe has relatively little bending stiffness or bending strength on its own. As loads are applied to the culvert, it attempts to deflect. In the case of a round pipe, the vertical diameter decreases and the horizontal diameter increases, as shown in figure 2.8.

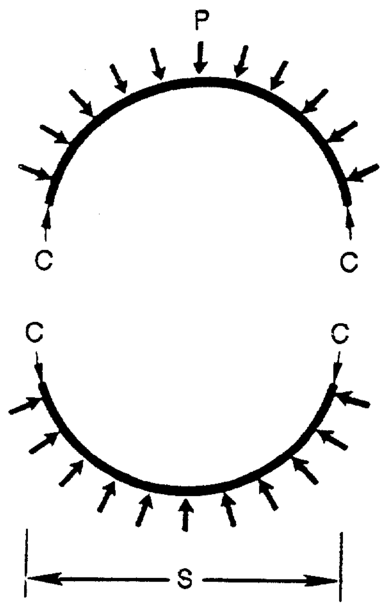


As vertical loads are applied a flexible culvert attempts to deflect. The vertical diameter decreases while the horizontal diameter increases. Soil pressures resist the increase in horizontal diameter.

Figure 2.8. Deflection of flexible culverts.[3]

When good embankment material is well compacted around the culvert, the increase in horizontal diameter of the culvert is resisted by the lateral soil pressure. With round pipe, the result is a relatively uniform radial pressure around the pipe that creates a compressive thrust in the pipe walls. As illustrated in figure 2.9, the compressive thrust is approximately equal to vertical pressure times one-half the span length ($C = P \times S/2$ or $C = P \times R$).

An arc of a flexible round pipe or other shape will be stable as long as adequate soil pressures are achieved, and as long as the soil pressure is resisted by



Summing the vertical forces on half of the pipe at a time shows that

$$C = P \times S/2$$

where

C = Compressive thrust in the culvert wall.

P = Sum of soil pressure acting on the culvert.

S = The span or diameter.

S/2 = The radius (R).

Figure 2.9. Formula for ring compression.[(3)]

the compressive force C on each end of the arc. Good quality backfill material and proper installation are critical in obtaining a stable soil envelope around a flexible culvert.

In long span culverts the radius (R) is usually large. To prevent excessive deflection due to dead and/or live loads, longitudinal or circumferential stiffeners are sometimes added. The circumferential stiffeners are usually metal ribs bolted to the outside of the culvert. Longitudinal stiffeners may be metal or reinforced concrete, as shown in figure 2.10. The thrust beams are added to the structure prior to backfill. The use of concrete stress-relieving slabs is another method used to achieve longer spans or reduce minimum cover. A stress-relieving slab is cast over the top of the backfill above the structure to distribute live loads to the adjacent soil.

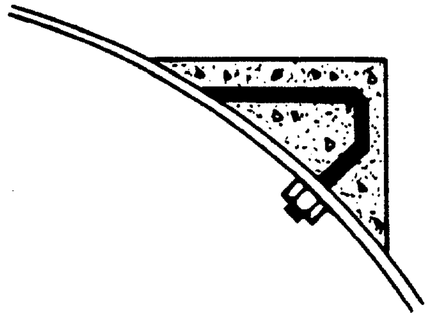


Figure 2.10. Concrete thrust beam used as a longitudinal stiffener.[3]

c. Rigid culvert behavior - The load carrying capacity of rigid culverts is essentially provided by the structural strength of the pipe itself and little benefit from the surrounding earth is required. When vertical loads are applied to a rigid pipe, zones of tension and compression are created as illustrated in figure 2.11. With the exception of non-reinforced circular pipe, reinforcing steel is added to the tension zones to increase the tensile strength of concrete pipe. Shear stress in the haunch area can be critical for heavily loaded rigid pipe on hard foundations, especially if the haunch support is inadequate. Because rigid pipe is stiffer than the surrounding soil, it carries a substantial portion of the load.

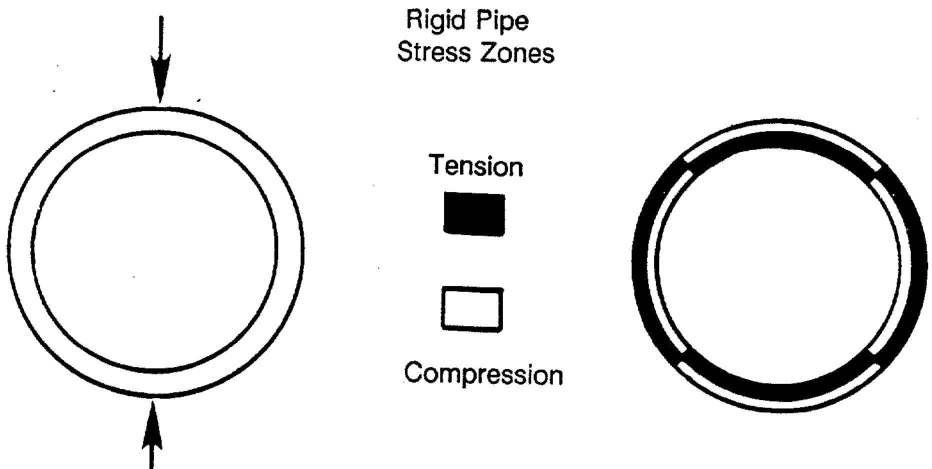


Figure 2.11. Zones of tension and compression in rigid pipes.[4]

The weight of earth that must be carried varies with soil characteristics and installation conditions. The installation conditions can have a significant influence on the loads that must be carried by a rigid culvert. There are two major classes of installation conditions: 1) trench, where culverts are placed in natural ground or compacted fill with a controlled trench width and 2) embankment, where culverts are placed in or covered by an embankment.

In narrow trench installations, the pipe is placed in a relatively narrow trench and covered with backfill material. The backfill tends to settle more than the undisturbed soil beside the trench. Friction between the backfill material and the sides of the trench tends to help support the backfill material, reducing the load on the pipe. In effect the width of the soil column over the pipe is decreased. This concept is illustrated in figure 2.12.

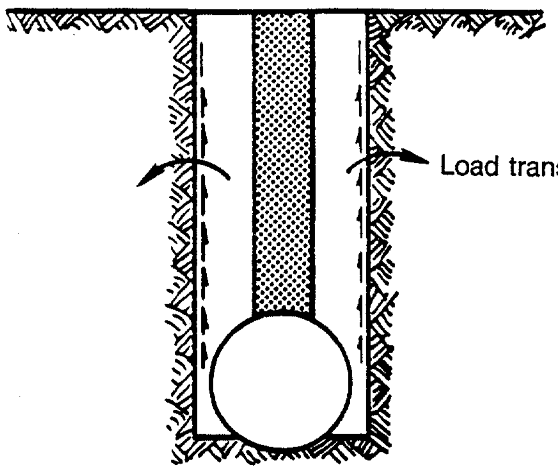


Figure 2.12. Trench installation. Friction on trench sides reduces the size of the column of fill carried by the pipe.[3]

As the trench width increases, the effect of the friction at the sides of the trench is reduced and dead load on the pipe is increased. The amount that the loading is increased depends on trench width and the amount of backfill settlement, which is related to compaction. Poorly compacted soil will settle more than well compacted soil. In a trench that is too wide, poor compaction can result in an increase in the dead load on the pipe. Pipes placed in a shallow bedding on top of the original ground surface and then covered by the embankment material will have loads similar to the very wide trench. Pipes placed in trenches in the original ground prior to being covered by embankment have reduced earth loads similar to those described for the narrow trench.

Durability - Although structural condition is a very important element in the performance of culverts, durability problems are probably the most frequent cause of replacement. Culverts are more likely to "wear away" than fail structurally. Durability is affected by two mechanisms: corrosion and abrasion. Each are discussed in the following sections:

a. Corrosion - Corrosion is the deterioration of metals due to chemical or electrochemical reaction to the environment. Corrosion of culvert materials may occur in many different soils and waters. These soils and waters may contain acids, alkalis, dissolved salts, organics, industrial wastes or chemicals, mine drainage, sanitary effluents, and dissolved or free gases. However, culvert corrosion is generally related to water and the chemicals that have reacted to, become dissolved in, or been transported by the water.

Certain soil and water conditions have been found to be particularly aggressive or hostile to culverts. Extremes in acidity or alkalinity are much more aggressive than more neutral conditions. The term pH is a measure of the relative acidity or alkalinity: 7.0 is neutral, values less than 7.0 are acid, and values greater than 7.0 are alkaline. For culvert purposes, values of less than 5.0 are strongly acid and those greater than 8.5 are strongly alkaline. Acid water stems from two sources: mineral and organic. Mineral acidity comes from sulfurous wells and springs and drainage from coal mines, with the water containing dissolved sulfur and iron sulfide that may form sulfurous and sulfuric acids. Mineral acidity with a pH as strong as 2.3 has been encountered. Organic acidity, which may be found in swampy land and barnyards, may have a pH as low as 4.0. Alkalinity in water is caused by strong minerals and limed and fertilized fields. Acid water is more common to wet climates and alkaline water is more common to dry climates.

The electrical resistivity of soil, which depends largely on the nature and amounts of dissolved salts, also influences the potential for corrosion. The greater the resistance the less the flow of electrical current associated with corrosion. High moisture content and temperature lower the resistivity and increase the potential for corrosion. The use of granular backfill around the entire pipe will increase electrical resistivity and reduce the potential for galvanic corrosion.

Corrosion can attack the inside or outside of the culvert barrel. The chemicals in drainage water can attack the material on the interior of the culvert. Culverts subject to continuous flows or standing water with aggressive chemicals are more likely to be damaged than those with intermittent flows. The exterior of culverts can be attacked by chemicals in the ground water that can originate in the soil, be introduced through contaminates in the backfill soil, or be transported by subsurface flow.

Corrosion affects all metals and alloys, although the rates can vary widely depending both upon the chemical and physical properties of the metal and upon the environmental condition to which it is exposed. When a metal corrodes, a very low voltage electrical current is established between two parts of a metal surface that have different voltage potential. The difference in voltage potential may be caused by slight variations in the material, changes in surface condition, or the presence of foreign materials. The current removes metallic ions from one location and deposits them at another location, causing corrosion, as shown in figure 2.13. The chemicals present in the water greatly influence its effectiveness as an electrolyte.

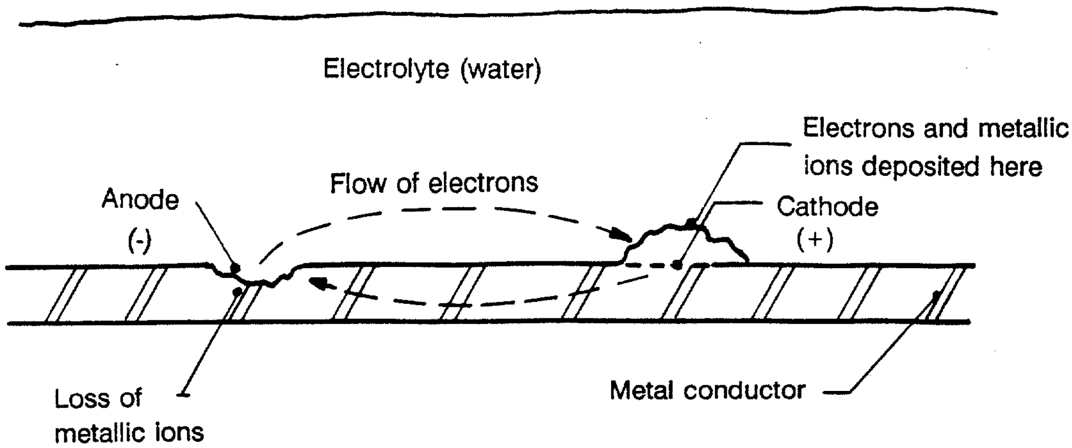


Figure 2.13. The corrosion process.

Although less common than with metal pipe, corrosion can occur in concrete culverts. Metallic corrosion can take place in the reinforcing steel when it is exposed by cracking or spalling, when the concrete cover is inadequate, or when the concrete is porous enough to allow water to contact the reinforcing steel.

If steel corrodes, the corrosion products expand and may cause spalling of the concrete. Corrosion can also take place in the concrete itself. It is not, however, the same type of electrochemical reaction that occurs in metal. Other reactions between the concrete materials and the chemicals present in the stream flow or ground water are involved and can result in deterioration of the concrete.

b. Abrasion - Abrasion is the process of wearing down or grinding away the surface material of culverts as water laden with sand, gravel, or stones flows through a culvert, as illustrated in figure 2.14. Abrasion forces increase as the velocity of the water flowing through a culvert increases; for example, doubling the velocity of a stream flow can cause the abrasive power to become approximately four-fold.

Often corrosion and abrasion operate together to produce far greater deterioration than would result from either alone. Abrasion can accelerate corrosion by removing protective coatings and allowing water-borne chemicals to come into contact with corrodible culvert materials.

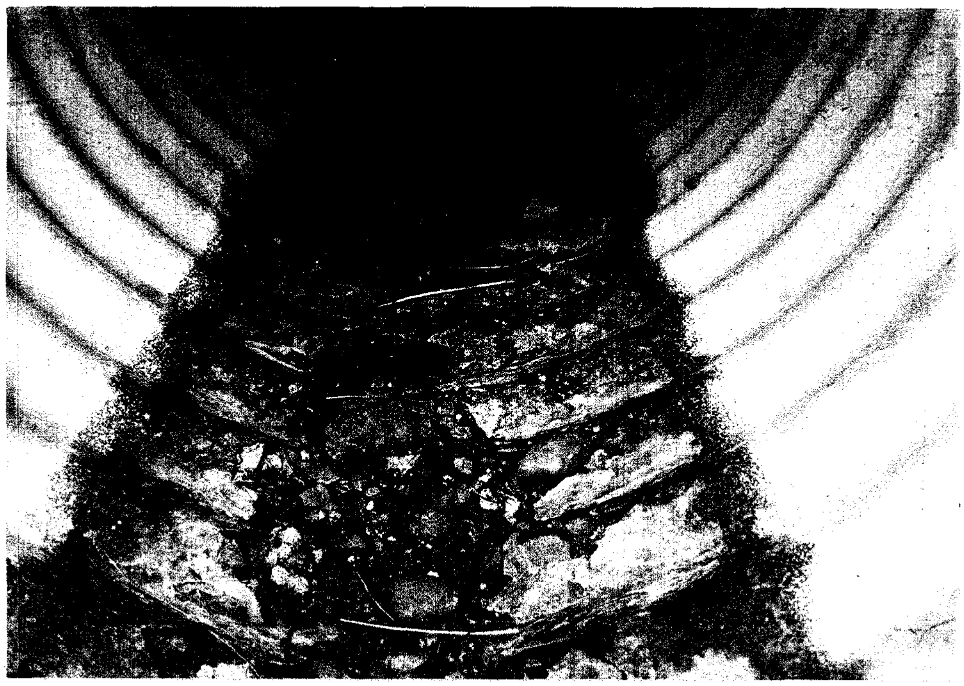


Figure 2.14. Corrugated steel culvert with invert perforation.

Economic Considerations

For the design of new culverts and major culvert repairs, an economic analysis usually includes factors such as construction cost, estimated service life, maintenance cost, replacement cost, risk of failure, and risk of property damage. The most economical culvert is one with the lowest total cost over the design life. It is not necessarily the culvert with the lowest initial cost nor the culvert with the longest service life. Most agencies have policies and/or procedures to guide these analyses. The importance is that short and long term costs should be considered in both original designs and in repairs or replacements.

Since this manual deals primarily with the repair, rehabilitation and retrofit upgrading of existing culverts, it is important to recognize that many additional cost and benefit factors must be considered for such work. The warrants for choosing one procedure over others will depend on many site-specific factors.

Other Factors

In addition to the factors cited above, there are several others of which designers should be cognizant during the design and construction of culverts. The following are three general areas that should be of concern:

Maintenance - Although the subject of maintenance, and the need for it, is discussed in detail in chapter 4, at this point it is appropriate to emphasize the need to consider maintenance needs in the design of culverts. That is, the designs should be such that the need for maintenance and repair work is minimized through the selection of the culvert type and the quality of the materials and construction methods that are used. For example,

- If abrasion problems are anticipated, then the designs should minimize the potential problem by flattening the slopes, providing stilling basins, or providing a tough, abrasion-resistant invert.

- If a problem with sedimentation is expected, it may be possible to steepen slopes or select a culvert shape (such as a box) that is easier to clean out with mechanized equipment.

Safety - Personnel safety should always be of concern during the construction, inspection, maintenance, repair, and rehabilitation of culverts. To the maximum extent possible the designer should highlight potentially hazardous periods of construction for certain types of structures. Inspection, maintenance, and repair personnel should be aware of the possibilities of poor air quality, toxic chemical, animals, and the potential for collapse of unstable structures. The subject of retrofitting culverts to reduce or minimize the dangers for errant vehicles is discussed in more detail in chapter 5.

Geotechnical - During design, particularly for larger culverts (over three to four foot span), the foundation conditions should be investigated to determine such factors as allowable bearing pressure, bedding requirements, and any condition requiring special treatments. In addition, determinations should be made concerning any unusual construction conditions such as groundwater, slope stability, and rock excavation. These factors apply to the end treatments, approaches, and barrel elements. The type, strength, slope, and bedding of soils and rocks all influence the design, construction and maintenance/repair operations.

Environmental - Water quality, the potential for hazardous or toxic materials, wetlands vegetation, and wildlife are other factors for which the highway agency must consider the applicable laws. Again, this applies to design, construction and maintenance/repair. Specific measures for erosion and sediment control, fish and animal passage, and preservation of vegetation are normally required in all types of operation.

Maintenance and Control of Traffic - Designers and maintenance personnel must consider if and how road traffic is to be maintained. This can be a very expensive item of construction and maintenance and must be carefully planned. The amount and type of traffic may require detours and requires safety provisions such as signs and/or barriers. The type and extent of repair work will dictate the measures required.

Adjacent Facilities - Particularly in urban and other developed areas the agency must consider preservation of existing facilities such as buildings, utilities, and site improvements. Measures such as underpinning structures, temporary relocation of utilities and restoration of sidewalks, and landscaping may be required.

CULVERT SHAPES

A wide variety of standard shapes and sizes are available for most culvert materials. Since equivalent openings can be provided by a number of standard shapes, the selection of shape may not be critical in terms of hydraulic performance. Shape selection is often governed by factors such as depth of cover or limited headwater elevation. In such cases a low profile shape may be needed. Other factors such as the potential for clogging by debris, the need for a natural stream bottom, or structural and hydraulic requirements may influence the selection of culvert shape. Each of the common culvert shapes are discussed in the following paragraphs. More details are included in the section on materials.

Circular

The circular shape is the most common shape manufactured for pipe culverts. It is hydraulically and structurally efficient under most conditions. Possible hydraulic drawbacks are that circular pipe generally causes some reduction in stream width during low flows. It may also be more prone to clogging than some other shapes due to the diminishing free surface as the pipe fills beyond the midpoint. With very large diameter corrugated metal pipes, the flexibility of the sidewalls dictates that special care be taken during backfill construction to maintain uniform curvature.

Pipe Arch and Elliptical

Pipe arch and elliptical shapes are often used instead of circular pipe when distance from channel invert to pavement surface is limited or when a wider section is desirable for low flow levels. These shapes may also be prone to clogging as the depth of flow increases and the free surface diminishes. Pipe arch and elliptical shapes are not as structurally efficient as a circular shape. They are normally used in areas with limited vertical clearance and low cover conditions.

Arches

Arch culverts have no culvert barrel material at the bottom and offer less of an obstruction to the waterway than pipe arches and can be used to provide a natural stream bottom where the stream bottom is naturally erosion and abrasion resistant. Foundation conditions must be adequate to support the footings. Riprap is frequently used for scour protection.

Box Sections

Rectangular or square cross-section culverts are easily adaptable to a wide range of site conditions, including sites that require low profile structures. Due to the angular corners, boxes are not as structurally and hydraulically efficient as other culvert shapes.

Multiple Barrels

Multiple barrels are used to obtain adequate hydraulic capacity under low embankments or for wide waterways. In some locations they may be prone to clogging as the area between the barrels tends to catch debris and sediment. When a channel is artificially widened, multiple barrels placed beyond the dominant channel are subject to excessive sedimentation. The span or opening length of multiple barrel culverts includes the distance between barrels as long as that distance is less than half the opening length of the adjacent barrels.

CULVERT MATERIALS

Modern culverts are primarily made with reinforced concrete, corrugated metal, and more recently, solid-wall, profile wall, and reinforced plastic, whereas old culverts may be constructed with stone masonry, terra cotta, or timber. The strength and physical characteristics of the materials depend upon their chemistry and the interrelationship between the constituent materials. Metals are homogeneous isotropic materials whereas concrete and masonry is a mixture or combination of materials. Timber is a fibrous material that has the fibers in a longitudinal direction and significantly different properties in all three directions. The method by which the materials are connected significantly influences whether the strength of the materials may be utilized structurally.

Concrete

Modern culverts may be made with either precast or cast-in-place reinforced concrete. This selection depends primarily upon proximity of a precast concrete plant to the job site and the size and complexity of the culvert design. Precast sections are uniform in size and shape and are made in sections that can easily be transported, lifted, and installed. Cast-in-place concrete construction is often used when ready-mix concrete is available and when the culvert should be constructed without joints. Precast concrete culverts may be made with high strength concrete, whereas cast-in-place concrete culverts may have special reinforcement at critical locations to resist high loads and stresses.

Precast - Precast concrete pipe is manufactured in eight standard shapes: circular, arch, horizontal elliptical, vertical elliptical, pipe arch, box sections, three-sided arch top, and flat top sections, as shown in table 2.1. With the exception of box culverts, concrete culvert pipe is manufactured in up to five standard strength classifications. The higher the classification number the higher the strength. Box culverts are designed for various depths of cover and live loads. All of the standard shapes are manufactured in a wide range of sizes. Circular and elliptical pipes are available with standard sizes as large as 144 inches in diameter, with larger sizes available as special designs. Standard box sections are also available with spans as large as 144 inches. Precast concrete arches on cast-in-place footings are available with spans up to 40 feet. A listing of standard sizes is provided in appendix A.

Cast-in-place - Reinforced culverts that are cast-in-place are typically either rectangular or arch-shaped. The rectangular or box shape is more common and is usually constructed with multiple cells (barrels) to accommodate longer spans. One advantage of cast-in-place construction is that the culvert can be designed to meet the specific requirements of a site. Due to the longer construction time of cast-in-place culverts, precast concrete or corrugated metal culverts are often selected. However, in many areas cast-in-place culverts are more practical and represent a significant number of installations.

Shapes - By the very nature of it, reinforced concrete may be used to make virtually any structural shape desired. Thus, if necessary and feasible, it is possible to make almost any shaped culvert with either precast or cast-in-place reinforced concrete.

Corrugated Steel

Corrugated steel culverts are made with factory-produced corrugated sheet steel. Corrugated pipe culverts are made with factory-produced corrugated pipe sections. Large corrugated culverts are normally field-assembled using structural plate products. Structural plate steel products are available as structural plate pipes, box culverts, or long span structures. Standard shapes for corrugated steel culverts are shown in table 2.2.

Table 2.1. Standard concrete pipe shapes.[2]

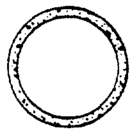
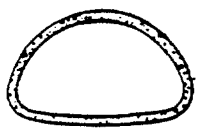
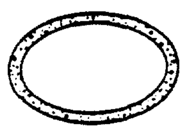
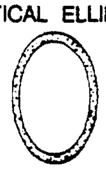
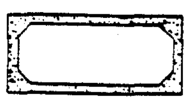
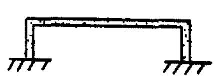
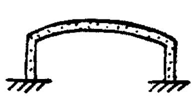
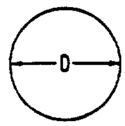
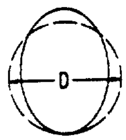
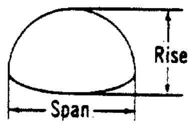
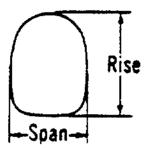
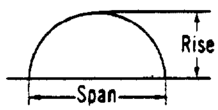
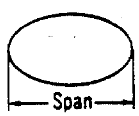
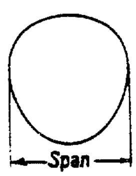
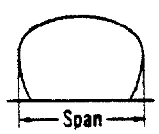
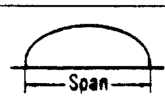
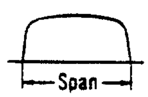
SHAPE	RANGE OF SIZES	COMMON USES
CIRCULAR 	12 to 180 inches reinforced 4 to 36 inches non-reinforced	Culverts, storm drains, and sewers.
PIPE ARCH 	15 to 132 inches equivalent diameter	Culverts, storm drains, and sewers. Used where head is limited.
HORIZONTAL ELLIPSE 	Span x Rise 18 to 144 inches equivalent diameter	Culverts, storm drains, and sewers. Used where head is limited.
VERTICAL ELLIPSE 	Span x Rise 36 to 144 inches equivalent diameter	Used where lateral clearance is limited.
RECTANGULAR (box sections) 	Span 3ft to 12ft	Culverts, storm drains, and sewers. Used for wide openings with limited head.
ARCH 	Span 24ft to 41ft	Culverts and storm drains. For low, Wide waterway enclosures.
FLAT TOP 3-SIDED 	Span 14ft to 35ft	Culverts and storm drains. For low, Wide waterway enclosures.
ARCH TOP 3-SIDED 	Span 16ft to 36ft	Culverts and storm drains. For low, Wide waterway enclosures.

Table 2.2. Standard corrugated steel culvert shapes.[4]

Shape		Range of Sizes	Common Uses
Round		6 in. – 26 ft.	Culverts, subdrains, sewers, service tunnels, etc. All plates same radius. For medium and high fills (or trenches).
Vertically–elongated (ellipse) 5% is common		4 – 21 ft. nominal; before elongating	Culverts, sewers, service tunnels, recovery tunnels. Plates of varying radii; shop fabrication. For appearance and where backfill compaction is only moderate.
Pipe–arch		Span x Rise 17 in. x 13 in. to 20 ft. 7 in. x 13 ft. 2 in.	Where headroom is limited. Has hydraulic advantages at low flows. Corner plate radius. 18 inches or 31 inches for structural plate.
Underpass*		Span x Rise 5 ft. 8 in. x 5 ft. 9 in. to 20 ft. 4 in. x 17 ft. 9 in.	For pedestrians, livestock or vehicles (structural plate).
Arch		Span x Rise 6 ft. x 1 ft. 9 1/2 in. to 25 ft. x 12 ft. 6 in.	For low clearance large waterway opening, and aesthetics (structural plate).
Horizontal Ellipse		Span 7 – 40 ft.	Culverts, grade separations, storm sewers, tunnels.
Pear		Span 25 – 30 ft.	Grade separtaions, culverts, storm sewers, tunnels.
High Profile Arch		Span 20 – 45 ft.	Grade separtaions, culverts, storm sewers, tunnels, ammo ammunition magazines, earth covered storage.
Low Profile Arch		Span 20 – 50 ft.	Low–Wide waterway enclosures, culverts, storm sewers.
Box Culverts		Span 10 – 26 ft.	Low–Wide waterway enclosures, culverts, storm sewers.
Specials		Various	For lining old structures or other special purposes. Special fabrication.

*For equal area or clearance, the round shape is generally more economical and simpler to assemble.

Material - Corrugated steel pipe is fabricated from sheets coated with zinc, aluminum, or an aluminum-zinc alloy. It is reasonably lightweight for shipping and comes in a large range of thicknesses and corrugations to provide the appropriate strength. However, it requires controlled backfill for proper soil support. Other options include various coatings and/or pavings for added protection.

Shapes - Corrugated steel may be used for a wide variety of shapes, sizes, and lengths of culverts. The culverts may be made from prefabricated sections that are factory produced or assembled in the field from specially fabricated plates. The shapes may be made from various thicknesses of plate stock.

a. Pipe - Corrugated steel pipe is factory-made in two basic shapes: round and pipe arch. Both round and arch shapes are available in a wide range of standard sizes. Round pipe is available in standard sizes up to 144 inches in diameter. Standard sizes for pipe arch are available in sizes up to the equivalent of 120-inch diameter round pipe. A listing of sizes available for each corrugation is provided in the appendix A. Both shapes are produced in several wall thicknesses, several corrugation sizes, as shown in figure 2.15, and with annular (circumferential) or helical (spiral) corrugations.

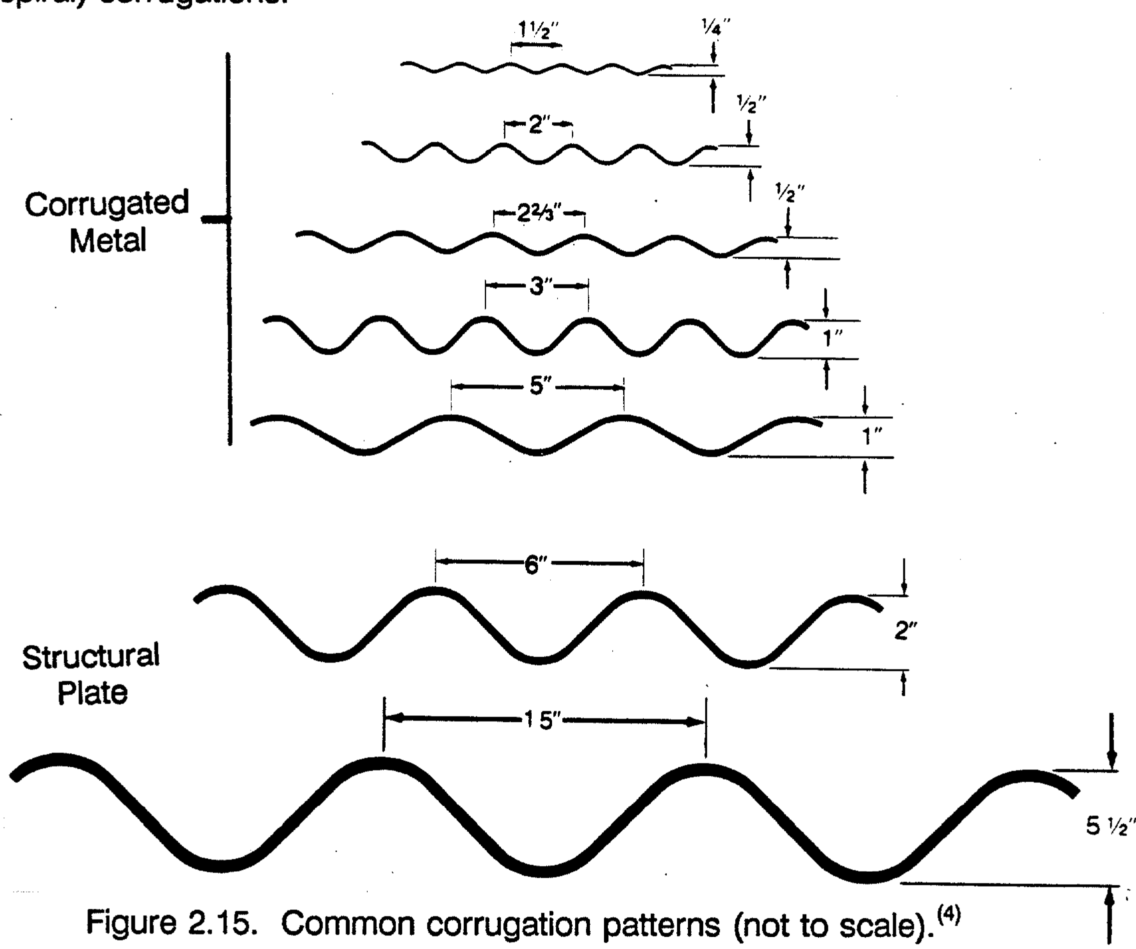


Figure 2.15. Common corrugation patterns (not to scale).(4)

Pipes with annular corrugations have riveted, spot welded, or bolted seams. Pipes with helical corrugations have continuously welded seams or lock seams. Corrugated steel pipe and pipe arch are usually zinc coated (galvanized). Other metallic coatings such as aluminum and aluminum zinc alloy coatings have recently been developed. Additional protective coatings are used with the metallic coating when there are potential corrosion or abrasion problems.

b. Structural plate - Structural plate steel pipes are field-assembled from standard corrugated galvanized steel plates. Standard plates have corrugations with a 6-inch pitch and a depth of 2 inches. Plates are manufactured in a variety of thicknesses and are re-curved for the size and shape of the structure to be erected. Standard plates have a nominal length of either 10 or 12 feet and are produced in standard widths of 3N, 5N, 6N, 7N, and 8N, where N equals 3 pi or 9.6 inches. Widths are measured along the circumference of the structure. Since the circumference of a circle equals pi times the diameter, the use of dimensions expressed in N or pi permits easy conversion from pipe circumference to nominal diameter. For example a 60-inch diameter round pipe has a circumference of 60 pi or 20N and would normally be assembled from four 5N plates. Structural plate pipes are available in four basic shapes: round, pipe arch, arch, and underpass. The standard sizes available range in span from 5 feet to 26 feet. Tables showing typical sizes and dimensions are provided in appendix A.

c. Box - Steel box sections use standard 6 by 2 inch corrugated galvanized steel plates with special reinforcing elements applied to the areas of maximum moment or 15 by 15 1/2 inch corrugated plate without ribs. Steel box culverts are available with spans that range from 9 feet 8 inches to 20 feet 9 inches. Typical sizes and dimensions are listed in appendix A.

d. Long Span - Long span steel structures are assembled using conventional 6 by 2 inch corrugated galvanized steel plates with longitudinal or circumferential stiffening members or 15 by 15 1/2 inch corrugated plate without ribs. There are five standard shapes for long span structures: horizontal elliptical, pipe arch, low profile arch, high profile arch, and pear shape. The long span pipe arch is not commonly used. The span lengths of typical sections range from 19 feet 4 inches to 40 feet. Tables illustrating sizes and dimensions of typical sections are provided in appendix A. Longer spans are available for some shapes as special designs.

Corrugated Aluminum

Corrugated aluminum culverts are constructed from factory assembled corrugated aluminum pipe or field assembled from structural plates. Structural plate aluminum culverts are available as conventional structural plate structures, box culverts, or long span structures.

Material - Corrugated aluminum pipe is fabricated from aluminum-alloy sheets. It is very lightweight for shipping and handling. It has good resistance to corrosion, especially in brackish waters but is subject to abrasion in fast-flowing streams with a significant load of sand or rock. It is generally more flexible than steel, requires greater care in installation, and is less tolerant of less-than-normal cover.

Shapes - Corrugated aluminum may be used for a wide variety of shapes, sizes, and lengths of culverts. The culverts may be made from prefabricated sections that are factory produced or assembled in the field from specially fabricated plates. The shapes may be made from various thickness of plate stock.

a. Pipe - Factory assembled aluminum pipe is available in two basic shapes: round and pipe arch. Both shapes are produced with several different wall thicknesses, several corrugation patterns, and with annular (circumferential) or helical (spiral) corrugations. Round aluminum pipe is available in standard sizes up to 120 inches in nominal diameter. Aluminum arch pipe is available in sizes up to the equivalent of a 96-inch diameter round pipe.

b. Structural plate - Structural plate aluminum pipes are field assembled with 9-inch-pitch by 2.5-inch-depth corrugations. Plates are manufactured in a variety of plate thicknesses and are pre-curved for the specific size and shape of the structure to be erected. Plates are manufactured in lengths of 8N through 18N, where N equals 3 pi or 9.6 inches. Plate length is measured along the circumference of the structure. Standard plates have a net width of 4 feet 6 inches. Structural plate aluminum pipes are produced in five basic shapes: round, pipe arch, arch, pedestrian/animal underpass, and vehicle underpass. A wide range of standard sizes are available for each shape. Spans as large as 30 feet can be obtained for the arch shape. More detailed listing of available sizes and key dimensions are provided in the appendix A.

c. Box - The aluminum box culvert utilizes standard aluminum structural plates with aluminum rib reinforcing added in the areas of maximum moments. Ribs are bolted to the exterior of the aluminum shell during installation. Aluminum box culverts are suitable for shallow depths of fill and are available with spans ranging from 8 feet 9 inches to 25 feet 5 inches. Standard sizes and geometric dimensions are provided in appendix A.

d. Long Span - Long span aluminum structures are assembled using conventional 9- by 2.5-inch corrugated aluminum plates and aluminum rib stiffeners. Long span aluminum structures are available in the same five basic shapes as steel long spans: including horizontal ellipse, pipe arch, low profile arch, high profile arch, and pear shape. The typical sizes for aluminum spans are essentially the same as the typical sizes available for steel long span structures. Spans range from 19 feet 4 inches to 40 feet. Listings of typical sizes and dimensions for each shape are provided in appendix A.

Plastic

"Plastic" pipe is as unspecified a term as is "metal" pipe. There are many types of materials that may be used to produce plastic pipe, and the resulting pipe will have strength and other properties that vary accordingly. The properties of the plastic will depend primarily on the type of base resin that is used as well as the blend (or formulation) of chemicals in the final resin material that is used to produce the pipe. Just as with the design of concrete mixes, it is a common practice to use special additives with the basic resin to facilitate the production process and/or to alter the resulting physical and chemical properties of the finished product.

In general, plastics may be divided into two basic groups: (1) thermoplastics and (2) thermosetting plastics. The primary difference between these classes of material is that thermoplastics may be remelted and reshaped whereas thermosetting plastic cannot be remelted. Thus, the strength and other properties of thermoplastics will depend on the ambient temperature, and thermosetting plastics will retain their strength properties under a wide range of temperatures. The strength of these plastics will depend more on the types of resins that are used than on whether they are thermoplastics or thermosetting plastics.

Although both types of plastic may be used for culvert and drainage products, they are usually constructed from thermoplastic-type materials, which are less expensive and more easily used to manufacture. Two of the most popular types of material that are used are polyvinyl chloride (PVC) and polyethylene (PE). Thermosetting type resins are commonly used for pipe that must handle fluids at high temperatures.

Plastic drainage products may also be classified according to whether they are made just of plastic or whether the plastic is reinforced with fibers, typically glass fibers. The latter may be called "fiberglass" pipe. Since glass fibers have a filament strength of over 300,000 psi, pipe products that are made with long continuous glass fibers will have greater strength properties over unreinforced plastic pipe.

Polyvinyl Chloride (PVC) - Polyvinyl Chloride (PVC) piping is made only from compounds that do not contain plasticizers and minimal quantities of other ingredients. It has been labeled as rigid PVC in the United States to distinguish it from flexible or plasticized PVCs from which such items as laboratory tubing, luggage, and upholstery are made. This pipe exhibits good long-term strength with high stiffness. It is for this reason that PVC has become an important material for both pressure and non-pressure pipe applications. There is a much broader range of PVC fittings, valves, and appurtenances available than in any other plastic. The pipe is manufactured in both solid wall and profile wall in sizes up to 48 inches.

Polyethylene (PE) - Polyethylene (PE) is perhaps the most well known of the plastics in the polyolefin group. These are plastics that are formed by the polymerization of straight chain hydrocarbons that are known as olefins. They include ethylene, propylene, and butylene. PE piping is tough and flexible, even at subfreezing temperatures. PE pipe has good abrasion resistance and is available in solid wall and profile wall with diameters up to 96 inches. It is often used to slipline deteriorating pipes.

Fiberglass - Fiber reinforced plastic (FRP) composite pipe products may be made with a wide range of combinations of resins, glass fibers, and fillers. This class of pipe products is made by (1) filament winding continuous glass fibers and a thermoplastic polyester resin around a cylindrical steel mandrel or by (2) centrifugally casting a mixture of resin, sand, and chopped glass givers against the inside of a rotating steel mold. Figure 2.16 shows the makeup of a filament-wound pipe, that in this case, uses a woven mat type of long continuous glass fibers.

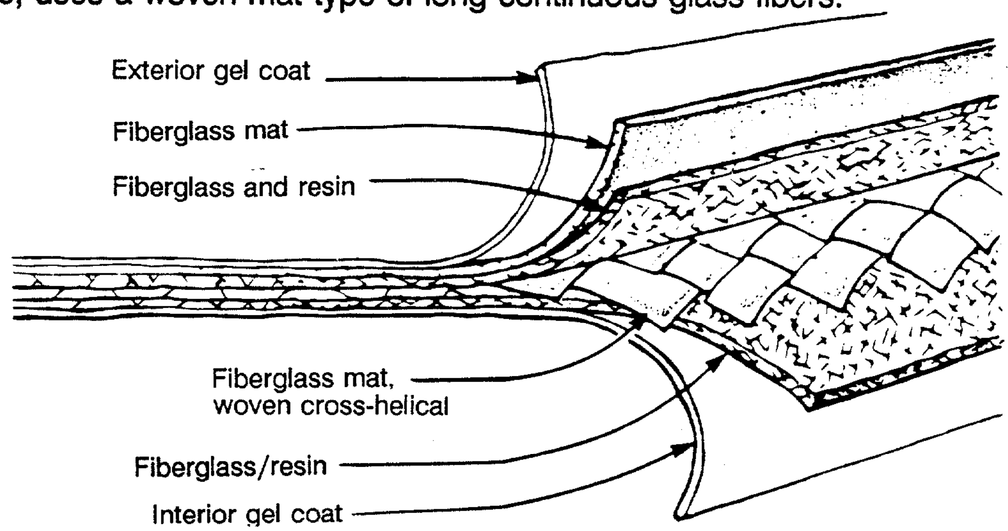


Figure 2.16. Fiberglass-reinforced pipe.[8]

Both types of fiberglass pipe are considered to be premium products that have much greater strength than unreinforced plastic pipe. Although such pipe may be made with a variety of combinations of materials, the finished products are designed to carry full structural loading for several types of site conditions, in compliance with ASTM and other specifications. Fiberglass pipe may be used for both new construction and for structurally relining existing pipelines or culverts. It may also be important to note that fiberglass pipe is very smooth, with a 0.009 Manning Factor, which may provide no reduction in flow capacity for a smaller diameter structural relining of a culvert. Although the resins are resistant to almost all chemicals, special resins may be selected for use in extreme chemical environments, including strong alkalis and acids. Fiberglass pipes, of certain types, are available in a range of sizes from 8 inches to 144 inches in diameter.

Fiber Reinforced Polymer Concrete (FRPC) - This type of pipe, that was developed in Europe 25 years ago, has recently been introduced into American markets, under the trade name of HOBAS™. The pipe may be used for gravity flow and high pressure (up to 250 psi) pipeline applications as well as for sliplining culverts. The pipe is manufactured from chapped glass fiber roving, polyester resin, and sand. The composite wall structure can be varied to produce the necessary wall strength characteristics needed for a variety of types of projects. The HOBAS™ pipe is made in 20 ft lengths, in diameters from 18 to 96 in. and in 9, 18, 36, and 72 psi stiffness classes, in accordance with existing AWWA and ASTM specifications.

The pipe is manufactured by a centrifugal casting method, that produces centrifugal forces 30 times that of gravity and a densely compacted resin, glass fiber and sand pipe product that has a high structural strength. The resin is polymerized by heating the pipe while it is still in the mold. After cooling the pipe is ready for shipment.

Other Materials

Masonry - Stone and brick are durable, low maintenance materials. Prior to the 1920's, both were used frequently in railroad and road construction projects because they were readily available from rock cuts or local brickyards. Although stone and brick are seldom used for constructing culvert barrels, stone is used occasionally for this purpose in locations that have very acid runoff. The most common use of stone is for headwalls where a rustic or scenic appearance is desired. Brick is frequently used in the construction of manholes and inlets in storm drainage systems, because it may easily be built up without the need for formwork.

Vitrified Clay Pipe - Vitrified clay pipe is manufactured from clays and shales that are the mineral aggregates remaining after the weathering process of nature. This weathering process leaches out the soluble and reactive minerals from the rock and soil, leaving an inert material. This chemically inert material is then burned in kilns at 1900-2100 degrees Fahrenheit at which "vitrification" occurs and the clay particles become fused into an inert chemically stable compound.

Vitrified clay pipe is resistant to internal and external attack from acids, alkalies, gases, and solvents. It is resistant to abrasion and scour and will not corrode.

Wood - Wood or timber is a renewable building material available in most locations. It has a high strength-to-weight ratio and, when properly protected, it is very durable. Its strength is influenced by straightness of grain and moisture and it is much stronger parallel to the grain than across the grain.

While green wood is more resilient and flexible than seasoned wood, proper curing decreases shrinkage, increases strength, reduces weight, increases resistance to decay and improved workability. In addition, cured wood is ready for preservation treatment. When adequately protected, wood is a very durable building material. It is sometimes used to construct box culverts where runoff is highly corrosive. It is also used in rustic settings or where other materials are not available.

Cast Iron - Cast iron is iron in which carbon has been dissolved. It is generally no longer used for culvert construction. It has poor tensile strength and is brittle and susceptible to cracking. The shapes are cast and are bulky in comparison to steel. Cast iron does, however, exhibit good corrosion resistance.

Coatings for Culvert Materials

A variety of types of coatings may be used either singularly or in a combination of layers to protect culverts from chemical and/or abrasion attack. The type(s) of coatings will depend upon the type of culvert material and the types of deterioration or distress they incur. The necessity for protective coatings depends upon a number of factors, including:

- Chemistry and acidity (pH) of the adjacent soil;
- Chemistry and acidity (pH) of the water passing through the culvert;
- Particle size and velocity of the solid material being transported through the culvert; and
- Environmental effects including freezing and thawing.

Coatings for metal culverts - Corrugated steel culverts are usually zinc coated (galvanized). Other metallic coatings such as aluminum and aluminum zinc alloy coatings have recently been developed. Protective coatings for metal culverts also include bituminous coatings, bituminous paving, fiber-bonded bituminous coatings, polymer, concrete paving, and concrete coatings. Additional protective coatings are used with the metallic coating when there are serious corrosion or abrasion problems.

a. Bituminous - This is the most common material used to protect corrugated steel pipe against corrosion. This procedure can also increase the resistance of metal pipe to acidic conditions if the coating is properly applied and it remains in place. Careful handling during transportation, storage, and installation is required to avoid damage to the coating. Bituminous coatings can also be damaged by abrasion. Field repairs should be made when bare metal has been exposed. Aramid fibers may be embedded in the zinc coating to improve the adherence to metallic-coated bituminous material pipe. It should be noted that the durability of bituminous coatings is dependent on strict adherence by the fabricator to proper coating procedures.

b. Polymer - There are several types of polymer coatings that may be applied for corrosion and/or abrasion protection. The term polymer generally refers to a variety of types of plastic that may be used either plain "neat" or as a matrix for binding aggregates together, much the same as Portland cement or asphaltic cement are used to make those respective types of concrete. Plain plastic coatings, often epoxies, may be applied directly to the metal or to other surface coatings. Culverts may also be coated with a polymer concrete, which is a mixture of plastic and aggregate. There have also been recent developments for coating metal culverts with fiberglass, which are (for these types of applications) short glass fibers held in a resin matrix. However, the 10 mil thick PVC and polyolefin plastic coatings that may be used to coat metal culverts do not provide increased resistance to abrasion, although polyethylene will to some extent.

c. Concrete/mortar - Metal culverts may be coated with a Portland Cement mortar or concrete for corrosion and abrasion resistance. Concrete of good quality is resistant to many corrosive agents. When the effluent has a pH of 5.0 or less, protective measures are generally required. One problem with using this type of coating is getting a good bond or connection between the metal pipe and the mortar or concrete lining.

d. Galvanizing - Galvanizing refers to the process of coating steel with a layer of zinc. Bare, uncoated, galvanized steel pipe generally performs well when the pH of the soil immediately adjacent to the pipe and the pH of the flow that the pipe will carry are between 6 and 10 and when the electrical resistivity of the soil is 2,000 ohm-cm or greater. Bare galvanized steel pipe should not be used in salt or brackish environments.

e. Aluminum cladding - Steel may also be coated with aluminum for corrosion protection. Aluminum generally performs adequately when the pH of the soil immediately adjacent to the pipe and the pH of the flow that the culvert will carry are between 5 and 9, and when the electrical resistivity of the flow and the minimum electrical resistivity of the soil is 1500 ohm-cm or greater. When backfilled with a clean, granular, well-drained soil, aluminum coated pipe has shown excellent resistance to corrosion, except when exposed to seawater and tidal flow. Aluminum coatings may not perform well in very acid or heavy metal (copper, iron, etc.) environments. An aluminum-zinc coating has been developed that has properties somewhat different than the two individual coatings.

Coatings for concrete culverts - Concrete culverts are rarely coated when they are constructed. However, when they are installed in particularly aggressive chemical environments, they may be coated with epoxy resins or special high density, low porosity concrete materials that have a high resistance to chemicals and chemical attack.

Invert protection - The inverts of corrugated metal culverts are frequently paved to extend the life of the culvert by protecting the invert against corrosion and abrasion. The paving also smooths the inside of the culvert, which improves the hydraulic capacity of such culverts.

a. Bituminous paving - Paving of CMP inverts with bituminous materials has been a common practice for many years. The bituminous coating is usually at least 1/8-inch (3 mm) thick over the inner crest of the corrugations. Generally only the lower quadrant of the pipe interior is paved. Fiber binding is sometimes used to improve the adherence of bituminous material to the metallic-coated pipe. Although bituminous paving has been widely used, it has been found that the coating may deteriorate and spall off after a number of years, particularly in some environments. After the coating starts to deteriorate, corrosion of the culvert will begin.

b. Concrete paving - The invert of culverts may also be paved with plain or reinforced Portland cement concrete. For both new and repair situations this type of paving would normally be applied after the culvert is installed. Although this would normally be done only for corrugated metal pipe culverts, it is occasionally used for precast concrete culverts, to provide additional thickness to resist abrasion and/or corrosion. Metal culvert sections may also be factory produced with a complete concrete lining.

c. Riprap - The inverts of culverts, particularly corrugated metal, may also be covered with riprap for both abrasion resistance and to facilitate fish passage. Use of riprap will have little benefit for corrosion resistance. The size of the riprap that should be used will depend upon the velocity of the water expected to be carried by the culvert, not only during normal flow but also during flood stage. Considerations must also be given to the possibility that use of riprap will worsen potential problems with siltation.

CULVERT INSTALLATION METHODS

There are two major classes of culvert installations, based upon the conditions that influence loads: 1) trenched, where culverts are placed in natural ground or compacted fill with a controlled trench width and 2) embankments, where culverts are usually placed in natural ground but are covered by a constructed embankment. A third method of installation for placing culverts is boring and jacking, used where deep installations are necessary or where conventional open excavation is not practical.

Trenched

Trench installations are made in relatively narrow excavations on a carefully prepared bedding to distribute the load and the culvert is covered with earth backfill that extends to the ground surface. The trench load theory is based on the following assumptions:

- Earth loads on the pipe develop as the backfill settles.
- The resulting earth load on the pipe is equal to the weight of the material above the top of the pipe minus the shearing (frictional) forces on the side of the trench.
- Cohesion is negligible because, with cohesive soils, considerable time must elapse before effective cohesion between the backfill material and the sides of the trench can develop, and with cohesionless soils, would never develop. The assumption of no cohesion yields the maximum probable load on the pipe.
- For a rigid pipe, the side fills may be relatively compressible and the pipe will carry a large portion of the load over the entire width of the trench.
- For rigid pipe, active lateral pressure is neglected, which, in effect, increases the required pipe strength. (However, it should be taken into account if investigations and experience indicate such pressure is significant.

For flexible culverts, a well-compacted soil envelope of adequate width is needed to develop the lateral pressures required to maintain the shape of the culvert. The width is a function of the strength of the surrounding in-situ soil and the size of the pipe.

The backfill load ultimately transmitted to the pipe is a function of the trench width. With rigid culvert placement, the determination of the backfill load is based on the trench width and a pipe strength is selected to withstand that load. If the actual trench width exceeds the width assumed in design, the load on the culvert will be greater than estimated and structural distress may result.

Figure 2.17 illustrates the load carried by a rigid culvert installed in a normal trench installation.

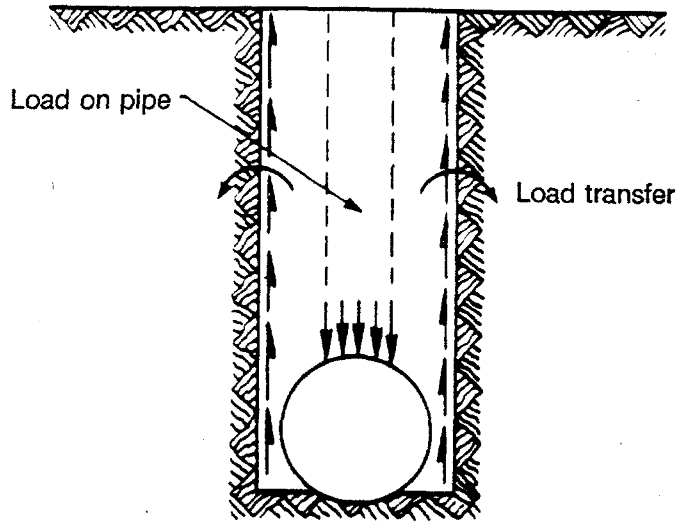


Figure 2.17. Trench installation.[2]

Figure 2.18 illustrates the increased load on the rigid culvert if the width of the trench is increased.

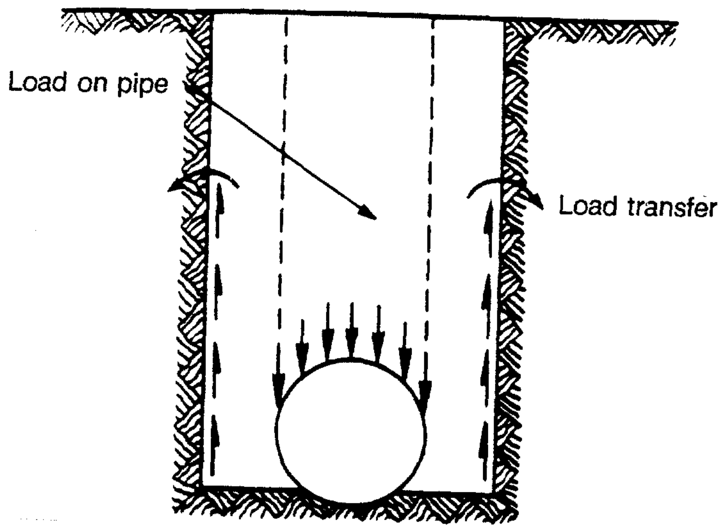


Figure 2.18. Wide trench installation.[4]

If an excessively wide trench is excavated or if the sides are sloped back, the culvert can be installed in a narrow subtrench excavated at the bottom of the wider trench, as shown in figure 2.19, to avoid an increase in the backfill load.

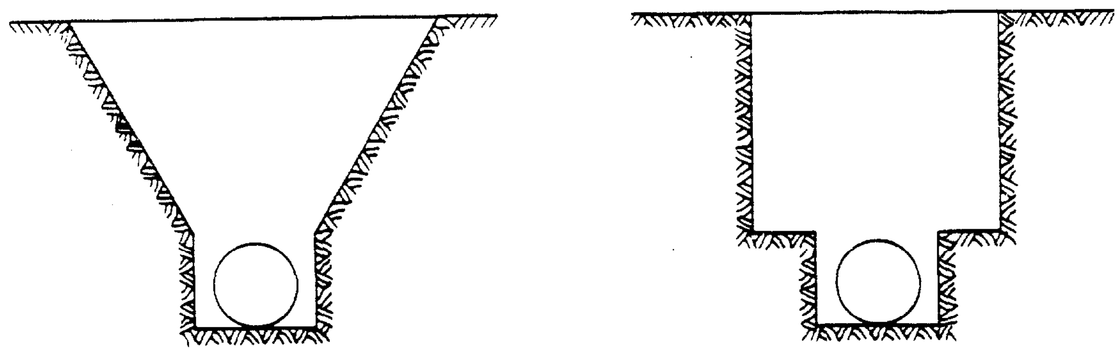


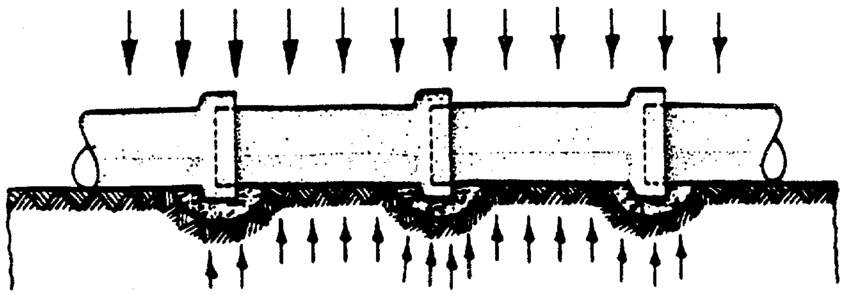
Figure 2.19. Subtrench installation in a wide trench.(2)

Bedding - A stable and uniform foundation is necessary for the satisfactory performance of any culvert. Once a stable and uniform foundation is provided, the bedding should be prepared in accordance with the plans and specifications.

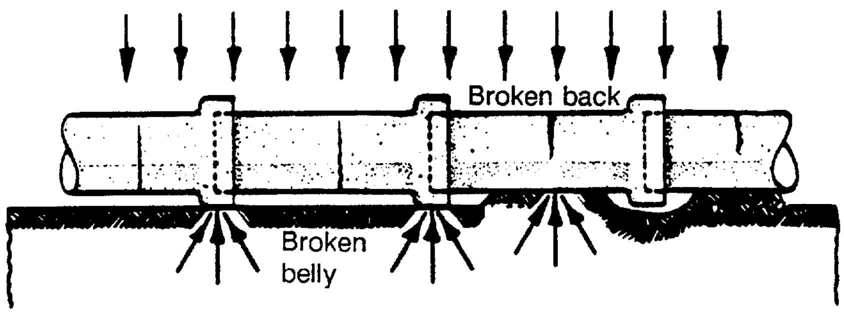
The bedding preparation is critical to both structural performance and service life. An important function of the bedding is to provide uniform support along the barrel of each pipe section. The bed should be placed to uniform grade and line to ensure good vertical alignment and to avoid excessive stresses at joints. The material should be free of rock formations, protruding stones, frozen lumps, roots, and other foreign matter that may cause unequal settlement. When a corrugated metal culvert is being placed, the corrugations should be firmly seated in the foundation material.

Transverse or circumferential cracks in rigid pipe may be caused by poor bedding. Cracks can occur across the bottom of the pipe (broken belly) when the pipe is only supported at the ends of each section. This is generally the result of poor installation practices such as not providing indentions (bell holes) in hard foundation material for the ends of bell and spigot-type pipe or not providing a sufficient depth of suitable bedding material. Cracks may occur across the top of pipe (broken back) when settlement occurs and rocks or other areas of hard foundation material near the midpoint of a pipe section are not adequately covered with suitable bedding material. Transverse cracking is illustrated in figure 2.20.

The bedding distributes the load reaction around the lower periphery of the pipe. The required supporting strength of the pipe is directly related to this load distribution. Pipe set on a flat foundation without bedding results in high load concentration at the bottom of the pipe and is likely to result in shear cracking of the pipe at the five o'clock and seven o'clock locations. Figure 2.21 illustrates how the distribution of the bedding over increasing percentages of the outside diameter can increase the supporting strength of the culvert. Any time a pipe is installed on a flat-bottom foundation, it is essential that the bedding material be uniformly compacted under the haunches of the culvert.



Properly prepared bedding evenly distributes loads.
Improperly prepared bedding may result in stress concentrations.



Improperly prepared bedding.

Figure 2.20. Transverse or circumferential cracks.[3]

Backfilling - The backfill is made up of two areas that may require different material and separate compaction criteria. The first area extends from the bedding to approximately 12 inches above the culvert. The second area includes the remaining fill.

The load-carrying capacity of an installed culvert depends largely on the initial backfilling around the culvert. Since proper compaction of backfill material is so important, material and density criteria is often included in the bedding requirements.

For trench installations, where space is limited, tamping by pneumatic or mechanical impact tampers is usually the most effective means of compaction. Impact tampers are most effective for clay soils while granular soils are consolidated best by vibration. Backfill material should be placed in layers approximately six inches deep, deposited alternately on opposite sides of the culvert. Each layer should be compacted carefully, until reaching a height of at least three-fourths of the structure.

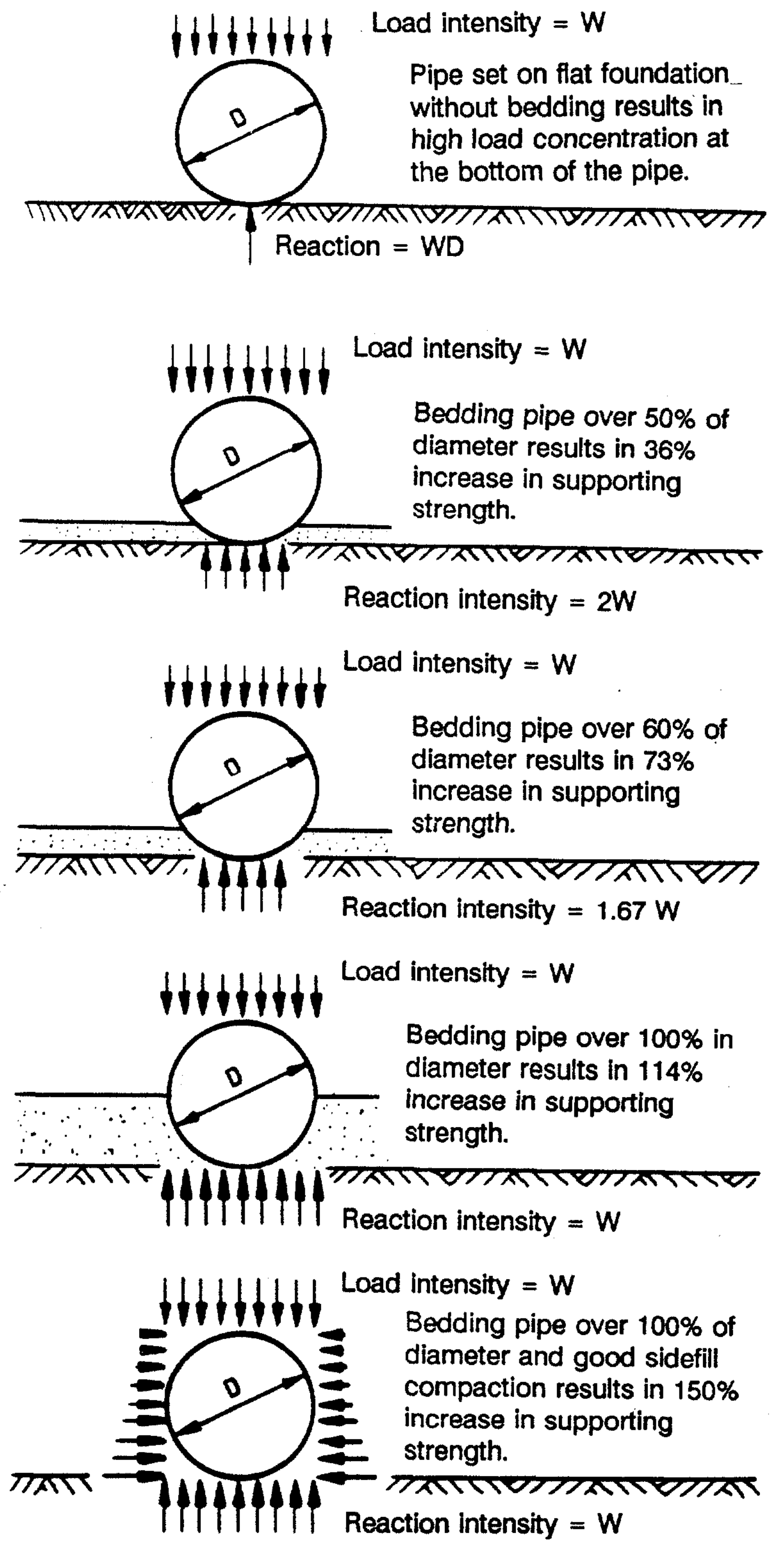


Figure 2.21. Correlation of bedding and supporting strength for rigid pipe.[4]

Embankments

Culverts placed in an embankment are usually bedded in natural ground but are overlaid by a constructed embankment. The required supporting strength of a buried pipe is determined by the total load that is imposed upon the pipe. The magnitude of the load is influenced by the uniformity and stability of the support soil, as well as conditions around and over the pipe. However, the load-carrying capability of rigid culverts is essentially carried by the structural strength of the pipe itself since rigid pipe is stiffer than the surrounding soil. A well-compacted soil envelope is required to develop the lateral pressures necessary to maintain the shape of flexible culverts.

Embankment installations can be divided into three groups: positive projection, negative projection, and induced trench. The essential features of these types of installations are shown in figure 2.22.

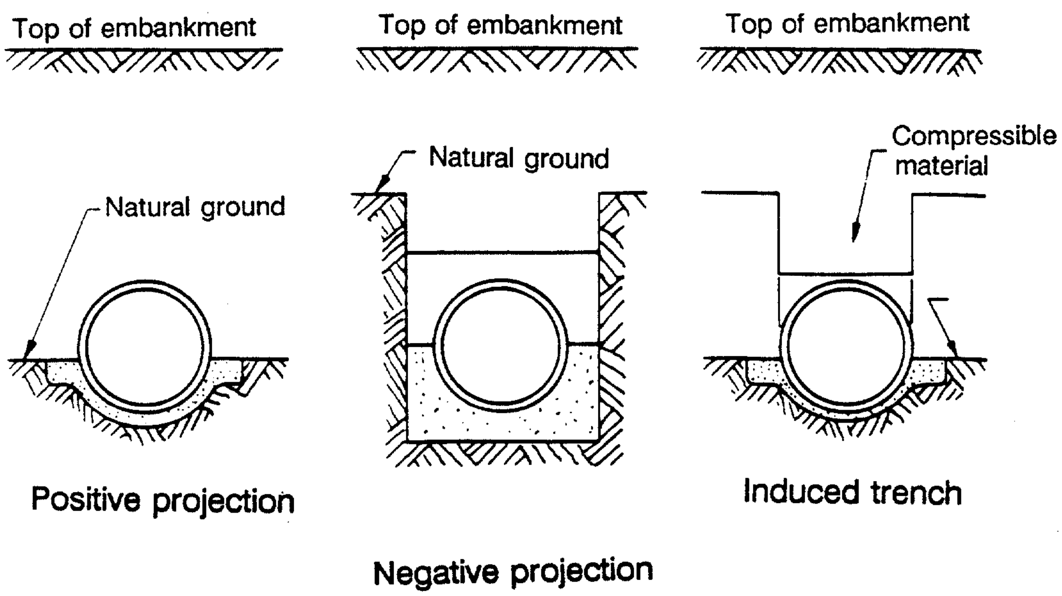


Figure 2.22. Essential features of various types of installation.[4]

Positive projection pipe is installed with the top of the pipe projecting above the surface of the natural ground, or compacted fill, and then covered with earth fill. Negative projection pipe in installed in relatively shallow trenches so that the top of the pipe is below the level of the natural ground or compacted fill. It is then covered with earth fill to the required depth. The induced trench pipe is usually installed as positive projection. However, when the fill has been placed to a depth of at least one pipe diameter over the proposed top of the pipe, a trench is excavated over the pipe and backfilled with a more compressible material.

Bored, Augured or Jacked

The process of tunneling and jacking pipe culverts is used where deep installations are necessary or where conventional open excavation and backfill methods may not be practical.

The usual procedure in jacking pipe is to equip the leading edge with a cutter, or shoe, to protect the pipe. As succeeding lengths of pipe are added between the lead pipe and the jacks, and the pipe is jacked forward, soil is excavated and removed through the pipe. Material is trimmed so that the bore size slightly exceeds the outside diameter of the pipe and excavation does not precede the jacking operation more than is necessary. Such a procedure usually results in minimum disturbance to the natural soils adjacent to the pipe. A typical installation for jacking pipe is shown in figure 2.23.

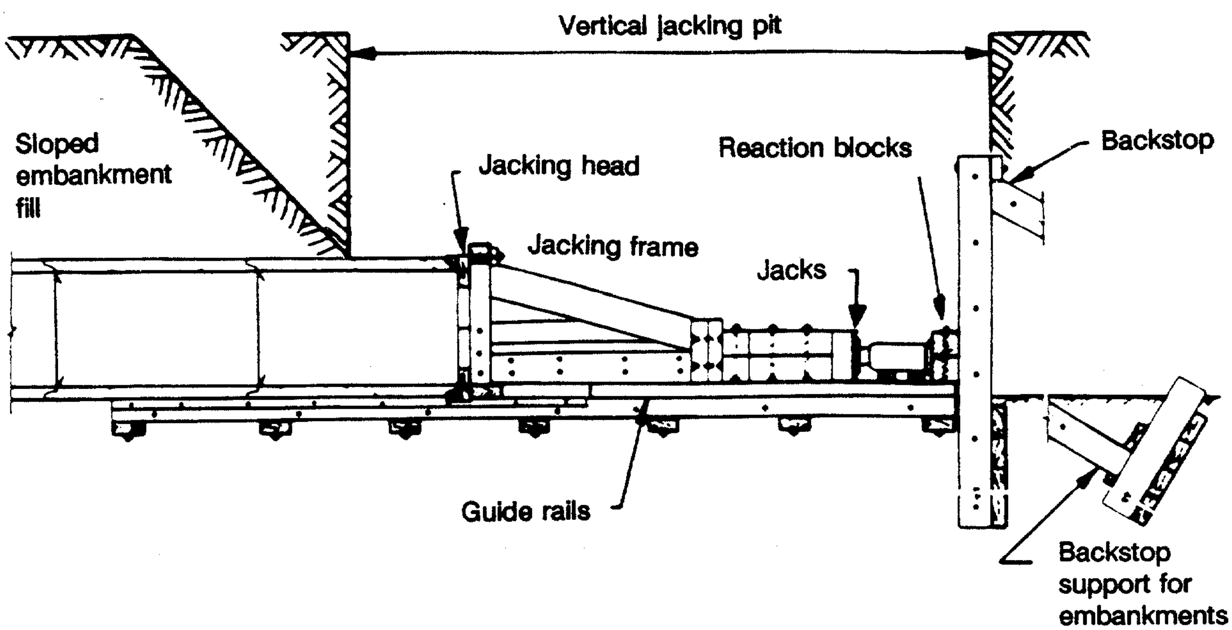


Figure 2.23. Typical jacking installation.[4]

A lubricant, such as a bentonite slurry, is sometimes pumped into the space between the tunnel bore and the outside of the pipe to reduce the frictional resistance. After the jacked piped has reached its final position, grout is frequently pumped into the same space to ensure continuous bearing with the surrounding soil.

Two types of loads are imposed upon concrete pipe installed by the jacking method: the axial load due to the jacking pressures applied during installation; and the earth loading due to the overburden, with some possible influence from live loadings, which generally become effective only after installation is completed.

There are several advantages to jacking pipe:

- Traffic is not interrupted on the overlying roadway.
- Depth of the installation is not a concern.
- Cutting and patching of the pavement can be avoided.
- Minimum disturbance to the natural soils is experienced.
- Loads on the pipe are less than loads in trenched installations.

The disadvantages are:

- Expensive equipment and skilled operators are required.
- There must be adequate room within the right-of-way to construct the jacking pit.

A procedure for jacking concrete pipe is described in appendix B. More detailed information can be found in the *Concrete Pipe Handbook* and *Design Data 13: Jacking Concrete Pipe*, both from the American Concrete Pipe Association.

CULVERT CONSTRUCTION

The performance of culverts and their appurtenances is dependent on practices during installation. Items that require particular attention during design and construction of new culverts and repairs include:

Backfills and Fills

Suitable backfill material and adequate compaction are of critical importance. A well-compacted soil envelope is needed to develop the lateral pressures required to maintain the shape of flexible culverts. Well-compacted backfill is also important to the performance of rigid culverts to prevent such things as settlement of the roadway and movement of water along the barrel. The design must specify material type and degree of compaction. Care should be taken that the backfill material does not contribute to corrosion of the culvert.

Trench Width

Trench width can significantly affect the earth loads on rigid culverts. It is, therefore, important that trench widths be specified on the plans and that the specified width for rigid pipe not be exceeded without authorization from the design engineer.

For flexible culverts a minimum trench width backfilled with premium backfill material is required to provide adequate side support. A narrower width of premium backfill for flexible pipe should not be provided without authorization from the design engineer.

Foundations and Bedding

A foundation capable of providing uniform and stable support is important for both flexible and rigid culverts. Establishing a suitable foundation requires removal and replacement of any hard spots or soft spots. Bedding is needed to level out any irregularities in the foundation and to ensure uniform support. When using flexible culverts, bedding should be shaped to a sufficient width to permit compaction of the remainder of the backfill, and enough loose material should be placed on top of the bedding to fill the corrugations. When using rigid culverts, the bedding should conform to the bedding conditions specified in the plans and should be shaped to allow compaction and to provide clearance for the bell ends on bell and spigot-type rigid pipes. Adequate support is critical in rigid pipe installations, or shear stress may become a problem. The necessary details should be provided by the designer.

Construction Loads

Culverts are generally designed for the loads they must carry after construction is completed. Construction loads may exceed design loads. These heavy loads can cause damage if construction equipment crosses over the culvert installation before adequate fill has been placed or moves too close to the walls, creating unbalanced loadings. Additional protective fill or other measures may be needed for equipment-crossing points.

Camber

In high fills the center of the embankment may settle more than the areas under the embankment side slopes. In such cases it may be necessary to camber the foundation slightly, as shown in figure 2.24. This should be accomplished by using a flat grade on the upstream half of the culvert and a steeper grade on the downstream half of the culvert. The initial grades should not cause water to pond or pocket. The method and dimensions for cambering should be provided by an experienced designer.

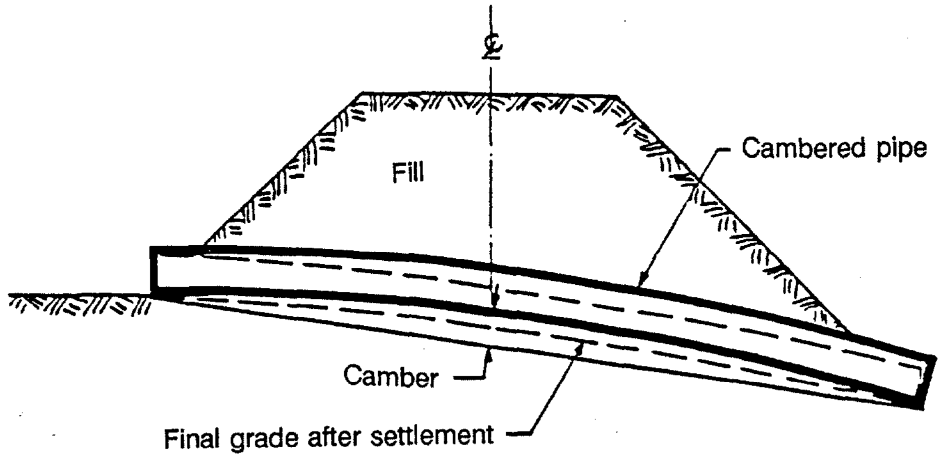


Figure 2.24. Camber allows for settlement of a culvert under a high fill.[6]

Materials

During construction, the materials delivered must be exactly as specified. Inadequate thickness, size, or quality of material can lead to maintenance problems or failure. During installation the materials must be handled properly to prevent defects and loss of intended shape, size, or quality.

CULVERT APPURTENANCES

Culvert appurtenances are those structural and functional portions of the total culvert that improve its flow characteristics and functionality. The following are descriptions of the primary appurtenances that may be added to the barrel of a culvert, regardless of its shape or material.

Endwalls and Wingwalls

Endwalls are built on the ends of the culvert barrels to reinforce the barrel and for protection against erosion of the embankment and scour of the streambed from beneath the end of the culvert barrel. They also act as a counterweight to offset buoyant forces. End walls are normally constructed parallel with the embankments at the ends of the culvert. Although endwalls (headwalls and tailwalls) are usually made of plain or reinforced concrete, they may also be made of timber, stone masonry, corrugated metal, steel sheet piling, gabions, or bagged concrete.

Wingwalls are flared structural walls that extend from the endwalls into the waterway. They function somewhat as the sides of a funnel to channel water into the culvert. The shape and direction of the wingwalls at both the inlet and outlet ends of a culvert are critical to the hydraulic efficiency of the culvert.

Energy Dissipators

Energy dissipators are used to reduce the velocity of water leaving a culvert. This, in turn, reduces the tendency for abrasion and abrasion-related corrosion of metal culverts, scour, and erosion of the streambed and adjacent land. Certain types can also facilitate migration of fish through a culvert.

Energy dissipators should be considered part of a larger design system that includes the culvert, channel protection requirements (both upstream and downstream), and may include a debris-control structure. The general types of energy dissipators include hydraulic jump, forced hydraulic jump, impact, drop structure, stilling well, and riprap. Design information for energy dissipators can be found in Hydraulic Engineering Circular No. 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels.*(7)

Aprons and Scour Protection

Plain or reinforced concrete aprons are frequently constructed at the inlet and outlet ends of culverts for scour protection. Concrete aprons generally extend at least 20 feet into the stream away from the culvert. They may also be sloped downward into the stream bottom with as much as 30 percent of their leading or trailing surfaces being covered by granular streambed material to minimize the potential for scour and undermining of the apron. Another related common practice is to construct a vertical cut-off wall below the entrance and outlet of a culvert for the same purpose. The wall should extend at least two feet into the soil below the culvert and more if the entrance of the culvert is perched above the channel bottom.

Safety Barriers and Grates

Safety is a primary concern in the design and construction of culverts. While structural and hydraulic adequacy is the first consideration, supplementary safety concerns include traffic safety and child safety. The safety of errant vehicles should be provided for by the appropriate location and design of culverts, such as locating culvert ends outside of the safe recovery area or extending culverts through medians if safe distances cannot be maintained. However, for abnormally steep fill slopes or in locations where adequate recovery distance cannot be achieved, the installation of guardrail along the roadside should be considered.

Traversable grates placed over culvert openings can also reduce vehicle impact forces and the likelihood of overturning. If clogging by debris is a problem, fencing around the culvert ends is an alternative solution.

Debris-Control Structures

Water-borne debris usually includes some combination of floating material, suspended sediment, and bedload as described in table 2.3. It can be deposited at the culvert entrance or inside the barrel and can cause the culvert to perform unsatisfactorily or to malfunction. In extreme cases, the result may be failure of the drainage structure or overtopping of the roadway by flood waters, which, in turn, can cause damage to the roadway and adjacent property. Where the waterway opening of a culvert is subject to clogging, a debris-control structure should be an essential part of the hydraulic structure design.

There are several advantages to the use of a debris-control structure. Planned maintenance can be provided on a scheduled basis rather than emergency maintenance required during floods. Washouts or accumulation of drift on the roadway caused by clogged culverts can be prevented. Drift problems can be averted at existing culverts, alleviating damage from buoyant forces. Increasing the size of the culvert to allow passage of the debris is the solution preferred by the Oregon Department of Transportation.

The AASHTO *Model Drainage Manual*[8] states that debris control shall be considered:

- where experience or physical evidence indicates the watercourse will transport a heavy volume of controllable debris;
- for culverts located in mountainous or steep regions;
- for culverts that are under high fills, and
- where clean-out access is limited. However, access must be available to clean out the debris control device.

Table 2.3. Classification system for debris types.[9]

1.	Very Light Floating Debris or No Debris.
2.	Light Floating Debris - Small limbs or sticks, orchard prunings, tules, and refuse.
3.	Medium Floating Debris - Limbs or large sticks.
4.	Heavy Floating Debris - Logs or trees.
5.	Flowing Debris - Heterogeneous fluid mass of clay, silt, sand, gravel, rock, refuse, or sticks.
6.	Fine Detritus - Fairly uniform bedload of silt, sand, or gravel more or less devoid of floating debris, tending to deposit upon diminution of velocity.
7.	Coarse Detritus - Coarse gravel or rock fragments.
8.	Boulders - Large boulders and large rock fragments carried as a bedload at flood stage.

Three methods can be used to control debris: interception of the debris at or above the culvert inlet, deflection of the debris away from the entrance for detention near the inlet, or passage of the debris through the structure. Common types of debris-control structures are described in table 2.4.

Proper design of a debris-control structure should begin with a preliminary field study. Maintenance personnel should be interviewed to establish the history of debris accumulation. Information gathered should include an estimate of the quantity and the type of debris, future land-use changes that would influence the type and quantity, and an estimation of stream flow velocities in the vicinity of the culvert. An adequate debris storage area should be located with proper access for periodic removal of debris.

Table 2.4. Types of debris control structures.[9]

1. Debris Deflectors - Structures placed at the culvert inlet to deflect the major portion of the debris away from the culvert entrance. They are normally "V"-shaped in plan with the apex upstream.

2. Debris Racks - Structures placed across the stream channel to collect the debris before it reaches the culvert entrance. Debris racks are usually vertical and at right angles to the stream flow, but they may be skewed with the flow or inclined with the vertical.

3. Debris Risers - A closed-type structure placed directly over the culvert inlet to cause deposition of flowing debris and fine detritus before it reaches the culvert inlet. Risers are usually built of metal pipe. Risers are also used as relief devices in the event the entrance becomes plugged with debris.

4. Debris Cribs - Open crib-type structures placed vertically over the culvert inlet in log-cabin fashion to prevent inflow of coarse bedload and light floating debris.

5. Debris Fins - Walls built in the stream channel upstream of the culvert. Their purpose is to align debris, such as logs, with the axis of the culvert so that the debris will pass through the culvert barrel without clogging the inlet. They are sometimes used on bridge piers to deflect drift.

6. Debris Dams and Basins - Structures placed across well-defined channels to form basins that impede the stream flow and provide storage space for deposits of detritus and debris.

7. Floating Drift Boom - Logs or timbers that float on the water surface to collect floating drift. Drift booms require guides or stays to hold them in place laterally. They are limited in use.

8. Combination Devices - A combination of two or more of the preceding debris-control structures at one site to handle more than one type of debris and to provide additional insurance against a clogged culvert inlet.

Table 2.5 is a guide for selecting the type of structure suitable for the various debris classifications. Design information for commonly used debris-control structures can be found in Hydraulic Engineering Circular No. 9, *Debris Control Structures*.[10]

Table 2.5. Guide for selecting type of control structures suitable for various debris classification.[10]

Debris Classification	Type of Structure: Deflector	Rack	Riser	Crib	Fin	Dam and Basin	Boom
Light Floating Debris		X		X			X
Medium Floating Debris	X	X					X
Heavy Floating Debris	X				X		
Flowing Debris			X			X	
Fine Detritus			X			X	
Coarse Detritus			X	X		X	
Boulders	X						

Junctions

A junction combines flow from two or more separate culverts or storm sewers into a single culvert barrel. A tributary and a main stream that intersect at a roadway crossing can be combined or joined at a culvert junction. A culvert barrel receiving a drainage pipe collecting runoff from the overlying roadway is an example of a storm sewer/culvert junction.

When analyzing flow conditions, attention should be paid to the timing of the arrival of the peak flow at each entrance. Loss of head may also be important in the hydraulic design of a culvert utilizing a junction. The junction should be configured to minimize turbulence and loss of head.

Erosion protection of culvert foundations and anchorage may be necessary in culverts with natural bottoms. Proper alignment, selective invert paving, and strategically placed energy dissipators within the culvert can alleviate problems with erosion.

Fish Passage

Where fish passage has been provided, it should be maintained as part of the culvert unless it has deteriorated or become non-functional. Changes in these structures will require coordination with the regulatory agency that dictated that fish passage be designed.

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CHAPTER 3. PROBLEM IDENTIFICATION AND ASSESSMENT

SCOPE

This chapter presents a discussion of the identification of problems associated with culverts and related appurtenances. The discussion will include how problematic conditions are identified through inspection and maintenance programs. The chapter presents specific signs of distress that maintenance personnel can recognize and identify. Symptoms of weakness that can be seen from the roadway approaches, those that show up in end treatments and appurtenances, waterway problems, and those associated with different barrel materials and shapes will be reviewed. Other problems associated with local water, soil, and climatic conditions will also be noted. The causes and impacts of inadequate hydraulic capacity will be presented. This discussion is partially based on the information presented in the *Culvert Inspection Manual*.[1]

GENERAL

In the past, culverts were considered minor structures, representing a lower investment than a bridge. In a failure, the safety hazard was also considered to be less. However, in the late 1960's, long span corrugated metal culverts with spans in excess of 40 feet were introduced. In many cases, smaller bridges were replaced with multiple barrel culverts, box culverts, or long span culverts. As a result, the size, complexity, and cost of these structures have increased. Failure of a major culvert may be both costly and hazardous. Therefore, it has become increasingly important for culverts to be maintained and repaired in a timely manner.

It is not enough simply to repair a culvert defect. It is equally, if not more, important to determine the underlying cause of a problem so that it will not recur or become more serious. Too often, culvert repairs are made in response to emergency conditions or citizen complaints and time is not allotted to study the problem and develop a plan for long-term solutions. Deterioration of culvert components give clues to underlying weaknesses that can signal trouble to come. The condition of roadway approaches, embankments, guardrails, or pavement structure over the culvert often betray serious impairment in the culvert structure. Knowing the tell-tale signs to look for is a definite advantage to maintenance personnel.

Successful, cost-effective culvert repair involves several steps. The first step in the culvert repair process is to identify the problem. Specifically, this means that the symptom must be detected and the underlying cause determined. Having determined the cause of the problem, alternative solutions can be formulated.

Therefore, the process is to take information from reports of problems, investigate the existing conditions, determine what has caused the problem, study potential solutions and, finally, decide what should be done. The remainder of this chapter deals with the process of identifying problems, the process of evaluating repair alternatives once the cause of the problem has been determined, and then the identification of problems with specific components.

IDENTIFYING CULVERT PROBLEMS

The process of identifying "problems" is a two or three stage effort. The first step is to recognize visually that the culvert, as a whole or one of its components, is not functioning properly or shows signs of distress that may lead to improper functioning. This is a "symptom". The types of "functions" are classified as: the ability to adequately handle water into, through and out of the culvert; and, the ability to safely carry traffic on the approaches and over the crossing.

The second step is to assess the cause and identify the basic type of problem. In some cases the underlying cause will be obvious. In other cases the cause will have to be determined by more investigation. This investigation may be visual with common tools or may involve detailed hydraulic, structural, geotechnical or other engineering studies. If the cause cannot be readily determined, the third step is to make a detailed investigation.

Following are general methods of accomplishing the first two steps. The more detailed studies are beyond the scope of this manual and should be conducted by specialists on a case-by-case basis.

Initial reports of problems come from many sources and have variable degrees of accuracy and completeness. The reports may range from careful periodic inspections by highway personnel to calls from concerned citizens and obvious failures due to floods or overloading.

The step of investigating existing conditions is comprehensively described in the FHWA *Culvert Inspection Manual* [(1)]. The methods described therein or other proven methods should be used to inspect the culvert components.

Inspection Programs

To consistently identify culvert problems and implement appropriate repairs to halt deterioration, a systematic program of culvert inspection should be adopted. A logical sequence for inspecting culverts aids in conducting a thorough and complete inspection. A general plan is useful to avoid oversights. More than just the components of a culvert should be evaluated. High water marks, changes in the drainage area, land use, settlement of the roadway, or other indications of problems should be observed. Careful records should be kept so that changes can be documented and a deteriorating condition can be rated as dynamic or static. For example, even though a corrugated metal culvert may show some shape distortion, the condition may be stable. Figure 3.1 illustrates the general elements of inspection.

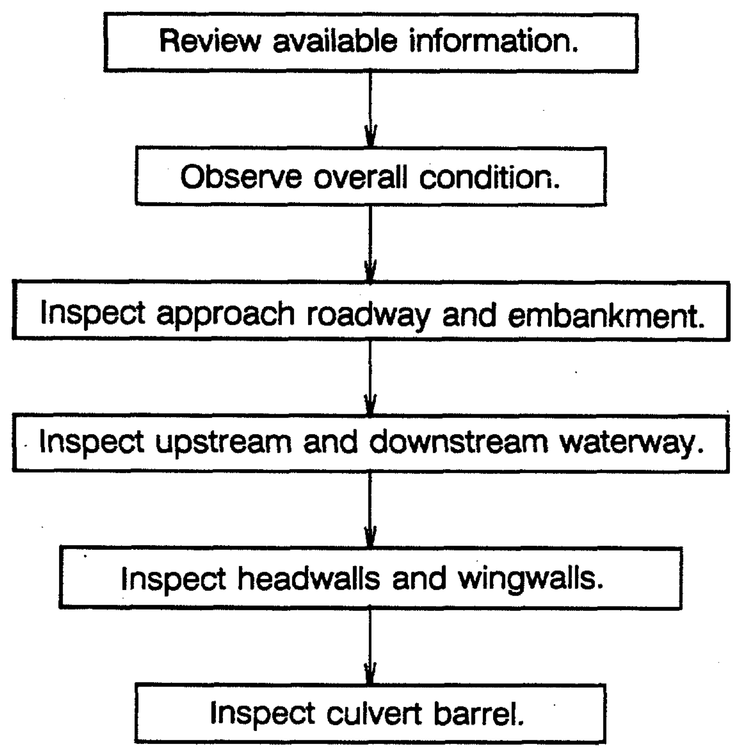


Figure 3.1. General elements of inspection.

There are three types of inspection programs that may be undertaken: (1) a program that is an extension of the National Bridge Inspection Program; (2) a program that focuses specifically on culverts as described in the Culvert Inspection Manual[1]; or (3) one that is conducted during periods of scheduled maintenance. These types of programs are described in more detail in chapter 4.

Routine Maintenance

During routine maintenance, the culvert and its appurtenances should be inspected for defects, minor defects should be corrected, and specific records kept of defects, corrections and recommendations for further inspections and maintenance repairs. Regular periodic inspections allow minor problems to be spotted and corrected before they become serious. Preventative maintenance is considered a primary deterrent to premature deterioration and resulting disfunction of culverts.

Culverts should be inspected regularly to identify structural and material deterioration and distress that may affect structural integrity. Inspection should include an examination of the adequacy of the hydraulic performance of the culvert and signs of erosion. The structure should be reviewed for structural compatibility with the roadway. Fixed object hazards, abrupt dropoffs over the ends of the culvert, or steep embankments should be noted and corrected.

Climatic conditions often present special problems that influence the behavior and life expectancy of culverts.

Moderate and warm climates - Corrosion is often a problem in warmer climates. High temperatures lower the electrical resistivity of soils, which increases the potential for and the rate of corrosion. Acid water (low pH) is more common to wet climates and alkaline water (high pH) is more common to dry climates. In periods of low flow, sedimentation can occur. However, periods of high discharge may provide a self-cleansing action that removes a buildup of sediment.

Heavy rains and the runoff from snow melt in higher, colder regions can cause flash flooding in stream beds that are usually dry. Routine maintenance can ensure that debris has been removed from these structures and the upstream channel so that these peak flows may be accommodated.

Cold climates - Aufeis, the buildup of ice in stream channels or within a culvert, is often a concern in colder regions. Even partial icing may constrict the culvert opening and cause an increase in the water velocity and cause scour. Scour at the inlet end is caused by turbulence that results when more water is collected at the inlet than can be carried by the pipe. Scour at the outlet end is caused by fast, uncontrolled discharge of a volume of water into a channel that is easily eroded. In extreme conditions and during periods of heavy flow, freezing can cause overtopping of the roadway.

Snow melt can cause higher-than-average flows in colder regions. Proper hydraulic functioning of culverts is a prime factor in accommodating the increased flow without damage to the roadway or culvert. Saturated ground stemming from snow melt can cause erosion of stream banks.

Emergency Situations

By definition emergency situations are those that require immediate action to prevent injury or loss of human life or failure of a structure. Although the lack of foresight and prior planning and action can contribute to the occurrence of emergency situations, this should not be the general rule. Emergency situations should normally be caused by such occurrences as major storms or overloaded vehicles.

Most culverts have been in place for many years and they are all in varying degrees of deterioration and or inadequacy. Maintenance personnel must be alert to circumstances that can cause serious impairment of structural integrity or hydraulic capacity, or cause a serious safety hazard. In addition to acting on reports from citizens or other agency personnel, the maintenance staff should make certain special inspections if they foresee potential problems. Most often, careful routine maintenance can alleviate emergency situations.

Annual inspections should be made before the rainy season begins. To reduce the hazards associated with emergency situations, such as flash flooding. Routine inspections should be made after heavy rains so that debris can be removed and damage assessed. In colder climates where snow and ice are problematic, inspections should be made before and after the snow and ice season.

Monitoring and Evaluation of Shape Distortion

Highway culverts are normally installed in the roadway embankment during construction of the highway. The height of the fill over the culvert will depend upon the specific location, but it may range from only a foot to over 50 ft deep. Chapter 2 presented information on the wide variety of types of materials and the sizes of culverts that may be constructed. It was stated that culverts may be classified as being either rigid or flexible, depending upon the types of materials that are used. It was also noted that culverts may be constructed on site with prefabricated sections of their cross-sectional shape, by casting concrete or by assembling individual plates or other types of structural members.

Specific requirements have been established for designing and constructing the embankments so that culverts are properly supported to carry vehicular loads. These requirements include specific criteria for selecting and compacting the soil below, around, and above the culvert so that the soil will not subside, shift, or consolidate under static (passive) soil or dynamic vehicular loads. Proper selection and consolidation of the embankment or backfill material creates a passive support for the culvert to resist these loads, in a manner that is consistent with the structural design of the culvert, regardless of whether the culvert is circular, arch, or, box shaped.

The critical problem is that movement of the soil surrounding a culvert will change the support condition around the culvert, by either reducing or increasing soil pressures on the culvert. Such changes in soil pressure can cause bending, cracking, and failure of a culvert. The initial indication of potential problems with rigid (concrete) culverts tends to be a slight deflection and the development of cracks whereas flexible (metal) culverts tend to bend and change their overall shape. Cracking and deformation of culverts reduces their capacity to safely carry soil and vehicular loads. Subsequent sections of this report will address procedures for assessing and correcting specific types of distress.

From the standpoint of inspection programs and the necessity to assess the structural capacity and integrity of a culvert, it is important to ascertain whether the existing conditions are stable or changing and if the structural integrity of a culvert is in jeopardy. Although the structural design and specifications for constructing the culvert and the surrounding embankment are very specific and displacement and/or distortion of the culvert are not anticipated or desirable, some movement may be allowable and not necessarily an indication of worsening conditions and eminent collapse. It should be recognized that some movement, cracking, and distortion may redistribute concentrated forces and stresses in the culvert structure and thereby permit it to carry subsequent soil and vehicular loads without further problems for a long period of time. Thus, it is important to determine whether a cracked or distorted culvert is continuing to crack and distort or whether it has stabilized. It could well be that the cracking and/or distortion occurred during or shortly after construction and the culvert is now stable and adequately carrying the applied soil and vehicular loads.

It is not possible for an inspector to make this determination during a single visit to the structure. Moreover, it will probably take specialized equipment and procedures to determine whether the conditions are changing by taking careful and exact measurements of the cross sectional shape of the culvert, at numerous sections, over a period of time. It should also be noted that although it is possible to measure the approximate width of cracks with a simple comparator gage, this procedure will not indicate slight changes in shape, which could be quite significant. Even slight changes in shape may be the result of significant changes in stress in a culvert, and there is a limit to the amount of distortion that can be accommodated without a reduction in structural load capacity. Although it will be difficult, time consuming and somewhat expensive, it is possible to accurately "map" the cross-sectional shape of a culvert so that computations may be made to determine and assess the significance of existing distortion. There are essentially the following three approaches that may be used to measure the shape of a culvert: (1) conventional survey equipment, (2) "Total Station" type survey equipment, and (3) "Close-Range" photogrammetry. Each of these has its advantages and disadvantages as described below. More detailed information on Total Station surveying and "close range" photogrammetry is provided in appendix B-33. Soil borings can also be taken to determine the condition of the soil around the culvert to determine if further movement is likely.

Conventional survey procedure - This is generally the least expensive, least accurate, and most time-consuming approach that may be undertaken. It frequently requires a three-person crew and considerable time and difficulty to set up the survey equipment so that direct measurements may be taken at points of interest inside of a culvert. Lighting conditions are frequently so low that measurements cannot be taken without supplemental light. Water flowing through a culvert presents a hazardous situation for the survey party who must access each point of interest. Perhaps the most serious limitation is on the feasibility of taking horizontal distance measurements inside of a culvert. Nonetheless, this approach may be viable if data is needed at only a few points within the culvert. It must also be recognized that it will be necessary to take the necessary measurements at exactly the same point several times and it will be necessary to calculate movement very accurately. It may be necessary to use at least second-order survey procedures to determine whether the culvert is actively distorting or whether it is stable in its present condition.

Total station survey procedure - This refers to a new class of electronic survey equipment that is probably now being used by most highway agencies, at least for special survey work. The principal piece of equipment is the instrument that is a combination of a transit, a level, an electronic distance-measurement instrument, and a theodolite, thus the name "Total Station." In addition, it may be purchased with an electronic data-gathering and storing device (sometimes called an electronic notebook) that may be brought back into the office for downloading data directly into a PC level computer for subsequent calculation of angles and distances between points. It is very important to note that it is possible to compute very accurate distances to and between two or more points that are, for example, all perpendicular and at varying angles to the line of sight of the instrument. Although it is necessary for each point of interest to be accessed, that may be done only once, at which time a reflector can be semi-permanently attached to the point. The instrument-person takes an electronic reading on the point with a laser-type beam of light. After setting the required reflectors, the entire survey crew may be only one person -- the instrument-person. Distance and angle measurements may easily be taken at many points on the inside periphery of the culvert as well as on the inlet or outlet features of the culvert, so that local distortion within the culvert as well as overall settlement of the entire culvert can be determined over a period of time from a series of measurements. Total-Station type equipment can be purchased for third-, second- and first-order levels of accuracy. Although the equipment is moderately expensive, in the range of $10,000 to $18,000, it is quite rugged and it may be used for a variety of special survey purposes. This type of equipment and approach may have some limitations for very long or small culverts, particularly for those that normally carry fast-moving water.

Close-Range photogrammetry procedure - This refers to a new type of photogrammetry work that frequently does not require that photos be taken from aircraft or the use of a stereoscope. This procedure involves: (1) setting targets/markers on the points of interest, (2) taking photo pairs with a special camera,

(3) printing (typically) 8 in x 10 in prints, (4) electronically scanning and digitizing the entire photo, including the targets, (5) entering the digitized numerical information into a special computer program, and (6) computing the distances to and between the reference target points. Except that completely different types of equipment are used for this procedure as compared with the Total Station survey procedure, the resulting numerical information is handled within a computer in a similar manner and comparisons of distances and relative movements between points can be computed over a period of time from photo sets that are taken at the appropriate time intervals.

With regard to advantages and disadvantages of the close-range photogrammetry procedure, each of the various pieces of equipment that are required are quite expensive, including the camera, the electronic digitizer and the computer program. The cost of the camera, which uses 35 mm size film, is in the range of $12,000. On the positive side, this procedure is (or can be) extremely accurate. Distances can be determined to thousandths of an inch when the camera is positioned within a few hundred feet of an object. There is some question as to whether this level of accuracy is economically justifiable.

It should be noted that this latter type of equipment has been purchased by the Ontario Ministry of Transportation and Communications--specifically for evaluation of displacement of highway culverts. Although this equipment was purchased within the past year or so, it has already been used in the field with promising results. Ministry personnel have indicated that this type of equipment and procedures is particularly useful for long culverts that are constantly carrying a quantity of fast-moving water. It was indicated that for these latter types of culverts, their field crews may have to set targets and take photos by floating through the culvert on a rubber raft. It may be necessary to use a powerful flash or strobe lights to illuminate the reflectorized targets so that they will show up in the photo prints. The number of culverts in this type of location was important in the Ministry's selection of the close-range photogrammetry type of equipment over the "Total Station" type of survey equipment.

Measurement of chords or chord ordinates with simple tapes and rulers is normally adequate to monitor shape change and is quite fast and inexpensive. This method is described in both the *Culvert Inspection Manual*[(1)] and *Evaluation of Corrugated Metal Structures (In-Situ)*.[(2)]

ANALYSIS OF PROBLEMS AND SOLUTIONS

The process of evaluating problems and alternative solutions consists of four steps: (1) determine the type and the cause of the problem(s); (2) select possible repair method(s); (3) obtain all the information required to evaluate the alternatives; and (4) analyze the alternatives. Figure 3.2 shows the process graphically.

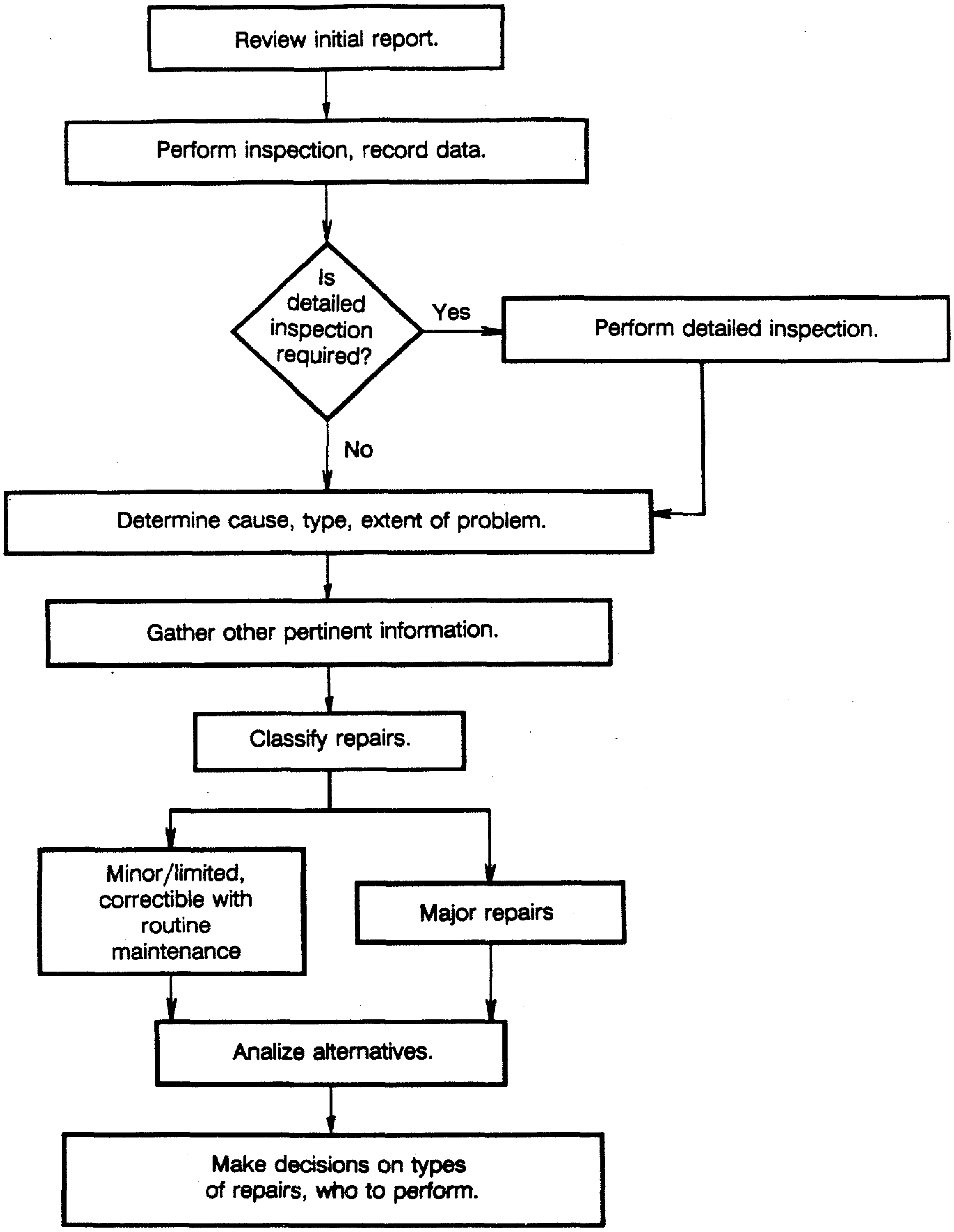


Figure 3.2 Analysis of problems and solutions. Overall process.

Determining the Cause and the Type of Problem

Based on the initial report of a problem, the agency should investigate further. This process includes positive identification of the symptoms, deciding on the need for and conducting additional investigation, determining the underlying cause, and finally, identifying the type of problem that must be addressed.

The process of problem identification are shown in Figure 3.3.

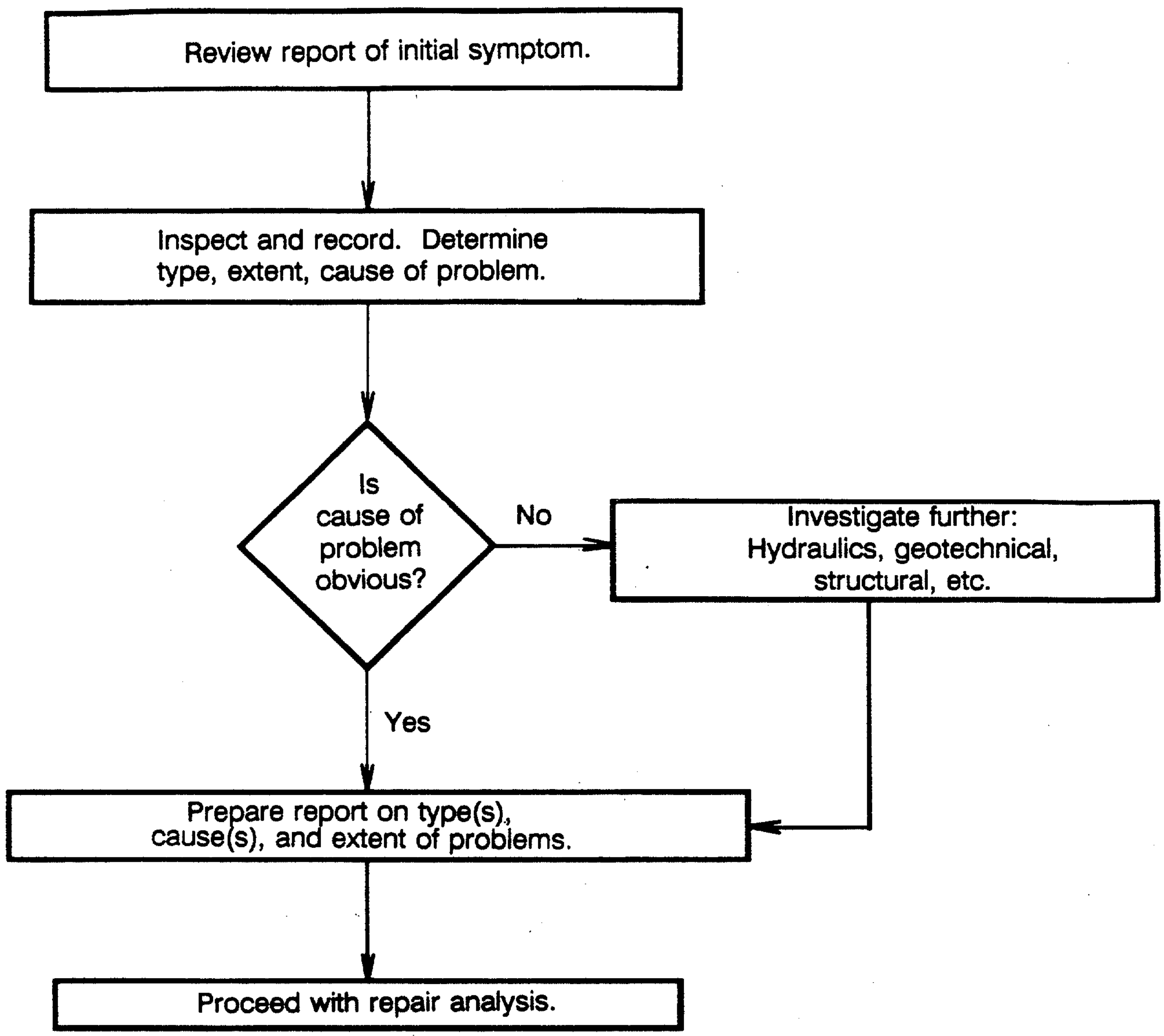


Figure 3.3. Process for identifying problems.

The elements are:

1. Review the report of the symptoms that are evident at the site. The report may be the result of inspection by agency staff or contractors, or it may come from highway users or property owners.

2. If the report is not the result of an inspection, the culvert should be thoroughly inspected and the symptoms and conditions documented. The underlying cause of the symptoms may be immediately evident, in which case this also can be documented. However, if the inspection does not reveal the underlying cause or extent of the damage, a detailed investigation must be undertaken.

3. When the cause has been positively identified, determine the type of problem for which a solution must be found.

4. Proceed to the analysis of the problem to determine the type and method of repair to be used.

Analysis of Potential Solutions

Knowing the type and the extent of the problem, the next step is to analyze potential solutions and decide upon the best course of action. The process, as shown in figure 3.4 consists of the following:

1. Gather all basic information: cause, type of problem, maintenance history, design data, and urgency of action required.

2. Classify repair actions: either routine/minor, which can be accomplished by readily available resources; or major/extensive, which requires further consideration of what to do and how it can best be accomplished.

3. Look at the alternatives for repair. Obtain information on materials, type of labor, available forces, costs. Decide on the method of repair and if it will be accomplished by in-house or contract forces.

Guidance on the steps for analyzing solutions is described in the following paragraphs.

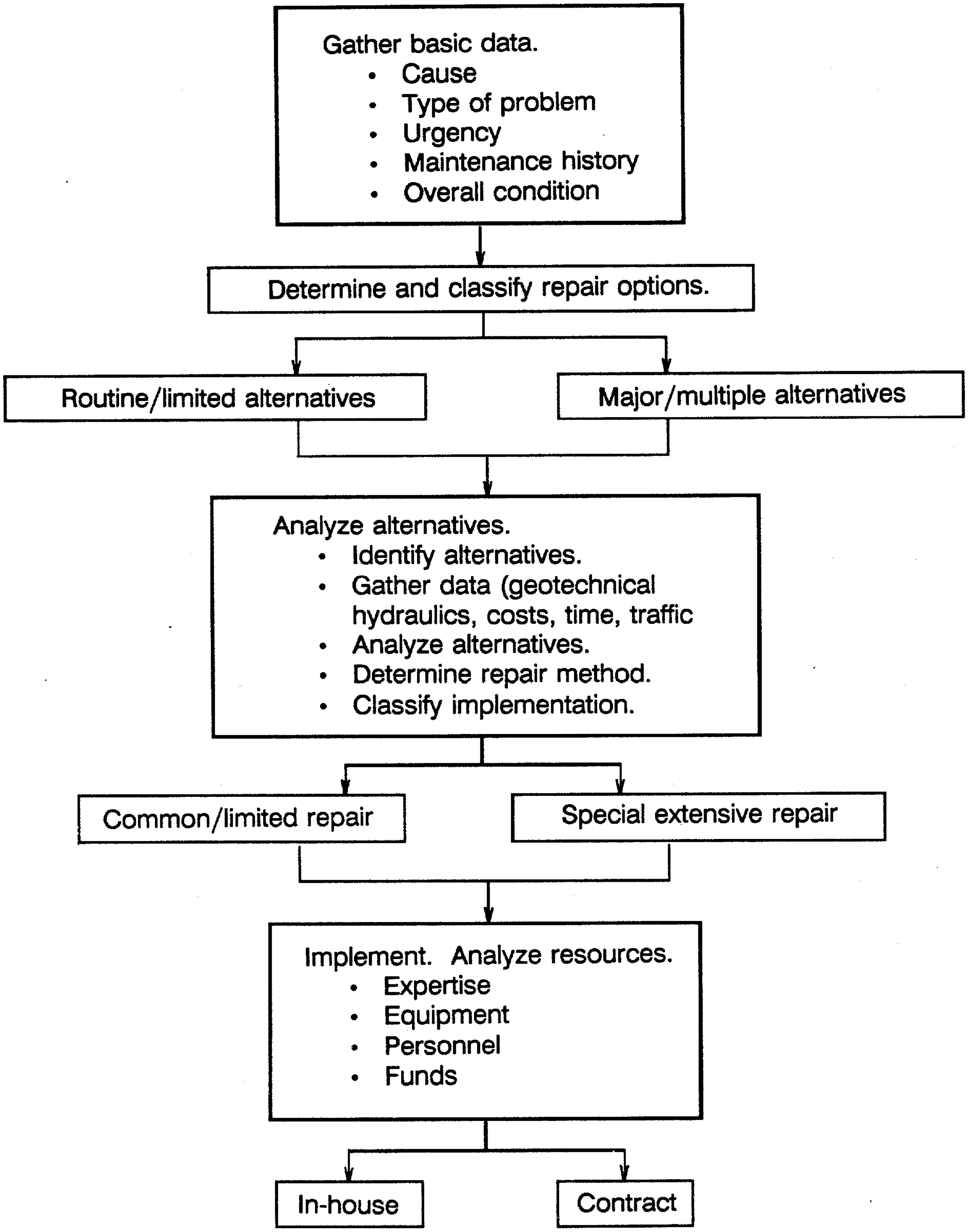


Figure 3.4. Process for analysis of potential solutions.

Determine and classify repair actions - Knowing the components of the culvert that are in question, refer to the applicable subsection in chapters 5 and 6. The following actions may be taken:

- Select the type or types of problem and look at the actions required.
- Determine if one or more types of actions are required. Assess the actions to determine if spot repairs will solve the problem or if more major treatment, such as reconstruction of the lining, appears warranted.

If spot repairs (patching, bolt replacement, etc.) are indicated, there is usually one method by which repairs can be made and no economic analysis is required. Prior local experience should indicate the best method. These minor repairs are similar to preventative maintenance tasks.

If a major, extensive repair is indicated, continue with the analysis as follows:

Gather basic information. From the field inspection, office records, and any detailed investigations, prepare a summary of pertinent information including:

- Cause, type, and extent of the problem(s);
- History of prior maintenance and repairs; and
- Urgency of repair from safety and hydraulic standpoints.

Analyze alternative. Obtain the required information. The required information for major decisions includes:

- Cost of materials, labor, and equipment;
- Availability of materials, labor, and equipment;
- Urgency to complete the repair; and
- Experience/capability of the agency work force.

Agency maintenance performance standards and other cost records should provide sources of such information. As applicable, contractor and suppliers should be contacted.

Develop alternative solutions. Several steps should be followed in developing alternatives.

1. For each alternative the following information should be tabulated:

   - Cost (in-house or contract);

   - Time frame (days or weeks) required;

     - must be completed (urgency);
     - prework (ordering, mobilization, etc); and
     - repair and clean-up.

   - Other information including proprietary product/method information.

2. Select the apparent best alternative.

3. Determine if the work can be done in-house with a standard crew and methods or if special arrangements may be required.

   Sometimes the best method is obvious, based on the time frame or cost considerations. Other cases may require a more rigorous analysis (more accurate), such as when a formal contract may be necessary.

4. If further analysis is required, determine the economics of doing the work in-house with special crews, materials, etc. vs contracting all or part of the work.

   A form for summarizing analysis information is shown in table 3.1. Local standard forms or modifications to the sample form or local forms should be made as applicable.

Table 3.1. Summary of information on alternatives.

ITEM	ALTERNATIVE 1	ALTERNATIVE 2	ALTERNATIVE 3
Description of Alternative			
1. Cost			
a. In-house			
b. Time/materials contract			
c. New contract			
2. Time Frame (days/week)			
a. Must be completed			
b. Pre-work completed			
c. Repair & clean-up			
3. Method of Accomplishment			
a. Can do in-house: standard			
b. Supplement in-house: standard			
c. Must contract			
d. Proprietary product/method			
4. Other information			
a. Availability of in-house forces b. Ability of in-house forces			

APPROACHES

The condition of roadway approaches may be indicative of current or future problems with culverts. Defects in the approach roadway can signify possible structural or hydraulic disfunctions. Inspection of the approach roadway should include an evaluation of both roadway condition and functional adequacy. Table 3.2 shows symptoms that occur on approaches that may be indicative of culvert problems.

The approach roadway and embankment should be inspected for the following as indicators of culvert defects:

1. Condition of roadway and embankment

   - Sag in roadway or guardrail;
   - Cracks in pavement;
   - Pavement patches or evidence that the roadway has been built up; and
   - Erosion or failure of side slope.

2. Functional requirements

   - Insufficient clearance;
   - Inadequate shoulder profile; and
   - Lack of safety features.

Settlement is a common problem with bridge and culvert approaches and is often due to poorly compacted embankment material. It can result from settlement of the culvert in soft foundation material, displacement of soft material, or piping along the culvert. Sudden dips or sags, cracks, pavement patches, and other symptoms of settlement may indicate a deteriorating culvert.

Settlement of backfill material and movement of the structure can have serious structural consequences in culverts. A stable soil envelope around culverts is necessary for side support that will minimize deflection of flexible culverts and reduce settlement of rigid or flexible culverts.

Depressions, pavement cracks, and other problems indicate that structural problems with the culvert might exist. However, the structural significance of approach defects depends upon the other findings of the inspection. Therefore, the underlying causes of approach defects should be determined and corrected.

Table 3.2. Identifying approach problems.

SYMPTOM	POSSIBLE CAUSE
<u>Embankment</u>	
• Deterioration of roadway shoulders and embankment	• Settlement, possible deterioration of the culvert barrel
• Piping, undercutting, and eventual rotation of the culvert footing, or severe differential settlement	• Erosion
• Piping and exposure of culvert ends	• Slope slippage
<u>Guardrail</u>	
• Bends, sags, or depression of guardrail	• Settlement, possible deterioration of the culvert barrel
<u>Pavement</u>	
• Cracking in rigid pavement • Irregular settlement in flexible pavement • Pavement patches • Evidence of built-up pavement	• Settlement of material under pavement caused by poorly compacted embankment material; displacement of soft material; piping along barrel; deteriorating culvert, erosion; slope slippage.
<u>Functional Evaluation</u>	
• Safety hazard	• Width of roadway surface too narrow; culvert ends too close to traveled way • Steep embankments

Some culvert designs use single or multiple-cell cast-in-place or precast concrete box sections, which serve as a dual function of carrying both water and traffic. The box structure is designed to carry full traffic loads without the benefit of an earth fill with a customary roadbed of base and sub-base courses of aggregate to distribute the wheel loads. The top of the box structure may have an additional layer of asphaltic concrete (AC), which was intended to provide a leveling and wear-resistant topping that would also provide protection against corrosion and freeze-thaw damage to the Portland cement concrete. Nonetheless, several types of deterioration may develop in the top flange of box culverts that carry traffic. Such culverts should be inspected to detect and evaluate cracking, spalling, scaling, corrosion, joint leakage and other types of distress that may affect both the structural and hydraulic capacities of the structure.

Embankments

Deterioration of roadway shoulders and embankments may also indicate defects in the culvert. Dips, sags, and other depressions can be a sign of culvert distress. Erosion can be a cause of piping, undercutting and eventual rotation of the culvert footing, or severe differential settlement. Slope slippage can cause piping and exposure of culvert ends.

Guardrails

Bends, sags, and displacement of guardrail may be an indication of settlement and, in turn, a deteriorating culvert. Distortions can often be detected by sighting along the guardrail.

Pavement

The type of defects that are found in the approaches may vary with pavement type, structure type, structure shape, maintenance history, and other factors. Rigid pavements (concrete) bridge over minor subsurface voids while flexible pavements (asphalt) have little bridging capability. Settlement of material beneath the pavement can lead to cracking in rigid pavements and irregular settlement in flexible pavements.

Flexible culverts will deflect if adequate lateral support is not provided by the surrounding soil. This may result in a loss of support for the approach pavement and usually produces settlement over the culvert, as illustrated in figure 3.5. Inadequate compaction of backfill for rigid culverts usually results in settlement beside the culvert, as shown in figure 3.6.

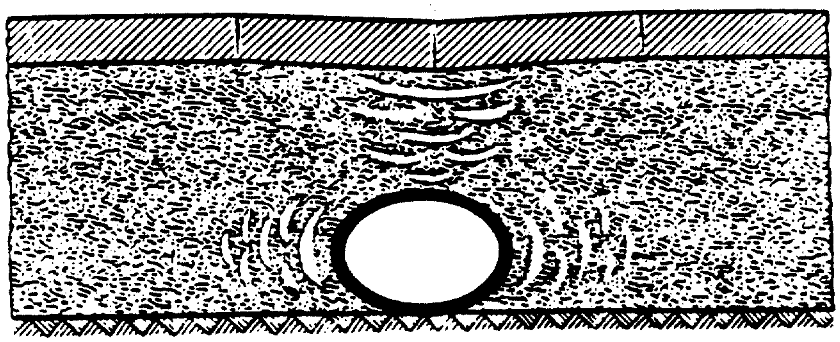


Figure 3.5. Pavement failure due to inadequate compaction of material quality adjacent to flexible pipe.[3]

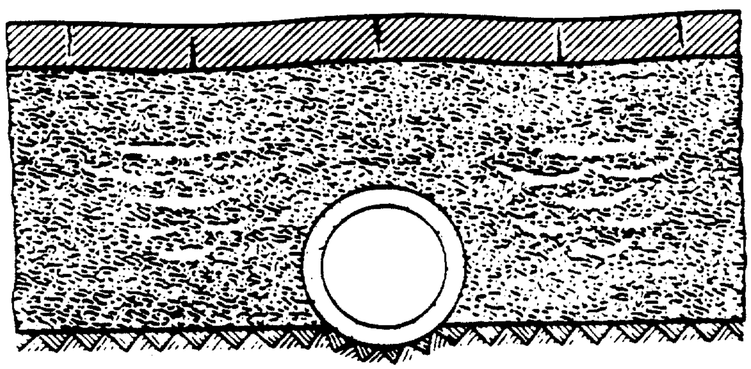


Figure 3.6. Pavement failure due to inadequate compaction of material quality adjacent to rigid pipe.[3]

Good performance of flexible culverts is related to symmetry close to the design shape, although round flexible pipe can stand some oval deflection and still be structurally stable. Culverts may deflect downward and displace material laterally. This may result in roadway settlement. However, the deeper the culvert, the less its deflection will affect the pavement above. For circular culverts, such settlement generally occurs directly over the culvert. Vertical ellipses, pear-shaped culverts, and arches may tend to peak or push up in the center, resulting in settlement and loss of pavement support beside the culvert. Pavement patches may be an indication that progressive settlement has occurred or is occurring, particularly if the pavement has been patched repeatedly.

Functional Evaluation and Retrofit

To improve a culvert to its maximum effectiveness, functional considerations, or how well it performs in terms of traffic safety, must be taken into account. Geometric design features, such as roadway width and alignment, as well as placement of culvert ends and traffic safety features, should be evaluated.

One of the most critical safety issues is the width of the roadway surface over the structure as compared to the width of the surface as it approaches the structure. Structures that are more narrow than the roadway or that have culvert ends that are close to the traveled way pose a substantial hazard to traffic. Headwalls that project above the surface of the roadway or are higher than the embankment become a fixed object hazard and can cause a motorist to lose control of a vehicle. Steep embankments should be treated with guardrail.

Common methods for safety-treating culverts include relocating the ends so that they are farther away from the edge of the roadway, installing guardrails or other barriers, modifying the opening to conform to the face of the slope, and installing grates that are structurally adequate to carry a vehicle over the opening. However, grates may require frequent cleaning and repair and may increase upstream flooding. In addition, modification of the end of the structure may reduce its structural integrity. Therefore, careful consideration should be given any safety treatment.

END TREATMENT AND APPURTENANT STRUCTURES

Several types of end treatments are commonly used at culvert inlets and outlets, ranging from no treatment to a constructed-in-place end structure. Table 3.3 shows symptoms and possible causes of problems in end treatments and appurtenant structures.

End structures are used to reduce erosion, retain fill material, inhibit seepage, improve hydraulic efficiency when the culvert operates under inlet control, provide structural stability to the culvert ends, and improve the appearance of the culvert. The capacity of culverts may be reduced by accumulations of drift and debris at the inlet end or by slope failure. Inlet ends may also be damaged by impact from floating debris, and either end can be damaged by mowing equipment and other maintenance vehicles. However, common end treatments include the following types:

Projecting Pipes

This type of end treatment does not have a structure attached to the ends of the culvert barrel. The barrel simply extends beyond the face of the embankment. Inspection of culverts with projecting ends should note the extent and location of any

Table 3.3. Identifying end treatment and appurtenance problems.

SYMPTOM	POSSIBLE CAUSE
<u>Projecting Pipes</u>	
• Piping	• Seepage along exterior culvert barrel • Seepage through open joints
• Uplift of culvert ends – Flexible culvert operating in inlet control – Flexible culvert with submerged outlet	• Hydrostatic uplift forces not balanced by a counter weight
<u>Endwalls and Wingwalls</u>	
• Cracking, tipping or separation of the culvert barrel from the headwall	• Undermining and settlement
• Voids behind the wall	• Loss of backfill
• Toe out of base	• Scour in front of wall
• Outward movement at the top	• Damage to anchor rods
<u>Mitered or Beveled Ends</u>	
• Deformation of ends	• Buoyant force damage due to reduced structural integrity of beveled end
<u>Aprons</u>	
• Undermining, settlement, or movement of concrete slabs	• Scour
• Displacement of stones in riprap	• High velocities
• Displacement of partially full baskets, wire deterioration	• Head cutting
<u>Mitered or Beveled Ends</u>	
• Deformation of ends	• Buoyant force damage due to reduced structural integrity of beveled end

erosion or undercutting around the ends of the culvert barrel, deterioration of the fill slope, accumulations of drift and debris, and damage to the ends of the barrel. Probing will indicate the actual rather than apparent depth of scour, since scour holes may fill with loose sediment or debris as high flows subside. The unprotected embankment slope may cause problems if it is eroded or saturated by flowing water.

Piping - Piping is caused by seepage along the exterior culvert barrel. Voids and hollows are formed under and around the outside of the pipe as fill material is lost. During periods of ponding and high velocity, erosion inside the fill may cause failure of the culvert or the embankment. Piping can also occur through open joints in the culvert barrel. Piping can be controlled by installing headwalls, curtain walls, bulkheads, or driving sheet piling at the inlet end of the culvert. Sealing the joints or using an anti-seep collar may also be necessary. Any voids under and around the culvert should be located and filled to prevent settlement and misalignment.

Buoyant force damage - In flexible pipe culverts, the pipe may be subject to buoyant forces that can cause uplift of the culvert end if the material surrounding the culvert is saturated or eroded. Damage due to buoyant forces usually occurs at the inlet end but may occur at submerged outlets. The potential for buoyancy failures due to hydrostatic uplift forces is greatest for flexible culverts that operate in inlet control and have no counterweight such as concrete headwalls or endwalls. The failure potential increases with the steepness of the culvert slope, depth of the potential headwater (which may be increased by debris blockage), flatness of the fill slope over the upstream end of the culvert, and the height of the fill.

Endwalls and Wingwalls

Headwalls and wingwalls may be used to retain the fill, resist erosion, improve hydraulic characteristics, resist uplift, and resist horizontal forces that tend to separate sections of precast culvert pipe. Headwalls are usually cast-in-place concrete but may also be constructed of timber, masonry, or other materials including precast concrete. Metal headwalls are fairly common on metal box culvert shapes.

Headwalls and wingwalls should be inspected for any signs of undermining and settlement such as cracking, tipping, or separation of the culvert barrel from the headwall. Settlement places additional stresses on the ends of the culvert and may cause blockage or end failure. Damaging ponding or washing out of the fill could result. Separations between the barrel and the headwall that expose fill material can be particularly serious and should be reported for special attention. Such separations permit the loss of the supporting soil, which could lead to failure anywhere along the length of the culvert. Additionally, headwalls should be high enough and long enough to protect the embankment from erosive flows and to keep the embankment from spilling over and blocking the flow. Metal headwall and wingwall inspections should include checking for voids behind the walls, which may indicate a loss of backfill; toe-out of the base, which may indicate scour in front of the wall; and outward movement of the top, which may indicate damage to anchor rods.

Mitered Ends

A mitered end treatment is a culvert end that has been cut to match the embankment slope. Slope paving is generally used with mitered ends, particularly with corrugated metal pipe culverts. Some agencies refer to this treatment as a beveled end.

Culverts with mitered end treatments and those with pipe sections should be inspected for the same types of problems as culverts with projecting ends. In addition, metal pipe culverts with either a mitered end or skewed end should be inspected for deformation. Cutting the ends to form a mitered or skewed treatment reduces the structural strength of the ends of a corrugated metal culvert. The cut ends cannot act as a ring in compression but act essentially as cantilevered retaining walls. If there is no fill-slope stabilization or reinforcement of the cut ends, uplift water forces may cause bending and deformation may occur of the culvert.

However, the Handbook of Steel Drainage and Highway Construction Products, Fourth Edition, states that:

> "Designing the ends of a flexible culvert requires additional considerations beyond those addressed in the ring compression design of the culvert barrel. End treatment design must also consider any unbalanced soil loadings due to skews or excessive cross slopes; the residual strength of any skew cut or bevel cut ends employed; as well as possible hydraulic action due to flow forces, uplift and scour."

The publication discuses the unbalance of soil loads on pipes skewed to an embankment. The following chart, Figure 3.7, is provided showing suggested limits for skews to embankments unless the embankment is warped for support or full headwalls are provided. For most applications square end pipes are recommended.

The publication suggests:

> "All types of bevel cut ends typically require protection, especially when hydraulic flow forces are anticipated. The cut portion should be anchored to slope pavement, slop collars or headwalls at approximately 19" intervals. Cutoff walls or other types of toe anchorage are recommended to avoid scour or hydraulic uplift problems.

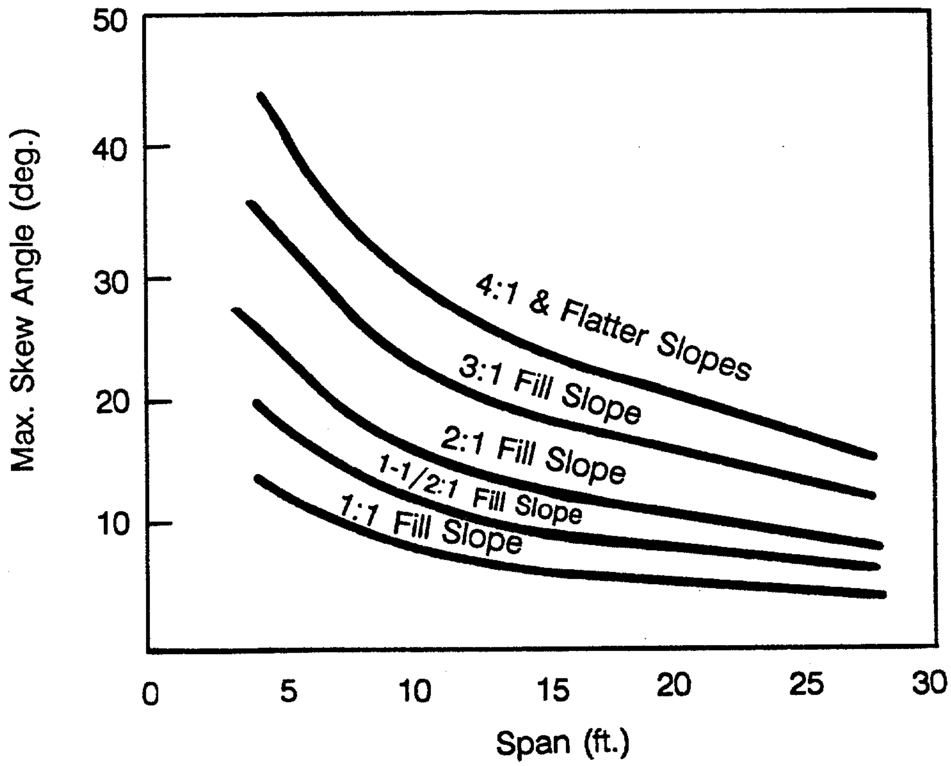


Figure 3.7. Suggested limits for skews to embankments unless the embankment is warped for support or full headwalls are provided.[4]

Aprons

Aprons are used to reduce erosion at the inlets and outlets of culverts and to improve hydraulic efficiency. Aprons may consist of a concrete slab, grouted or ungrouted riprap, or other material. Most aprons include a cutoff wall to protect against undermining.

Aprons should be checked for signs of undermining, settlement, or movement. Dry stone or ungrouted riprap should be inspected for displaced or moving stones. A scour hole with a downstream mound will often form in riprap aprons and should generally not be disturbed by maintenance activities. Additional rock may be needed if the scour has penetrated through the riprap. Wire-enclosed riprap, gabions, should be checked for displaced baskets, partially full baskets, and wire deterioration. Concrete slabs should be checked for undermining and settlement. Undermining is checked by probing along the edge of the apron. Settlement can be detected by checking for cracks and signs of movement at the joint with the headwall. The joints between concrete aprons and headwalls should also be checked to ensure that they are watertight. In locations where fish passage is a concern, depth of flow over aprons should be maintained to allow migration of fish.

Other

Other appurtenant structures are used with end treatments to improve drainage or reduce erosion. Typical items are listed below.

Ditches - Flumes and side ditches may be used to direct roadside drainage to the stream channel. A flume is a permanent channel, usually lined with concrete or riprap, constructed to conduct concentrated runoff from the top to the bottom of a slope without causing erosion on or below the slope. A ditch is a permanent channel designed to carry concentrated flows without erosion. This definition includes both man-made channels and natural channels that are modified to accommodate increased flows generated by land development. Ditches may be either natural or lined channels. These structures should be cleaned regularly to remove debris or sedimentation that would impede flow or cause the ditch to overflow its banks.

Excessive quantities of sediment in ditches can indicate uncontrolled erosion upstream, possibly from land undergoing highway construction or other land development. Sediment causes costly damage to private and public lands, culverts and storm drainage systems, municipal and industrial water supply reservoirs, recreational impoundments, and navigable channels as well as altering the aquatic environment. Therefore, in addition to the regular cleaning of permanent channels, sources of excessive quantities of sediment should be determined and controlled.

Energy dissipators - Energy dissipators are used to reduce the velocity of running water. When water velocities are likely to cause erosion of the stream bed downstream from the culvert or in open channels, energy dissipators may be employed to transform the kinetic energy of water to potential or dissipated energy, resulting in a velocity reduction.

The objective is to return the flow to the downstream channel in its natural condition. This also implies guarding against over-design that would reduce flow below natural or normal channel conditions. In locations concerned with fish passage, care must be exercised to avoid constructing a physical barrier to fish migration. However, excessive velocity also presents a barrier to fish passage and, therefore, it should be controlled.

Energy dissipators should be considered as part of a larger design system that includes the culvert, channel protection requirements upstream and downstream, and, in some cases, a debris-control structure. The interrelationship of the various parts of individual designs within the system must be considered. For example, the addition of an energy dissipator may change culvert performance and channel protection requirements. Some debris-control structures can cause energy losses not anticipated. Changes in the culvert design can reduce the need for energy dissipators. All these factors should be considered.

Numerous energy dissipation solutions might be used in combination, such as a combination of a dissipator and channel protection. The area in the vicinity of the culvert outlet should be checked for two types of scour: local scour, which is the result of high-velocity flow at the culvert outlet, and general channel degradation, which is a long-term lowering of the stream channel through natural processes.

WATERWAYS

The primary function of most culverts is to carry surface or stream water from one side of a roadway embankment to the other side. The hydraulic design of culverts usually involves the determination of the most economical size and shape of culvert necessary to carry the design discharge without exceeding the allowable headwater depth. It is essential that the culvert be able to handle the design discharge. Table 3.4 shows possible problems often found in waterways.

If the culvert is blocked with debris or the stream changes course near the ends of the culvert, the culvert may be inadequate to handle design flows. This may result in excessive ponding, flooding of nearby properties, and washing out of the roadway and embankment. In addition, changes in upstream land use such as clearing, deforestation, and real estate development may change the peak flow rates and stream stability. It is, therefore, important to inspect the condition of the stream channel and evaluate the ability of the culvert to handle peak flows.

The stream channel should be inspected to determine whether conditions exist that would cause damage to the culvert or surrounding properties. Factors to be checked include culvert location (horizontal and vertical alignment), scour, and accumulation of sediment and debris. These factors are closely related to each other. Poor culvert location can result in reduced hydraulic efficiency, increased erosion and sedimentation of the stream channel, and increased damage to the embankment and surrounding properties. A brief discussion of each of these factors is provided.

Horizontal Alignment

The condition of the stream banks and any bank protection at both ends of the culvert should be checked. Evidence of erosion and indications of changes in the direction of the stream channel should also be observed. Sketches and photographs should be used to document the condition and alignment at the time of inspection. Abrupt changes in stream alignment retard flow and may require a larger culvert since these alignment changes cause increased erosion along the outside of the curve, damage to the culvert, and increased sedimentation along the inside of the curve. Where sharp channel curves exist at either the entrance or exit of a culvert, the inspector should check for sedimentation and erosion.

Table 3.4. Identifying waterway problems.

SYMPTOM	POSSIBLE CAUSE
<u>Horizontal Alignment</u> • Erosion • Retarded flow • Sedimentation	• Abrupt changes in stream alignment; obstruction in streambed; or excessive velocities cutting into stream bank.
<u>Vertical Alignment</u> • Scour • Accumulation of sediment	• Excessive velocities • Low velocities
<u>Scour</u> • Local scour • General scour or headcutting	• Obstruction that causes a constriction of flow • Downstream lowering of the channel
<u>Sediment and Debris</u> • Blockage of the culvert • Local scour in the stream channel • Scour of the streambed or roadway embankment • Changes in the channel alignment • Reduced capacity of the culvert • Increased chances of damage from buoyant forces	• Deposited debris or settlement

Vertical Alignment

Vertical alignment problems are usually indicated by scour or accumulation of sediment. Culverts on grades that differ significantly from the natural gradient may present problems. Culverts on flat grades may have problems with sediment build-up at the entrance or within the barrel. Culverts on moderate and steep grades generally have higher flow velocities than the natural stream and may have problems with outlet scour. Scour and sediment problems may also occur if the culvert barrel is higher or lower than the stream bed.

Scour

Erosion generally refers to loss of streambank material and a lateral movement of the channel. Scour is more related to a lowering of the stream bed due to the removal and transporting of stream bed material by flowing water. Scour can occur at both the inlet and the outlet end of a culvert.

A culvert barrel normally constricts the natural channel and forces the flow through a constricted opening. As the flow contracts, areas of high velocity strike against the upstream slope and may tend to scour away the embankment adjacent to the culvert. A scour hole may also form upstream of the culvert floor as a result of the acceleration of the flow as it leaves the natural channel and enters the culvert.

Scour at culvert outlets is a common occurrence and may be classified into two types: local scour and general scour.

- Local scour is located at and usually is caused by a specific flow obstruction or object that causes a constriction of the flow. Local scour occurs primarily at the culvert outlet.

- General scour extends farther along the stream and is not localized around a particular obstruction. General scour can involve a gradual, fairly uniform degradation or lowering of the stream channel. It can also result in abrupt drops in the channel that move upstream during peak flows. This type of scour is referred to as head cutting. Head cutting may be a serious problem if it is occurring in the channel downstream from the culvert, since it may threaten the culvert as it moves upstream. Head cutting may also occur in the stream channel immediately upstream from depressed inlets. While upstream head cutting is usually not as serious a problem for the culvert, it can affect upstream structures and properties. It should be noted that downstream channel degradation is not caused by the culvert."

The upstream channel should be checked for scour that may undermine the culvert or erode the embankment. Scour that is undermining trees or producing sediment that could block or reduce the culvert opening should also be noted. The stream channel below the culvert should be checked for local scour caused by the culvert's discharge and for general scour that could eventually threaten the culvert.

Sediment and Debris

Deposits of debris or sediment that could block the culvert or cause local scour in the stream channel should be noted. Accumulations of debris and sediment in the stream may cause scour of the streambanks and roadway embankment, or could cause changes in the channel alignment. Debris and sediment accumulations at the culvert inlets or within the culvert barrel reduce the culvert's capacity and may result in excessive ponding. It also increases the chances for damage due to buoyant forces. Downstream obstructions that cause water to pond at the culvert's outlet may reduce the culvert's capacity. Debris collectors are used in some culverts so that the opening is not blocked by floating materials.

Hydraulic Adequacy

The preceding paragraphs dealt with evaluating the condition of the stream channel and identifying conditions that could cause damage to the culvert or reduce the hydraulic efficiency of the culvert. A closely related condition that must be evaluated is the hydraulic adequacy of the waterway or ability of the culvert to handle peak flows. The evaluation should include observation of high water marks, changes in the watershed, and changes in the stream channel that might affect the hydraulic performance.

Partial flow - Culverts are designed according to standards related to peak flows. Culverts on interstate highways are designed for a 50 year flood frequency and checked for the 100 year storm. Primary road culverts are generally designed for a 25 year storm and checked for a 50 year flood. Culverts on secondary roads are usually designed for a 5 to 10 year flood and checked for the 25 year storm. However, most often, culverts flow only partially full.

Minimum velocity is a consideration during periods of partial flow. Sediment tends to precipitate out during reduced flows and velocities and sediment may build up in the culvert barrel. In addition, in culverts subjected to low flows or standing water with aggressive chemicals, corrosion damage may be extensive. Some culvert barrels are designed with a low-flow trough to increase velocity and remove sediment or chemically-aggressive flows.

Peak flow - Ideally, culverts should be checked to evaluate hydraulic adequacy during or immediately after peak flows to determine whether water is being ponded to excessive depths, flooding adjoining properties, or overflowing the roadway. High water marks are needed to define the upstream pond elevation and the downstream tailwater elevation. High water marks in the culvert barrel, in the draw-down area near the inlet, or near turbulent areas at the outlet are generally misleading. An inspection can also determine high water levels for peak flows by looking for debris caught on fences, lodged in trees, or deposited on the embankment. Indications of excessive ponding, flooding, or overtopping of the roadway should be investigated to determine the cause.

Changes in the drainage parameters may have an effect on the discharge that culverts must handle. Replacement of an upstream culvert with a larger structure may eliminate ponding at the upstream site, causing more water to reach the downstream culvert sooner. Land-clearing construction, channel improvements, or removal of upstream dams or sediment basins may also affect discharge rates. Similarly, changes in land use may increase or decrease the amount of rainfall that infiltrates the ground and the amount that runs off. Changes a considerable distance upstream may affect the performance of downstream structures. Obstructions downstream from a culvert that back water up to the culvert may also affect the performance of the culvert. In addition, accumulation of debris and sediment at the inlet or within the culvert barrel reduces both the size of the opening and the culvert's capability to handle peak flows.

CORRUGATED METAL PIPE CULVERTS

Corrugated aluminum and corrugated steel culverts are classified as flexible structures because they respond to and depend upon the soil backfill to provide structural stability and support to the culvert. The flexible corrugated metal acts essentially as a liner for the hole through the soil. The liner acts mainly in compression. It can carry a large ring compression thrust, but very little bending or moment force. (Rib-reinforced box culverts are exceptions.) Inspection of the culvert determines whether the soil envelope provides adequate structural stability for the culvert and verifies that the "liner" is capable of carrying the compressive forces and protecting the soil backfill from water flowing through the culvert. Verification of the stability of the soil envelope is accomplished by checking culvert shape. Verification of the integrity of the "liner" is accomplished by checking for pipe and plate culvert barrel defects.

Shape Distortion

The single most important feature to observe and measure when inspecting corrugated metal culverts is the cross-sectional shape of the culvert barrel. The corrugated metal culvert barrel depends on the backfill or embankment to maintain its proper shape and stability. When the backfill does not provide the required support, the culvert will deflect, settle, or distort. Shape changes in the culvert, therefore, provide a direct indication of the adequacy and stability of the supporting soil envelope. By periodic observation and measurement of the culvert's shape, it is possible to verify the adequacy of the backfill. Symmetrical shape and uniform curvature around the perimeter are generally the critical factors. If the curvature around the structure becomes too flat, and/or the soil continues to yield under load, the culvert wall may not be able to carry the ring thrust without either buckling inward or deflecting excessively to the point of reverse curvature. Either of these events leads to partial or total failure. An arc of a circular pipe or other shaped structure will be stable and perform as long as the soil pressure on the outside of the pipe is resisted by the compression force in the pipe at each end of the arc.

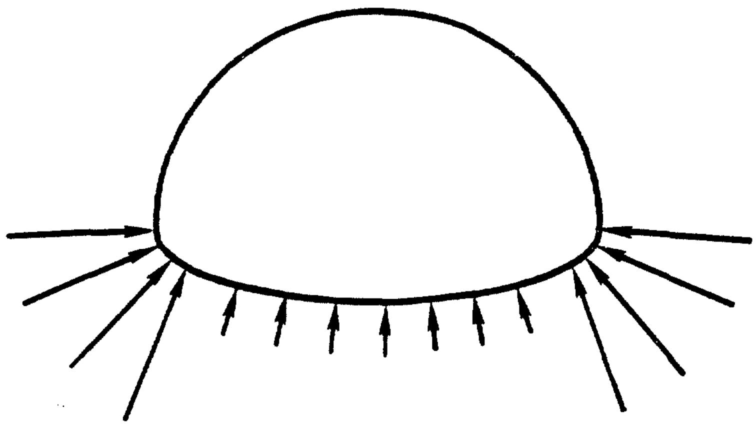
Round and elliptical - The structural integrity of corrugated metal culverts and long-span structures is dependent upon their ability to perform in ring compression and their interaction with the surrounding soil envelope.

Round and vertically elongated pipes are expected to deflect vertically during construction resulting in a slightly increased horizontal span. Round pipes are sometimes vertically elongated five percent to compensate for settlement during construction. It is frequently difficult to determine in the field if a pipe was round or elongated when installed. Large round pipes may appear to be elongated if they were subjected to minor flattening of the sides during backfill.

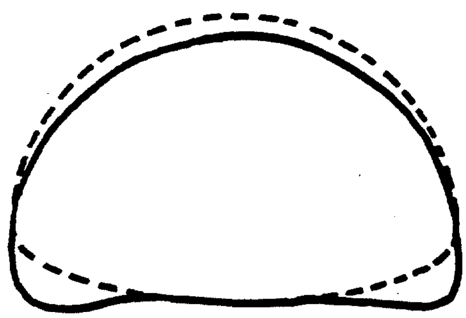
In shallow cover situations, adequate curvature in the sides is the important factor. The soil pressures on the sides may be greater than the weight of the shallow fill over the pipe. The result is a tendency to push the sides inward rather than outward as in deeper buried or round pipes. Side flattening can be caused by unstable backfill. A deteriorated invert may have contributed to the problem by reducing the pipe's ability to transmit compressive forces.

Flattening of the top arc is an indication of possible distress. Flattening of the invert is not as serious. Pipes not installed on shaped bedding will often exhibit minor flattening of the invert arc. However, severe flattening of the bottom arc would indicate possible distress.

Pipe arch - The pipe arch is a completely closed structure but is essentially an arch. The load is transmitted to the foundation principally at the corners. The corners are much like footings of an arch. There is relatively little force or pressure on the large radius bottom plate. The principal type of distress in a pipe arch is a result of inadequate soil support at the corners where the pressure is relatively high. The corner may push down or out into the soil while the bottom stays in place. The effect will appear as if the bottom pushed up. This problem is illustrated in figure 3.8.



Pressure is much greater at corners than at invert.



With inadequate corner support, corners sink and spread, invert stays in place.

Figure 3.8. Settlement and invert distortion of pipe arches.[1]

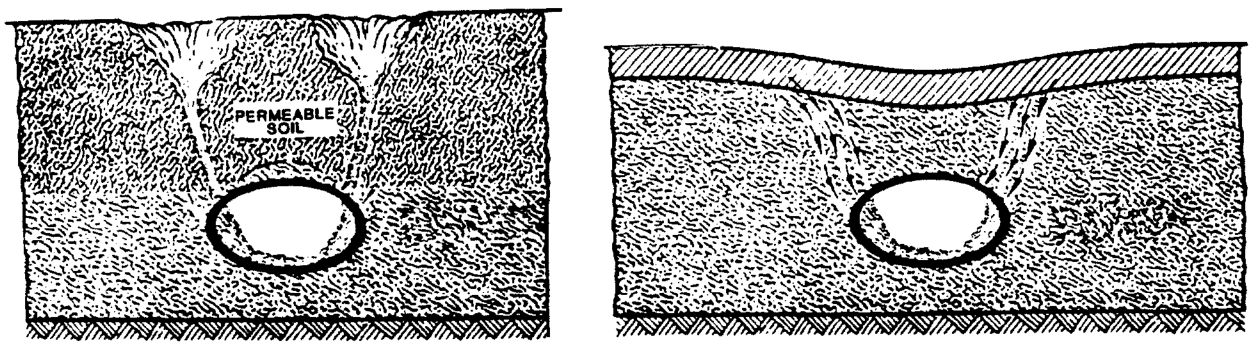
Defects in the culvert barrel itself, which can influence the culvert's structural and hydraulic performance, are discussed in the following paragraphs.

Misalignment

The vertical alignment should be checked visually for sags and deflection at joints. Poor vertical alignment may indicate problems with the subgrade beneath the pipe bedding. Sags trap debris and sediment and may impede flow. Since most highway culverts do not have watertight joints, sags that pocket water could saturate the soil beneath and around the culvert, reducing the soil's stability. The horizontal alignment should be checked by sighting along the sides for straightness. Vertical alignment can be checked by sighting along bolt lines. Minor horizontal and vertical misalignment is generally not a significant problem in corrugated metal structures unless it causes shape or joint problems. Occasionally culverts are intentionally installed with a change in gradient.

Joint Defects

Field joints in factory-produced pipe serve to maintain the water conveyance of the culvert from section to section, keep the pipe sections in alignment, keep the backfill soil from infiltrating, and help prevent sections from pulling apart. Joint separation may indicate a lack of slope stability. Indications of joint defects include open joints, deflection, seepage at the joints, and surface sinkholes over the culvert. Key factors to look for in the inspection of joints are indications of backfill infiltration and water exfiltration. Excessive seepage through an open joint can cause soil infiltration or erosion of the surrounding backfill material, piping, and a reduction of lateral support. Indications of infiltration at the road surface are illustrated in figure 3.9. Open joints may be probed with a small rod or flat rule from inside the culvert to check for voids.



Effect on unpaved areas

Effect on pavement

Figure 3.9. Surface indications of infiltration.[1]

Dents and Localized Damage

All corrugated metal culverts should be inspected for localized damage. Pipe wall damage such as dents, bulges, creases, cracks, and tears can be serious if the defects are extensive. They can impair either the structural integrity of the barrel in ring compression or permit infiltration of backfill. Small, localized examples are not ordinarily critical. When the deformation-type damages are critical, they will usually result in a distorted cross-sectional shape. The inspector should document the type, extent, and location of all significant wall damage defects. When examining dents in corrugated steel culverts, the plate should be checked, if possible, for cracking or disbonding of the protective coating.

Durability Problems

Durability is defined as the ability to last a long time with retention of original qualities, abilities, or capabilities. Durability problems are the most common cause for the replacement of pipe culverts. Durability of culvert material refers to the ability of a material to resist corrosion and abrasion. Corrosion and abrasion of corrugated metal culverts can be a serious problem, with adverse effects on structural performance.

Abrasion - Abrasion is the wearing away of culvert materials by the erosive action of bedload carried in the stream. It is generally most serious in steep or mountainous areas where high flow rates carry sand and rocks that wear away the culvert invert. Abrasion can also accelerate corrosion by wearing away protective coatings.

Corrosion - Corrosion is the deterioration of metal due to electrochemical or chemical reactions. Metal culverts are subject to corrosion in certain aggressive environments. For example, steel rapidly corrodes in salt water and in environments with highly acidic (low pH) conditions in the soil and water. Aluminum is fairly resistant to salt water but will corrode rapidly in highly alkaline (high pH) environments, particularly if metals such as iron or copper and their salts are present. Determination of the electrical resistivity of soil and water may provide an indication of the likelihood of corrosion. Many agencies have established guidelines in terms of pH and resistivity that are based on local performance.

CORRUGATED METAL STRUCTURAL PLATE CULVERTS

Large corrugated metal culverts are constructed with individual corrugated metal structural plates that are formed, curved, and galvanized at the factory. They are delivered to the job site where they are assembled and bolted together to form full circular pipe, arch, or pipe-arch structures. These structural plate shapes act in compression and can carry large ring compression thrust. On the other hand, box culvert shapes behave as a combination of ring compression action and conventional structure action.

Shape Distortion

Structure shape is the most significant factor in flexible culverts. Good curvature and rate of change are critical. Significant changes in shape since the last inspection should be carefully evaluated, even if the structure is still in fairly good condition.

Round and elliptical - Shape distortion in the structural plate culvert is essentially the same as that of metal pipe culverts. However, distortion at seams, as discussed below, must be considered.

Pipe Arch - A pipe arch is a closed structural shape that has a relatively wide and almost flat invert, with the springline being considerably lower than the center of the section. The springline is the horizontal line (or plane) that passes through the widest portion of the cross-section. The invert of a pipe arch should be inspected for signs of total flattening, which may be caused by horizontal spreading of the arch. It is also possible for the springline edges of a pipe arch to deflect downward and inward because of rotation of the corners. This may also be exhibited by flattening, and even a rise, of the invert.

The top arc of the structure is designed to carry the soil and traffic loads above it. The curvature of the top arc of the arch is important from the standpoint that it directly relates to the ability of the cross-section to carry the superimposed loading. Flattening, shifting or other differential movement in this arc may be an indication of a significant loss in structural strength of the arch.

Arches - Arches are open arch-shaped structures that are anchored into concrete footings, usually below or at the springline, whereas a pipe arch is a closed structure. The arch structure may have a paved or unpaved invert. The differences between these two types of structures will influence their response and potential differential displacement during improper backfilling procedures. Because the pipe arch is an enclosed shape it may distort and even shift in its location. On the other hand, the footings of an arch tend to remain stationary because they are cast into either undisturbed or well compacted soil. As a result, excessive or uneven compaction of the embankment around an arch may cause vertical flattening of the sides with a corresponding rise (or peaking) of the crown of the section. Inadequate compaction of the embankment may eventually lead to a flattening of the top arc. Comparisons of these problems for pipe and simple arches are shown in figure 3.10.

Another important factor in the inspection of arches is that their shape should be symmetrical. If the arch was erected with the base channel not square to the centerline, it will cause racking of the cross section. A racked cross-section is one that is not symmetrical about the centerline of the culvert. One side tends to flatten, and the other side tends to curve more while the crown moves laterally and possibly upward. If these types of distortions are not corrected before backfilling the arch, they usually will get worse during backfilling.

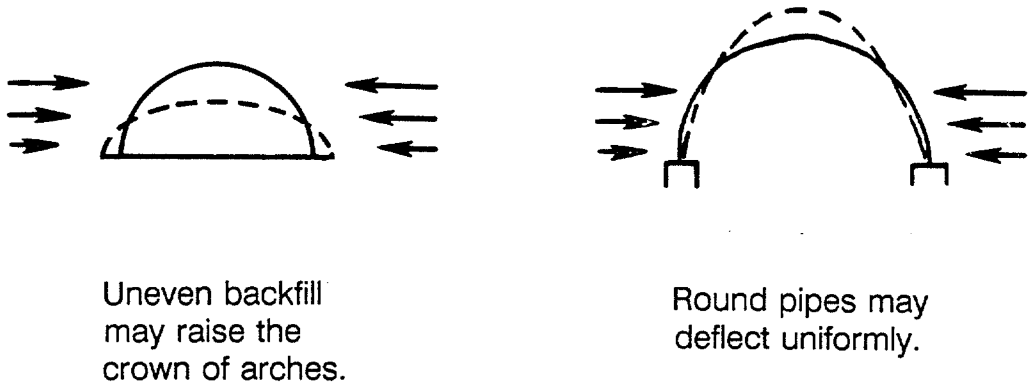


Figure 3.10. Arch deflection during installation.[1]

Figure 3.11 illustrates a racked and peaked arch. Visual observation of the shape should involve looking for flattening of the sides, peaking or flattening of the crown, or racking to one side.

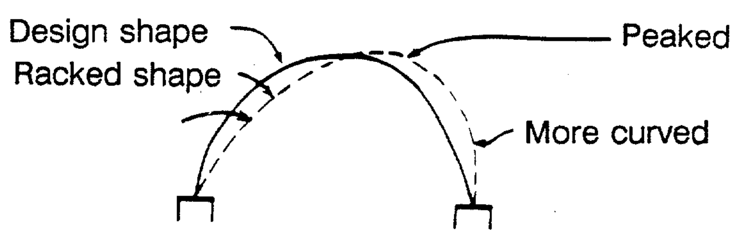


Figure 3.11. Racked and peaked arch.[1]

Boxes - The box culvert is not like other buried flexible metal structures. It behaves as a combination of ring compression action and conventional structure action. The sides are straight, not curved, and the plates are heavily reinforced and have moment or bending strength that is significantly greater in relation to the loads carried and the strength of corresponding circular or arch shapes.

The key shape factor in a box culvert is the top arc. The design geometry is clearly very "flat" to begin with and, therefore, cannot be allowed to deflect much. The span at the top is also important and cannot be allowed to increase much. Shape factors to be checked visually include flattening of top arc, outward movement of sides, or inward deflection of the sides.

Long span - Long-span structures include four typical shapes: low profile arch, horizontal ellipse, high profile arch, and pear. The evaluation of shape characteristics of long-spans will vary somewhat depending upon the typical shape being inspected. However, the top or crown sections of all long-span structures have very similar geometry. The crown sections on all long-span structures can be inspected using the same criteria.

Shape inspections of long-span structures will generally consist of (1) visual observations of shape characteristics such as smooth or distorted curvature and symmetrical or non-symmetrical shape, (2) measurements of key dimensions, and (3) elevations of key points. Additional measurements may be necessary if measurements or the observed shape differs significantly from the design.

The most important part of a long-span shape is the standard top arch geometry. Adequate curvature of the large radius top arc is critical. Inspection of the crown section should consist of a visual inspection of the general shape for smooth curvature (no distortion, flattening, peaks, or cusps) and symmetrical shape (no racking).

For horizontal ellipses the most important shape factor is adequate curvature in the crown section. Inspectors should look for indications of bottom flattening and differential settlement between the side and bottom sections, and differential settlement between the side and bottom sections, as illustrated in figure 3.12.

Misalignment

Vertical alignment should be checked for sags or deflection at joints. Horizontal alignment should be checked by sighting along the sides for straightness. The circumferential seam may be distressed by the movement of fill. It can also be caused by foundation failure, but this should be evident by the vertical alignment.

Joint Defects

Field joints generally are found only with factory manufactured pipe. There are ordinarily no joints in structural plate culverts, only seams. In a few cases, preassembled lengths of structural plate pipe have been coupled or banded together like factory pipe. The types of joint defects and how they may be repaired are discussed in Chapter 6.

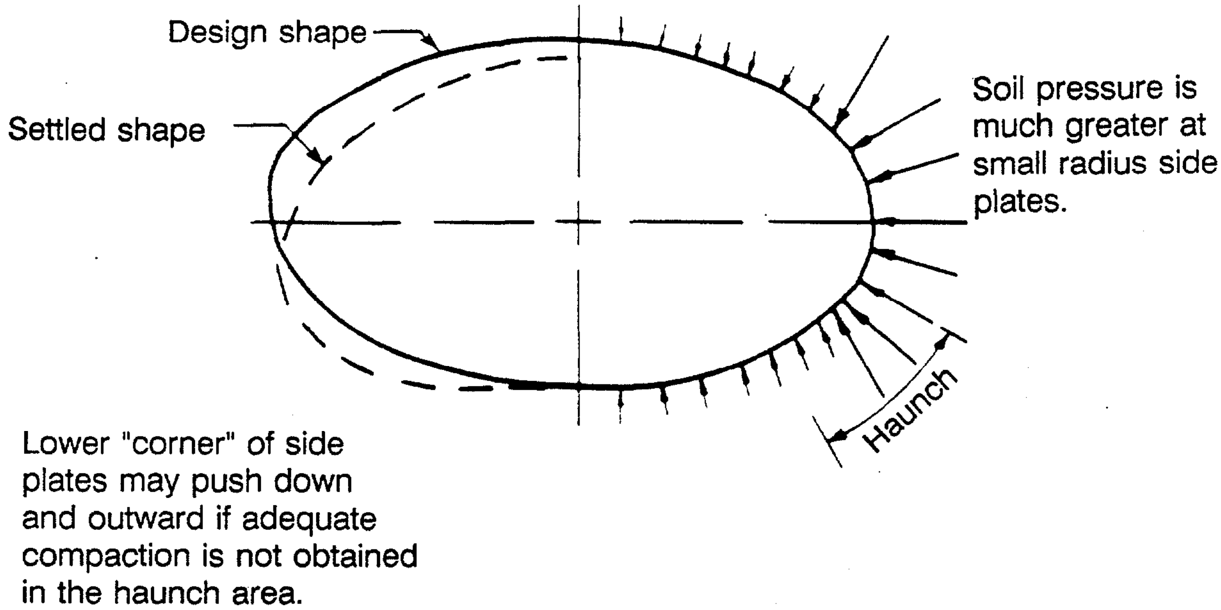


Figure 3.12. Differential settlement of a horizontal ellipse.[1]

Seam Defects

Longitudinal seams in structural plate culverts should be visually inspected for open seams, cracking at bolt holes, plate distortion around the bolts, bolt tipping, cocked seams, cusped seams, and for significant metal loss in the fasteners due to corrosion.

Loose fasteners - Seams should be checked for loose or missing fasteners. For steel structures, the longitudinal seams are bolted together with high-strength bolts in two rows: one row in the crests and one row in the valleys of the corrugations. These are bearing-type connections and are not dependent on a minimum clamping force of bolt tension to develop interface friction between the plates. Fasteners in steel structural plate may be checked for tightness by tapping lightly with a hammer and checking for movement.

For aluminum structural plate, the longitudinal seams are bolted together with normal strength bolts in two rows with bolts in the crests and valleys of both rows. These seams function as bearing connections, utilizing bearing of the bolts on the edges of holes and friction between the plates. Fasteners can be checked for tightness with a hammer as described for steel plates.

Cocked and cusped seams - The principal difference between factory pipe and structural plate is the presence of longitudinal seams in the structural plate. The shape and curvature of the structure is affected by the lapped, bolted longitudinal seam. Improper erection or fabrication can result in cocked seams or cusped effects in the structure at the seam, as illustrated in figure 3.13. Slight cases of these conditions are fairly common and frequently not significant. However, severe cases can result in failure of the seam or the entire structure. When a cusped seam is significant the structure's shape, appearance, and key dimensions will differ significantly from the design shape and dimensions. The cusp effect should cause the structure to receive very low ratings on the shape inspection if it is a serious problem. A cocked seam can result in loss of backfill and may reduce the ultimate ring compression strength of the seam.

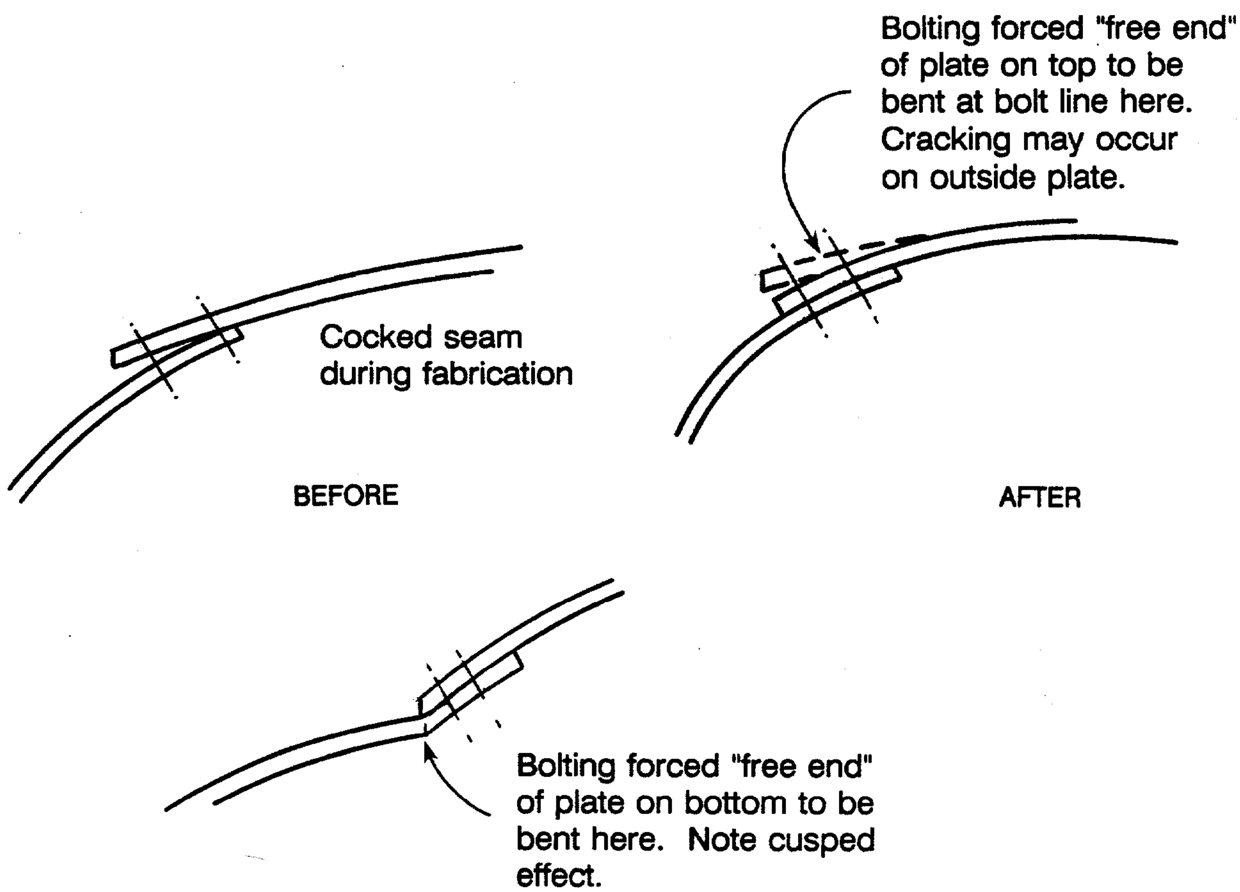


Figure 3.13. Results of cocked seam during fabrication.[1]

Seam cracking - Cracking along the bolt holes of longitudinal seams can be serious, particularly if it is allowed to progress. As cracking progresses, the plate may be completely severed and the ring compression capability of the seam lost. This could result in deformation or possible failure of the structure. This condition is most prevalent in pipe arches because of the way the seam on one side is lapped. Longitudinal cracks are most serious when accompanied by significant deflection, distortion, and other conditions indicative of backfill or soil problems. Longitudinal cracks are caused by excessive bending strain, usually the result of deflection, figure 3.14. Cracking may occasionally be caused by improper erection practices such as using bolting force to "lay down" a badly cocked seam.

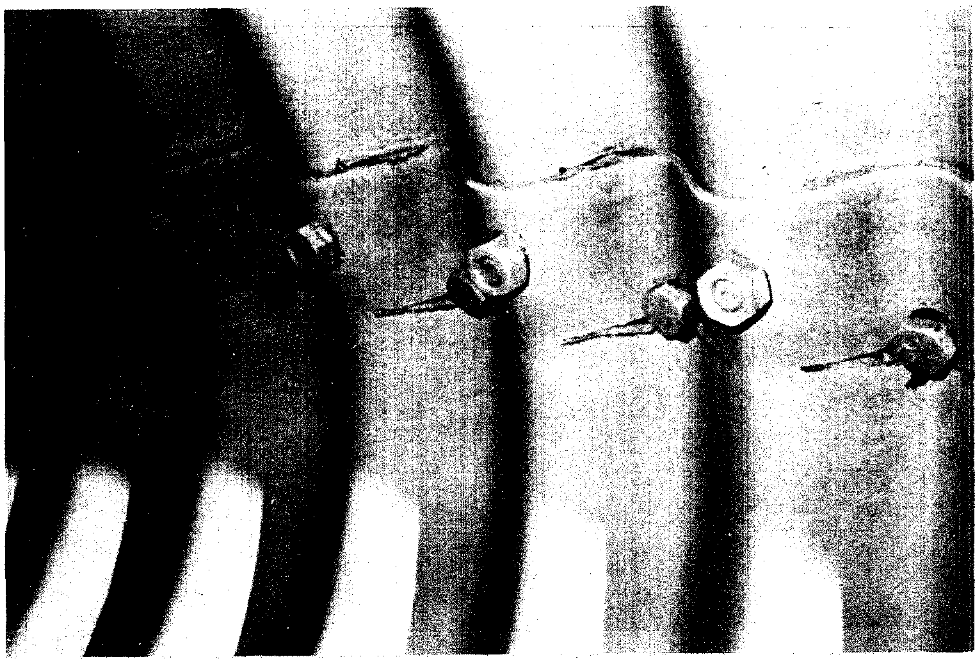


Figure 3.14. Longitudinal cracking at bolt holes.

Bolt tipping - The bolted seams in structural plate culverts only develop their ultimate strength under compression. Bolt tipping occurs when the plates slip. As the plates begin to slip, the bolts tip, and the bolt holes are plastically elongated by the bolt shank. High compressive stress is required to cause bolt tipping. Structures have rarely been designed with loads high enough to produce a ring compression that will cause bolt tip. However, seams should be examined for bolt tip, particularly in structures under higher fills. Excessive compression on a seam could result in plate deformations around the tipped bolts and failure is reached when the bolts are eventually pulled through the plates.

Circumferential Seams

The circumferential seams, like joints in factory-produced pipe, do not carry ring compression. They do make the conduit one continuous structure. Distress in these seams is rare and ordinarily will be a result of a severe differential deflection or distortion problem or some other manifestation of soil failure. For example, a steeply sloping structure through an embankment may be pulled apart longitudinally if the embankment moves down. Plates should be installed with the upstream plate overlapping the downstream plate to provide a "shingle" effect in the direction of flow.

Movement of the fill may cause a distress at more than one circumferential seams along the culvert. Such distress is important to note during inspections since it would indicate a basic problem of stability in the fill. Circumferential seam distress can also be a result of foundation failure, but in such cases should be clearly evident by the vertical alignment.

Dents and Localized Damage

All corrugated metal culverts should be inspected for localized damage. Pipe wall damage such as dents, bulges, creases, cracks, and tears can be serious if the defects are extensive. They can impair either the integrity of the barrel in ring compression or permit infiltration of backfill. Small, localized areas of distress are not ordinarily critical. When the deformation-type damages are critical, they will usually result in a distorted cross-sectional shape. The inspector should document the type, extent, and location of all significant wall damage defects. When examining dents in corrugated steel culverts, the plate should be checked, if possible, for cracking or disbonding of the protective coating.

Durability Problems

Durability of corrugated metal structural plate culverts is essentially the same as for any corrugated metal culvert as far as abrasion and corrosion is concerned, although seepage of corrosive groundwater through the seams is an added consideration in structural plate pipe culverts. However, due to assembly of structural plate culverts in the field, care should be taken to assess localized damage caused by handling. Protective coatings are particularly vulnerable. Bolt holes should be checked for punch-through of bolts. Peaking can cause cracks that allow infiltration and concentration of rust.

Footing Defects

Structural plate arches, long-span arches, and box culverts are built with concrete footings. Metal footings are occasionally used for the arch and box culvert shapes. The metal "superstructure" is dependent upon the footing to transmit the vertical load into the foundation. The structural plate arch is usually bolted in a base channel that is secured in the footing.

The most likely structural defect in the footing is differential settlement, often due to scour. One section of a footing settling more than the rest of the footing can cause wrinkling or other distortion in the arch. Flexible corrugated metal culverts can tolerate some differential settlement but will be damaged by excessive differential settlement. Uniform settlement will not ordinarily affect a metal arch but can affect the clearances in a grade- separated structure if the footings settle and the road does not. The significance of differential footing settlement increases as the amount of the difference in settlement increases, the length it is spread over decreases, and the height of the arch decreases.

The inspection of footings in structural plate and long-span arches should include a check for differential settlement along the length of a footing. This might show up in severe cracking, spalling, or crushing across the footing at the critical spot. If severe enough, it might be evidenced by a compression or stretching of the corrugations in the culvert barrel. Deterioration may occur in concrete and masonry footings that is not related to settlement but is caused by the concrete or mortar. Arches with no invert slab should be checked for erosion and undermining of the footings and for any indication of rotation of the footing, as illustrated in figure 3.15.

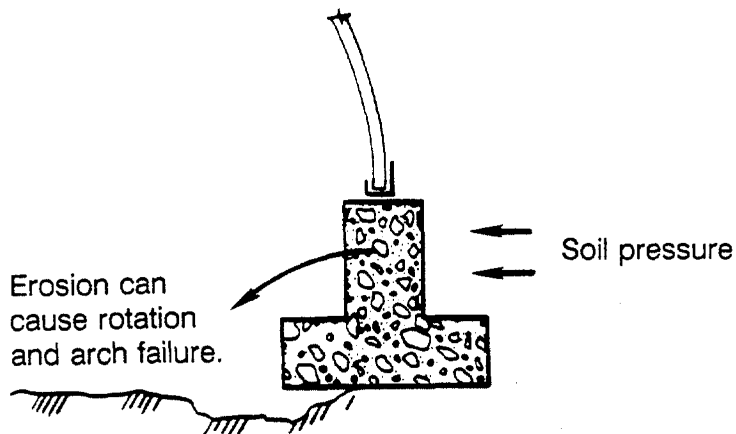


Figure 3.15. Footing rotation due to undermining.[1]

CAST-IN-PLACE CONCRETE CULVERTS

Most cast-in-place reinforced concrete culverts are single or multi-cell box culverts. Rigid frame structures are similar to concrete box culverts but are constructed without a bottom slab. Some agencies also consider small concrete arches as culverts. Cast-in-place box culverts are constructed using conventional bridge construction techniques but may function hydraulically and structurally as a culvert rather than as a bridge.

Cracks and Spalls

The top slab and walls should be inspected for cracks and spalls. When either is observed, the area around the defect should be tapped with a hammer to detect incipient spalls. Longitudinal cracks in the top slab of box culverts may indicate either flexure or shear problems. Transverse cracks may indicate differential settlement. Spalls may occur along the edges of cracks or in the concrete covering corroded reinforcing steel. Cracks in the sides may be caused by settlement or earth pressure. The location, size, and length or area of all cracks and spalls should be noted.

Undermining

When an invert slab is not used and the footings are exposed, they should be inspected for scour and undermining. A probing rod or bar should be used to check for voids and scoured areas that may have filled with sediment.

Durability Problems

The concrete surfaces should be checked by visual inspection and by tapping with a hammer for unsound concrete due to chemical attack or abrasion. The underside of the top slab, the invert slab, and the water line on the walls are the most likely areas to be damaged. Freeze-thaw action can also damage the concrete, particularly the headwalls and wingwalls.

PRECAST CONCRETE PIPE CULVERTS

There are certain important considerations related to concrete used in culverts. Machine-made, round concrete pipe is manufactured in a plant rather than in the field. The entire manufacturing process is under controlled conditions enabling the production of a uniform quality, high-density concrete product. Both cast-in-place and precast concrete culverts are somewhat protected by the soil backfill from rapid fluctuations in surface temperature and direct-application chloride (salts) used for deicing. As a result they are generally more resistant to surface deterioration than concrete bridge elements. Concrete culverts are classified as rigid structures because they do not deflect appreciably under the applied loads. However, uneven or excessive loads will cause such structures to crack rather than bend. Inspections must, therefore, concentrate on defects in the alignment, joints, and walls of the structure.

Misalignment

Misalignment may indicate the presence of serious problems in the supporting soil. The vertical and horizontal alignment of the culvert barrel should be checked by sighting along the crown and sides of the culvert and by checking for differential movement or settlement at joints between pipe sections. Vertical alignment should be checked for sags, faulting, and heaving. Pipe sections are occasionally laid with a camber or a grade change (broken back grade) to allow for fill settlement.

Sags and open joints that trap water may aggravate settlement problems by saturating the supporting soil. Horizontal alignment should be checked for straightness or smooth curvature for those culverts constructed with a curved alignment. Alignment problems may be caused by improper installation, undermining, or uneven settlement of fill. An attempt should be made to determine which of those problems is causing the misalignment. A determination should be made as to whether the undermining is due to piping, water exfiltration, or infiltration of backfill material.

Joint Defects

Joint defects are fairly common and can range from minor problems to problems that are serious in nature. Typical joint defects include leakage (exfiltration and infiltration), cracks, and joint separation. Past and current criteria should be reviewed, as some agencies design culverts with open joints to perform as subdrains.

Exfiltration - Exfiltration occurs when leaking joints allow water flowing through the pipe to leak into the supporting material. Many culverts are built with joints that are not watertight or with mortar joints that crack with minor deflection, movement, or settlement of the pipe sections. Minor leakage may not always be a significant problem unless soils are quite erosive. However, if leaking joints contribute to or cause piping, then serious misalignment of the culvert or even failure may result. Leaking joints may be detected during low flows by visual observation of the joints and by checking around the ends of the culvert for evidence of piping.

Infiltration - Infiltration is the opposite of exfiltration. Many culverts are essentially empty except during peak flows. When the water table is higher than the culvert invert, water may seep into the culvert between storms. Infiltration can occur during flood events by suction from pressure differentials in inlet control culverts. This infiltration of water can cause settlement and misalignment problems if it carries fine grained soil particles from the surrounding backfill. Infiltration may be difficult to detect visually in its early stages although it may be indicated by open joints, staining at the joints on the sides and top of the culvert, deposits of soil in the invert, or by depressions over the culvert.

Cracks - Circumferential cracks in the joint area may be caused by improper handling during installation, improper gasket placement, and movement or settlement of the pipe sections. Cracked joints are more than likely not watertight even if gaskets were used. However, if no other problems are evident, such as differential movement between pipe sections, and the cracks are not open or spalling, they may be considered a minor problem. Severe joint cracks are similar in significance to separated joints.

Separation - Joint separations may be caused by the same forces described under misalignment (settlement, undermining, or improper installation). Joint separations are significant because they accelerate damage caused by exfiltration and infiltration resulting in the erosion of the backfill material. Separated joints are often found when severe misalignment is found. In fact either problem may cause or aggravate the other. Movement of the soil in the general direction of the culvert's centerline may cause sections to gradually pull apart. Embankment slippage may also cause separations to occur.

Longitudinal Cracks

Concrete is strong in compression but weak in tension. Reinforcing steel is provided to handle the tensile stresses. Hairline longitudinal cracks in the crown or invert indicate that the steel has accepted part of the load. Longitudinal cracking in excess of 0.1 inch in width may indicate overloading or poor bedding. If the pipe is placed on hard material and backfill is not adequately compacted around the pipe or under the haunches of the pipe, loads will be concentrated along the bottom of the pipe and may result in flexure or shear cracking, as illustrated in figure 3.16.

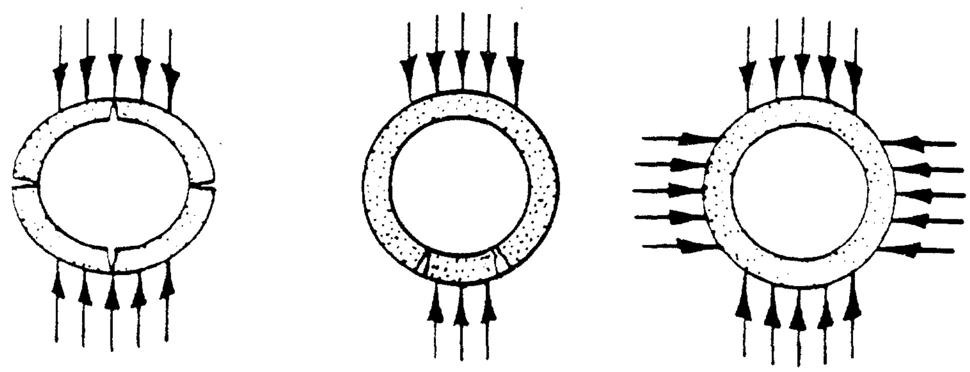
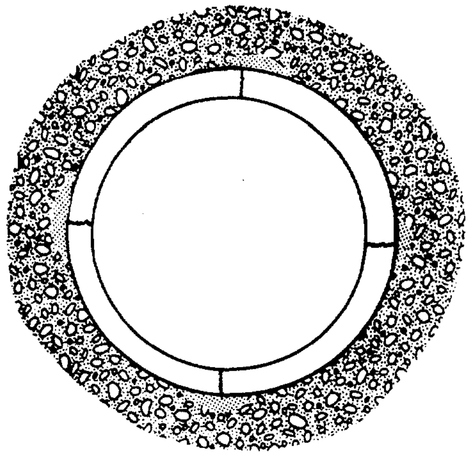
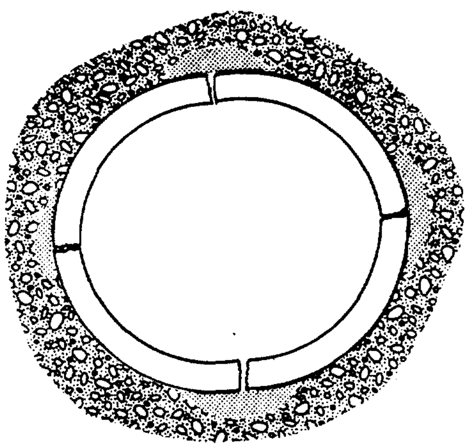


Figure 3.16. Results of poor and good side support for rigid pipe.[1]



STAGE 1
Pipe cracking is caused by bad laying practice or subsequent overloading or disturbance. The sewer remains supported and held in position by the surrounding soil.

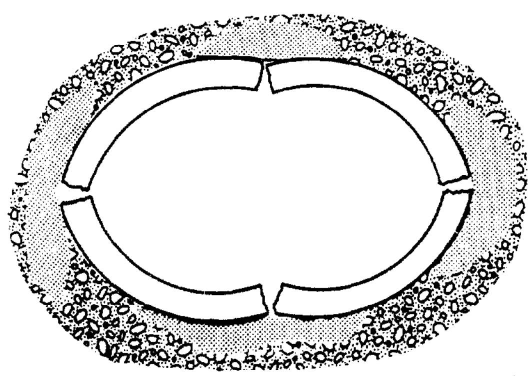
Visible defects: cracks at soffit, invert and springing. Infiltration may also be visible.



STAGE 2
Infiltration of groundwater or infiltration/exfiltration caused by surcharging of the sewer washes in soil particles. Side support is lost allowing further deformation so that cracks develop into fractures.

Side support may also be insufficient to prevent deformation if the original backfill was either poorly compacted or of an unsuitable material.

Visible defects: fractures, slight deformation. Infiltration may or may not be visible.



STAGE 3
Loss of side support allows side of pipe to move further outwards and the soffit to drop once deformation exceeds 10%, the pipe becomes increasingly likely to collapse.

Visible defects: fractures and deformation, possibly broken.

Figure 3.17. Illustrates the deformation of cracked pipes, the cause of the deformation and the visable effects.[5]

Transverse Cracks

Transverse or circumferential cracks may also be caused by poor bedding. Cracks can occur across the bottom of the pipe (broken belly) when the pipe is only supported at the ends of each section. This is generally the result of poor installation practices such as not providing indentations (bell holes) in hard foundation material for the ends of bell and spigot-type pipe or not providing a sufficient depth of suitable bedding material. Cracks may occur across the top of pipe (broken back) when settlement occurs and rocks or other areas of hard foundation material near the midpoint of a pipe section are not adequately covered with suitable bedding material.

Spalls

Spalling is a fracture of the concrete parallel or inclined to the surface of the concrete. In precast concrete pipe, spalls often occur along the edges of either longitudinal or transverse cracks when the crack is due to overloading or poor support rather than simple tension cracking. Spalling may also be caused by the corrosion of the steel reinforcing when water is able to reach the steel through cracks or shallow cover. As the steel corrodes, the oxidized steel expands, and causes the concrete covering the steel to spall. Spalling may be detected by visual examination of the concrete along the edges of cracks. Tapping with a hammer should be performed along cracks to check for areas that have fractured but are not visibly separated. Such areas will produce a hollow sound when tapped. These areas may be referred to as delaminations or incipient spalls.

Slabbing

The terms slabbing, shear slabbing, or slab shear refer to a radial failure of the concrete that occurs from straightening of the reinforcement cage due to excessive deflection or shear cracks. It can also be attributed to inadequate concrete cover. It is characterized by large slabs of concrete "peeling" away from the sides of the pipe and a straightening of the reinforcing steel. Slabbing is a serious problem that may occur under high fills.

Durability Problems

Durability is a measure of a culvert's ability to withstand chemical attack and abrasion. Concrete culverts are subject to chemical attack in strongly acidic environments, such as drainage from mines and may also be damaged by abrasion. Abrasion damage is a wearing away of the concrete surface by sediment and debris as it is transported by the stream. Abrasion can be a serious problem in mountain areas where moderate-to-large sized rock is carried by fast-moving water, particularly during the spring and time of snow melt. For example, when water velocity is greater than five feet per second and the upstream channel has a course aggregate bed, abrasion-related problems can be expected. Mild deterioration or abrasion less than 1/4 inch deep should be noted. More severe surface deterioration should be reported as a potential candidate for maintenance. In severe cases where the invert is completely deteriorated, maintenance forces should be given immediate notification. When linings are used to protect against chemical attack or abrasion, the condition of the lining should be noted. Seepage and joint deterioration are a consideration for shallow boxes and three sided boxes.

End Section Drop-off

This type of distress is usually due to outlet erosion. It is caused by the erosion of the material supporting the pipe sections on the outlet end of the culvert barrel. It also may be the result of piping, a process of subsurface erosion where seepage along the culvert barrel may remove supporting material.

MASONRY CULVERTS

At the present time, masonry construction is limited primarily to headwalls, wingwalls, and inlet structures. While culvert barrels are rarely constructed from masonry, a wide variety of masonry culvert barrels are still in service. Masonry culverts are generally arch-shaped or box-shaped and may be constructed of stone, brick, or concrete blocks. Stone culverts may be dry (no mortar), pointed (stones set in mortar), or cemented (stones set in concrete) masonry.

Masonry Units

The individual stones, bricks, or blocks should be checked for displaced, cracked, broken, crushed, or missing units. For some types of masonry units, surface deterioration or weathering can also be a problem. Occasionally, seams or cracks open up in rocks, eventually breaking them into smaller pieces. This may be caused by freeze-thaw action.

Mortar

In most masonry arch culverts, mortar is used to cement the masonry units together. The condition of the mortar should be checked to ensure that it is still holding strongly. It is particularly important to note cracked, deteriorated, or missing mortar if other deterioration is present, such as missing or displaced masonry units. Although mortar is generally used, masonry culverts have been constructed that rely on the friction between well-fitted stones or on the interlocking of rough-worked stones. An increase in loss of mortar may lead to displacement and/or loss of masonry units, which may result in a loss of load-carrying capacity and structural integrity of the masonry culvert.

Shape

Masonry arches act primarily in compression. Flattened curvature, bulges in walls, or other shape deformations may indicate unstable soil conditions that may lead to serious structural problems.

Alignment

The vertical and horizontal alignment of masonry units should be checked visually. Any settlement should be noted, as well as ponding of water due to sagging or misalignment.

Footings

Solid foundations are essential for masonry arch and box culverts. Since many of these culverts do not have a paved invert, the footings should be carefully inspected for scour and undermining. A probing rod should be used to check for voids and scoured areas that may have filled with sediment.

OTHER BARREL MATERIALS

Both timber and vitrified clay pipe may be used in areas where the runoff is very corrosive. Timber is also used in areas where other types of materials may be difficult to transport. Some of the older culverts may be cast iron pipe.

Vitrified Clay Pipe

Vitrified clay pipe is manufactured from natural clays and shales, the mineral aggregates that are the end products yielded by the weathering forces of nature. Since all the soluble and reactive minerals have been leached out, the remaining material from which the pipe is manufactured is inert.

Shape - Vitrified clay pipe is only manufactured as round pipe. It is available in sizes of 6-inches in diameter to 42-inches in diameter. With the exception of spalling, structural problems are similar to those of round concrete pipe.

Durability - Vitrified clay pipe is chemically inert. It is resistant to internal and external attack from acids, alkalies, gases, and solvents. It is exceptionally resistant to abrasion and scour. This pipe is sometimes used when corrosive wastes from industry or mining may be carried in the runoff.

Timber

When adequately protected, timber is a very durable building material. Certain precautions can have a significant impact on the service life of treated timber. Cured wood is ready for preservation treatment. The penetration of the preservative normally ranges from 1 to 3 inches into the surface. If moisture is allowed to penetrate into the core, decay will follow. Debris holds moisture that will penetrate into timber. Therefore, in areas that tend to accumulate debris, wood surfaces should be avoided. Timber ends should be protected by a preservative or be capped. Timbers placed on the ground or at the waterline and continually exposed to wet and dry are problem-prone. It is helpful to elevate these members with concrete footings or enclose them in concrete. Holes from connectors, such as anchor bolts, drift pins, and lag bolts should be protected from moisture penetration.

Timber has obvious advantages in the rehabilitation of culverts in remote areas where other materials are difficult to transport, or where the work crew has limited skills and equipment. Timber culverts are generally box shaped. Timber is also used for endwalls or wingwalls where a rustic appearance is required. In a few cases, the Ohio Department of Transportation has installed box culverts out of timber in regions where acidic runoff from mining operations is a problem.

Cast Iron

Cast iron should be inspected similarly to steel. Cast iron is subject to defects such as checks (cracking due to tensile cooling stresses) and blow-holes. The latter has a serious effect on both the strength and toughness of the cast iron.

AREA-SPECIFIC PROBLEMS

Certain soil and water conditions have been found to have a strong relationship to accelerated culvert deterioration. These conditions are referred to as "aggressive" or "hostile" environments. Culvert corrosion may occur in many different soil and water conditions. These soils and waters may contain acids, alkalis, dissolved salts, organics, industrial waste and other chemicals, mine drainage, sanitary effluents, and dissolved and free gases.

Soil and water conditions also cause culverts to deteriorate due to abrasion. Erosive large-grained materials such as sand, gravel, and stones can wear away the bottom of the culvert and damage protective coatings. The higher the velocity of the water passing through the culvert, the more the potential for abrasion.

Water

Material durability is an important factor in the determination of the type of pipe selected for a specific culvert site. Culvert materials react differently to hostile conditions. Corrosion in metal pipe culverts can be aggravated by both acidic and alkaline conditions. Salt water corrodes steel while aluminum is fairly resistant to salt water. Concrete will resist deterioration from salt-water action although alternate wetting and drying may be detrimental. Most culvert materials should be treated with some type of protection when exposed to salt water. Aluminum will corrode rapidly in alkaline environments, particularly if metals such as iron or copper and their salts are present. Steel is rapidly corroded by acidic conditions although it resists alkaline conditions well. Water containing sulfates and carbonates cause deterioration of concrete although the use of some cement types will provide additional resistance. Very acid water as found in coal strip-mining areas can cause rapid deterioration of concrete and can then cause corrosion of the reinforcing steel if it becomes exposed.

Soil

The chemical and physical characteristics of the soil that will come into contact with a culvert can be analyzed to determine the potential for corrosion. The presence of base-forming and acid-forming chemicals is important. Chlorides and other dissolved salts increase electrical conductivity and promote the flow of corrosion currents. Sulfate soils and water can be erosive to metals and harmful to concrete. The permeability of soil to water and to oxygen is another variable in the corrosion process.

The electrical resistivity of the soil is also important. This measurement depends largely on the nature and amount of dissolved salts in the soil. The greater the resistance, the less the flow of electrical current associated with corrosion. Soil resistivity generally decreases as the depth increases. The use of granular backfill around the entire pipe will increase electrical resistivity and will reduce the potential for galvanic corrosion.

Several states rely on soil and water resistivity measurements as an important index of corrosion potential. Some states and the FHWA have published guidelines that use a combination of the pH and electrical resistivity of soil and water to indicate the corrosion potential at proposed culvert sites. The collection of pH and electrical resistivity data during culvert inspections can provide valuable information for developing local guidelines.

Climate

Climatic conditions also affect corrosion. Acid water (low pH) is more common to wet climates and alkaline water (high pH) is more common to dry climates. In addition, high moisture content and temperature lower the electrical resistivity of soils and increase the potential for corrosion.

Climatic factors also influence the amount of runoff from a drainage area. These factors include rainfall intensity, storm duration, rainfall distribution within the drainage area, soil moisture, snow melt, rain or snow, rain-hail, and other factors. In colder climates, the buildup of ice in stream channels or culverts, a process known as aufeis, can completely fill culverts, resulting in the water overtopping the roadway. The ice buildup also can reduce the cross-sectional area of the culvert and cause velocities to increase. Culverts in areas subject to flash floods require special design precautions to avoid overtopping.

Other

Topographic features may affect culverts and appurtenances. Debris collectors may be required when the terrain is steep and velocities are high. Wave action can cause debris to collect in tidal areas. Dense vegetation can become dislodged and wash downstream to a culvert entrance. Installations in a flood plain may require a debris riser for interception of debris.

HYDRAULIC CAPACITY OF CULVERTS

When the hydraulic performance of a culvert is inadequate, potential safety, economic, and environmental impacts may result. The flooding of adjacent properties from unexpected headwater depth may occur. Downstream areas may be flooded by failure of the embankment. The roadway embankment or culvert may be damaged because of erosion.

Causes of Problems

The hydraulic design of a culvert must be such that risks to traffic, potential property damage, and failure from floods is consistent with good engineering practice and economics. Recognizing that floods cannot be precisely predicted and that it is seldom economically feasible to design for the very rare large flood, all designs should be reviewed for the extent of probable damage should the design flood be exceeded. Design headwater/backwater and flood frequency criteria should be based upon the following and other considerations. If such problems exist it may indicate that culvert repair work may be needed.

- Damage to adjacent property;
- Damage to the structure and roadway;
- Traffic interruption;
- Hazard to human life; and
- Damage to stream and flood plain environment.

Traffic Impacts

The inadequate hydraulic performance of a culvert can have several undesirable and potentially disastrous impacts on traffic. Overtopping of the roadway can delay traffic, cause accidents, and, in some cases, cause traffic to detour to a route that is passable. In extreme cases that result in failure of the culvert and, in turn, the roadway, the safety of the traveling public can be severely compromised.

There are certain routes that, for the well being of residents of the community, should remain open. For example, those routes used by area occupants who are relatively immobile or cannot be moved quickly, such as hospitals, nursing homes, and schools, should take precedence. Other routes that should remain operational during a flood include such facilities as power generation plants, fire houses, ambulance services, and water supply facilities.

Economic Impacts

The result of the hydraulic inadequacy of culverts generally is flooding, either of adjacent property or the roadway. In some cases, both are affected. As ponding elevations increase upstream from a culvert, detrimental economic consequences can occur. Some costs are to the agency responsible for maintaining the roadway. Some costs are those incurred by the motorist. Other costs relate to damage to adjacent property.

Flooding - Flooding can cause overtopping of the roadway and, in extreme cases, failure of the culvert and the roadway above. In addition, flooding can damage property adjacent to the structure as well as property both upstream and downstream of the culvert. Flooding will cause incurrence of costs to the agency, the motorist, and to the owners of adjacent property. Costs to the responsible agency may include:

- Repair or replacement of the culvert;
- Repair of the roadway; and

- Repair of the embankment and appurtenances.

Costs to the motorist when the roadway is flooded may involve the following factors:

- Time loss due to traffic restoration delay; and
- Accident costs;

Costs to the property owner may be due to the following:

- Erosion and sedimentation damage;
- Backwater damage losses; and
- Costs due to loss of use of property;

Route closure - Route closure can result in excessive delay to the traveling public as well as increased operating costs of the vehicle. Businesses along the route may suffer economic loss due to the closure.

Environmental Impacts

Off-site erosion, flooding, and pollution due to urban development and land-disturbing activities in a watershed have become significant problems to environmental control. The development of stormwater management standards to protect streams and other bodies of water from the effects of erosion and sedimentation are among the first priorities of transportation and environmental agencies.

Erosion - Soil erosion is the process by which the land surface is worn away by the action of wind, water, ice, and gravity. Water-generated erosion is unquestionably the most damaging problem, particularly in developing areas. Both the force of falling rain and the motion of the water as it runs off the surface of the ground performs the work of detaching and transporting soil particles. Table 3.5, which defines the steps in the erosion process, describes the effects of a rainstorm on the soil. Figure 3.21 depicts the effects of these types of erosion. The inherent erosion potential of any area is determined by four principal factors: the characteristics of the soil, vegetative cover, topography, and climate. Channel erosion can undermine culvert headwalls and footings, causing structural failure. Therefore, culverts on degrading streams should be inspected more often than usual.

Flooding - The frequency, intensity, and duration of rainfall are fundamental factors in determining the amounts of runoff produced in a given area. Where storms are frequent, intense, or of long duration, the risk of flooding increases. If drainage structures are not capable of handling the increased runoff from heavy rainfall or snowmelt, flooding of the areas adjacent to streams may occur. Overtopping of the roadway may result.

As the volume and velocity of the runoff increases, its capacity to transport soil particles increases. Excessive quantities of sediment are derived by erosion during these periods of high flows, to be deposited in culverts and streambeds as the flows subside. Seasonal changes in temperature and amount of rainfall define times of the year when flooding and erosion is most likely to occur. When precipitation falls as snow and the ground is frozen, no erosion will ensue. However, the melting snow contributes to runoff. Soils with high moisture content are subject to uplift by freezing action and are often easily eroded upon thawing.

Sedimentation - The companion problem to erosion is sedimentation. Normally, excessive runoff accumulates rapidly to a peak and then diminishes. It is during this period of peak runoff that excessive quantities of soil particles are dislodged and transported. During lower flows as runoff decreases, these transported materials are deposited, only to be picked up again by other peak flows. In this manner, sediment is carried downstream, intermittently and progressively.

Excessive quantities of sediment cause costly damage to waterways as well as private and public lands. The hydraulic capacity of stream channels and navigable rivers is reduced by deposited sediment, increasing subsequent flood crests and related flood damage. Sediment fills channels, especially along highways, and constricts culverts and storm drain systems, necessitating frequent and costly maintenance.

Sediment alters the aquatic environment by screening out sunlight and by changing the rate and the amount of heat radiation. Particles of silt settle on stream and lake bottoms and form a blanket that creates a hostile environment for the organisms living there.

Table 3.5. The erosion process of a rainstorm on soil.[7]

Raindrop erosion is the first effect of a rainstorm on the soil. Raindrop impact dislodges soil particles and splashes them into the air. These detached particles are then vulnerable to the next type of erosion. Sheet erosion is the erosion caused by shallow sheets of water as it runs off the land. These very shallow moving sheets of water are seldom the detaching agent, but the flow transports soil particles that are detached by raindrop impact and splash. The shallow surface flow rarely moves as a uniform sheet for more than a few feet on land surfaces before concentrating in the surface irregularities. Rill erosion is the erosion that develops as the shallow surface flow begins to concentrate in the low spots of the irregular conformation of the surface. As the flow changes from the shallow sheet flow to deeper flow in these low areas, the velocity and turbulence of flow increase. The energy of this concentrated flow is able to both detach and transport soil materials. This action begins to cut tiny channels of its own. Rills are small but well-defined channels that are at most only a few inches deep. They are easily obliterated by harrowing or other surface treatments. Gully erosion occurs as the flow in rills comes together in larger and larger channels. The major difference between this and rill erosion is a matter of size. Gullies are too large to be repaired with conventional tillage equipment and usually require heavy equipment and special techniques for stabilization. Channel erosion occurs as the volume and velocity of flow causes movement of the streambed and bank materials. Figure 3.18 illustrates the five types of erosion.

Scour - Placement of a culvert introduces a foreign element into a naturally occurring dynamic environment--the continuous interplay of erosion, sedimentation, and debris movement. The result is that serious problems often occur, including erosion at the inlet and outlet, sediment buildup in the barrel, and clogging of the barrel with debris.

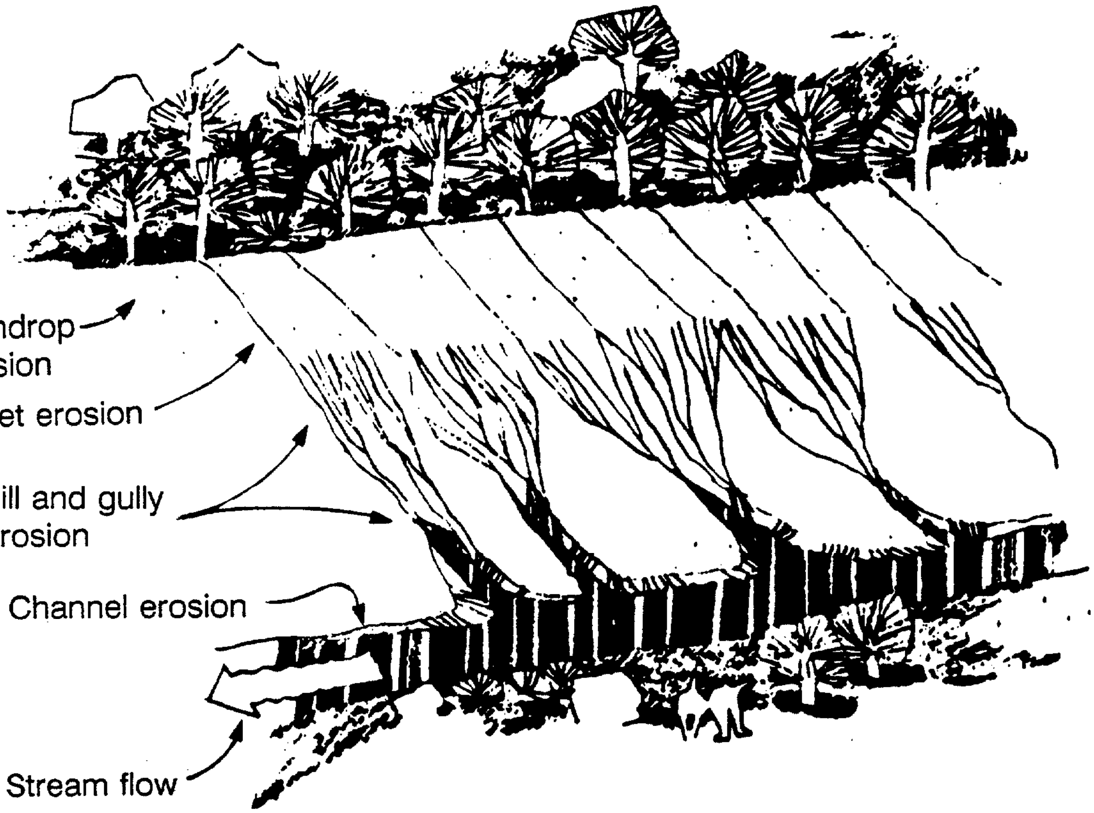


Figure 3.18. Types of erosion.[5]

As a result of these dynamics, scour holes often form, both at the inlet and the outlet of culverts. Since the culvert barrel normally constricts the natural channel, the flow is forced through a reduced opening. As the flow contracts, areas of high velocity flow strike against the upstream slopes of the fill and tend to scour away the embankment adjacent to the culvert. In addition, scour holes may form upstream of the culvert floor as a result of the acceleration of the flow as it leaves the natural channel and enters the culvert.

Scour at culvert outlets is also a common occurrence. Flow through the culvert is usually constricted in width and may be at a greater depth than the natural streambed. As the velocity through the barrel increases, potential for erosion also increases. Turbulence and erosive eddies form as the flow expands to conform to the natural channel. Other factors contribute to scour-hole formation at outlets. The characteristics of the channel bed and bank material, the velocity and depth of flow in the channel at the outlet, and the amount of sediment and other debris present all contribute to scour potential.

Two types of scour can occur in the vicinity of culvert outlets: local scour and general channel degradation. Local scour is the result of high-velocity flow at the culvert outlet and is typified by a scour hole produced at the culvert outlet. This effect extends only a limited distance downstream. Coarse material from the scour hole is deposited immediately downstream, often forming a low bar as shown in figure 3.19. Finer material is deposited further downstream. The dimensions of the scour hole change due to sedimentation during low flows and varying erosive effects during peak flow. A stable scour hole is not a problem unless it poses a safety hazard or has undermined the headwall. In fact, it acts as an energy dissipator.

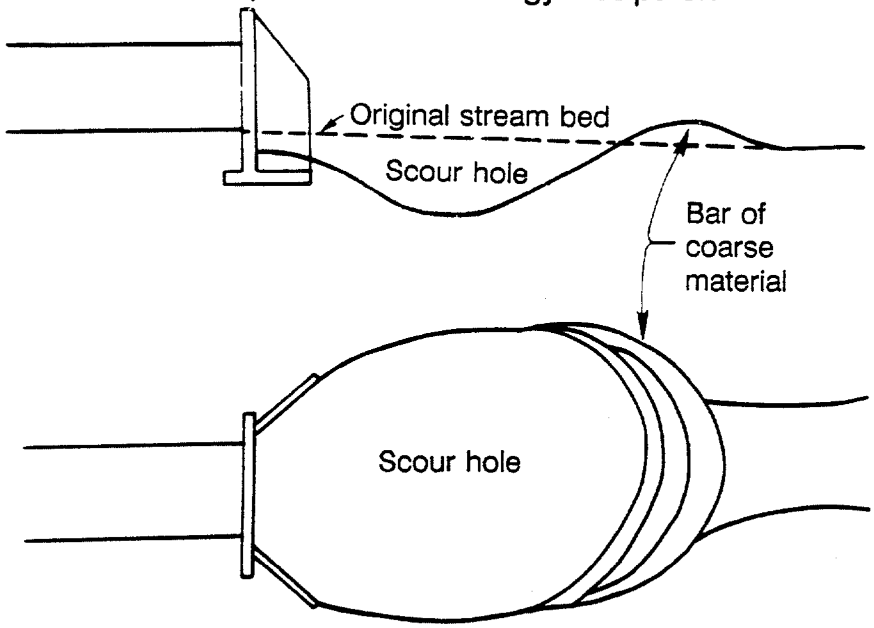


Figure 3.19. Scour hole at culvert outlet.[8]

Channel degradation generally proceeds in a uniform manner over a long distance. It may also be evidenced by one or more abrupt drops progressing upstream with every runoff event. This type of channel degradation is known as head cutting.

Fish Passage

Many species of fish migrate up and down state and national forest stream systems. This migration is essential to survival of the species. However, highway culverts typically have been designed to pass the anticipated maximum flow through the smallest space possible while minimizing scour and sedimentation. This conventional approach has led to some designs that impede fish passage, particularly those culverts that operate under inlet-control criteria.

Many states have become much more aware of fish passage issues and legislation has been enacted to compel consideration of requirements to enable fish passage. The U.S. Forest Service is responsible for ensuring that the installation, operation, and maintenance of structures in streams on national forest lands will not interfere with the migration or passage of any fish species. Most states now have laws that generally make it illegal for anyone to create a barrier to fish life in any stream in which migrating fish are present. States that have migrating and fish passage concerns include California, Massachusetts, Montana, New Jersey, Pennsylvania, Oregon, Washington, Virginia, and Alaska. However, the Oregon Department of Transportation solves fish passage problems only if requested by the Department of Fish and Wildlife.

The U.S. Forest Service and many states presently have requirements for the design and installation of new culverts that are based on the results of several research studies. This research has heightened awareness that there are many existing culvert installations that severely limit normal migration patterns of fish. Some research is underway to develop techniques for retrofitting existing culverts to facilitate adequate fish passage while allowing the culvert to meet the hydraulic requirements for which it was designed.

Parameters - There are several factors that are recognized as being important to mitigating the effects of fish passage barriers. Potential solutions must take into account the swimming capabilities of fish. Whereas much of the early research focused on salmon and steelhead trout, these fish represent the stronger swimmers of the salmonoids. The arctic grayling, which is one of the weaker swimmers, is now often used as the design fish, particularly in Alaska.

Other elements that must be considered are the hydraulic characteristics of the culvert, the flow characteristics of the culvert, the flow characteristics of the stream, and the relative timing of fish migration and flood events. If velocities are too high, fish are delayed in their up-stream migration. Eggs that are deposited before the spawning ground is reached may be washed away or covered with silt. However, if the stream flow is too low, the depth of water in the culvert barrel may be too shallow to allow fish passage.

Obstacles to Fish Passage - There are three main problem areas a fish must navigate in attempting culvert passage: (1) the culvert outlet and downstream area, (2) the culvert barrel, and (3) the culvert inlet.

At the culvert outlet, a migrating fish may be faced with the following obstacles, illustrated in figure 3.20.

- Accelerating flow at the outlet, especially if the culvert is operating under inlet control;
- No resting or take-off pool below the culvert;
- The flow over the bottom of the culvert is too shallow; and

Figure 3.20. Culvert installations that block fish passage.[9]

- A perched culvert outlet presenting too high a jump for fish to enter the culvert. Perching is the tendency to develop a falls or cascade at a culvert outfall due to erosion of the stream channel downstream from a culvert or drainage structure.

The culvert barrel may present further barriers to fish passage:

- Insufficient water depth in the barrel due to low flows or sedimentation;
- Inadequate resting areas within long culverts with high water velocities; and
- Increased velocities, particularly where the culvert type reduces the channel cross-sectional area. The velocity may be further increased by the reduction of channel roughness and increased slope.

The following problems may be associated with the culvert inlet:

- High velocities and turbulence, especially if the culvert is operating under inlet control;
- Partial blockage of the entrance, causing formation of high-velocity jets; and
- Lack of a resting pool at the inlet.

Problems with Modifications of Culverts - The modification of an existing culvert to facilitate the movement of fish upstream to spawning ground can introduce several problems in the operation of an installation. Culverts are designed to operate as efficiently as possible under a determined design flow and will lose efficiency with most in-culvert modifications. The decrease in efficiency, and related increase in water depth, will decrease the flow capabilities of the culvert and, in turn, increase sedimentation problems. It should also be recognized that devices that facilitate fish passage may be damaged by rock and debris passing through a culvert, and that they may need to be repaired periodically. Potential retrofit solutions are discussed further in chapter 5 and in appendix B-23.

Beaver Control

Throughout the United States many states have problems with beavers building dams and causing drainage water to pond and damage highway structures. One of the easiest ways for a beaver to build a dam is simply to plug the inlet of a culvert. A plugged culvert often results in a flooded or washed-out road. Unplugging the culvert can take a considerable amount of labor and equipment. One of the most troublesome aspects of the problem is that after unplugging a culvert, the culvert may be plugged again the next day. At sites where beavers are active and detailed cost records have been kept, the average cost to keep a culvert cleared of a beaver dam is approximately $800 per year. However, the cost to repair a specific site that has been damaged by beaver activity may exceed one million dollars.

Agencies responsible for public waterways generally recognize the beaver as an animal capable of causing severe damage to streams and adjacent property. These agencies will usually aid citizens in dealing directly with the problem, if possible, rather than employing direct control by the agency.

Responsible agencies often have policies that address the management of beaver population. Examples of such policies are listed below:

- Populations are maintained primarily by the use of a general trapping season;
- Issuance of special permits may allow the complainant to trap out of season;
- In areas of dense beaver population, the trapping season may be extended;
- Reported beaver complaint sites may be marked on maps that are available during the trapping season to interested trappers. These maps aid trappers in locating beaver colonies while relieving specific problems.

There are several options for controlling the beaver population and the damage inflicted on trees, streams, and adjacent property. The option or combination of options selected depends on the magnitude of the problem.

- If the damage is minor, such as beavers gnawing on an ornamental tree, the property owner may elect to do nothing. Since beavers are very mobile, they may move on without causing significant damage. However, if the beavers persist, trees may be protected if only a few are endangered. Wire mesh wrapping or a heavy hardware cloth may be cut to a height of three feet and wrapped around the tree trunks.
- The use of chemical repellents may discourage beavers. For single ponds, the dam is opened to allow the pond to drain. A cord is run across the stream about 2 feet above the dam. Rags soaked with a commercial deer repellent are hung along the cord with the ends touching the dam. The repellent may also be sprayed or painted on tree trunks.
- Removing the beaver during the trapping season is the most effective solution. If trapping the beaver outside the trapping season is desirable, local trapping regulations must be followed.
- Destroying or shooting beavers is usually prohibited by law. However, some states issue special permits to allow destroying the beaver under certain conditions.

- The effects of flooding caused by beaver dams is one of the most extensive problems related to beavers. Beaver dams often result in plugged culverts, blocked drainage ditches, and flooding of adjacent property. However, beaver houses or lodges are protected by law and cannot be damaged or removed. Licensed blasters are usually the only individuals authorized to use explosives to remove these structures. State and local laws must be complied with in removing these structures by blasting.

- There are several physical deterrents that have been employed in some jurisdictions. These appurtenant structures, one of which is shown in figure 3.21, are discussed further in chapter 5 and appendix B-24.

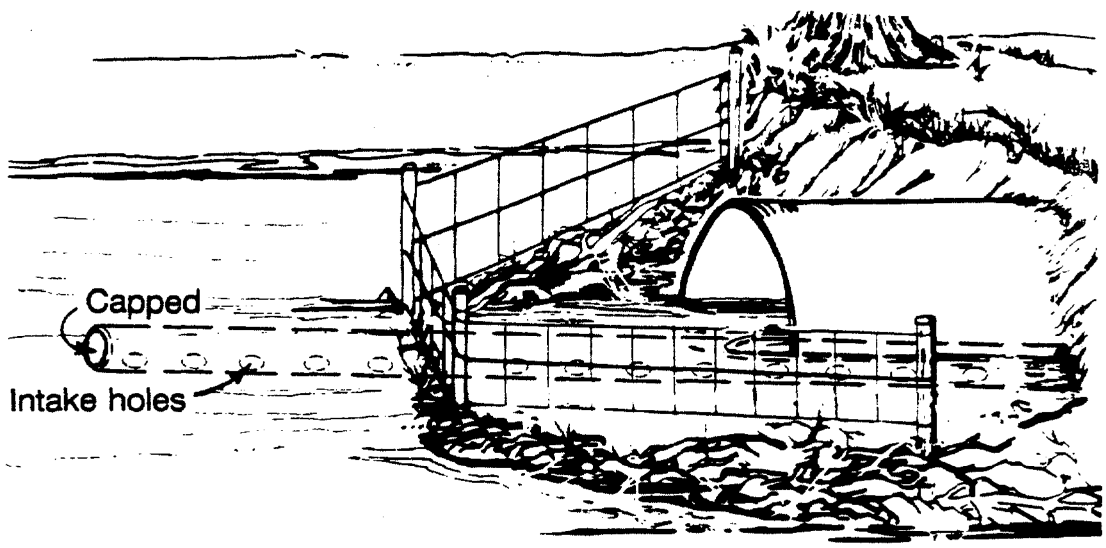


Figure 3.21. Horseshoe-shaped fence and plastic tube used to prevent plugging of roadway culverts by beavers.

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CHAPTER 4. CULVERT MAINTENANCE

SCOPE

This chapter presents information on the benefits of regular and preventive maintenance and on maintenance procedures for highway culverts.

GENERAL

One of the most important duties of maintenance personnel is maintenance and repair of the highway drainage system. The drainage system is an integral part of a highway that is designed to keep water from damaging the pavement by controlling or directing the flow of water over, under, or adjacent to the roadway. A road may have its serviceability seriously reduced or it may even be made impassable as a result of improper drainage maintenance. The *AASHTO Maintenance Manual*(1) states that "maintenance functions include:

1. Keeping water courses free from accumulations of dirt, debris, vegetation and other obstructions,

2. Correcting malfunctioning parts of systems, e.g., erosion and breaks or shifts in structures, waterways, conduits and pavings, and

3. Anticipating problems and making limited changes or modifications."

Maintenance of culverts and appurtenant structures may be divided into routine, preventive and emergency maintenance. Routine drainage maintenance is work that should be done on a planned basis to ensure that all parts of the drainage system receive attention on a regular schedule. Preventive maintenance may be considered to be a type of regular maintenance that is not performed on a regular time schedule, but rather to correct a specific problem before it gets worse. Emergency drainage maintenance is work that is caused by storms, floods, and other conditions that are not routine nor anticipated, in order to restore the structural integrity or hydraulic capacity of the culvert.

Emergency maintenance can be reduced through properly planned and scheduled routine maintenance. Many items of emergency maintenance can be eliminated through routine and special inspection with appropriate action taken when warranted. Special attention should be given to areas of new construction where there is a possibility of rapid erosion of soil. These types of problem locations should be checked more often and appropriate corrections made to prevent or curtail emergency conditions. Emergency maintenance work caused by storms, floods, or other conditions should be promptly repaired. It is also important to recognize that even though the work is emergency (or unexpected) in nature, it should be prioritized, planned, scheduled, and undertaken properly. If at all possible the emergency nature of the situation should not be an excuse for poor workmanship and inadequate procedures.

It is a well-known fact that there is never enough money, personnel, or equipment to properly maintain all elements of the highway system. This may be particularly true for culverts. Historically, many maintenance departments have operated on a "fight brush fires" basis, where only the most critical problems were taken care of and routine-type work was done only if personnel and equipment were available. Over the past few years, there has been increased interest in developing various types of management programs, with considerable success for pavement management, equipment management, and bridge management. Some of these programs are mandated by the Federal Highway Administration. Although it is not required, it may be appropriate to establish a Culvert Management System (CMS). The basis of such a system would be the same as for other types of management systems, which is to establish a rational plan for and undertaking the various types of work at the most appropriate time.

Establishment of a workable and cost-effective Culvert Management System may take considerable effort. However, as with the other management systems, once the system is set up and implemented and adequate records are taken and updated, the advantages of such a system becomes obvious. The longer the system is operated and as more comprehensive records become available, the better culverts and appurtenances can be maintained.

Some of the major problems that inhibit organized planning of maintenance work include the following: there may not be a complete inventory of the facilities, records have not been made and updated on the type of materials and the amount of effort that was previously used, and the frequency with which the work needed to be repeated has not been recorded. The situation for culvert maintenance is no exception.

Regardless of whether it is to establish a CMS or to rationally plan culvert maintenance, it is desirable that all culvert structures be inventoried and rated. Inspection programs are discussed later in this chapter. The information can then be used to determine the maintenance, repair, or replacement work that must be undertaken and to establish priorities for accomplishing the work.

BENEFITS OF REGULAR AND PREVENTATIVE MAINTENANCE

Most types of operational and serviceability-related culvert problems occur gradually over a period of time during which the structure or its appurtenances slowly deteriorate. If the degradation continues unchecked, other parts of the roadway system may be affected, especially during and after storms and adverse weather conditions. Thus, it is reasonable and prudent to establish a maintenance program that is based on an annual schedule for doing all types of culvert maintenance work. Such a program will facilitate the scheduling of personnel and equipment, so that the work can be of a routine maintenance nature rather than repair, retrofit, or replacement. Timely preventive maintenance will frequently minimize the amount of distress or damage that occurs during major storms, floods, or other events. In this context, it may be appropriate to do many types of work that will either prevent culvert damage or select where the damage will occur so that the damage to the structure and adjacent land and/or the hazard to the public will be minimized.

Costs

Although the cost of culvert maintenance work is high and it is always difficult to justify sufficient funds and personnel to do a completely adequate job, the cost of culvert repair and replacement work is even higher. Regular and preventive maintenance will often prevent development of more serious deterioration, which is even more expensive to correct.

Historically, one of the operational principles of highway maintenance departments has been that their staff be flexible and unincumbered by rigid rules of when work should be done, so that their personnel can respond to urgent maintenance needs and do other general maintenance work when time permitted. As a result, minimum records have been kept and, frequently, the highway drainage systems have gradually deteriorated to the point where the maintenance personnel were only taking care of urgent problems. Little money was available for routine and/or periodic maintenance. The results of several studies and the acceptance of other management systems have clearly shown that the "old way" is not the most cost-effective way to maintain the highway system.

These latter studies and developments have also indicated other factors that influence the overall cost of performing adequate maintenance functions, including:

- The highway facility with the lowest first cost (installed) usually is not the least expensive to maintain.

- Repair work and materials with the lowest costs may not be the longest lasting and most trouble-free solution to a problem.

- The decisions for the type and timing of maintenance work should include consideration of costs for mobilization and traffic control as well as safety of the maintenance personnel and the traveling public.

Legal Implications

Although the purpose of this manual is to present information on culvert repair practices, it is also appropriate to mention the fact that there are legal implications to doing, or not doing, maintenance work in a timely manner. The amount of legal exposure that governmental agencies face depends on many factors that are beyond the scope of this document. However, the lack of timely maintenance or repair work to correct known problems may increase the possibility of legal action, particularly if the public is injured or land, buildings, or crops are damaged through negligence by the highway agency.

After decades of design and construction, the major challenge to highway agencies has shifted to operation and maintenance of the highway system. With this change in emphasis, several operational concerns have moved to the forefront, including environmental quality, social concerns, and safety. The concept of the forgiving roadway has evolved.

Another factor affecting Federal, State, and Municipal Governments is the erosion, over the past few decades, of the doctrine of sovereign immunity, which held that these agencies were immune from suits brought against them without their consent. Concurrently, there has been a large increase in litigation involving highway accidents. The number of tort liability cases against highway agencies has been increasing rapidly in the last 20 years.

The legal concepts of the elements employed in tort liability suits that are pertinent to highway design and maintenance are too numerous to review in this publication. However, there are several legal precepts that are important in any maintenance program, including:

- The duty to correct a dangerous condition or take other appropriate action arises when notice is received.

- Under the concept of "constructive notice," the duty to act may arise when the agency should have known of the existence of a situation.

- When existing hazards cannot be eliminated immediately, there is at least a duty to warn motorists of such known hazards.

Public agencies can best reduce their liability risk by taking prudent and reasonable steps to reduce the risk that the public faces. Some of the practical steps are listed below:

- Schedule regular inspection of all drainage facilities.

- Establish a safety improvement program to identify hazardous situations, prioritize needs, and schedule improvements.

- Evaluate repair or improvement alternatives to demonstrate that comprehensive and logical procedures are used.

- Conduct additional inspections of potentially hazardous sites during emergency conditions, such as seasonal periods of flood.

- Comply with all regulations that require that permits be obtained prior to initiation of work and that work be conducted in a prescribed manner.

- On waterways, floodplains, or their connected wetlands, comply with all requirements of the U.S. Army Corps of Engineers, the U.S. Coast Guard, State departments of environmental resources, or fish and game commissions.

- Document decisions and actions concerning the safety of the traveling public. Maintain adequate records.

Some conditions that may increase legal exposure are:

- Annual or seasonal flooding of land and flooding and icing of highways during the winter because of blocked culverts.

- Continued and worsening drainage problems that are not corrected.

- Lack of maintenance or repair work on potentially hazardous structural conditions, after the condition has been identified and documented.

- Lack of compliance with various regulations that require that permits be obtained prior to initiation of the work and that the work be done in a certain manner. These regulations may require that the following procedures be followed:

  - Installation and maintenance of erosion and sediment pollution control devices may be required by governmental agencies before construction can begin.

  - An earth disturbance permit may be required by a State department of environmental resources.

- Conduct of work in waterways, floodplains or their hydrologically connected wetlands may be controlled by requirements of the U.S. Army Corps of Engineers, the U.S. Coast Guard, or State departments of environmental resources or fish and game commissions.

Culvert Inspection Programs

Safety to the traveling public is the most important reason that culverts should be inspected. To ensure that a culvert is functioning adequately, the inspection should evaluate structural integrity, hydraulic performance, and roadside compatibility.

a. Structural integrity - The failure of culverts can present a life-threatening safety hazard. Identification of potential structural and material problems requires a careful evaluation of indirect evidence of structural distress as well as actual deterioration and distress in the culvert material.

b. Hydraulic performance - When the hydraulic capacity of a culvert is inadequate, potential safety hazards may result. The flooding of adjacent properties from unexpected headwater depth may occur. Downstream areas may be flooded by failure of the embankment. The roadway embankment and/or the culvert may be damaged because of erosion.

c. Roadside compatibility - Many culverts, like older bridges, present roadside hazards. Headwalls and wingwalls higher that the road or embankment surface may constitute a fixed-obstacle hazard especially if the shoulder is narrow. Abrupt dropoffs over the end of a culvert or steep embankments may represent roll-over hazards to vehicles that leave the roadway.

Conducting and reporting inspections are important elements of an overall program for maintenance of all hydraulic structures. A systematic inspection program also requires planning to establish the purpose and scope of the program, as well as budgeting and scheduling to accomplish the planned program. The usefulness of the information that is collected in the field depends to a large extent upon how well the inspection is accomplished and documented. The information must be recorded in a manner that provides a permanent record, is easy to understand, furnishes an accurate assessment of conditions at the time of inspection, makes information readily available for a variety of uses, and is easily verified and updated.

Although the above deals with routine and scheduled inspections, it should be recognized that prompt, unscheduled inspections should also be conducted at the first signs of impending problems. Situations such as unusual depressions in a roadway, washout of shoulder embankments, or unusual flooding adjacent to roadways may be indicative of culvert problems. For some situations the development of small signs of distress may be the only signs of impending collapse. Timely inspections and prompt maintenance or repair work will usually take considerably less time and money than if the condition is allowed to continue and the problems become larger and more serious.

As part of bridge inspection program - The National Bridge Inspection Program was established to ensure the safe passage of vehicles and other traffic over highway structures. Under this mandated program all bridges with a span length over 20 feet must be inspected every two years, and more frequently if they have serious deficiencies. According to the National Bridge Inspection Standard's definition, culverts that have a transverse length of more than 20 feet along the centerline of the road are considered to be bridges and they must be inspected every two years. [2,3] This criteria also applies to multiple barrels that have a distance between openings of less than half of the barrel opening.

These inspections must be conducted in accordance with the National Bridge Inspection Standards (NBIS), which establishes definitions and criteria of the features to be inspected and the criteria for rating their condition. The criteria covers both structural and functional features.

As a separate culvert program - All culverts in the highway system should be inspected and evaluated, at least periodically. Although all culverts that have a single or combined width less than 20 feet are not required to be inspected at least every two years, it may be appropriate to establish a separate inspection program. It should be recognized that very small culverts may not require the same rigorous level of inspection or inspection frequency as large culverts. Some state highway agencies inspect these smaller culverts on a four-year cycle. Procedures for implementing a culvert inspection program can be found in the Culvert Inspection Manual. [2]

In conjunction with maintenance - An alternative to a separate inspection program for smaller culverts is that the inspections may be conducted during periods of scheduled maintenance. However, it should be emphasized that these should still be formal inspections that are conducted in accordance with established procedures and criteria. The culvert condition and rating information should be gathered and recorded with the same level of accuracy as required for separate programs.

MAINTENANCE PROCEDURES

Regular and special scheduled maintenance of highway culverts is one of the most important functions of maintenance personnel. To the maximum extent possible, standardized methods should be established to conduct specific maintenance procedures. However, it should be recognized that each culvert is unique, and it presents its own set of requirements for maintenance. In addition, as the life of a culvert progresses and land use in the vicinity of the culvert changes, the type and frequency of maintenance that is required may also change.

A wide variety of types of equipment and amount of manpower may be used for each type of maintenance procedure. The maintenance procedure that is used to accomplish the same objectives will depend upon the level of manpower available, the level of experience of the personnel, the types of equipment that are available, and the size of the project to be undertaken. Equipment used for culvert maintenance is diverse and depends upon the circumstances, culvert size and material, location, and type. The following paragraphs describe and provides guidance on routine types of work that are necessary to maintain highway culverts in good operating condition.

Debris Removal

Since culverts generally constrict flow, there is an increased potential for waterway blockage by debris and settlement of soil and rock material, especially for culverts subject to seasonal variations in flow. Multiple barrel culverts tend to be particularly susceptible to debris accumulation. In colder climates, the problem may be increased where openings can also be clogged by ice. Scour problems may be caused by turbulence at the inlet end and high velocity flow at the outlet end. Debris that collects at culvert openings during a period of high water should be removed prior to succeeding periods of high water to help reduce the potential for scour problems.

Vegetation, growing and standing in areas of the stream bed and banks adjacent to a culvert structure can impede stream flow. This vegetation can become dislodged and cause hazardous conditions in the future. Although authorization from environmental agencies may be required before standing vegetation may be removed, the extra effort may be warranted.

At culvert sites where experience or physical evidence indicates that the watercourse will transport a heavy volume of debris during high flows, consideration should be given to debris-control structures. The need for debris-control structures will be more prevalent in steep or mountainous areas and where the culvert is under a high fill. In addition to blockage, rock debris may cause moderate to severe abrasion damage to culverts. Recommendations for designing debris-control structures are provided in Reference 4. Information on debris removal procedures are provided in appendix B-1.

Flushing/Sediment Removal

Clogging of culverts with silt and sediment is a common occurrence, especially in areas undergoing continuous land development. In areas where construction activities have drastically altered or destroyed protective vegetative cover and soil mantle, the probability of the accumulation of sediment in culverts increases.

Excessive quantities of sediment are the result of erosion, principally during periods of high flow. During lower flows, as the velocity of runoff decreases, the transported materials are deposited, to be picked up by later peak flows.

Sediment deposits at the inlet or within the culvert barrel reduce both the size of the opening and the capacity of the culvert to handle peak flows. Small pipes are sometimes completely blocked, particularly if they are never cleaned. Under extreme conditions they may be blocked, hidden by plant growth, and only found when the cause of land flooding is being investigated. Therefore, culverts should be kept reasonably clear and unobstructed. However, culverts should not be hydraulically cleaned with a large volume of high pressure water unless adequate measures are take to protect the drainage way and prevent stream siltation or increased turbidity. Procedures for sediment removal can be found in appendix B-2.

Thawing

Roadway flooding and icing is a major problem in several northern States, especially during the spring thawing period. At this time of year, below-freezing soil temperatures surrounding roadway culverts can cause water to freeze inside the culvert. Construction and possible closure of a culvert may cause roadway flooding and icing, which can be a serious hazard to the traveling public. Several techniques that may be used to thaw frozen culverts are described in appendix B-3.

Ditch Cleaning and Repair

Ditches and open channels that carry water from roadways and adjacent land and drainage facilities to culverts should be maintained so that they have a uniform flow line with sufficient depth and grade to ensure free drainage to and from culverts, roadways, and other roadside areas and drainage facilities, such as underdrains. Unpaved channels should be kept free of obstructions with proper depth and width to provide adequate drainage. Paved channels should be maintained free of all vegetation and debris. Procedures for cleaning and repair of lined ditches are described in appendix B-4. A procedure for cleaning and repair of unlined ditches is described in appendix B-5.

Streambed Maintenance

Regardless of how stable a stream is perceived to be, its bed and banks are in a constant state of change. Placement of a culvert in this environment presents yet another factor in the interplay or erosion, sedimentation, and debris movement.

A culvert barrel usually constricts the natural channel and forces water to flow through a reduced opening. As the flow is constricted, eddies or areas of high velocity are formed that strike the upstream slopes and tend to scour away the embankment adjacent to the culvert. Similarly, as the water exits the culvert barrel, turbulent and erosive eddies form as the flow expands to conform to the natural channel. The removal and transporting of streambed material by flowing water results in scour damage at the outlet end of the culvert.

Scour hole repair - Attention should be given to detection, maintenance and repair of scour holes that develop in streambeds in the vicinity of culverts before they become a major problem. The scour hole is usually deepest during passage of peak flows; suspect locations should be inspected after major storms.

Scour holes may be filled, at least temporarily, with crushed stone, rubble, or riprap. Since prediction of scour at culvert outlets is difficult and protection is expensive, a practical approach is to provide a minimum amount of protection that is monitored by periodic site inspection. The installation should be inspected to assess its performance after a number of storm events. If the protection is inadequate a more permanent repair should be installed.

Care must be exercised to ensure that the potential for scour is not increased by the retrofit concept. Information on repair and mitigation of scour holes is presented in chapter 5.

Channel - The upstream channel should be inspected for scour undermining of the culvert or eroding of the embankment. Scour that is undermining trees or producing sediment that could block or reduce the culvert opening should be noted. Areas of the channel around culvert inlets and outlets should be controlled to limit vegetation and permit free flow of water. Inspections should be made after heavy rains or storms and any debris that would constrict the channel and contribute to high water velocities should be removed.

Protective systems that line the streambed should be inspected for gaps or openings. Riprap that has shifted or moved should be returned to its original location or replaced with larger units. Gabions should be replaced if the wire mesh has deteriorated. If the lining system appears to be insufficient, other methods of channel lining should be considered. Paving should be inspected for cracking or undermining.

Alignment - Indications of erosion and changes in the horizontal direction of the stream channel should be noted. Sketches and photographs can be used to document the condition and alignment at the time of inspection. Abrupt stream-alignment changes retard flow and may require a larger culvert. Horizontal alignment changes frequently cause increased erosion along the outside and inside of the curve

as well as damage to the culvert. The condition of the streambanks and any bank protection at both ends of the culvert should be checked.

Vertical alignment problems are usually indicated by scour or accumulation of sediment. A culvert barrel that is higher or lower than the streambed can cause scour and sediment problems. Culverts on grades that differ significantly from the natural gradient may present problems. Culverts on flat grades may have problems with sediment build-up at the entrance or within the barrel.

Vegetation Control

The objective of roadside and waterway vegetation management is to provide utility, economy, and beauty to the roadside. Utility is provided by stabilizing roadside and embankment soils, preventing erosion, and by growing and encouraging desirable vegetation in place of undesirable and future problem vegetation. Economy is provided by the selection of vegetation, such as Crownvetch, that needs no mowing or fertilization, or by the type of vegetation that can withstand roadside environmental contaminants such as salt. Beauty is provided by green and well-maintained turf, by spring flowering roadside plants (such as Crownvetch), and by screening unsightly areas adjacent to the highway.

Roadside ditch mowing is an essential maintenance activity that contributes to motorists' safety, vegetation control, roadside appearance, and the functional operation of ditches that must carry runoff water without creating an erosion problem. The need and frequency of mowing depends upon the type of vegetation present and climatic factors that influence the growth of vegetation.

For certain areas along the roadway, in drainage channels, and near the inlet and outlet of culverts, mowing may not be feasible or safe to undertake. For such areas, vegetation must be controlled by herbicides and plant growth inhibitors. The purpose of herbicide application is to control or eradicate prohibited and noxious plants, as required by law, and to control other undesirable vegetative growth within the highway right-of-way. Through prudent and timely application of herbicides, the frequency of side dozing, mowing, tree trimming, and future tree removal may be substantially reduced. This may result in substantial cost savings for maintenance operations.

Herbicide materials that are used by most, if not all, highway agencies are classified as (1) selective and (2) non-selective. Selective herbicides are those that affect only certain plant species or types whereas non-selective herbicides affect all plant species and types in the treated area. Non-selective herbicides are generally used under guardrails, around highway sign posts, and near other highway structures where vegetation growth would interfere with the normal function of the structure. The use of such herbicides near the inlet and outlet of culverts may be warranted, although care must be taken not to introduce erosion problems. It is possible that vegetation growth can be eliminated by paving at the ends of pipes if fish passage is not impeded. All herbicides that are used should be registered for right-of-way use by

Federal and State regulatory agencies and all should be of the "non-restricted" use classification.

All personnel involved with the use of herbicides must be familiar with and utilize all herbicides in accordance with labeled instructions. The misuse of herbicide materials is a violation of Federal law. The cardinal rule in herbicide application is to read the label and not violate any of the instructions that could lead to improper use.

REFERENCES

1. *AASHTO Maintenance Manual*, American Association of State Highway and Transportation Officials, Washington, DC, 1987.

2. *National Bridge Inspection Standards*, Code of Federal Regulations, Title 23-Part 650, (enacted in about 1969).

3. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, Report No. FHWA-ED-89-044 (OMB No. 2125-0501), Federal Highway Administration, Office of Engineering, Bridge Division, Washington, DC, December 1988.

4. *Debris-Control Structures*, Highway Engineering Circular No. 9, Federal Highway Administration, Office of Engineering, Bridge Division, March 1971.

CHAPTER 5. END TREATMENT AND APPURTENANT STRUCTURE REPAIRS AND RETROFIT IMPROVEMENTS

SCOPE

This chapter presents information on the repair and retrofit improvement alternatives of the inlet and outlet ends of culverts, the approach and downstream channels, and the appurtenant structural elements. These elements include headwalls, tailwalls, and wingwalls as well as safety appurtenance structural members.

GENERAL

The rationale for selecting and carrying out repair and/or retrofit procedures for the wide range of types and sizes of culverts, which may have an even wider range of problems or deficiencies, will depend on many factors. These factors include:

- The type, size, and length of the culvert;
- The degree of deterioration of the culvert;
- The age of the culvert;
- Other deficiencies of the culvert;
- The type and amount of work to be done;
- The location of the culvert: depth of fill, classification of roadway, etc.;
- The general location: urban or rural;
- The area of the United States; and
- Whether the work will be done by contract or in-house personnel.

Similarly, the cost of repairing and/or correcting problems will also depend on the above factors, plus others, including:

- The type and amount of equipment necessary and available to do the work;
- The size of the job and/or the number of culverts in a repair contract;

- Environmental conditions present: volume and velocity of water passing through the culvert, weather conditions, etc.;

- The urgency of the work; and

- The range of options that are available for the corrective action.

Although the primary focus of this manual is on culvert repair practices, some of the procedures presented may be used to correct design and operational problems and to increase the strength and hydraulic efficiency of culverts. Procedures used to correct design problems should be referred to the engineer. The following are considered to be retrofit improvements, since they would not be considered either maintenance or repair work:

- Adding slope erosion protection;

- Paving approach channels for scour protection;

- Adding headwalls, tailwalls, and wingwalls;

- Strengthening for increased load capacity;

- Lengthening for roadway widening;

- Adding grates for vehicle safety; and

- Retrofitting to facilitate fish passage.

Table 5-1 provides a summary of the types of problems and repair options available for correcting the upstream and downstream channel deficiencies. Table 5-2 provides similar information for the inlet and outlet ends of the culvert. Each of the repair procedures and warrants for their use are discussed in the following sections of this chapter. Specific details and additional information on repair options are provided in appendix B.

EROSION CONTROL

Erosion of soil around and in the vicinity of culverts is a common occurrence that should be prevented through periodic repairs and/or retrofit construction work to protect against future erosion and related damage. Erosion of embankments may be caused by high velocity stream flow as well as by surface-water runoff and piping. It may occur during normal flow or only during peak flow periods associated with

Table 5-1. Problem and corrective action options, upstream and downstream channels.

General Location	Type of Problem	Repair Options	
		Action Required	Specific Options
Upstream and downstream channels	Erosion, Slopes	Vegetation	Grass/Ground Cover
		Geotextiles	Several types available
		Barriers	Rubble/riprap
			Gabions
		Retaining walls	Modular or cast-in place concrete
			Loffelstein block
			Steel
			Timber
		Pave slopes	Concrete, cast-in-place or shotcrete
	Scour, streambed	Fill holes	Rubble or riprap
		Pave apron	Rock or concrete, CIP or shotcrete
		Energy dissipators	Several types
		Realign	Modify channel
	Fish passage	Retrofit	Modify channel

infrequent large storms. It may also occur during spring snow melt times. Erosion is more likely if the outlet features of a culvert are not designed and constructed properly. It is important to evaluate the causes of erosion before planning the corrective action that should be taken. It may be necessary to incorporate two or more protective systems to repair and/or correct the erosion problems.

Table 5-2. Problem and corrective action options, inlet and outlet ends.

General Location	Type of Problem	Repair Options	
		Action Required	Specific Options
Inlet & Outlet (Head & Wing Walls & General)	Erosion behind wings	Backfill	Rock or Soil
	Undermining	Fill hole	Rock or concrete
		Underpin	Concrete or piling
	Masonry, Mortar	Repoint	Mortar
	Masonry, Loss of	Replace	Masonry block
	Concrete spalling & deteriorating	Patch	Mortar or concrete
		Resurface	Concrete
	Strength Loss	Jacket	Reinforced concrete
	Alignment	Reconstruct	Reinforced concrete
	Displacement	Underpin	Concrete
			Piling
	Safety	Retrofit	Widen or add grates
		Retrofit	Change from inlet to outlet control
			Add sections to reduce slope
			Eliminate dropoff

Backfilling

In the context of erosion control, backfilling generally refers to the replacement of soil that has been removed from a location or the placement of soil behind a newly constructed retaining wall. Well-established procedures should be followed in placement and compaction of the soil or rock backfill materials to ensure that they are well compacted and that pressures from the soil and any live load will not create constructed retaining wall. Well-established procedures should be followed in placement and compaction of the soil or rock backfill materials to ensure that they are well compacted and that pressures from the soil and any live load will not create uneven pressures on the structure. Poor placement of backfill is one of the causes of piping, resulting in the erosion of backfill that can cause end-section dropoff, misalignment and opening of joints in rigid pipe installations. In flexible pipe installations, it can lead to weakening of the soil envelop surrounding the pipe.

Slope Stabilization

Stabilization of slopes in the vicinity of culverts is necessary to prevent erosion of embankments and possible loss of soil from behind wingwalls that may severely weaken the entire culvert structure. Continued loss of soil may also lead to undermining of the inlet and a considerable length of the entire culvert. Slope stabilization techniques using vegetation, geotextiles, rubble, modular retaining wall systems, gabions, earth reinforcement systems, timber retaining walls, and steel retaining walls should be referred to the engineer.

Vegetation - Planting grass or other types of ground cover on slopes adjacent to culverts is frequently the most cost-effective and efficient method of preventing or minimizing erosion. Although a variety of types of vegetation may be planted, certain types will be more effective than others, depending upon the steepness of the slopes, the vegetative zone of the streambank, and the velocity of the water at the location. Once the plant life is well established, it will normally require minimal attention unless it is lost during periods of peak runoff. Highway agencies are normally quite familiar with the local types of plant life that are recommended for slope stabilization in specific areas. If erosion is a continuing problem, more resistant forms of slope stabilization may be required. Further information on vegetative streambank stabilization can be found in appendix B-6.

One of the more advanced systems related to the use of vegetation to solve erosion and sedimentation problems is known as soil bioengineering. Soil bioengineering is a method of land stabilization that combines mechanical, biological, and ecological concepts to construct living structures for erosion, sediment, and flood control.

Soil bioengineering uses plant parts as the major structural or engineering component. Unrooted, live vegetation is installed in various systems to act as structural members. These plants, or parts of plants, grow together with earth, rock, and groundwater, utilize the inherent strengths of the site to provide direct mechanical soil stabilization, protect the soil, and reduce water velocity. Live plants stabilize the soil; top growth intercepts raindrops, filters sediment out of runoff, increases infiltration, and enriches the soil; and the root system mechanically reinforces and restrains the soil.

Soil bioengineering includes several methods of land stabilization:

- Live staking - This is the simplest and least expensive system to install and should be used on a slope before erosion problems start. It should be part of a routine maintenance program.

- Brushlayering - This system includes brush layers cut into a slope and those used in a new or repair fill that abuts the slope face. The brush layers act as a lateral drain.

- Live facine system - This system works as a pole drain immediately after installation to control and redirect surface runoff.

- Live cribwall system - A live cribwall incorporates stems and living roots that eventually permeate the interior fill of the wall, bind and tie the cribfill together, and root behind the unit to improve resistance to external forces.

All of these systems have specific site planning, preparation, and installation requirements.

Live bioengineering structures have several advantages over conventional structural methods:

- They are flexible in that they can yield and rebound under stress and tend to be self-healing when damaged.

- Rather than deteriorating, a live system expands and becomes more structurally sound with time.

- When properly installed, they provide immediate bank stability and protect the new vegetation until it becomes rooted and established.

- Plants remove excess moisture from the banks, lowering the saturation line and reducing the weight of the soil mass, thereby lessening the chance of slope failure.

- Generally, living structures are less costly than traditional measures.

- When they become established, they look like a natural part of the environment.

- The live system improves water quality and provides covering and food for fish and wildlife.

- Little or no heavy equipment is required and energy costs are correspondingly low.

- Cuttings are native plants and can usually be obtained at no cost. Since they are obtained nearby the site, transportation costs and also low.

Live systems also have disadvantages:

- Live systems such as shrubs and trees are potential debris producers.

- Intensive site assessment, careful species selection, exacting design, and proper installation is very important to the success of Soil Bioengineering projects.

- The installation of the system is labor-intensive.

- Live systems can only be installed in the dormant season.

Geotextiles - Over the past several years, geotextiles have become an increasingly important construction material. According to the American Society of Testing and Materials (ASTM), a geotextile is defined as any permeable textile material used with foundation, soil, rock, earth, or any other geotechnical engineering-related material, as an integral part of a man-made project, structure, or system. Geotextiles are generally selected because of a substantial cost savings over alternative solutions or because it is effective in improving a design. Improvements may include increased life, reduced maintenance, or a more effective installation.

Geotextiles or geotextile-related products are usually made from synthetic polymers, such as polypropylene, polyester, polyethylene, polyamide, or nylon. These polymers are highly inert to biological or chemical degradation. Some are made of glass fibers. Natural fibers, such as cotton, wool, or acetate are seldom used because they are biodegradable and will rot when they come in contact with the soil. However, biodegradation may be a desired function, in which case a biodegradable material, such as a wood fiber, can be selected.

The use of geotextiles has been found to be a satisfactory method for providing long-term bank stability and bank protection. Geotextiles may be sized to prevent piping or erosional scour of underlying soil, with sufficient permeability to prevent buildup of excess hydrostatic pressure in the soil beneath the fabric. Geotextiles can also be used to retain soil, preventing it from eroding, as in the erosive undermining of drainage structure appurtenances.

One of the most difficult problems in using geotextiles is choosing the correct material to meet the specific requirement. In an effort to provide objective specification guidelines to end users, specifically state departments of transportation, a subcommittee, referred to as Task Force 25, was formed in 1982 by the Joint Committee on New Highway Materials to develop specifications for geotextile applications in transportation. The Joint Committee is made up of representatives of the American Association of State Highway Officials (AASHTO), the Associated General Contractors of American (ACG), and the American Road and Transportation Builders' Association (ARTBA). Specifications have been prepared and approved for paving fabric, silt fence, drainage geotextiles, erosion control geotextiles, and separation geotextiles. These specifications have been published in a manual entitled *Task Force 25 Specification Guides*[1] and is available through AASHTO. Another exhaustive manual is the *Geotextile Engineering Manual, Course Text*[2]. The Geotextile Division of the Industrial Fabrics Association has published *A Design Primer: Geotextiles and Related Materials*[3]. This is a design manual for geotextiles and related geosynthetic materials that has been produced for the design-oriented professional considering the use of a geosynthetic. It presents basic concepts related to design and construction for common applications. More material on uses and placement of geotextiles can be found in appendix B, section 7.

Rubble - Rubble is a type of riprap made up of broken fragments of rock or debris, usually resulting from the decay or destruction of a building or pavement. The types of rubble that have been used as riprap include broken concrete, rock spoils, and steel furnace slag. Since these materials are considered to be waste products, rubble is a very economical riprap material. Broken concrete is available from demolition of buildings or other structures made of concrete. Rock spoils can often be acquired from excavation sites or road cuts. Steel furnace slag may be found in the vicinity of steel smelting plants.

Good quality control of material is essential to the successful use of rubble. The important elements of quality include specific gravity, shape, gradation, and durability or resistance to weathering. Specific weight can be corrected for in the design procedure. However, shape and gradation can be problematic. The length-to-width ratio of most of the material should be 1:3 or less. An approximate guide to stone shape is that neither the breadth or thickness of a single stone should be less than one-third its length. In addition, the rubble should contain the appropriate mix of particle sizes to form an adequate material. Plating, a procedure in which the rubble is placed on the embankment and then stamped into place with a steel plate, can overcome these problems.

The lack of adequate material durability can cause the failure of rubble riprap. Rock spoils that contain a large percentage of shale or weakly layered structures should be avoided. Those materials subject to chemical breakdown or weathering are poor choices for rubble riprap since it will be subjected to environmental extremes.

There are several advantages to the use of rubble riprap:

- The material is inexpensive.
- It is generally available.
- Construction is not complicated.
- Local damage or loss can be repaired easily by placement of additional rubble although, to be effective, it should be installed by plating.
- Rubble that has been plated can be used on steeper slopes than dumped riprap.

There are also disadvantages to the use of rubble riprap:

- Quality control of material must be firmly monitored to avoid inadequate durability.
- Material must be plated to provide adequate shape and gradation.
- Riprap plating results in a more rigid riprap lining than loose riprap, making it susceptible to failure as a result of minor bank settlement.
- Rubble riprap is often not as attractive as other types.
- Extreme care must be exercised in selecting rubble that is not contaminated with such materials as asbestos, if the rubble would be used to line streambanks and streambeds or would endanger groundwater.

Block Retaining Wall Systems

There are several retaining wall systems available that rely on gravity, weight, and friction resistance based on material shape to resist lateral earth pressure. These are generally precast concrete shapes that are mortarless systems with either pinned or interlocking connections. Uses include channel and streambed lining for erosion control and retaining walls. They can be used to protect against wave action.

These systems provide free drainage of the hydrostatic loads. They are flexible systems and, in some cases, the voids can be filled with topsoil and reseeded with grass or other vegetation.

Loffelstein Block - One such system is the Loffelstein block retaining wall system. This system originated in Switzerland in the mid-1970's. In German, loffel means spoon and stein means stone. A Loffelstein module is a cast-concrete block with spoonlike hollows. The Loffelstein retaining wall system is a gravity retaining wall that uses mass, gravity, wall inclination, unit infill density, and friction to resist lateral soil forces.

The Loffelstein is only one of three related products known by that name. A smaller version is called the MiniLoffel. A third module is called the Waterloffel and was developed for the purpose of lining the sides of water channels and streambanks, preventing soil erosion, and performing the function of a retaining wall. Unlike its antecedent, Loffelstein, the Waterloffel includes interlocking wings or ears on each side of the unit that lock the modules together and prevent the loss of fill material behind and between the modules. They also have an additional crossmember that creates two independent troughs for the purpose of retaining backfill. Figure 5.1 shows a typical Waterloffel module.

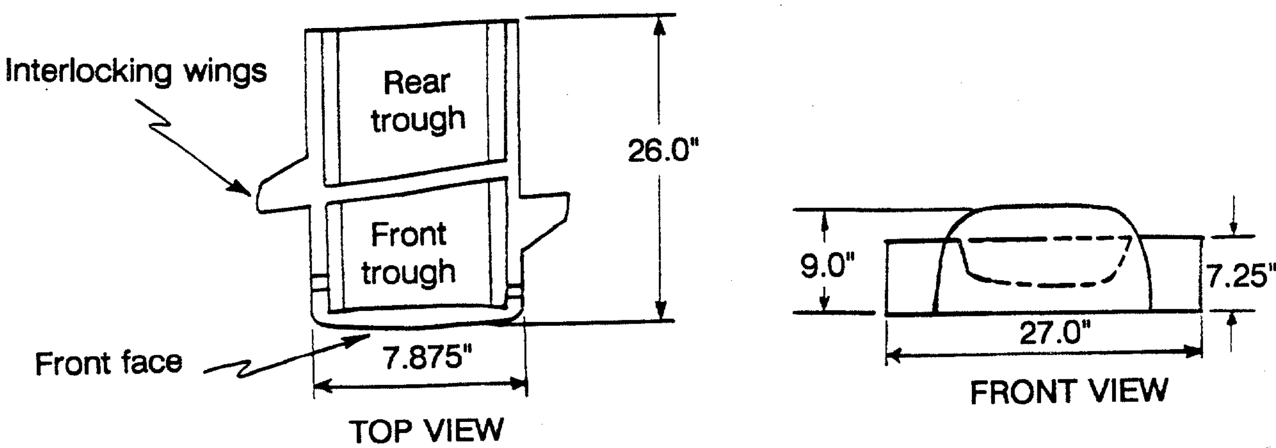


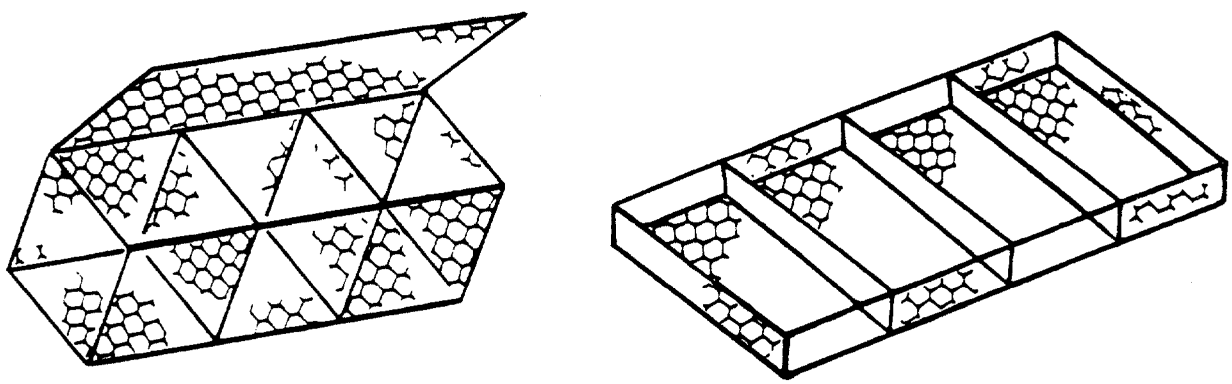
Figure 5.1. Typical Waterloffel module.[4]

Although Waterloffel installations must be carefully designed to meet existing site conditions, a general procedure for installation is given in appendix B-8. The design should be conducted by an engineer with the assistance of the manufacturer.

The Keystone retaining walls system is also an interlocking paver system that is installed by placing reinforced fiberglass pins into the paired holes of each module. Other Loffelstein block type systems include T-wall, Double Wall, and Sta-Wall.

Gabions - The use of gabions can be an effective technique for stabilizing slopes against movement and erosion, especially where slopes are too steep for conventional riprap methods. A gabion is essentially a pre-assembled wire-mesh basket filled with rock. Gabion containers are backfilled with nondegradable stone of a size greater than the openings of the container.

There are two types of gabion revetment designs that are distinguished by the shape and placement of the gabion: mattress and block as shown in figure 5-2. In the mattress design, the individual wire baskets are placed end-to-end and side-to-side to form a continuous mattress layer on a prepared channel bed or bank. The individual baskets are attached to each other and anchored to the base material. The wire baskets forming the mattress generally have a depth dimension that is much smaller than the width or length. The block design is formed by stacking the individual gabion blocks in a stepped fashion. Block gabions are typically rectangular or trapezoidal in shape and generally equidimensional.



Gabion

Reno mattress

Figure 5.2. Gabion and Reno mattress.[5]

The advantages to the use of gabion baskets include the following:

- Gabion baskets can be stacked to form almost vertical banks where the banks cannot be graded economically to the stable slope required by other methods.
- Foundation footings are not required.
- Gabion baskets have the ability to span minor pockets of bank subsidence without failure.
- Gabions are unaffected by frost heave.

- Smaller, lower quality rock that is less dense than conventional riprap can be used in the baskets.

- To encourage rapid growth of vegetation, gabions can be brushed with soil or biodegradable matting can be laid down before the mesh panel lid is placed.

Disadvantages to the use of gabion revetments are as follows:

- The wire baskets are susceptible to corrosion and abrasion damage, which can cause failure of the wire baskets and loss of the rock. However, the wire mesh is usually heavily galvanized and can be given an additional PVC sheathing.

- Fabricating and filling of the baskets can be labor-intensive and costly. Although the baskets are prefabricated, they must be assembled, wired together, and filled.

- A gabion revetment can be more difficult and expensive to repair than standard rock protection.

- Gabion revetments are less flexible than standard rock protection. They will span the void left by subsidence only until the stresses in the rock-filled baskets exceed the tensile strength of the wire strands. At this point the baskets will fail.

- In high-velocity, steep-slope environments, the rock in individual baskets can shift downstream, deforming the basket as the material moves. The movement of the material may expose the filter or base material causing erosion and subsequent failure of the revetment system.

Guidelines for construction installation of gabions are provided in appendix B-9.

Earth Reinforcement Systems - The reinforcement of earth may be defined as the inclusion of resistant elements in a soil mass to improve its mechanical properties. Many soils, when at a suitable density and water content, can be strong enough to be structurally useful, particularly when loaded only in compression. Like portland cement, soil is very weak in tension. This fact often limits usefulness for some applications, such as those conditions in which slopes are steeper than the internal angle of friction of the soil, usually about 30 degrees. However, as in the case of reinforced concrete, the inclusion of reinforcements that are strong in tension can produce a composite material that combines the best load-carrying features of both components.

An earth reinforcement system has three major components: the composition of the backfill or in-situ ground within which the system is to be constructed; the reinforcement element chosen to supply tensile strength to the earth mass; and the facing element, the material provided to cover the face of the system. These components are described as follows:

- Reinforcements can be described in terms of the types of materials used and their geometry. Materials are differentiated broadly as metallic and nonmetallic. Geometrics can be categorized as strips, grids, sheets, rods, and fibers.

- Backfill type or the composition of the existing soil is an important variable in determining performance of the composite reinforced soil structure. Granular material is generally used for constructed embankment-type structures to meet stress transfer, durability, and drainage requirements.

- Facing elements are commonly provided to retain fill material at the face and prevent slumping and erosion. These facing elements include precast concrete panels, prefabricated metal sheets and plates, gabions, welded wire mesh, shotcrete, inclusion of intermediate reinforcement between the main reinforcement layers at the face, seeding of the exposed soil, and looping of geotextile reinforcement at the face.

There are two main mechanisms of stress transfer between the reinforcement and the soil: (1) friction between plane surface areas of the reinforcement and the soil, as in strip, rod, and sheet reinforcements; and (2) passive soil bearing on reinforcement surfaces oriented normal to the direction of relative movement between the soil and the reinforcement. Deformed rod and grid reinforcement transfer stress to the soil primarily by passive resistance, or both passive resistance and frictional stress transfer.

The following are brief descriptions of the types of available constructed embankment-type earth reinforcement systems:

- <u>Strip Reinforcement</u> - A coherent, reinforced soil material is created by the interaction of longitudinal, linear reinforcement strips and the soil backfill. The strips, which can be either metal or plastic, are normally placed in horizontal planes in successive lifts of soil backfill. An example of a strip reinforcement system, which uses either ribbed or smooth prefabricated galvanized steel strips, is shown in figure 5.3.

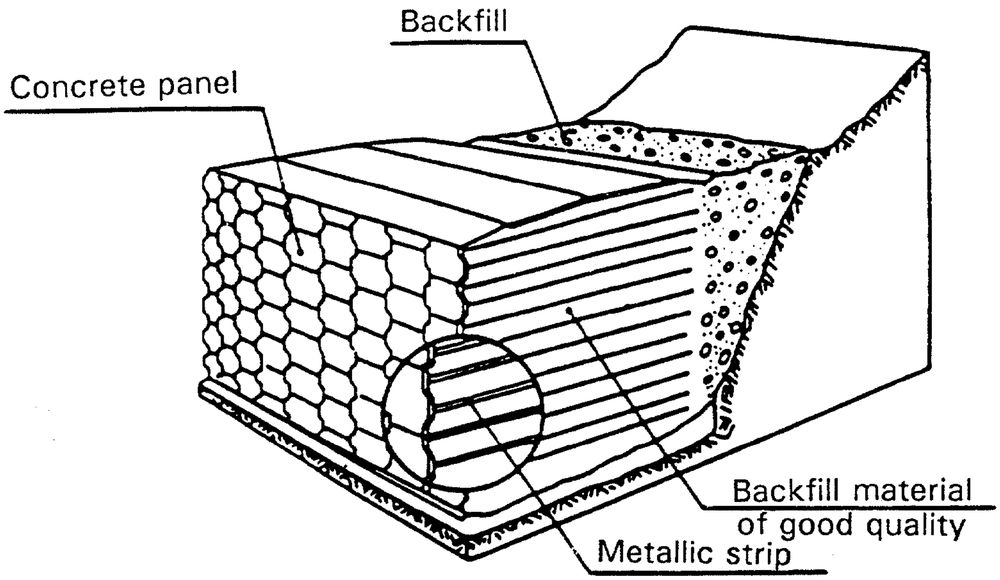
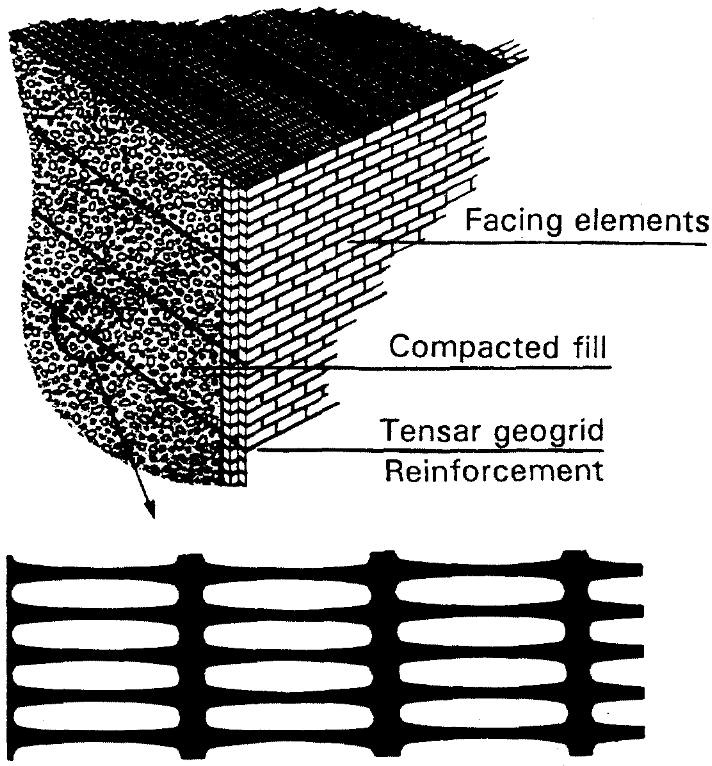


Figure 5.3. Schematic design of reinforced earth wall using strip reinforcement.[6]

- Grid Reinforcement - Metallic or polymeric tensile-resistant elements are arranged in rectangular grids and placed in horizontal planes in the backfill to resist outward movement of the soil mass. Grids transfer stress to the soil through passive soil resistance on transverse members of the grid, and friction between the soil and horizontal surfaces of the grid. Grid reinforcement may include prefabricated steel bar mats, welded wire mesh, and stable polymer materials. An example is shown in figure 5.4.

  An example of a system using metallic tensile-resistant elements is shown in figure 5.5.



PLAN VIEW OF GEOGRID REINFORCEMENT

Figure 5.4. Schematic diagram of a reinforced soil wall using geogrid reinforcement.[6]

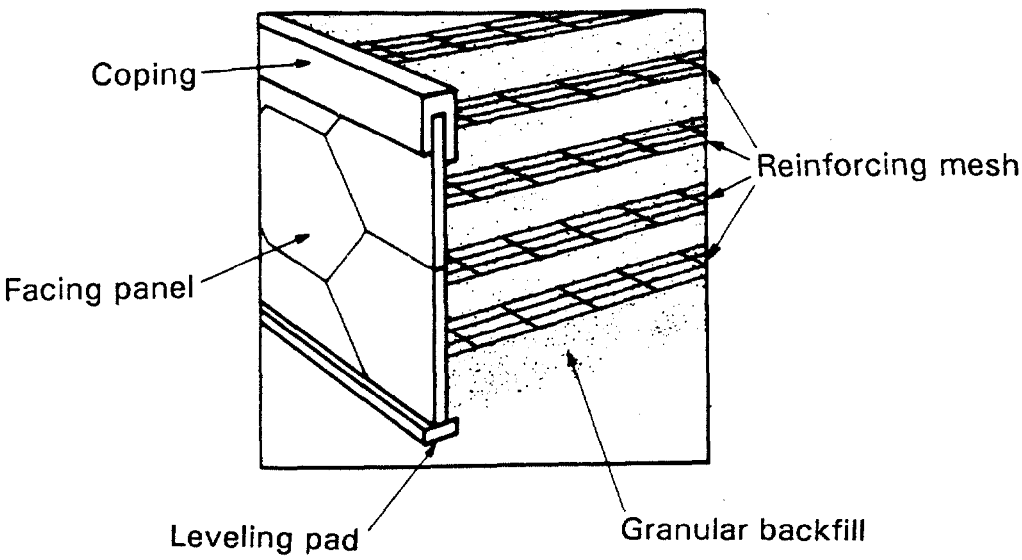


Figure 5.5. Schematic diagram of a VSL retained earth wall.[6]

- Sheet reinforcement - In this system, continuous sheets of geotextiles are laid down alternately with horizontal layers of soil to form a composite reinforced soil material, as shown in figure 5.6. The mechanism of stress transfer between the soil and sheet reinforcement is primarily friction.

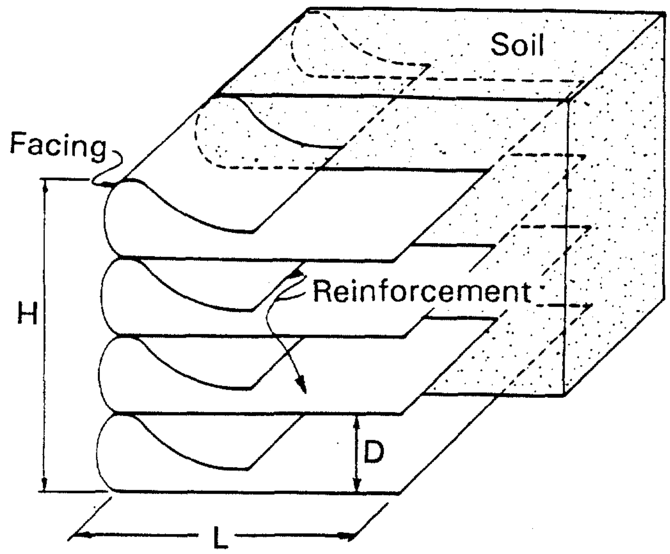


Figure 5.6. Schematic diagram of a reinforced soil wall using geotextile sheet reinforcement.[6]

- Other Systems- Other systems still being developed include bent rod reinforcement and fiber reinforcement, created by the inclusion of tensile-resistant strands (fibers) within a soil mass.

Soil nailing is an in-situ reinforcement technique that consists of inserting long rods or "nails" into an otherwise undisturbed natural soil to stabilize the soil mass. The method can be used to support the sides of excavations or to improve the stability of relatively unstable natural slopes. When combined with reinforced shotcrete or precast panel facings, the system can provide permanent support of vertical cuts.

The Federal Highway Administration has recently published a volume on the design and construction of reinforced soil structures: *Reinforced Soil Structures - Volume I. Design and Construction Guidelines.*[7]

Studies of several mechanically stabilized embankment systems also have been conducted by the California Department of Transportation. The results of some of these studies are available in the following publications:

Table 5.3. Comparison of reinforced soil systems.[6]

	REINFORCEMENT TYPE		SOIL GEOMETRY (Slope – Wall: 30, 60, 90)	SOIL TYPE (Clay .002, Silt .02, Sand .2, Gravel 2mm)	STRESS TRANSFER MECHANISM: Surface Friction	STRESS TRANSFER MECHANISM: Passive Resistance	REINFORCEMENT MATERIAL: Metal	REINFORCEMENT MATERIAL: Non-Metal	PROPRIETY SYSTEMS/PRODUCT NAMES
IMPORTED EMBANKMENT TYPE APPLICATION	STRIP	Smooth	├──┤	├──┤	●		●		Reinforced Earth
								●	
		Ribbed	├──┤	├──┤	├──┤ (Surface Friction to Passive Resistance)		●		Reinforced Earth
								●	Paraweb
	GRID		├──┤	├──┤		●	●		VSL, MSE, GAS, RSE, & Welded Wire Wall
								●	Tensar Geogrids
	SHEET		├──┤	├──┤	●			●	Geotextiles
	BENT ROD		├──┤	├──┤		●	●		Anchored Earth
	FIBER		├──┤	├──┤		●	●	●	
IN SITU GROUND IMPROVEMENT APPLICATIONS	STRESS TRANSFER MECHANISM		◄──┤	IN SITU. SOILS	●		●		
	REINFORCEMENT MATERIAL		◄──┤	IN SITU. SOILS		●	●	●	

- *Evaluation of Welded Wire Retaining Walls*;[8]

- *Tensar Reinforced Soil*;[9]

- *Field Performance of Experimental Tire Anchor Timber Wall*;[10]

- *Soil Pressure and Stresses on Wood Faced Retaining Wall with Bar-Mat Anchors*;[11] and

- *Experimental Tied Back Crib Wall with Salvaged Guardrail Facing.*[12]

Timber retaining walls - Timber retaining walls are used most often in remote areas where timber is plentiful but where it is difficult to transport other types of building materials, such as along streambanks with extremely steep slopes. It is also used where construction workers are less skilled in the use of other materials. Therefore, construction of timber retaining walls is sometimes the least expensive alternative, at least in terms of initial cost. It may be chosen where a rustic appearance is desirable.

Timber, while it is not as strong as steel, approximates ordinary concrete in compressive strength. It is rated strongest in flexural strength. It has an allowable compressive strength, parallel to the grain, of about 75% of the flexural value. Perpendicular to the grain, compressive strength is only 20% of the flexural strength. Horizontal shear is limited to 10% of the flexural strength. Consequently, it has different strength depending on the manner and direction of loading.

Timber can withstand a greatly increased load momentarily. Hence, neither impact nor fatigue are serious problems. Under certain conditions, and when properly treated or protected, it is quite durable. It is low in thermal and electrical conductivity.

Timber-faced walls can combine with geotextile or geogrid reinforcement with timber facing for a rustic appearance that fits a rural setting. A geotextile or geogrid can support the wall or timber face, sandwich the timbers, or wrap around them. An intermediate board can be placed between the main members, resulting in a lattice structure that reduces the amount of face timber required.

Spikes or rebar can also pin timbers together. The timbers must be tied to the reinforcing at every member, or at least every other member, at a 6-to 16-inch vertical spacing. These methods are often used by the U.S. Forest Service.

One of the accepted uses of timber for erosion control is in the construction of crib retaining walls. Suppliers generally design, furnish the required materials, manufacture, and install several types of walls. At least three types of walls are available:

- A gravity interlocking cellular crib structure that may be configured as a single depth wall; a multiple depth wall having up to three cells where the rear cells are shorter in vertical height than the front cell; or a reverse wall with up to three cells where the front cells are shorter in vertical height than the rear cells. Configuration of these gravity retaining walls are shown in figure 5.7.

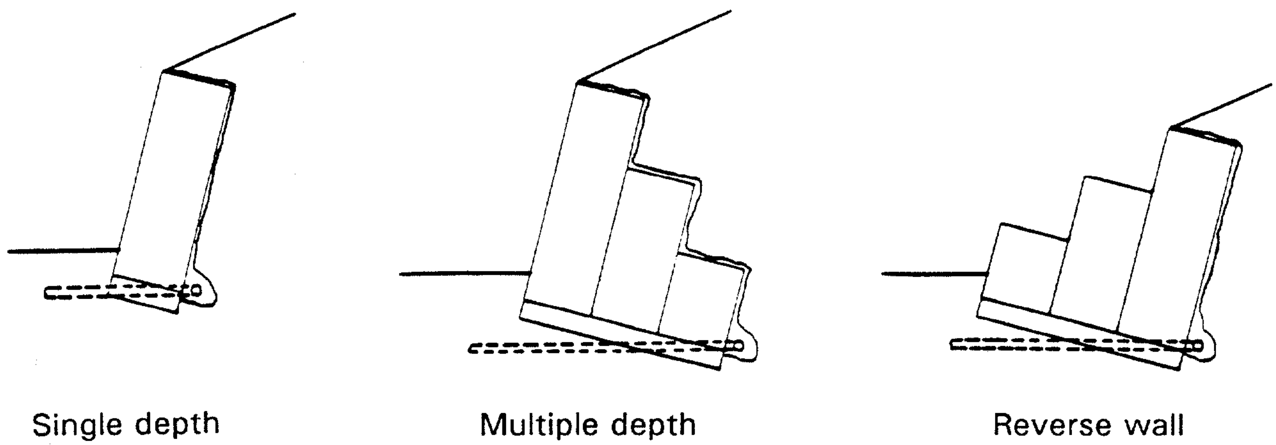


Figure 5.7. Gravity retaining wall configuration.

- A strapped retaining wall, as shown in figure 5.8, which is a soil block comprised of layers of soil interspaced with geosynthetic geogrid straps connected to a timber facing.

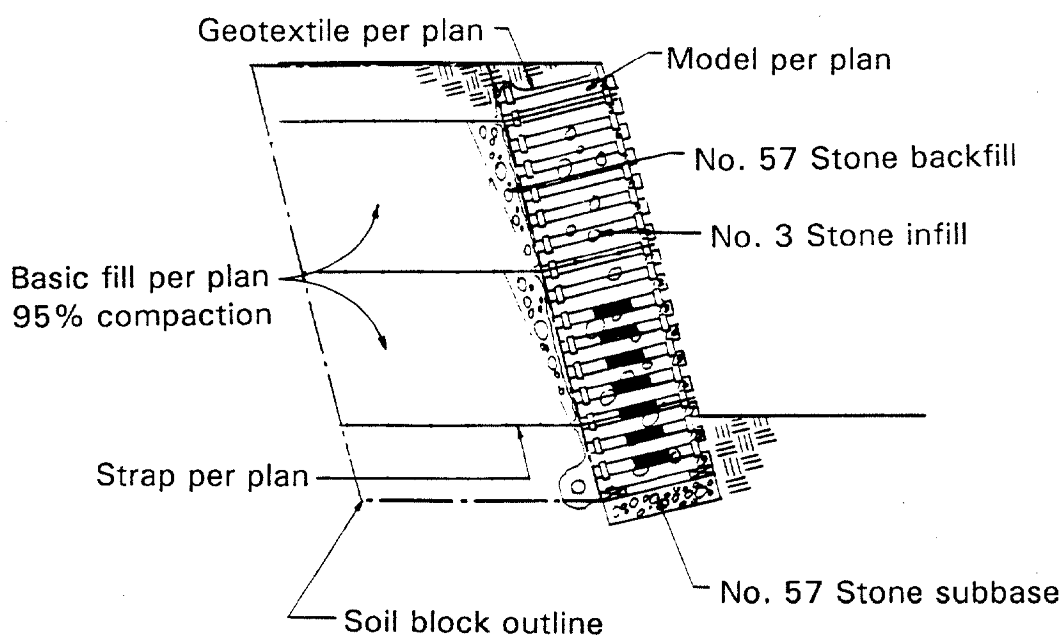


Figure 5.8. Strapped wall configuration.

- An anchored retaining wall, shown in figure 5.9, which is a soil block comprised of cells of soil or rock contained by a mechanical or grouted anchor connected to a surface anchor pad. The anchor is then extended beyond the anchor pad to the timber facing wall.

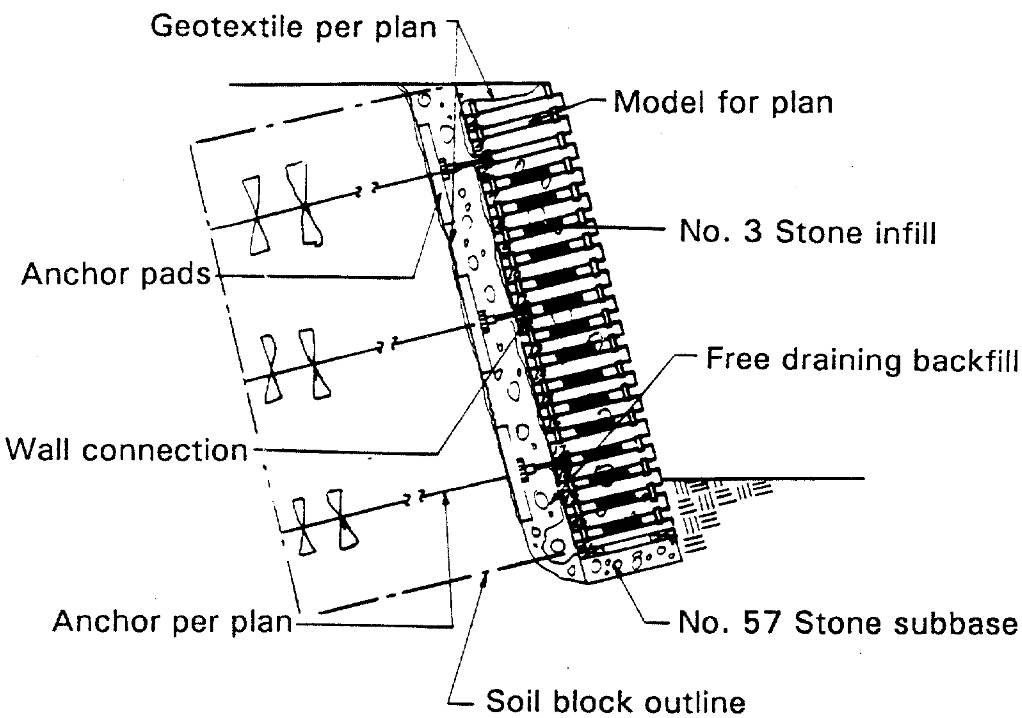


Figure 5.9. Anchored wall configuration.

Soil pockets can be installed within the cribwalls where plantings are desired, as shown in figure 5.10. Bioengineering techniques can also be used within a crib wall structure.

Information on repair of timber structures can be found in appendix B-10.

Steel retaining walls - Steel is a highly reliable and versatile construction material. It has exceptional tensile and compressive strength and is highly resistant to shear forces. However, thin steel sections are vulnerable to compressive buckling. Steel is extremely durable when properly protected. Most steel sheeting or other types of steel used in retaining walls are hot-dipped galvanized or aluminized, which protects the metal from the effects of air and moisture, corrosion, and industrial fumes. In some locations, the use of deicing agents may be problematic with unprotected

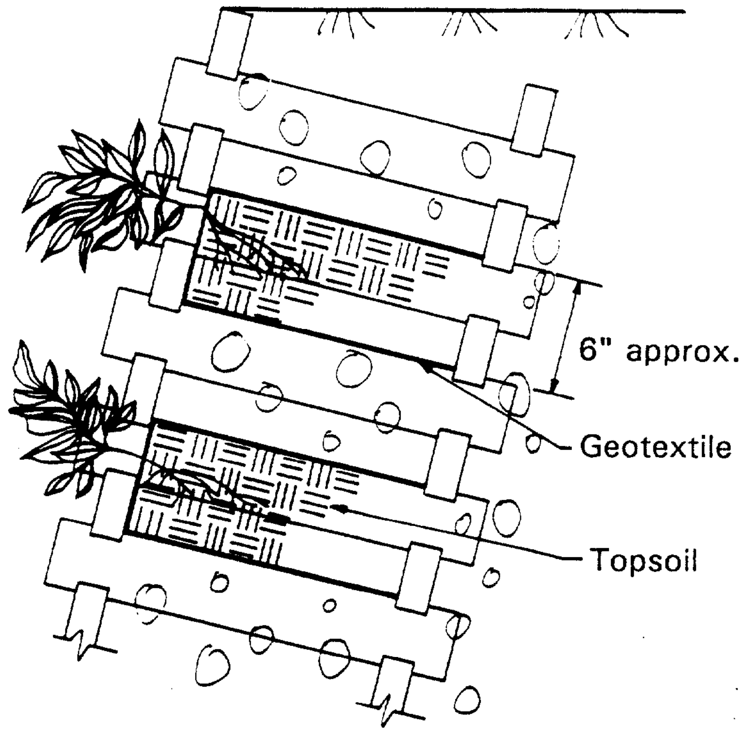


Figure 5.10. Soil pockets for planting.[13]

steel members. Seawater and mud can cause serious deterioration and loss of section when the material is immersed in water if it is not protected properly. Extreme heat can cause loss of strength and deformations.

There are several types of medium-width steel sheeting that is galvanized or aluminized for use in low retaining walls, wingwalls, or shore protection. Applications also include checkdams, cut-off walls, trench protection, and ditch checks. This sheeting is usually configured to give a high degree of stiffness and a good strength-to-weight ratio.

The bin-type retaining wall is another type of system that can be used to protect against shore or bank erosion. This type of retaining wall is a series of adjoining closed-face bins about ten feet long. They are bolted together at the job site and can flex against ground movements that might damage or destroy rigid walls.

Concrete paving - For some installations, it may be appropriate or necessary to pave the slope with reinforced concrete. It should be noted that paving with conventional readymix concrete may be difficult and it may be more practical to use shotcrete. Information on placement of shotcrete is provided in appendix B, section 11. The dry-type shotcrete gunite may be particularly appropriate for steeper slopes.

Ditches

There are two types of water courses that handle surface drainage: natural and manmade. Natural water courses generally consist of rivers and streams but may include valleys or swales. All surface water should eventually lead to a natural water course. In order to accomplish this, manmade water courses, such as ditches or flumes, are constructed to carry runoff to streams.

Ditches are commonly classified as parallel ditches, diversion ditches, and inlet or outlet ditches. Parallel ditches are channels that are constructed parallel to the roadway for the purpose of carrying runoff coming from the pavement, shoulders, and adjacent areas. They are usually open unless crossing under sideroads, driveways, or walkways. A parallel ditch may be lined with paving material in mountainous terrain, or it may be sodded or in a natural state, provided the lining is adequate to accommodate the design velocity.

Diversion ditches are constructed parallel to the top of a cut and are intended to intercept surface drainage from flowing over the face of the slope, thus preventing erosion and slides due to excessive moisture. They may be paved or unpaved, depending on design velocity.

Inlet and outlet ditches serve primarily to carry water to and from cross pipes, are generally perpendicular or slightly skewed to the centerline of the road, and often extend from or onto private property.

Construction of ditches may be an effective way to prevent general erosion of slopes by providing a controlled path for surface water to flow down to the waterway adjacent to a culvert. Depending upon the slope of the ditch, it may be lined with grass or rock or it may be paved. Information on construction of ditches is provided in appendix B-12.

SCOUR HOLES AND STREAMBEDS

Scour is defined as the removal and transportation of material from the bed and banks of streams as a result of the erosive action of running water. Some general scouring takes place in all stream beds, particularly at flood stage. The characteristics of the channel influence the amount and nature of scour.

Accelerated local scouring occurs where there is interference with the stream flow. The amount of scour depends on the degree of disturbance and the susceptibility of the stream bottom to scour action.

At the culvert inlet, the culvert barrel restricts the natural channel, forcing the flow through a reduced opening. As the flow contracts, areas of high velocity strike against the upstream bank causing turbulence, which tends to scour away the embankment adjacent to the culvert. In some cases, a scour hole may form upstream of the culvert floor as a result of the accelerated flow as it leaves the natural channel and enters the culvert.

At the culvert outlet, the increased velocity of the stream flow results in potentially erosive capabilities as it exits the barrel. In addition, the characteristics of the channel bed and bank material, velocity, and depth of flow in the channel at the culvert outlet, and the amount of sediment and other debris in the flow are all contributing factors to local scour potential at the outlet. Coarse material scoured from the circular or elongated hole is deposited immediately downstream, often forming a low bar. Finer material is transported further downstream. The dimensions of the scour hole change due to sedimentation during low flows and the varying erosive effects of storm events or high flows.

As the water level subsides after flooding, the scour holes that are produced tend to refill with sediment, making it difficult to assess the true scour depth. However, since the material transported and deposited by water is usually somewhat different in character from the material in the substrata, it is often possible to determine depth of scour by sounding or probing.

At the upstream end of the culvert, upstream slope paving, or the addition of headwalls, wingwalls, and cutoff walls help to protect the slopes and channel slopes. Protection against scour at the culvert outlet varies from limited riprap placement to complex and expensive energy dissipating devices. Riprapped channel expansions and concrete aprons protect the channel and redistribute or spread the flow. Headwalls and cutoff walls protect the fill.

It should be recognized that a scour hole at the outlet end of a culvert may be the least expensive and best form of protection against further scour. Outlet scour holes should be eliminated through maintenance only when they pose a threat to the culvert, prevent land-use access, cause costly property damage, hamper fish migration, or are a safety hazard. Often a sufficiently deep and wide cut-off end wall is all that is needed to prevent detrimental scour. Design techniques are available for the experienced hydraulics engineer to use in determining these dimensions.[14,15] Some types of outlet scour protection can void land-use requirements for multiple use culverts. Riprap or stilling basins can preclude the use of a culvert by stock or vehicles.

Riprap

Large rock riprap can be used effectively to fill scour holes and armor streambeds to prevent further scour and damage to culvert structures. Riprap is defined as a permanent, erosion-resistant ground cover of large, loose, angular stones installed wherever soil conditions, water turbulence and velocity, or expected vegetative cover, are such that soil may erode under design flow conditions.

To determine the appropriate size of the riprap, reference should be made to Hydraulic Engineering Circular No. 15, *Design of Roadside Channels with Flexible Linings.*[16] A condensed design method is described in appendix C, section 2, that has been adapted from HEC 15. This methodology was taken from the Virginia Erosion and Sediment Control Handbook.[17]

Riprap should be placed carefully so that individual rocks will remain in place during periods of peak runoff. Dislodged riprap can result in high-velocity flows that hinder fish passage. A geotextile filter fabric is frequently installed under the riprap to prevent future loss of fine material from under the riprap. Specifications for geotextile filter fabric are contained in appendix C, section 1. Riprap is not recommended at culvert inlets as it reduces approach velocity. Paving is preferred at culvert inlets where protection is required unless fish passage is an issue. Guidelines for placement of riprap are provided in appendix B-13.

Gabions

Gabions can be effective in protecting streambeds against erosion and scour due to high velocity water flow. Information and examples of gabion use are provided in appendix B-9.

Energy Dissipators

Energy dissipators are used to reduce the energy of flowing water. To protect the highway, the streambed, and the adjacent property, it is sometimes necessary to employ an energy-dissipating device. Energy dissipators include several types: riprap basins, impact basins, stilling wells, drop structures, hydraulic jumps, and forced hydraulic jumps. These dissipators are described in Hydraulic Engineering Circular 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels.*[18]

A riprap basin, figure 5.11, is a riprapped floor constructed at the approximate depth of the scour. The depth, length, and width of the basin is related to the characteristic size of the riprap, discharge, brink depth, and the tailwater depth. Riprap is classified as either graded or ungraded. Graded riprap contains a mixture of stones that vary in size from small to large. Uniform riprap contains stones which are close in size. For most applications, graded riprap is preferred to uniform riprap.

Graded riprap forms a flexible self-healing cover, while uniform riprap is more rigid and cannot withstand movement of the stones. Uniform riprap requires placement in a more uniform pattern, requiring more hand or mechanical labor and is, therefore, more costly to install.

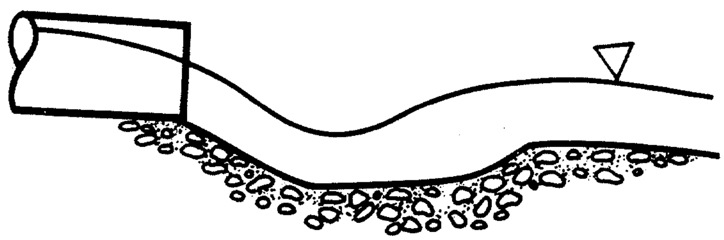


Figure 5.11. Riprap basin.[18]

Impact basins, figure 5.12, dissipate energy through the impact of flowing water with various devices in the basin. One such device is a hook-type dissipator developed primarily for large arch culverts with low tailwater, but it can be used with a box or circular conduits. Another is a hanging-baffle design that requires no tailwater for successful performance. A third is known as the Contra Costa dissipator and utilizes two baffles and an endsill.

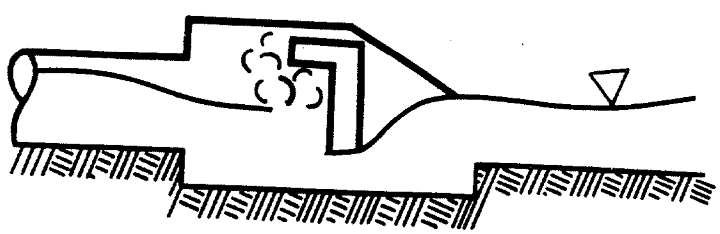


Figure 5.12. Impact basin.[18]

A stilling well, figure 5.13, dissipates kinetic energy by forcing the flow to travel vertically upward to reach the downstream channel. It is used primarily where a drop in elevation is involved, discharge is controlled, and debris is minimal.

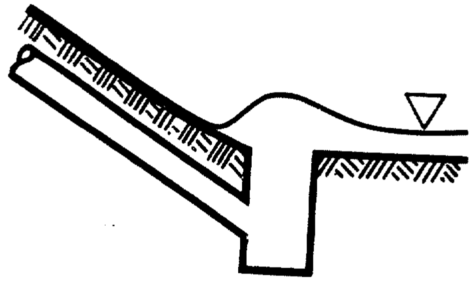


Figure 5.13. Stilling well.(18)

Drop structures, illustrated in figure 5.14, are commonly used for flow control and energy dissipation. Changing the channel slope from steep to mild, by placing drop structures at intervals along the channel reach, changes a continuous steep slope into a series of gentle slopes and vertical drops. Instead of slowing down and transferring high erosion-producing velocities into low non-erosive velocities, drop structures control the slope of the channel in such a way that the highly erosive velocities never develop. The kinetic energy or velocity gained by the water as it drops over the crest of each structure is dissipated by a specially designed apron or stilling basin.

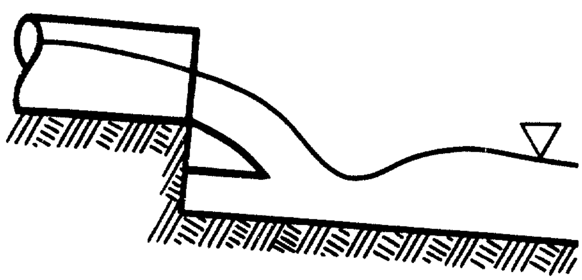


Figure 5.14. Drop structure.(18)

The hydraulic jump, illustrated in figure 5.15, is a natural phenomenon that occurs when supercritical flow changes to subcritical flow. This abrupt change in flow condition is accompanied by considerable turbulence and loss of energy. Within certain flow ranges, the hydraulic jump is an effective energy-dissipation device that is often employed to control erosion at hydraulic structures.

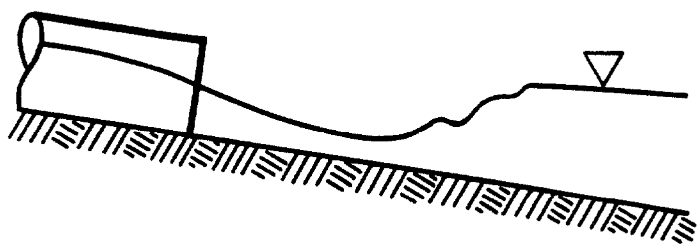


Figure 5.15. Hydraulic jump.[18]

A hydraulic jump can be forced, as shown in figure 5.16a, by utilizing blocks, sills, or other roughness elements to impose exaggerated resistance to flow. Roughness elements provide a versatile tool for forcing and stabilizing the hydraulic jump and shortening the hydraulic jump basin. Internal ring segments, as shown in figure 5.16b, can be used where space at the end of the pipe is limited.

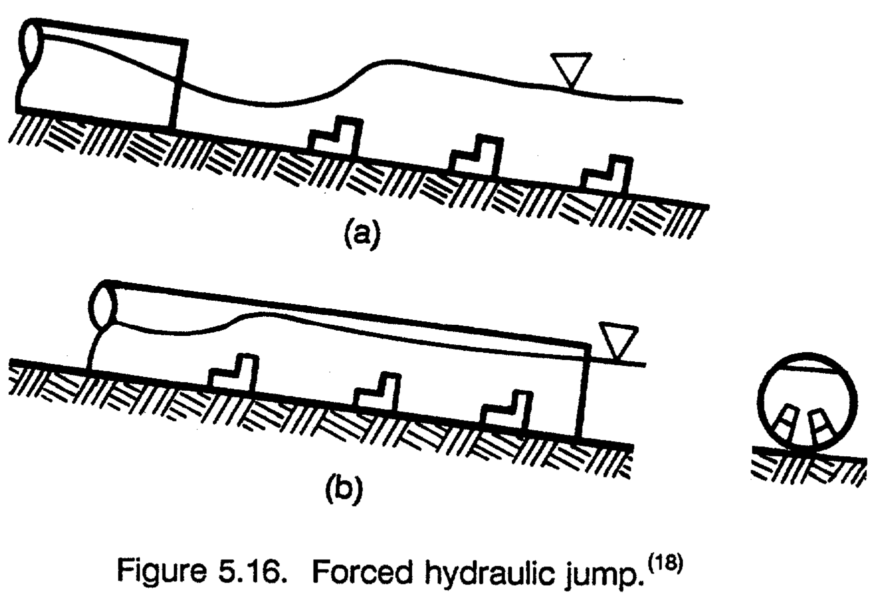


Figure 5.16. Forced hydraulic jump.[18]

Selection criteria for choosing among the types, in addition to hydraulic factors, include the amount of debris expected, the initial cost of the structure, the cost of required right-of-way, and anticipated maintenance. Further information on the selection and design of these structures can be found in Hydraulic Engineering Circular Number 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels*.[18]

Aprons

Use of rock or paved aprons in front of and at the end of culverts is frequently recommended to prevent scour and undermining of culverts. Aprons are used to reduce scour from high headwater depths or from approach velocity in the channel and to eliminate clogging by vegetation growth. A vertical concrete cutoff wall should be constructed under the upstream end of paved aprons. The apron should extend at least one pipe diameter upstream.

The State of Colorado recommends that the apron at the outlet end of culverts be extended below the level of the streambed, so that the streambed material protects the apron from being undermined. The apron should not protrude above the normal streambed elevation. If rock is provided after the apron, a cutoff wall should extend down below the bottom of the rock.

Care should be exercised in installing aprons. An apron can make fish passage difficult or impossible because of increased velocities resulting from a lower roughness coefficient or because many aprons are installed at steeper gradients than the culvert. Depth of water flow over aprons can also be a problem for fish when concrete aprons are employed to prevent scour and undermining. A method of repairing or replacing an apron is shown in appendix B-14.

Streambed Paving

Although streambed paving is expensive and difficult to accomplish, it is occasionally necessary as a permanent solution to a longstanding problem of erosion. This is particularly true when more traditional forms of erosion control are not effective, for example, the use of riprap, gabions or various types of energy dissipators. Streambed paving may be essential to protect the footings of arch culverts. Guidelines for paving streambeds are provided in appendix B-15. Although conventional cast-in-place concrete may be used, it may be faster and less expensive to use shotcrete. Information on shotcrete is provided in appendix B-11.

End Sections

The addition of end sections can greatly improve the flow characteristics of a culvert. The use of beveled edges at the entrance of a culvert is one method of increasing inlet performance for culverts operating under inlet control. Beveled edges reduce the contraction of the flow by effectively enlarging the face of the culvert.

End sections provide other benefits as well. The tapered sides of the end section merge with the slope to provide a neat and harmonious appearance. Erosion, sedimentation, and scour are reduced. Vegetation growth and debris collection and blockage at the culvert ends are greatly reduced.

Prefabricated end sections for corrugated metal pipe are available for both round and pipe-arch shapes. For added corrosion resistance, end sections are available in pregalvanized steel, aluminum, or aluminized steel. Precast concrete as well as plastic pipe end sections are also available. Metal and sections may also be used with plastic pipe.

HEADWALLS, ENDWALLS, AND WINGWALLS

Modern culverts are almost always constructed with headwalls, endwalls and wingwalls, for several reasons. The primary benefits are to increase hydraulic capacity and to protect the culvert. Thus, under certain hydraulic related, site-specific, circumstances replacement of an older style culvert inlet with an improved inlet can dramatically increase the culvert's capacity, or justify downsizing the culvert barrel, which will occur with sliplining. This analysis and evaluation must be done by a hydraulics engineer. Specific benefits of head-, end- and wingwalls include the following:

Endwalls are used to:

- Maintain the fill material;
- Reduce erosion of the embankment slope;
- Shorten the culvert length;
- Provide structural protection to inlets and outlets;
- Act as a counterweight to offset buoyant forces; and
- Inhibit the flow of water along the outside of the barrel (piping).

Headwalls with bevels:

- Increase the efficiency of metal pipe and concrete box culverts;
- Provide embankment stability;
- Provide embankment erosion protection;
- Provide protection from buoyancy;
- Shorten the required structure length; and
- Reduce maintenance damage.

Wingwalls are used:

- To retain the roadway embankment to avoid a projecting culvert barrel;
- Where the side slopes of the channel are unstable;
- Where the culvert is skewed to the normal channel flow;
- Can affect hydraulic efficiency if the flare angle is $< 30^\circ$ or $> 60^\circ$.[19]

Although a variety of materials are used to construct endwalls and wingwalls, the most common material is concrete. The appurtenant structures are often made of cast-in-place concrete. They can also be constructed of precast concrete, as well as corrugated metal, timber, steel sheet piling, gabions, or bagged concrete.

Concrete is inherently slightly porous and permeable since the cement paste never completely fills the spaces between the aggregate particles. This permits absorption of water by capillary action and the passage of water under pressure. It is, therefore, susceptible to deterioration caused by freezing and thawing, the use of salt or other de-icing agents on the roadway that spills over onto the structure, sulfate compounds in the soil and water, leaching, chemical attack, and rusted reinforcing steel. Deterioration can also result from unsound aggregate or low quality concrete. It may be necessary to repair or replace certain headwalls and wingwalls.

In northern climates, where freeze-thaw action and salt (chloride) related corrosion occurs, the concrete should be air entrained and there should be at least 2-1/2 inches of concrete cover over reinforcing steel. At some sites it may be possible to seal pavements and divert road salt-laden water so that it does not pass over or through the culvert and its appurtenances.

Although stone for masonry is more durable than most materials, there is a wide range in durability between the different varieties. While suitable stone has more than adequate strength for most loads, it is porous, absorptive, and subject to thermal expansion.

Stone masonry endwalls and headwalls are subject to chemical attack by the gases and solids dissolved in water, which can also dissolve cementing compounds between the stones. These appurtenant structures are also affected by seasonal expansion and contraction, frost and freezing, abrasion, and plant growth.

Replacement of Concrete Wingwalls

If wingwalls have severely deteriorated or have collapsed due to lateral pressure or undermining they can be replaced, assuming that the endwall is sound and the work can be performed in dry conditions. The existing wingwall must be removed and excavated to sound material. All existing concrete that will come in contact with new concrete must be thoroughly cleaned. A procedure for replacing concrete wingwalls is provided in appendix B-16.

Partial Replacement and Patching of Concrete Endwalls and Wingwalls

If a wingwall or endwall is in sound condition except for an isolated broken section, it can be repaired or partially replaced. It is important, however, that the deterioration of the concrete is not related to lack of entrained air or bad aggregate and the wall is not in an overturned position. A procedure for partial replacement or repair of basically sound wingwalls and endwalls can be found in appendix B-17.

Weep holes with a properly designed filter should be provided as required in replaced sections. It may be necessary to place weep holes in existing endwalls and wingwalls. If weepholes are used to relieve uplift pressure, they should be designed in a manner similar to underdrain systems. A procedure for repairing severely deteriorated wingwalls or endwalls is provided in appendix B-18.

Retrofit of Endwalls and Wingwalls

Although culvert barrels are commonly constructed with endwalls and headwalls, there are many existing culverts that do not have these appurtenant structures. In most cases, this is not problematic. However, there are some situations where the addition of endwalls and wingwalls would be advantageous. Endwalls maintain the fill and reduce erosion of the embankment slope. They also provide structural protection to inlets and outlets, counteract buoyant forces, and inhibit piping.

All of these factors are important. The addition of wingwalls, however, may also improve the hydraulic capacity of a culvert. Since the natural channel is usually wider than the culvert barrel, the culvert inlet edge represents a flow contraction and may be the primary flow control. The provision of a more gradual flow transition will lessen the energy loss and create a more hydraulically efficient inlet condition as shown in figure 5.17. Beveled edges are therefore, more efficient than square edges. A side tapered inlet, as shown in figure 5.18, commonly referred to as an improved inlet, further improves the culvert efficiency. Wingwalls can also help to align the culvert with the natural flow of the stream and assist in maintaining the approach velocity at the inlet end, wingwalls can also reduce turbulence by gradually transitioning the flow back to the normal stream width and aligning the flow with the natural stream bed.

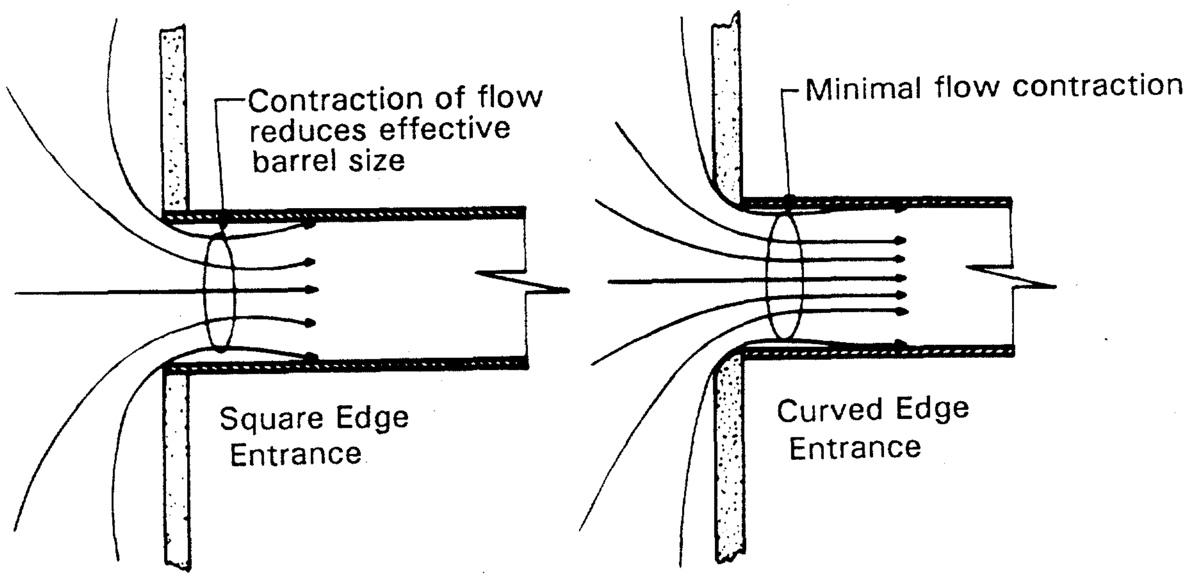


Figure 5.17. Entrance contraction schematic.[19]

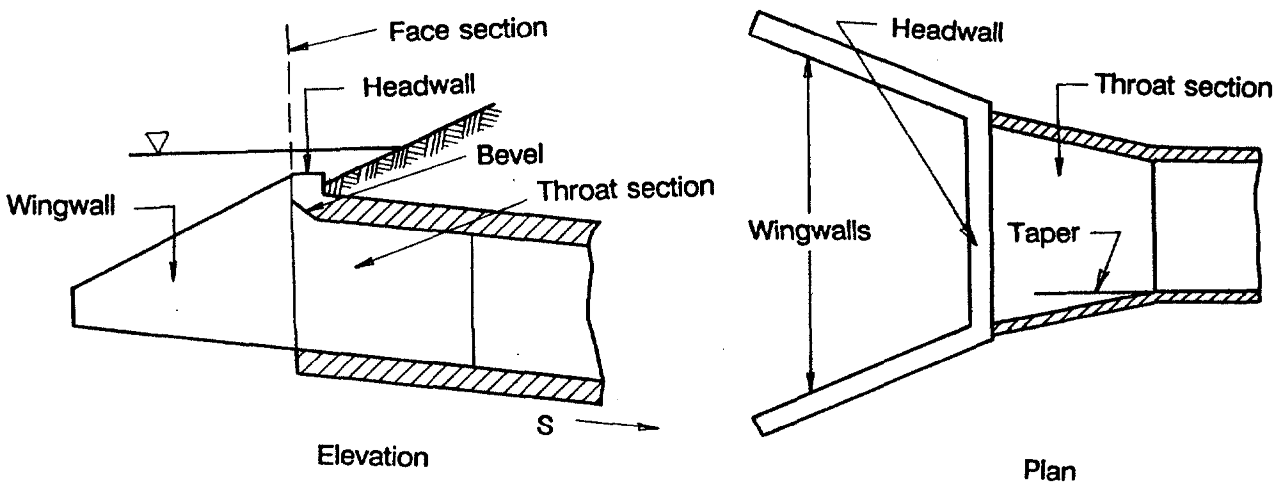


Figure 5.18. Side-tapered inlet.[18]

In some cases where a standard endwall or wingwalls are not required for maintaining fill or reducing erosion, a standard flared end section may be used. Such a section for corrugated metal pipe is shown in figure 5.19. Sections for concrete pipe are also available.

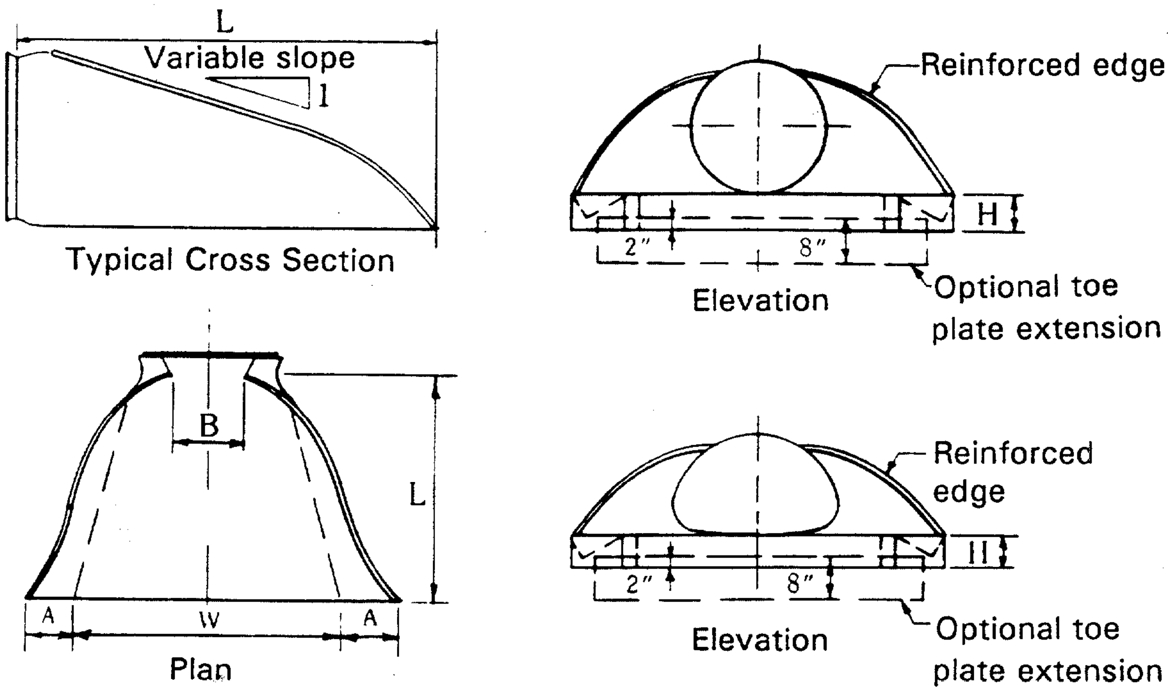


Figure 5.19. Corrugated metal end section.[20]

Commercial end sections are available for both corrugated metal and concrete pipe. They retard embankment erosion and generally incur less damage from maintenance procedures. They are effective in improving projecting metal pipe entrances by increasing hydraulic efficiency, improving their appearance, and reducing the accident hazard.

Jacketing of Concrete or Masonry Endwalls or Wingwalls

To repair a deteriorated face of a concrete endwall or wingwall, the face can be jacketed with concrete assuming that the deterioration of the concrete is not related to lack of entrained air in the concrete, poor aggregates, or another progressive concrete deterioration problem.

If the face of a masonry endwall or wingwall is deteriorated, it also may be jacketed with concrete, assuming that the wall is not overturning and is structurally sound. This procedure generally involves facing the wall with a six-inch layer of reinforced concrete that is fastened to the wall with dowels so that it becomes an integral part of the wall. In masonry walls, it is important to dowel into existing joints between individual stones rather than drilling into the stone. Several concepts for jacketing deteriorated concrete and stone masonry culvert structures are shown in appendix B-19.

Underpinning of Concrete Footings

One of the more serious situations that can develop is the undermining of headwalls, endwalls, and wingwalls by scour action of flowing water. Erosion of soil and/or rock from under the footings of these structural elements may lead to their settlement and collapse.

Scour and loss of soil support may be difficult to detect before significant damage has occurred. Similarly, it is difficult to underpin or otherwise increase the structural support for existing structures, especially when they are located in, or adjacent to, water. The very process of dewatering and preparing the site for retrofit work may worsen the existing conditions. When these structural elements were originally constructed, the supporting soil was compacted and the footings were cast on a firm base. Merely filling voids below footings will not reinstate the structural bearing forces on the filled area. Thus, higher than anticipated bearing loads will continue to be exerted on the original soil area.

It is difficult to completely fill the void so that the added concrete will carry future structural loads. Although pouring rock in front of a footing may prevent further scour, it will not fill the void and replace the lost structural support. Depending on the conditions, it may be necessary to drive piles and construct a reinforced concrete support for the existing structure. General procedures and several concepts for underpinning culvert headwalls, endwalls, and wingwalls are provided in appendix B-20. It also may be necessary to construct an integral reinforced concrete wall in front of the deteriorated structure. This procedure is known as jacketing. Information on jacketing is provided in appendix B-19.

Repointing of Masonry

The repointing of masonry structures becomes necessary when the existing mortar has deteriorated and the bonding and support characteristics of the mortar are no longer adequate. Hand pointing, which acts only as a short-lived superficial improvement, is generally ineffective in restoring the structural integrity of masonry structures. In contrast, pressure repointing provides a dense, low water-cement ratio mortar that is more likely to restore structural strength and resistance to weathering. Guidelines for repointing are provided in appendix B-21.

Tying Arch for Support of Masonry Endwalls and Wingwalls

The endwalls of culverts serve as a retaining wall for the fill material on either side of the barrel. The culvert barrel in a masonry arch is surrounded by voussoirs, which are the wedge-shaped stones that create the arch ring. The center voussoir is called the keystone.

Over time, the courses of stones immediately over the voussiers tend to bulge or bow out. This may occur as the result of several factors:

- The pressure of the fill and/or hydrostatic pressure behind the wall;
- The weathering and weakening of the stones; and
- The deterioration and failure of the mortar.

To help distribute the load on the end-walls, tie rods are sometimes placed from endwall to endwall, through the fill material. Loads are distributed on the face of the endwall by securing the rods with large washers, often in a decorative shape. To further distribute the load, steel plates may be placed over the face of the wall and fastened to the tie rods.

Repairs Using Steel Sheeting

Although steel sheeting is most often used for low retaining walls and shore protection, it is sometimes used for endwalls and wingwalls. It can also be used to jacket existing wingwalls and, to some extent, heads. It is effective as a temporary measure for stabilizing a deteriorating structure. This sheeting is generally configured to give a high degree of stiffness and a good strength-to-weight ratio. It is highly durable when properly protected. Steel sheeting should be protected when it is used in locations where deicing agents may be used.

Repairs Using Gabions

Use of gabions may be an effective technique for protecting culvert headwalls, endwalls, and wingwalls from scour and undermining. They may be particularly effective where there is fast moving water and riprap will not remain in place. However, when placed in an area where there is an abrasive bedload, the bedload may abrade the basket wire leading to the eventual failure of the gabion. As noted above, construction of gabions is labor intensive and should be done during periods of low water flow. Examples of how gabions may be used are provided in appendix B-9.

Repairs Using Shotcrete

The terms shotcrete and gunite refer to the process of pneumatically transporting and placing Portland Cement-based mortar or concrete with compressed air. Although the term shotcrete may generally be used for all related processes, both wet and dry, the term gunite frequently refers to a dry mix.

The concept of transporting and placing Portland cement-based mixes through pipelines by compressed air first began in 1910. Since that time, significant advances have been made in the development of the equipment and the mortar and concrete mixes that may be used. There are now two basic types of mixes: a wet mix and a dry mix. For wet mix shotcrete, all of the ingredients, including water, are mixed before they are pumped. For dry mixes, the water is introduced at the nozzle through a water-ring that has several jets or orifices that disperse the water into the mix.

As with conventional Portland cement concrete, the physical properties of wet and dry shotcrete mixes depend upon many factors, including the relative amounts of water, cement, and chemical admixtures, as well as the maximum size of the aggregate that is used. The wet mix process allows the use of larger aggregate size than a dry mix, which essentially uses a common concrete sand. The water-cement ratio for dry-mix shotcrete is normally in the range of 0.30 to 0.50 by weight and 0.40 to 0.55 for wet-mix shotcrete. The drying shrinkage of shotcrete varies with the mix design, but it generally falls within the range of 0.06 to 0.10 percent, which is slightly higher than most low slump conventional concrete that can be placed in heavier sections using larger aggregate and leaner mixes. The 28-day strength of shotcrete normally ranges from 3,000 to 7,000 psi, although dry mixes may have strengths higher than 10,000 psi.

There is some information that indicates high-strength concrete is more resistant to abrasion and freeze-thaw damage. Steel fibers may also be used, particularly with dry mixes, to provide improved flexural and shear strength, toughness, and impact resistance. Special care and equipment may be required for adding the fibers to the mix to prevent clumping or kinking of the fibers and to ensure they are properly distributed in the mix.

Shotcrete has advantages over conventional concrete for many types of repair work. These advantage are significant, especially where formwork is impractical or where forms can be reduced or eliminated, where access to the work area is difficult, and where thin or variable thicknesses are necessary. Properly applied shotcrete is structurally sound and durable. It has excellent bonding characteristics with concrete, masonry, rock, and steel. However, these properties are very dependent upon the use of good materials and procedures executed by a knowledgeable and experienced nozzleman. This is particularly true for the dry mix process, which allows the nozzleman to adjust the amount of water.

Use of shotcrete may be an effective method to repair and/or protect deteriorating headwalls, endwalls, and wingwalls of culverts. Consideration should be given to the type of shotcrete that is used and the methods used to install it. Guidelines are provided in appendix B-11.

OTHER REPAIRS AND RETROFIT IMPROVEMENTS

Piping can be a serious problem that can affect both the condition of the culvert and the adjacent roadway. Culverts may have been installed previously in the safe recovery area and it may be necessary to retrofit devices to increase the safety of these installations. In some areas of the country, fish passage and the control of beavers are issues in culvert design and repair. These improvements are discussed below.

Piping

Piping is a process of subsurface erosion in which water runoff flows along the outside of a culvert and, with sufficient hydraulic gradient, erodes and carries away soil around or beneath the culvert. This process is referred to as piping since a hollow similar to a pipe-shaped tube is often formed. The water may come from stream flow, surface flow, groundwater or leakage from inside the culvert.

Piping can cause end-section displacement and drop-off in rigid pipe culverts, particularly at the outlet end of culverts. In corrugated metal pipe culverts, the pipe may be subject to buoyant forces if the material surrounding the culvert is eroded or saturated. Good backfill material and adequate compaction of that material are important to the prevention of piping.

Antiseep collars - Piping is controlled by reducing the amount and velocity of water seeping along the outside of the culvert barrel. In some cases, an anti-seep collar may be required, especially on culverts with mitered ends. A collar is a type of end treatment for a culvert, usually consisting of a concrete ring surrounding a cut-end treatment. The collar is usually attached to a cutoff wall, a vertical wall buried below the inlet end of a culvert. A diaphragm may also be used. A diaphragm is a metal collar at right angles to a culvert pipe for the purpose of retarding seepage, especially on drainage structures designed to operate under static head, or head ponding the inlet.

Grouting - Field joints are generally only found with factory-manufactured pipe. There are ordinarily no joints in structural plate pipes, only seams. Joints should be checked for backfill infiltration. Excessive seepage through an open joint can cause soil infiltration into the culvert or erosion of the surrounding backfill material by exfiltration that will reduce lateral support.

Open joints that are allowing seepage can be sealed by grouting. There are several types of chemical grouts that mix readily with water at the time of application and provide good penetration of wet joints, cracks, and surrounding soils. These compounds are available as a foam, which expands to fill the crack, a gel, or in conjunction with a carrier medium such as oil-free oakum.

Since these grouts react with water to change from a free-flowing liquid to a water-impermeable solid, they allow quick and effective shut-off of water that is infiltrating into the culvert. The grouts are tough and highly flexible. Properly grouted joints and cracks can withstand normal ground movement and still maintain their seal.

Large diameter pipe is sealed either with large-diameter packers, hand-held injection equipment, or by hand-packing in conjunction with a carrier medium, such as oil-free oakum. The grout can also be injected through pre-drilled holes, either directly in the crack or in the general area that requires sealing. Additional information on grouting can be found in appendix B-30.

Safety Considerations

The appropriate location of culverts inlets and outlets outside the safe recovery area can contribute to the safety of errant vehicles. However, existing culvert ends may be already located within this zone and may present conditions that need to be addressed. How these problems are addressed depends on the size of the culvert; the speed limit on the existing road, the clear zone distances, and whether the culvert can be extended; the degree of side slope; and the possibility of flooding.

When culvert ends are located within the area required for the safe recovery of an out-of-control vehicle, appropriate inlet and outlet designs may reduce the effect of the obstruction. For small culverts, 30 inches in diameter and under, an end section or a sloped headwall may be used. Inlets and outlets can be mitered to conform to the fill slope. For culvert with endwalls, fill may be warped behind the endwalls to limit their exposure.

For culverts greater than 30 inches in diameter, one of the following treatments may be employed:

- Extend the culvert to the appropriate clear zone distance in accordance the AASHTO *Road Design Guide*.[19]

- Shield with a traffic barrier, such as a guardrail, under the following conditions:

  - the culvert is very large;

  - the culvert cannot be extended;

- the culvert has a channel that cannot be safely traversed by a vehicle; or

- the culvert presents a significant flooding hazard if fitted with a traversable grate.

- Treat the culvert with a grate if the consequences of clogging and causing a potential flooding hazard is less than the hazard of vehicles impacting an unprotected end. If a grate is used, provide an open area between the bars of approximately 1.5 to 3.0 times the area of the culvert entrance. Culvert capacity should be reviewed by a hydraulic engineer where a grate is added to a culvert. A procedure for retrofitting grates to openings of culverts existing within the recovery zone can be found in appendix B-22.

In some areas where the terrain is flat and a limited amount of fill covers the culvert, endwalls may be replaced with end sections to improve safety. In other areas where full height endwalls are in place and may constitute a hazard, full-height endwalls may be replaced with half-height endwalls.

Fish Passage Devices

Culverts and other drainage structures represent a variety of potential obstacles to fish passage. The two most common of these problems are excessive water velocities through the culvert or vertical barriers that are too high for fish to overcome. Perching, which is the tendency of a stream to develop a falls or cascade at a culvert outlet due to the erosion of the stream channel outlet due to the erosion of the stream channel downstream from a culvert, is commonplace.

Other problems may include:

- Depth of water in the culvert at high, moderate, or low flows;

- The coincidence of design flows with seasonal time of fish migration;

- The size and species of fish passing through the culvert;

- The velocity of water over a given length of structure in relation to the swimming capabilities of the fish; and

- Icing and debris problems.

Figure 3.19 illustrates some common conditions that block fish passage.

In addition to the conditions in existing culverts that presently blocks or hinder fish passage, there are literally millions of culverts approaching the end of their useful life. If the structure is presently only marginal for fish passage, repair or retrofitting of these structures can further block the remaining fish runs.

When fish passage is a design issue when placing new culverts, an installation should not change the conditions in the waterway that existing prior to placement of the culvert. This means the cross-sectional area of the stream should not be restricted by the culvert, the slope should remain the same or less, and the roughness coefficients should not change. Alteration of these elements will result in increased velocity, making fish passage more difficult or altering the sediment transportation capacity of the stream.

The result is that repair, rehabilitation, or retrofit methods must be found that will balance biological, engineering, and hydraulic considerations. In addition, the solution must be cost-effective and easy to maintain. the resolution of these diverse factors requires the combined efforts of biologists, engineers, and hydrologists. All three disciplines must be considered and balanced. Table 5.4 lists the design considerations in these categories that should be considered.

In new installations where fish passage is a concern, the best culvert installation is one that allows open-channel flow with no increase in flow pressure, either at the outlet or the inlet. However, in existing culvert, the most effective area for modification depends on whether the culvert is operating under inlet or outlet control. Culverts are generally designed to operate under inlet control where the flow capacity is controlled at the entrance by the depth of headwater and the inlet geometry. In culverts with inlet control, a fish is subjected to increasing stress levels as it progresses through the culvert and then must face high velocities and turbulence at the culvert inlet. However, in culverts operating under outlet control, once a fish overcomes the barrier the culvert outlet presents, the fish experiences continually decreasing stress levels. This condition minimizes the length of time a fish has to maintain high biokinetic swimming. Therefore, one important modification is to retrofit the culvert installation so that it is changed from inlet control to outlet control.

When a culvert is flowing under inlet control, the capacity of the culvert is controlled by flow factors:

- Depth of headwater;
- Cross-sectional area;
- Inlet edge configuration; and
- Barrel shape.

Table 5.4. Design considerations of fish passage through culverts.[22]

A. BIOLOGICAL CONSIDERATIONS

1. Species of fish potentially impacted
   a. Age
   b. Velocity tolerances of fish over the design culvert length
   c. Time of migration
   d. Allowable delays (length of time)
2. Quality and quantity of upstream habitat
3. Presence of fish barriers and downstream
4. Upstream channel stability and debris potential
5. Upstream management activities that may affect or impact fisheries

B. ENGINEERING CONSIDERATIONS

1. Road profile
2. Road cross section
3. Proposed culvert parameters
   a. Culvert length
   b. Type of inlet
   c. Proposed culvert alignment
4. Streambed foundation
5. Site access
6. Constraints
   a. Regulatory constraints (i.e. flood plains)
   b. Arbitrary constraints (i.e. allowable headwater depth)
7. Desired life expectancy of structure
   a. Corrosive soils
   b. Excessive streambed loads
   c. Options for repairing/replacing culvert once installed

C. HYDRAULIC CONSIDERATIONS

1. Design peak flows
2. Streambed parameters
   a. Gradient
   b. Cross section
   c. Roughness coefficient
   d. Hydrograph
   e. Bedload quantity
3. Debris considerations
   a. Amount and type
   b. Ice buildup
4. Upstream water storage
5. Upstream and downstream conditions that could affect culvert performance

Under outlet control, factors at the culvert outlet or immediately downstream are determining the flow capacity of the culvert. The flow capacity is determined by the following factors:

- Depth of headwater;
- Cross-sectional area;
- Inlet edge configuration;
- Barrel shape;
- Culvert slope;
- Culvert length;
- Culvert roughness; and
- Depth of tailwater.

The culvert barrel may be modified to decrease the velocity and increase the depth of flow by increasing roughness elements. The barrel may be modified by the retrofit installation of baffles of two types: the offset and spoiler baffles. Conventional fish ladders have also been successful at providing fish passage through the barrel.

Modifications at the culvert outlet and downstream of the culvert outlet may include fish ladders, backwater structures (weirs, gabions, etc.) and a fish pool at the culvert outlet. Two types of fish ladders that have few problems with sedimentation and minimal effect on culvert flow are the vertical slot orifice fishway and the Alaska steeppass fishway. However, in culverts operating under inlet control, the danger exists that fish may be able to progress through the barrel only to be stymied at the inlet by high velocities and turbulence. Modifications may include the construction of a resting pool to allow the fish to rest and also provide room for the fish to gain swimming speed and vertical thrust.

Adding baffles, weirs or other features to facilitate fish passage will constrict the culvert and possibly cause operational problems. In addition, consideration should be given in the designs to possible damage of the devices by water-borne rock and debris.

Baffles - In existing culvert installations that are experiencing high velocities that exceed the maximum allowable for fish passage, baffles can act as an energy dissipator and produce controlled, lower flow paths. The purpose of a baffle system is to produce a pocket of low velocity water in the culvert where fish can momentarily rest during high flows.

Although baffles may enhance fish passage, their use is not a recommended practice if other solutions are available. A baffle system can significantly reduce the hydraulic efficiency of a culvert. The system may collect debris or sedimentation and is susceptible to icing. If the stream carries a significant bedload, cleaning a culvert equipped with a baffle system will be a problem. Therefore, periodic maintenance is required. In addition, some installation may significantly reduce the life expectancy of a culvert.

Round metal culverts that are less than 5 feet in diameter should not be equipped with baffles. Since corrugated metal pipes and pipe arches are designed as flexible structures, the baffle system should be should be equally flexible.

Baffles can be constructed of wood, metal, or concrete. Since wood is more resilient when hit by moving objects and can also be replaced more easily, it is sometimes preferred. Metal baffles are normally bolted onto the culvert floor, using metal plates for a added strength. Simply bolting the baffle to the culvert floor is inadequate; it usually pulls loose during flood flows. In some cases, plates are connected with chains that are fastened to the upstream lip of the culvert. Concrete baffles may be precast and grouted into place.

The baffle design shown in figure 5.20 is taken from the Idaho Fish and Game Department and derived from the McKinley and Webb report prepared for the Washington Department of Fisheries in 1956. Some states, such as Oregon no longer use the baffle configuration as it was found to be susceptible to plugging with debris at the inlet. The design presently favored by the Oregon Department of Transportation is a series of wiers that create a succession of pools and one-foot high waterfalls through the culvert barrel. Culvert inverts have also been placed below the channel bottom and backfilled with native material to provide a natural channel bottom through the culvert. All fish passage designs are reviewed and approved by the Oregon Department of Fish and Wildlife.

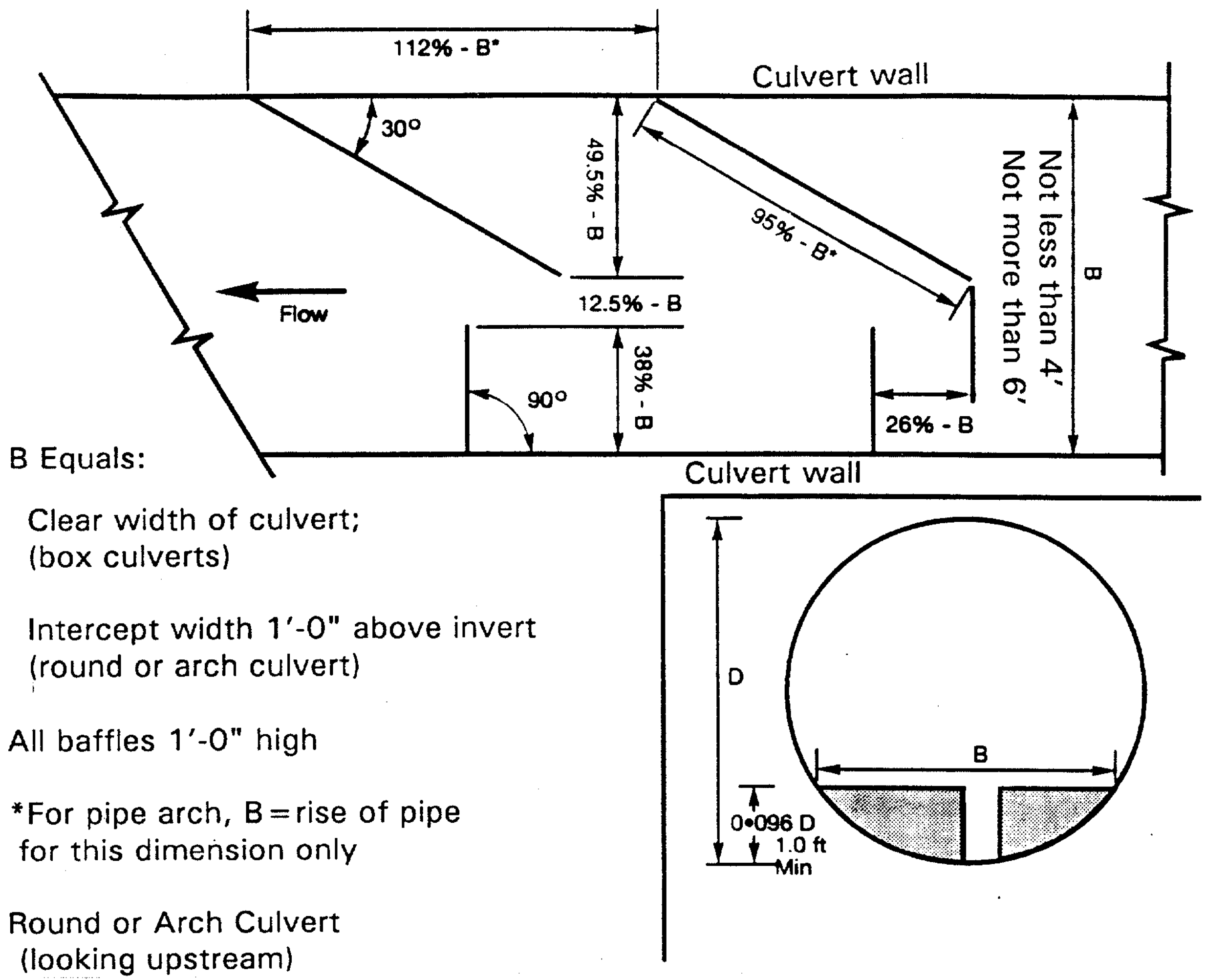


Figure 5.20. Culvert baffle recommended for general use.[22]

Figure 5.21 shows a divided box culvert in which two channels, separated by a low divider wall, have been constructed to minimize the reduction in capacity of the culvert. In addition to controlling velocity, this type of baffle design can increase water depth in the pipe during periods of low flow, as well as create a series of pools in culverts with steep gradients, allowing it to act like a fish ladder.

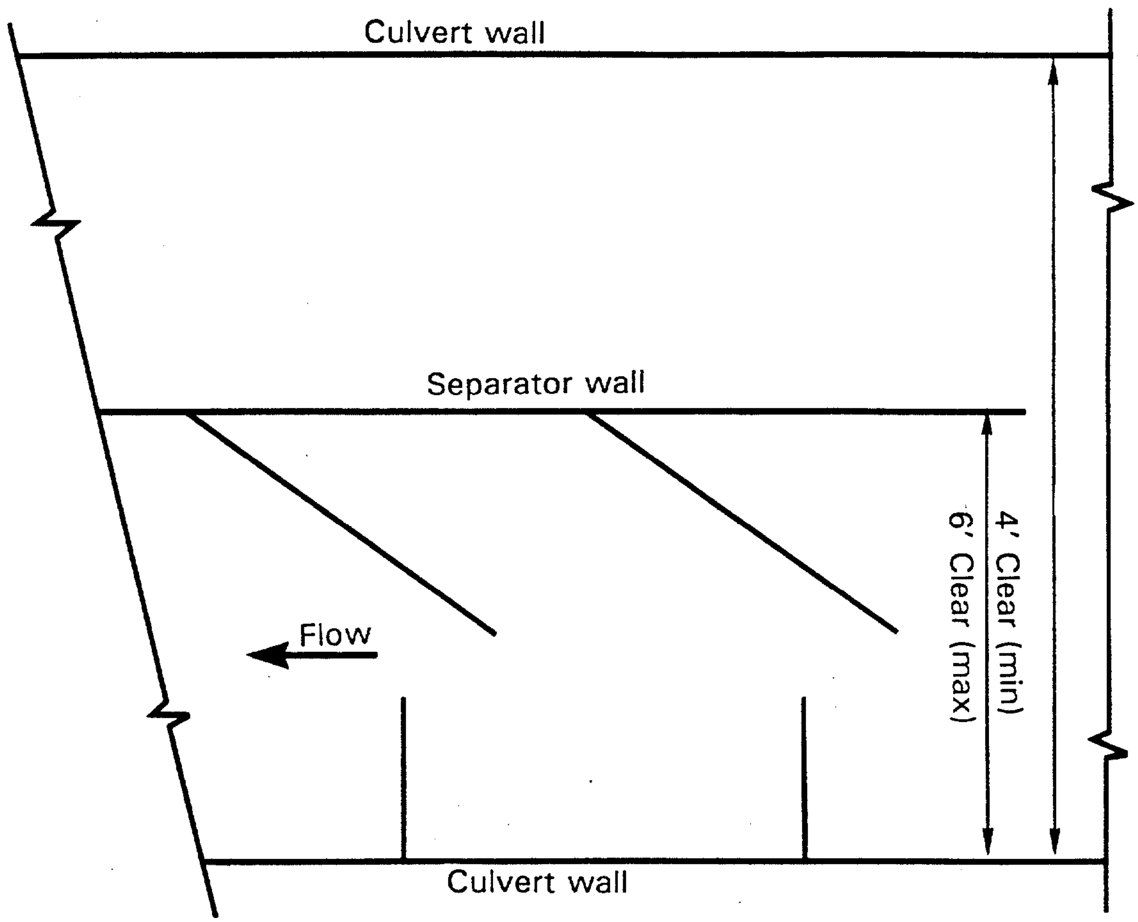


Figure 5.21. Separator baffles for box culverts.[22]

The second type of baffle is the spoiler baffle shown in figure 5.22. This type of baffle system is less prone to damage by ice and debris than offset baffles.

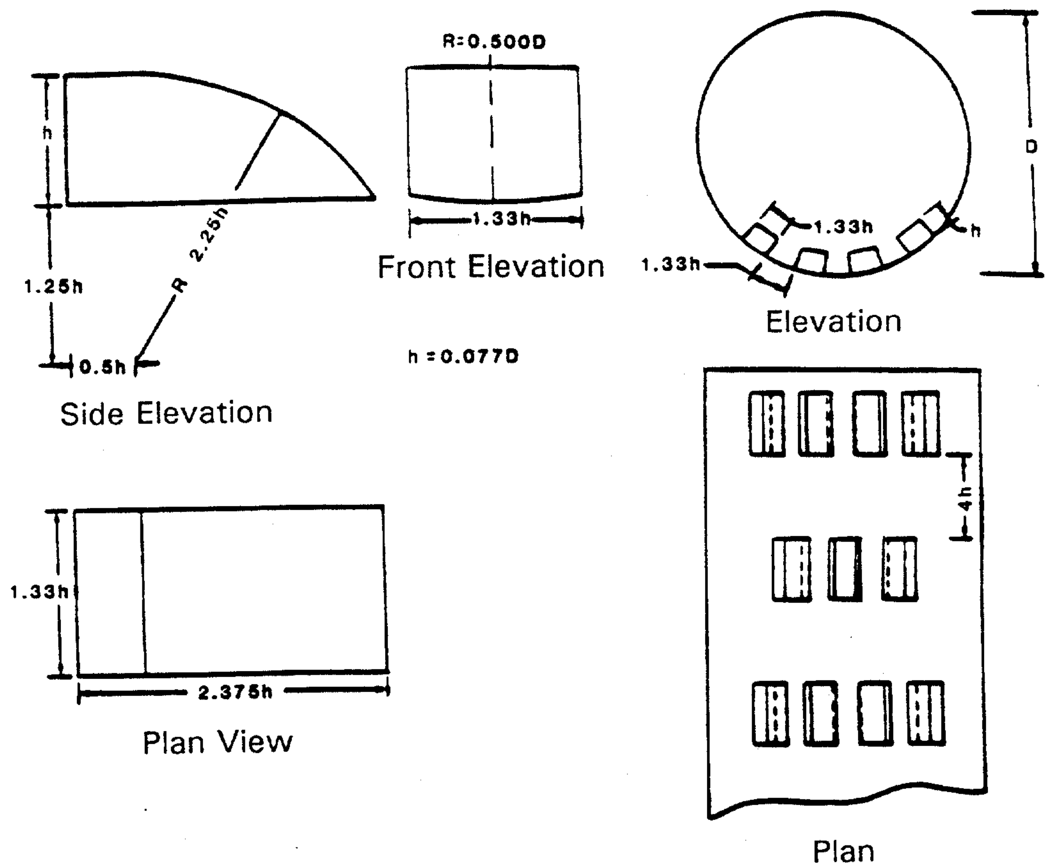


Figure 5.22. Spoiler baffle configuration.[23]

The slot orifice fishway, a rectangular shaped channel with a series of full-depth vertical slots, allows fish passage around unfavorable flow patterns. The fishway can be constructed outside the culvert barrel for box culverts, as illustrated in figure 5.23.

Fish Ladders - Conventional fish ladders have been used successfully to allow migrating fish to overcome the effects of steep slopes and high water velocities. Two types of fish ladders that have few problems with sedimentation and minimal effect on culvert flow are the vertical orifice fishway and the Alaska steeppass fishway. However, in culverts operating under inlet controls, the danger exists that fish may be able to progress through the barrel only to by stymied at the inlet by high velocities and turbulence.

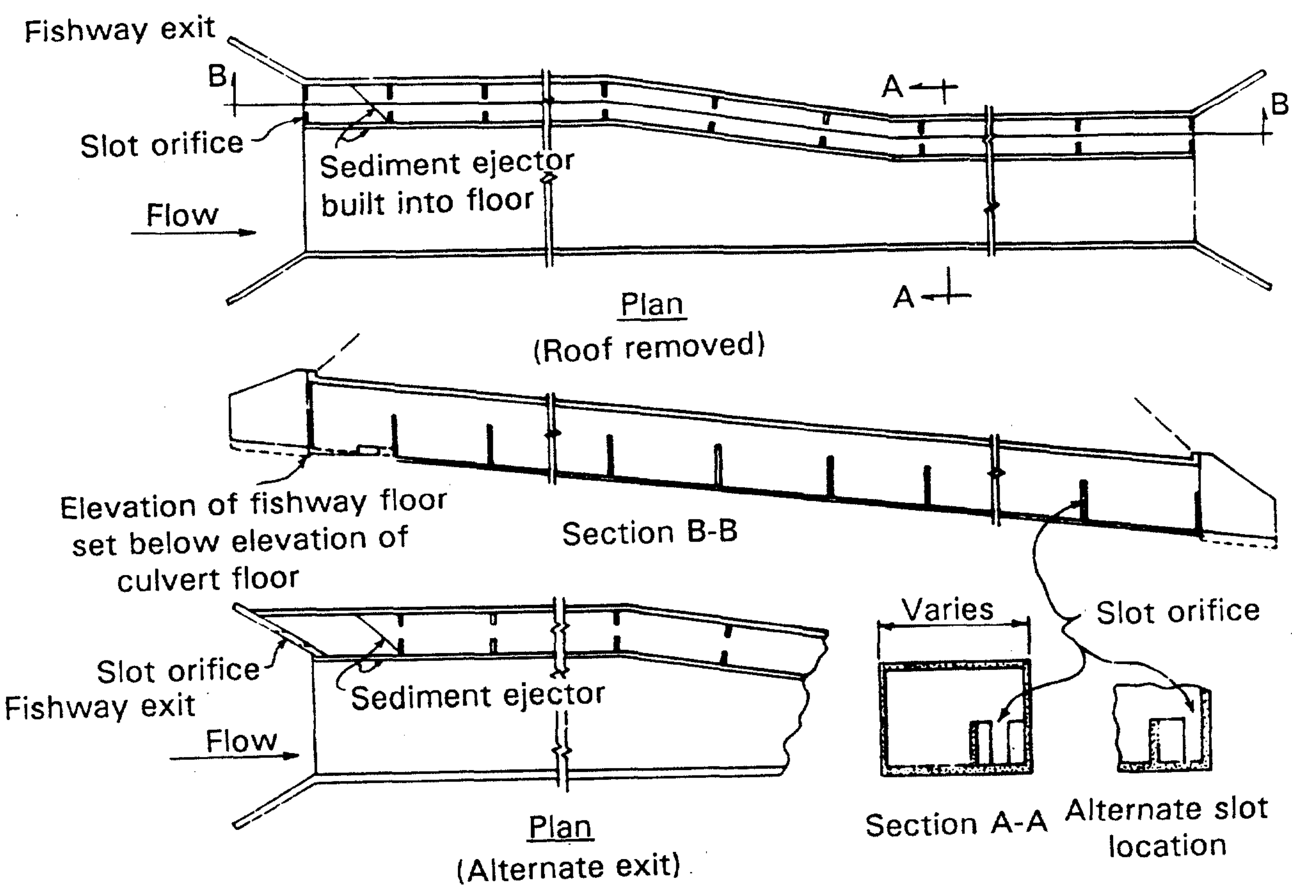


Figure 5.23. Box culvert with vertical slot orifice fishway.[24]

A modified design, shown in figure 5.24 can also be used with corrugated metal pipe and pipe arches. However, any installation requires design by an engineer.

The slot orifice fishway is simple and economical to construct. It is self-cleaning and there is no decrease in culvert efficiency since the critical cross section for culverts on steep grades is the entrance section. It provides stable low water flow for a wide range of headwater and tailwater depths.

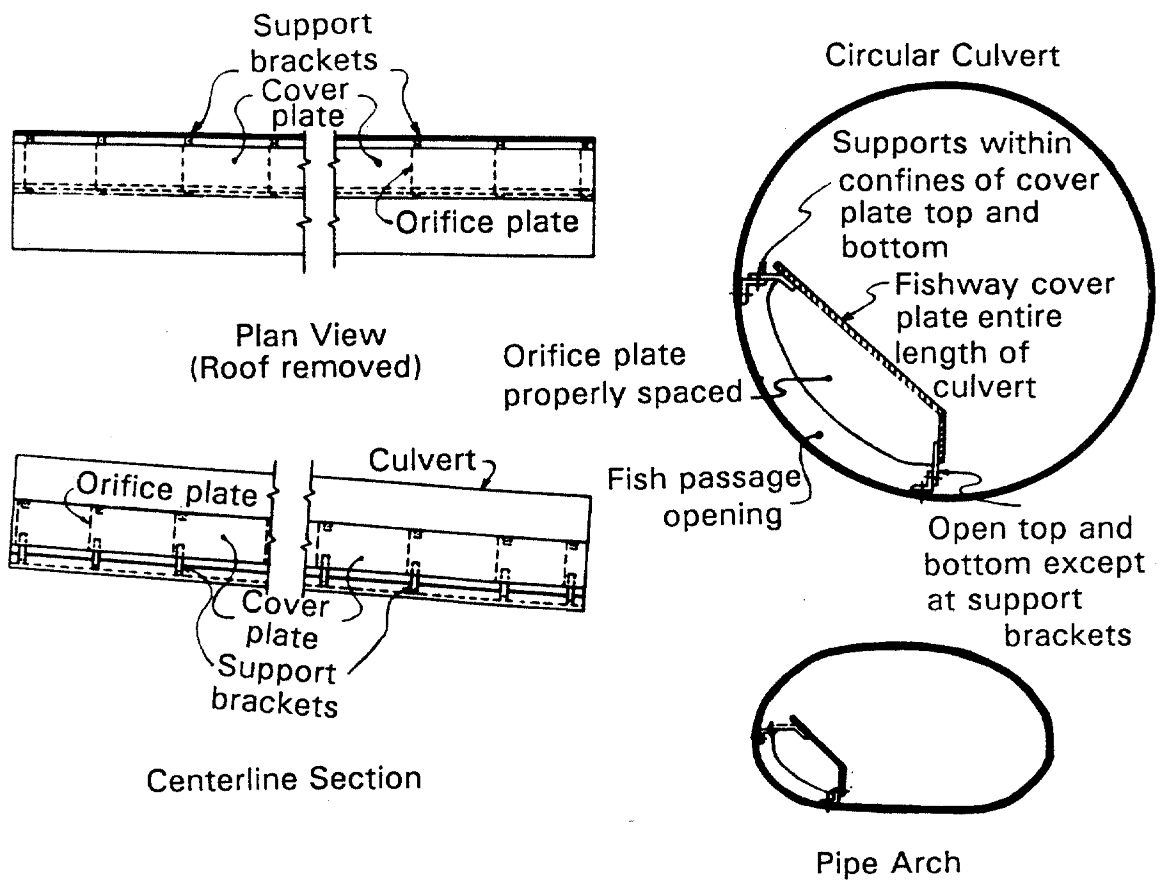


Figure 5.24. Slot orifice fishway modified for use with corrugated metal pipe and pipe arches.(24)

Steeppass fishways are another tool for overcoming fish passage problems. These fishways are being used to pass migrating salmon over low head barriers in Alaska and spawning trout over jump barriers, such as perched culverts, in Montana. A steeppass fishway is shown in figure 5.25.

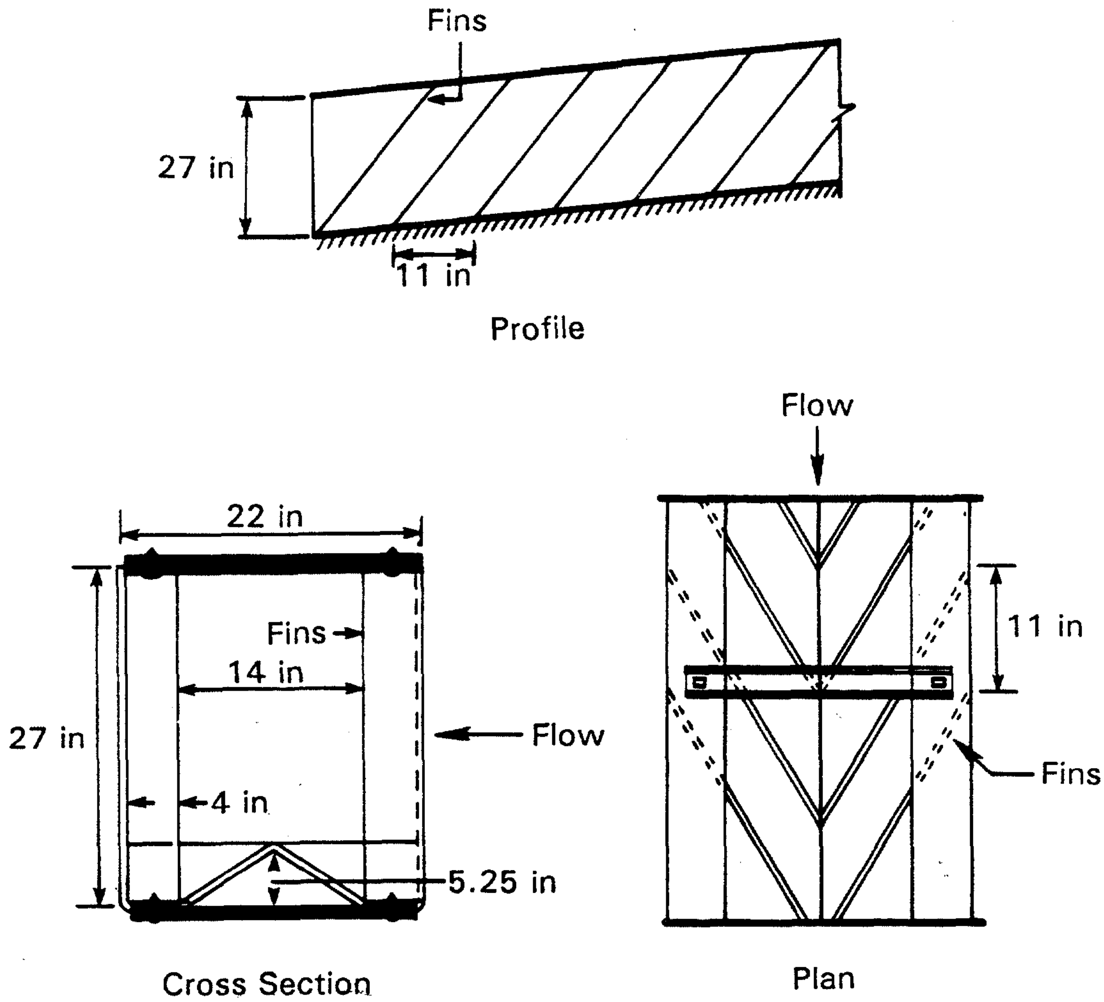


Figure 5.25. Alaska steeppass fish ladder.[24]

Resting Pools - Resting pools at both the culvert inlet an the outlet and will facilitate fish passage. The system should be designed by an engineer. A resting pool located at the culvert outlet allows a fish to rest before attempting passage through the culvert. The pool should also be deep enough to provide room for the fish to gain the swimming speed and vertical thrust necessary to make the jump into the culvert. It should be large enough to accommodate several fish. The length and width of the pool should be twice the diameter of the culvert and the bottom should be at least two feet below the invert elevation of the culvert outlet. A pool should also be provided at the inlet end to allow fish to rest before continuing upstream.

The pools may be formed by creating backwater using weirs or gabions as shown in figure 5.26. If the culvert outlet is perched, several tiers of gabions or concrete sills can raise the tailwater elevation to facilitate fish passage as shown in figure 5.27.

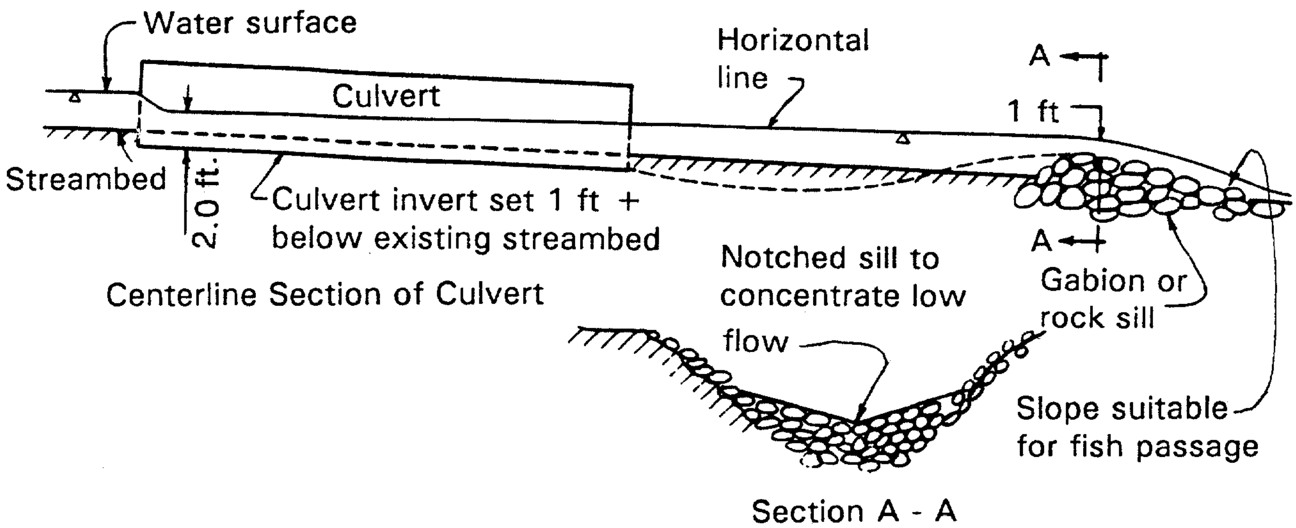


Figure 5.26. Creating backwater with a gabion or sill.[24]

Further information on devices to improve fish passage is located in appendix B-23.

Beaver control devices

Over the years a number of approaches have been tried to minimize the problem of beavers building dams that plug highway culverts. One research study that was conducted to evaluate various methods and beaver characteristic traits concluded: (1) they normally do not try to plug a culvert if the area to be plugged is very much greater than the culvert opening itself and (2) they usually will not try to plug an opening through which water flows vertically upward. Information on beaver control practices and control devices for highway culverts is provided in appendix B-24.

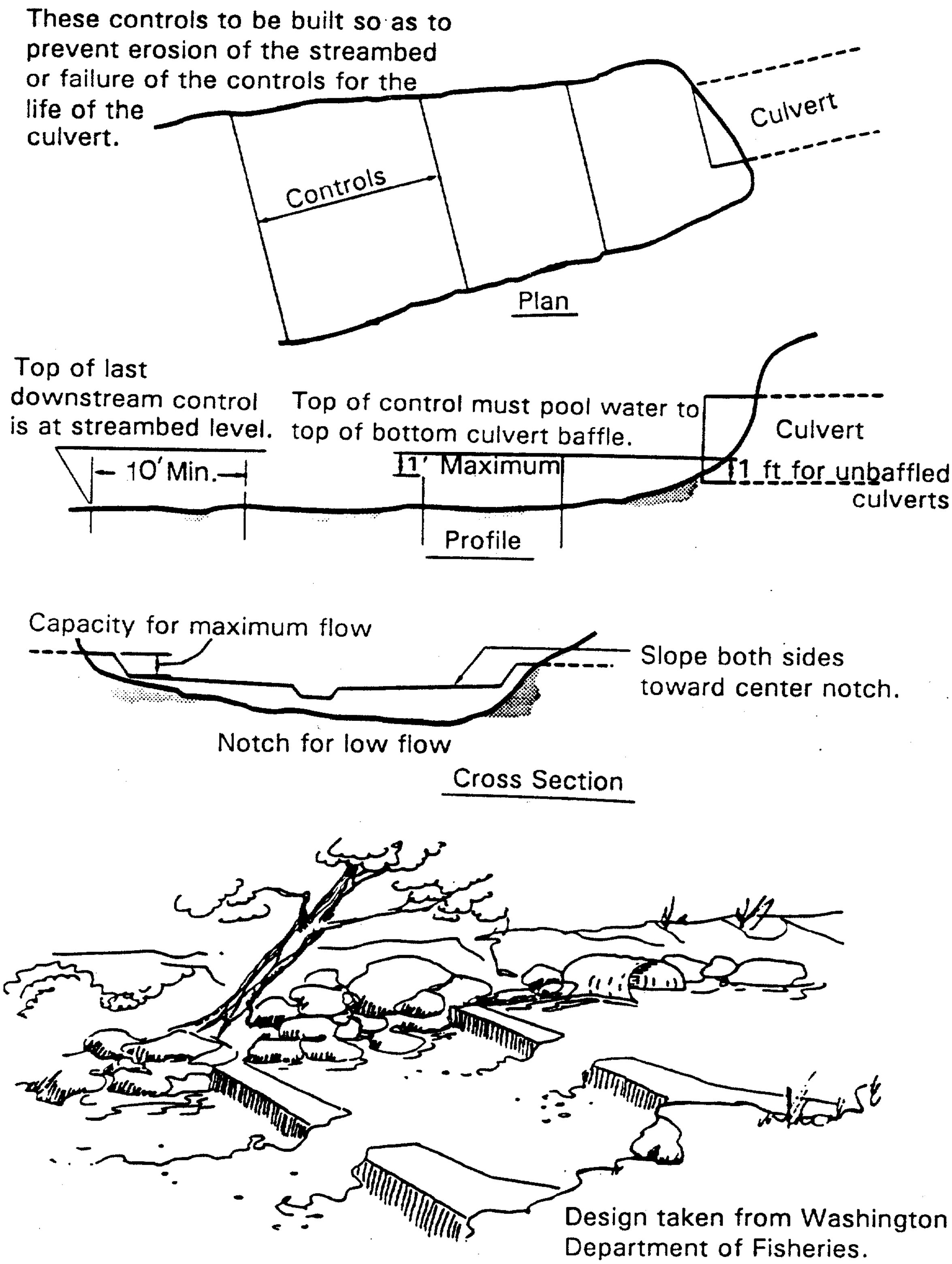


Figure 5.27. Use of gabions or concrete sills to raise tailwater to facilitate fish passage.[22]

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CHAPTER 6. CULVERT BARREL REPAIR AND REHABILITATION PROCEDURES

SCOPE

This chapter presents information on procedures that may be used to repair and rehabilitate the barrels of a wide range of culvert types. The types of problems range from those associated with corrosion and abrasion to those of joint leakage, deformation and loss of structural integrity and hydraulic capacity. The repair and rehabilitation techniques include use of traditional materials as well as innovative techniques to line the culverts by sliplining, inversion lining, and cement mortar lining. Detailed procedures for the concepts are provided in the associated appendix B.

GENERAL

The following discussion provides information on repair and rehabilitation techniques that may be used on a wide range of types of problems for all types of culverts and culvert materials. The rationale for selecting the most effective and least expensive procedure for repairing, rehabilitating, or replacing the barrels of culverts will depend upon a large number of factors, including:

- The type, size, and length of the culvert;
- The depth of cover;
- The type and degree of deterioration;
- The hydraulic adequacy of the existing culvert;
- Effluent characteristics;
- The nature and amount of work needed on the inlet and outlet ends;
- Design life;
- Service life;
- Whether the work can be done by agency personnel or if it must be done by a contractor;
- Maintenance of traffic; and
- Required future maintenance.

The range of combinations and costs for the best or most appropriate repair or rehabilitation concept is almost infinite, especially if the decision can be evaluated on both a short-term and a long-term basis. There is certainly a question of whether to repair the culvert or to replace it. The answer to this question may depend upon whether the funds necessary to replace it are available.

Table 6.1 presents established sewer renovation techniques that have been used in England as documented in the British publication, *Sewerage Rehabilitation Manual*.[1] The following pages provide information on techniques that may be used to repair or rehabilitate deteriorating culverts.

PRECAST REINFORCED CONCRETE CULVERTS

Precast concrete culverts are generally quite durable for a wide range of flow conditions. From the design standpoint they are considered to be rigid structures that will not bend and deform. However, if they are not installed properly, they are subject to certain types of distress and deterioration that are a function of their material and the fact that such culverts are made by assembling sections of precast concrete.

Their problems may be categorized into groups associated with (1) joint defects, (2) cracking, (3) spalling, (4) scaling (5) slabbing and (6) invert deterioration. Under each of these categories there are many individual types of problems and possible courses of remedial action. For example, scaling may be due to freeze-thaw action or sulphate attack. The proper course of action will depend on the type and severity of the problem as it relates to the type, size, and location of the structure.

Joint Defects

Precast concrete culverts have problems that are associated with a variety of conditions that are focused on behavior at the joints between the individual segments, which is a natural plane of weakness. As an example, reinforced concrete pipe bells with O-ring gaskets may break if the gaskets are too large or poorly installed.

Cracking - Circumferential cracking at the joints of precast concrete culverts is somewhat rare because tensile stresses that create cracking will tend to open the joints rather than cause cracking. Under certain circumstances it may be possible to develop compression or shear cracks due to rotation and displacement of sections, commonly caused by poor foundations with differential settlement. Repair of such cracks will normally be cosmetic in nature, unless more involved procedures are undertaken to correct the problem that caused the distress. Information on crack repair with mortar, mastics and structural adhesives is provided in appendix B-25.

Table 2.1. Established sewer renovation techniques.

TECHNIQUES			ME	MA	NME	ADVANTAGES	DISADVANTAGES
STABILSATION		Hand Pointing and Pressure Pointing	●			Minimal disruption. Materials and equipment inexpensive. Possible improvement to hydraulic capacity. Existing access normally suitable.	Existing sewer must be structurally sound. Quality control difficult. Flows diverted when working in invert. Control of infiltration required.
STABILSATION		Chemical Grouting	●	●	●	Minimal disruption. Access via existing manholes. Low flows tolerated. Infiltration reduced therefore possible extra capacity.	Monopoly on non man entry system. Difficult to seal packers where surface is irregular.
PIPE LININGS		Glass Reinforced Plastic (GRP) Design type I, II or III	●	●		High strength: weight ratio. Variety of cross sections available.	May require temporary support during grouting. Care to prevent barrier layer damage or excessive strain. Must often work away from lined sewer.
PIPE LININGS	Polyolefins	Butt Fusion Welded (Polytheylene) —Conventional Sliplining	●	●	●	Quick insertion. Large radius bends accommodated.	Circular cross section only. Lead in trench disruptive. Relatively high loss of cross section. Flotation during grouting. Less cost effective where deep.
PIPE LININGS	Polyolefins	Screw Joints (PP) Design type II			●	Access via existing manholes. Cost effective for short and deep lengths. Quick insertion. Large radius bends accommodated.	Circular cross section only. Relatively high loss of cross section. Flotation during grouting. Large number of joints.
PIPE LININGS		Insituform	●	●	●	Rapid installation. No excavation required. Bends/minor deformation accommodated. Capacity maximized. Grouting not normally required.	Full overpumping required during insertion. Monopoly. site set up high proportion of costs on small schemes.

ME = Man entry. MA = Man accessible. NME = Non man entry.

Source: Sewer Rehabilitation Manual, Second Edition.[1]

Table 6.1. Established sewer renovation techniques (continued).

TECHNIQUES			ME	MA	NME	ADVANTAGES	DISADVANTAGES
SEGMENTAL LININGS	Glass Reinforced Cement (GRC) Design type I		●	●		Variety of cross sections available. Easily cut to form connections.	Labour intensive jointing. Strutting often required.
SEGMENTAL LININGS	Glass reinforced plastic	Single piece lining (single longitudinal joint) Design type III	●	●		Deforms to suit variety of cross sections. High strength: weight ratio.	Requires temporary support during grouting. Acts only as permanent corrosion resistant formwork. Care to prevent damage to barrier layer, or excessive strain. Not suitable below water table.
SEGMENTAL LININGS	Glass reinforced plastic	Two piece linings Design type I or III	●	●		Variety of cross sections available. High strength : weight ratio	Care to prevent damage to barrier layer, or excessive strain. May require temporary support during grouting. Labour intensive jointing.
SEGMENTAL LININGS	Resin Concrete (PRC) Design type I		●			Variety of cross sections available. Units very stiff. Strutting not required during grouting.	Heavy. Monopoly supplier. Labour intensive jointing. Not suitable below 900 x 600mm.
SEGMENTAL LININGS	Precast Gunite Design type I		●			Variety of cross sections available. No strutting required. Variety of cross sections accommodated	Heavy. Labour intensive jointing. Not suitable below 1070 x 760mm.
COATINGS	Insitu Gunite		●			Connections easily accommodated. Access via existing manholes. Variation of cross section readily accommodated.	Dusty and difficult to supervise. Dependent on operator skill. Control of infiltration required. Not suitable below 1800mm diameter.

ME = Man entry. MA = Man accessible. NME = Non man entry.

Mortar and mastic for leakage - Cracks in the vicinity of joints between precast concrete segments should be repaired, particularly if they are causing leakage that may cause corrosion or a combination of infiltration and exfiltration. Cracked and loose concrete should be removed to expose good sound concrete. It is common practice to replace the missing concrete with a Portland cement based mortar to protect reinforcing steel that may have been exposed and to provide resistance against abrasion and further deterioration. Exposed reinforcing steel should be painted with epoxy before the mortar is applied. Use of a Portland cement based mortar is more durable and longer lasting than merely filling the void with a flexible mastic type material. However, in the interest of expediency or when it is determined that continued movement is likely, it may be necessary to fill the void or cracks with a flexible asphaltic or polymeric type material that will create a seal but which will also permit some movement without cracking.

Structural adhesives - For some types problems with joint cracking it may be appropriate and necessary to use structural adhesives (including epoxy) to develop a structural repair at the crack site. Structural adhesives bond the adjoining concrete together to form a complete uncracked section so that forces may be transferred from one side of the crack to the other side. The technology for the use of structural adhesives is well developed and reliable; providing that appropriate procedures are followed for preparation of the crack area and application of the adhesive.

Differential settlement - Differential settlement may occur because of scour under the ends, piping along the sides and inadequately compacted bedding under the culvert. For precast concrete culverts this will then cause differential settlement of the segments, and frequently rotation and opening of the joints or circumferential cracking. Closure and sealing of joints is important from the standpoint that if they are not closed infiltration and exfiltration will occur and create even more serious problems. The cause of the problem must be corrected, not just the symptoms. For example, scour may be prevented by adding riprap or energy dissipators.

Joint sealing for minor settlement - Segments that are exhibiting minor settlement and slight opening of the joints may be sealed in the same manner as cracks are sealed. Information on crack sealing is provided in appendix B-25.

Steel bands and shotcrete - It may be difficult to obtain a secure and reliable closure for joints that have wider openings with the crack filling procedures and materials, and a more positive and permanent procedure may be needed. One possible concept for repairing such joints would be to install a steel expansion band and then cover it with shotcrete for corrosion and abrasion protection. Procedures for placement of shotcrete and installing bands is provided in appendices B-11 and B-26.

Connecting sections to prevent end section drop off - The problem of end section dropoff is primarily caused by erosion of the soil embankment from under the entrance or exit ends of the culvert. It can also be caused by the tilting of poorly founded endwalls and headwalls. With a loss of soil support from under the end sections and a continued soil pressure being applied by the embankment above them, the only possible result is that the end sections begin to rotate and slide into the scour hole, since the sections of the precast concrete culvert are not attached to one another. A restraining device may be helpful in connecting the last three sections of the pipe together.

The latter fact then suggests that the solution to the problem is to prevent erosion by adding riprap or other protective features. Precast concrete sections may be connected together, either during construction or by retrofitting existing culverts if, because of possible water conditions and/or details of the design and installation, end section dropoff is a likelihood. Although this has rarely been done in the past, some highway agencies are now routinely connecting such sections together during construction. Few highway agencies have established procedures for connecting sections of precast concrete culvert sections together after the culvert has been constructed, and especially after dropoff has begun. Information on concepts for connecting sections of precast concrete culverts together to prevent end section dropoff is provided in appendix B-27.

If some procedure is used to prevent end section drop off it should be recognized that the problem may be stopped, but the cause of it has not been. That is, additional remedial action is probably also necessary to fill in scour holes and to provide adequate bedding under the ends of the culvert. Installation of a head wall, rip rap, or some other form of protection may be warranted. If scour under the ends of a precast concrete culvert (with connected sections) is allowed to continue, a long cantilevered section of the culvert may develop and extend to the point that sufficient bending and tension is created in the top of the culvert to create structural cracks. This problem is much more serious and difficult to correct.

Relaying of misaligned sections - Problems with joints that are caused by scour and differential settlement may be too serious, or too much movement has occurred to be corrected by sealing or connection the sections together. If this is the case, the only effective alternative may be to excavate the culvert and to relay the misaligned sections. The procedures to be used for such work are the same as for the installation of new culverts, and guiding documents for such work is readily available.

Longitudinal and Transverse Cracks

Longitudinal and transverse cracks in precast concrete culverts will be almost always be caused by structural loading. The significance of such cracks will depend upon their location, their width and depth and the cause of them. The proper corrective or repair action warranted will depend upon an evaluation and/or analysis of the culvert.

Corrosive and non-corrosive environments - A variety of environmental conditions may cause or result in some types of cracking in precast concrete culverts. Corrosive waters from mine or chemical plant effluent or fertilizer laden water from farm runoff water may cause corrosion and/or deterioration of concrete to the point that the concrete is weakened and cracked. Strong alkalies in the water will also cause concrete deterioration and cracking. Both classes of problems are somewhat difficult to correct. It may be possible to extend the life of the culvert by applying a protective coating to the concrete.

The life of the culvert can also be extended by paving the invert with concrete doweled into the existing pipe or by adhering vitrified clay tiles to the inverts. Procedures for paving of inverts can be found in appendix B-29.

Sealing - As noted above, cracks may be caused by structural loading or by chemical action or reaction with the concrete. Information on crack sealing is provided in appendix B-25.

Patching - Surface deterioration of concrete may occur because of spalling, abrasion, impact or some types of structural loading. Information on procedures for patching concrete is provided in appendix B-28.

Spall Repair

Spalling is generally the result of corrosion of reinforcing bars that initially causes horizontal (or in plane) cracking of the concrete and then subsequent delamination and spalling of the surface concrete off of the reinforcing bars. Information on concrete patching is provided in appendix B-28.

Slabbing Repairs

The terms slabbing, shear slabbing, and slab shear refer to a problem of radial failure of the concrete over the inner layer of reinforcement, due to excessive deflection and straightening of the reinforcing cage. The deformation causes radial tension and diagonal shear tension in the concrete that splits the concrete at the level of the interior layer of reinforcement. It is characterized by large slabs of concrete "peeling" away from the reinforcement. Slabbing is a serious problem that may occur under high fills with reinforced concrete pipe of inadequate D-load strength and/or on an inadequately deep bedding on a rock foundation. Slabbing is a phenomena that occasionally occurs during installation of precast concrete culverts as well as the result of bad soil conditions and a high water table.

The corrective action that should be undertaken will depend upon the amount of bending and distortion that has taken place in the concrete section and the likelihood that additional movement and slabbing will occur. If it is determined that the cause of the slabbing has been corrected (during construction) or that additional distortion and slabbing is unlikely, then the corrective action is rather simple and straightforward. If this is the case, and it may be determined that the culvert is structurally stable, then the primary concern is protection of the inner (and exposed) layer of steel reinforcing against corrosion. Information on procedures for patching concrete is provided in appendix B-28.

Invert Deterioration

The inverts of precast concrete culverts are normally quite durable and resistant to damage or progressive deterioration. However, under special conditions of high flow velocity water flow they are sometimes subject to deterioration due to abrasion and cavitation related loss of concrete. In areas of acid water runoff they may also be subject to chemical attack that deteriorates and removes concrete. In mountainous country they may be subject to severe impact by large rocks and boulders that are transported down steep slopes by high flow velocity. Such boulders may be several feet in diameter. Continued loss of concrete may lead to a reduction in structural strength of the culvert. This may be particularly critical since precast concrete culverts are considered rigid culverts, that are designed to withstand structural loads without deformation. Thus, loss of section strength may lead to cracking, deformation and collapse of the culvert. The following addresses specific aspects of the problem and associated remedial action.

Concrete repair - Deteriorated inverts in precast concrete culverts generally require paving to restore them to an acceptable functional condition. In order to accomplish such paving it is necessary to divert all water flow so that the invert may be dried, deteriorated concrete may be removed and other necessary work be done to prepare the invert for paving. A variety of Portland cement-based concretes may be used for such paving including conventional concrete, high strength concrete, and steel fiber-reinforced concrete as well as latex modified or low slump concretes of the type used for bridge deck overlays. Regardless of the materials selected for the paving it should be reinforced and securely anchored to the existing/remaining invert. In areas where there is acidic water it may be necessary to coat the concrete surface with a epoxy sealer or a polymer concrete. Specific information and guidelines for invert paving and protection is provided in appendix B-11 and B-29.

Flow neutralization basin - Since abrasion and rock-impact damage to culvert inverts is the result of fast moving water, elimination of the cause of the damage will thereby eliminate, or minimize, such problems. Specifically, this would be to reduce the velocity and energy of the water flowing through the culvert. The subjects of flow neutralization basins and other forms of energy dissipators are discussed in Chapter 5.

Nonetheless, it should be recognized that although such concepts may be very effective in reducing the velocity and energy of the water they also cause the water to drop sand, rocks, and boulders that are being carried, which thereby causes a buildup of these materials in the channel ahead of the culvert entrance. This may not only reduce the effectiveness of the energy dissipator system but also constrict the channel and cause an increase in water velocity and other associated problems. Thus, they should be designed to facilitate regular or scheduled maintenance.

Crown Deterioration

Precast concrete culverts may sustain damage in their crown section due to the depth of cover being too shallow to adequately support and distribute vehicle live loads. The result may be cracking, spalling and distortion in the crown area. Some information on procedures that may be used to repair such problems is provided in appendix B-37.

CAST-IN-PLACE CONCRETE CULVERTS

Cast-in-place concrete culverts are normally not circular or elliptical, but rather box or arch shaped. Their size ranges from perhaps as small as 3 foot square for a single cell box to as large as 12 feet high by 40 feet wide for multi-cell boxes. Their attributes include the fact that they may be constructed by highway agency personnel or general contractors. They are generally easy to construct and may be less expensive than precast concrete culverts, particularly in remote areas that are a long distance from a precasting plant.

One of the characteristics of cast-in-place concrete culverts is that they are not constructed with modular precast sections, but rather in long sections that run the length of the structure. Box culverts are made with horizontal top and bottom slabs (or flanges) and arch culverts may be constructed with arc-shaped sections, that are either tied together with a bottom (invert) slab or supported on footings that run the length of the structure. There are no unconnected or unreinforced joints between the sections. Although cast-in-place-type construction will have joints, the joints are designed to keep the sections of concrete together with steel reinforcing that passes through the "cold" joint. The joints will frequently have a rubber or plastic waterstop cast into them to prevent water migration through the joint.

There is also a difference in the concrete that is used for cast-in-place and precast concrete culvert construction. The cast-in-place concrete will usually have a 28-day compression strength of about 3,000 psi, whereas precasting concrete may have a 28-day compression strength of at least 5,000 psi. There may also be a considerable difference in workmanship for the concrete products.

Another aspect of box culvert type construction is that although they will normally have some height of embankment over them and under the roadway pavement system, occasionally they do not. That is, for some box culverts, the top (flange) of the box is also the roadway pavement.

Considering the above factors, it may be seen that the design and construction of cast-in-place concrete culverts are substantially different from precast concrete culverts. By the nature of their design and method of construction it is to be expected that the types of structural and serviceability problems that they will exhibit are also somewhat different, although the procedures for repairing them may be comparable.

Joint Defects

The joints of cast-in-place concrete culverts are oriented longitudinally, rather than transversely. They run the length of the structure, rather than across it. Also, as noted above, reinforcing steel and waterstop seals are built into (and across) the joint. Thus joints in cast-in-place concrete culvert construction can transfer (or carry) tensile, compression and shear forces but possibly not bending or rotational forces. Joint problems can occur because of differential settlement, unbalanced soil forces, or because of chemical and environmental conditions.

Repair or replacement of seals - Waterstop seals may be damaged because of excessive differential displacement of the sections of the culvert or because of freeze-thaw action that damages the surrounding concrete and then the waterstop.

Waterstop seals are flat strips of material that run the length of the culvert. They are frequently about eight inches wide with half of the width cast into the adjacent sections of concrete. Repair of damaged seals is quite difficult and time consuming, and there is some question of whether they may be effectively repaired. The most practical solution will probably be to replace the damaged section of the seal unless another repair or protection procedure may be effective. The replacement procedure involves removal of the facing concrete in the damage zone and insertion of a replacement section of waterstop. This then requires removal of at least four inches of concrete on both sides of the joint to access the waterstop seal. The damaged seal is then removed and a replacement section is installed and the facing concrete is then replaced.

This procedure should be done with some reluctance because the joint will probably be carrying a significant structural load. Removal of any significant length of concrete (half the thickness of the concrete section) may double the in-plane forces on the remaining portion of concrete and, thereby, cause compression failure of the concrete at the repair area. Even if the section does not fail, the replacement concrete will undoubtedly shrink away from the original concrete because of drying shrinkage, and any additional load that was shifted to the remaining original concrete will not be shifted and distributed across the full cross-section. Information on concrete patching is provided in appendix B-28.

Spall repair - Spalling of cast-in-place concrete, because of corrosion of the reinforcing steel, is probably more common than with precast concrete culverts. This is due to the lower quality concrete that is used, which is not only of a lower strength but also it is much more porous. Moisture migration through the concrete takes much less time as does the time to corrosion and the time to delamination and spalling. Procedures for patching concrete and repairing spalls are provided in appendix B-28.

Grouting - Although the likelihood that infiltration and exfiltration will occur is much less for cast-in-place type construction, it is still possible, particularly if the joint has been damaged because of differential settlement or other types of structural loading. Procedures for grouting behind such culverts is provided in appendix B-30.

Cracks and Spalls

Cracks and spalls are almost to be expected in cast-in-place type culvert construction because of a variety of factors including:

- The structures are relatively large or, at least, long. Any appreciable bending or deformation will cause cracks, whereas, precast concrete sections may rotate at the joints to relieve excessive local stresses.

- The cast-in-place sections are cast at somewhat different ages. Differential drying shrinkage will cause stresses between the sections that may cause cracking.

- There may also be differential drying shrinkage between the bottom half and the top half of the culvert because the lower half may be continuously wet whereas the top half may be continuously dry.

Sealing - Information on sealing of cracks is provided in appendix B-25.

Patching - Information on patching spalled and delaminated areas of concrete is provided in appendix B-28.

Underpinning Footings

Cast-in-place concrete arch culverts are supported on concrete footings that carry and resist compression thrust forces from the arch. Differential forces that are applied to the arch through the embankment must be resisted without cracking of the footing. If cracking occurs, then there may be displacement of the footing with an associated shift in stresses in the arch of the culvert. Cracking of a footing may also occur because of scour and undermining of the footing. In either case, the footing must be repaired or strengthened so that it can reliably carry the required structural loads without cracking or being displaced. This strengthening can only effectively be done by underpinning the footing.

Underpinning involves dewatering the construction zone, excavation of the soil under portions of the footing, installation of reinforcing steel (in most cases), and then placing concrete to develop a structural reinforced concrete "footing" under the existing footing. If there is a scour problem, then the depth of the underpinning must certainly extend a considerable distance below any possible future scour line. Information on underpinning is provided in appendix B-20. Depending on the site of the culvert and the nature of the water and debris that may pass through it, it may be necessary to protect the footings with riprap or to pave the invert. Information on installing riprap and invert paving is provided in appendix B-13 and B-29.

Invert Repair

As noted for precast concrete culverts, the inverts of cast-in-place concrete culverts are also normally quite durable and resistant to damage or progressive deterioration. However, under special conditions of high velocity, aggressive chemicals contained in the water or steep slopes, the inverts of such culverts are subject to deterioration due to chemical attack, abrasion, and impact damage. Since cast-in-place concrete culverts are classified as rigid culverts a significant loss of concrete section, with possible related structural cracking, could lead to collapse of the culvert. It should be recognized that many cast-in-place concrete culverts are quite large single or multiple-cell box culverts, that carry structural loads in a different manner than circular or elliptical precast shapes. Distress of the inverts in box culverts should be carefully considered with regard to structural safety.

Repair of deteriorated inverts in cast-in-place concrete culverts generally requires paving to restore them to an acceptable functional condition. In order to accomplish such paving it is necessary to divert all water flow so that the invert may be dried, deteriorated concrete may be removed and other necessary work be done to prepare the invert for paving. A variety of Portland cement-based concretes may be used for such paving including conventional concrete, high strength concrete, and steel fiber reinforced concrete. Regardless of the materials selected for the paving it should be reinforced and securely anchored to the existing/remaining invert. In areas where there is acidic water it may be necessary to coat the concrete surface with a epoxy sealer or a polymer concrete. Specific information and guidelines for invert paving and riprap protection is provided in appendices B-11 and B-29.

As for precast concrete culverts, it may be appropriate to modify the approach channel, or even the invert of the culvert, to reduce the velocity or the hydraulic energy of the water passing through the culvert. A flow neutralization basin may be constructed in the channel before the entrance of the culvert or energy dissipators may be installed in the invert of the culvert to reduce the velocity of the water and to reduce abrasion and impact damage to the concrete.

CORRUGATED METAL PIPES AND PIPE ARCHES

Corrugated metal pipe and pipe arches are widely used throughout the country, and most of them have served very well for many years. Corrugated metal culverts are considered to be flexible structures because they require interactive soil support to maintain their shape and functionality. These culverts can develop certain conditions that should be recognized in their evaluation and the planning and scheduling of repairs. As with any structure, it is normally easier and less expensive to properly maintain culverts or to correct problems when they are just beginning to develop than it is to correct the more serious, and frequently more complex, problems or conditions that may threaten their structural and functional adequacy.

The primary conditions that may affect corrugated metal pipe and pipe arch culverts may be grouped into three categories: (1) joint defects, (2) deterioration of the inverts, (3) shape distortion and corrosion. Although each of these may occur independently they may also occur simultaneously and be interrelated. Thus, it is imperative that assessment of such problems be made on the basis of the condition of the entire structure. Determination of the primary and secondary causes of the problems and the nature of the repairs that may be necessary to restore the structural strength and hydraulic capacity of the culvert should be reviewed from the perspective of how each repair procedure or modification will affect the structure as a whole.

One of the most serious fundamental problems that can occur with corrugated steel pipe and pipe arch culverts is corrosion due to chemicals in the surrounding soil and in the water that passes through the culvert. The observed problems with such culverts may be distress at the joints and the inverts, as well as localized distortion. However, these problems may be caused by or directly related to corrosion that reduces the thickness of the pipe wall and, therefore, reduces its strength.

Over the past few years some research has been conducted to evaluate the rate and magnitude of corrosion damage to buried steel culverts. The results of this study provide at least a limited amount of information on the corrosion susceptibility of corrugated steel culverts.[2][9] Perhaps of even more importance are the results of a current research study that is evaluating the potential benefit of protecting steel culverts by cathodic protection techniques. Information on this study and procedures that are being used is provided in appendix B-31. The interim results of this study tend to indicate that cathodic protection of buried steel culverts is a viable and, probably, economical, technique for protecting them against external corrosion.[3]

Joint Defects

Corrugated metal pipe and pipe arch culverts are subjected to a variety of external loads and changing soil conditions that may cause the circumferential joints to open, although this is unlikely if the proper bands are used. When this occurs infiltration and exfiltration frequently develop and cause a progressively worsening condition. Open joints permit water from the culvert to pass into the supporting soil by exfiltration. This saturates the soil, reduces its supporting strength and leads to return infiltration of the water (possibly with groundwater) together with backfill soil. This then creates voids in the backfill and a loss of structural support for the culvert. Saturation of the soil may also allow significant freeze-thaw cyclic forces to develop and aggravate the situation during the winter season.

Occasionally the first noticeable evidence of such problems is development of sink holes in the roadway shoulders or cracking and depressions in flexible pavements. Left unattended soil, surrounding the culvert may eroded away to the point that inadequate soil support remains and severe distortion and even collapse may occur.

The amount and complexity of remedial action will depend upon the site conditions and the level and severity of the deterioration of the culvert. Site conditions include such factors as location, height of fill over the culvert and the amount of hydraulic head pressure the water from infiltration is under. The solution to the problem may involve excavation and external repair, grouting, installation of interior seals, or combination of the latter two.

Excavation and exterior repair - Depending on the size, age, and condition of the culvert and the amount of fill over it as well as traffic related factors for the overhead roadway, it may be feasible to excavate the embankment and repair open or damaged joints from outside of the culvert. Several types of external collars are available for such repairs. This approach would be most practical when the joint defects are caused by soil conditions that may be corrected so that the culvert will have a good life expectancy thereafter.

Grouting - Pressure and gravity grouting are processes that are routinely employed to fill voids in the soil that surrounds and supports almost all types of pipelines, particularly water lines and storm drains. The techniques and materials that are used for such purposes are well developed and they are directly applicable to the repair of culverts. However, some of the materials and techniques are expensive, but necessary for long underground utility lines that pass under buildings or other types of structures and they may not be economically viable for culvert work. Nonetheless, the principles of good gravity and pressure grouting practice should still be followed for culvert work. Grouting may be necessary to fill voids due to piping or other surface water related causes as well as because of open joints and infiltration of soil into and through the culvert. Additional information on grouting is provided in appendix B-30.

Interior seals - Corrugated metal pipe and pipe arch culverts are subjected to a variety of external loads, and changing soil conditions that may cause the circumferential joints to open. When this occurs infiltration and exfiltration frequently develop and cause a progressively worsening condition that creates voids and loss of support in the backfill that leads to distortion and possible localized failure in the culvert.

The amount and complexity of remedial action will depend upon the site conditions and the level and severity of the deterioration. The solution to the problem frequently involves installation of an expansion ring that bridges and closes the open joint and pressure grouting to fill voids in the soil behind the joint. The closure ring may have to carry structural loads or external hydraulic pressure. Several techniques and types of closure rings and grouts that may be used for such work are described in appendix B-26 and B-30.

Invert Durability Repairs

One of the most common problems with corrugated metal culverts is deterioration of the invert, usually due to a combination of corrosion and abrasion. It is for this reason that corrugated steel culverts are galvanized and frequently also coated with an asphaltic or other type of protective coating. Unfortunately these coatings do not have unlimited durability against abrasion and impact from sand and rocks. Eventually the coatings are abraded or broken away. Corrosion that attacks the bare steel is accelerated by abrasion that constantly removes the somewhat protective oxide layer formed by corrosion. Continuation of this action frequently results in almost total loss of the invert and the creation of deep scour holes under the culvert. Since a corrugated metal culvert is classified as a flexible structure that requires interaction with soil pressures for stability, loss of the invert may result in severe distortion and collapse of the culvert. Thus, repairs for severely deteriorated inverts in metal culverts must be structural repairs that restore the structural integrity of the culvert.

Many types of repairs and corrective action may be taken to restore large corrugated metal culverts and to alleviate or minimize future invert durability problems. The work may be classified in three categories: (1) invert paving, to restore or replace weakened inverts, (2) steel armor plating, to provide increased resistance to abrasion and impact damage, and (3) conversion of pipe arches to arch structures, to eliminate the metal invert.

Invert paving with concrete - One of the most effective ways to rehabilitate corroded and severely deteriorated inverts of CMP is by paving them with reinforced concrete. The concrete may be either conventional ready-mix type concrete or it may be shotcrete. Sufficient steel reinforcing should be installed and securely anchored to re-establish the structural capacity of the culvert to resist circumferential thrust loads. Guidelines for paving inverts are provided in appendix B-11 and B-29. There are advantages to both types of materials and application methods that are discussed in these appendices.

Steel armor plating - In hilly or mountainous country culverts may be subject to severe abrasion or impact damage due to sand, rocks, and boulders that are carried by fast moving water. In some cases paving with conventional or even special concrete will not provide an adequate durability and a tougher and more resistant protective system is required. One approach that has been occasionally used by several highway agencies is to armor plate the invert with steel plates. Although this may seem to be an extreme remedy it may be necessary for some installations. Information and examples of steel armor plating is provided in appendix B-32.

Pipe arch conversion to arch - For some pipe arch culverts that are subject to severe abrasion or impact damage that cannot be controlled in any other way, there is a third option to convert them to simple arch-type structures. This involves removal of the metal invert and constructing concrete footings under both sides to support the structural arch. This is a difficult and hazardous solution because of the necessity to adequately block and brace the existing pipe arch against collapse after the invert is removed. The amount of horizontal and vertical soil forces that must be resisted will depend upon the design and size of the culvert as well as the amount of fill over the culvert. Following removal of the invert, it will then be necessary to construct footings along both sides that are large and strong enough to resist soil and vehicle loads. The invert area under the culvert must subsequently be constructed to conform to the streambed. This solution is only recommended as a last resort.

Another possible advantage of this solution is that the cross sectional area of the culvert may be increased by excavating and constructing deeper footings. This option would only be possible in locations where the elevation of the approach and downstream channels may be lowered, which is not normally possible.

Shape Distortion

As noted previously, corrugated metal culverts are flexible structures that maintain their shape by support from the surrounding soil. Thus, distortion of the shape of a corrugated metal pipe or pipe arch culvert is an indication of uneven or unsymmetrical soil pressures that are being exerted around the periphery of the culvert. This distortion may occur during construction because of improper construction practices or it may occur during the service life of the culvert. If the latter is the case it is indicative of a developing problem. The rate at which the problem will worsen and the solutions to the problem will depend on site specific details of the design, the location, and the cause of the problems.

It is important to determine whether the culvert is stable in its distorted shape or whether it is continuing to distort, and of course, the rate at which it is distorting. It is quite common to have at least some symmetrical or unsymmetrical distortion in corrugated metal culverts. It is also common that the culvert can stabilize in the distorted shape, that is, not continue to distort. If this is the case, corrective action is not necessary. On the other hand, if the distortion continues to progress, determination of the rate of progression will give the agency an idea of how rapidly corrective action should be taken. Information on procedures for measuring and evaluating distortion is provided in appendix B-33. Additional information can be found in a study from the Ohio Department of Transportation, *Evaluation Procedures for Corrugated Metal Structures (In-Situ).*[10] Repair procedures are provided in appendix B-34.

Temporary bracing - One of the first measures that may be taken to prevent continuing distortion and possible collapse of the culvert is to install temporary bracing or shoring. Highway agencies and maintenance personnel are generally quite familiar with such work and guidelines have been developed for installation of temporary bracing or shoring. Nonetheless, it is perhaps worthwhile to highlight the fact that the bracing must not only be adequate to support the anticipated loads but it must also be installed in such a manner that it is secure against movement due to water flowing through the culvert. Consideration must also be given to the possibility that debris may become lodged against it and thereby present a large surface area against which water pressure may be exerted. Moreover, the buildup of debris will cause a constriction in the culvert that will cause the level of the water to rise. This may then create additional problems. Thus, a value judgement must be made as to how large, complex, and secure the bracing should be. A balance may have to be made between the potential for loss of the bracing versus. the creation of problems with the culvert during a time of flooding. Consideration should be given to construction of a trash rack at the upstream end of the culvert. Procedures for temporary timber bracing of culverts can be found in appendix B-35.

Excavation and backfilling - Depending upon a number of site specific details, it may be feasible to correct distortion of corrugated metal pipe and pipe arch culverts by excavating the embankment surrounding the culvert and rebuild it so that the culvert has the proper symmetrical shape. Although the distortion may primarily be in the upper quadrant or two quadrants of the culvert it will probably be necessary to excavate at least below the spring line to correct the distortion. The existing backfill should be checked to see if it is suitable structural-quality backfill before it is used.

Rerounding - As noted above, rerounding may be done for some culverts by excavating the embankment, correcting the shape as the embankment is built up again to the level of the roadway. The practicality of this will depend on many site specific details, including such items as the height of the fill and the amount of traffic on the roadway. It should be noted that not all states permit rerounding of culverts.

For culverts under deeper fills that have one or only a few distorted sections, it may also be possible to correct the problem from the inside of the culvert. Techniques for rerounding or reshaping corrugated metal culverts are provided in appendix B-36.

Corrugated metal pipes and pipe arches may sustain damage in their crown section due to the depth of cover being too shallow to adequately support and distribute vehicle live loads. The result may be distortion and tearing at bolt holes in the crown area. Some information on procedures that may be used to repair such problems is provided in appendix B-37.

CORRUGATED METAL STRUCTURAL PLATE

Corrugated metal structural plate culverts are also widely used throughout the United States, but not as frequently as corrugated metal pipe and pipe arch culverts. They are generally quite large, and many of them are under fairly high fills. Thus, they tend to be more expensive and more important structures.

Since they too are flexible structures that are made of metal, they suffer from the same types of problems as do corrugated metal pipe and pipe arch structures. In addition they also suffer from problems that are unique to their style of construction, which is assembly with individual pieces of metal that are fastened together with bolts. The following describes their various types of problems and the corrective action that may be taken.

Seam Defects

The longitudinal seams of CMSP culverts are subject to displacement and cracking due to incorrect assembly of the plates and also due to differential soil pressures that may distort the culvert from a symmetrical shape. The type of corrective action will depend upon the condition of the culvert and the magnitude and severity of the problems.

Excavation and repair of cocked and cusped seams - As noted above, the cause of rotation of the seams is frequently incorrect assembly of the plates, which may allow localized soil pressures to rotate the plates by causing the bolts to yield or tearing the plates. If this condition is occurring it may be possible to correct the problem by excavating the embankment, weld repairing cracks in the plates and assembling the plates in the proper position and replacing defective bolts.

Seam cracking - Although there are a number of possible causes of seam cracking in corrugated metal structural plate culverts, the primary cause appears to be incorrect assembly of the lap joint (seam). It has been found that for properly assembled joints that the bolts nearest the visible edge should be in the valley of the corrugations. This rule is valid regardless of whether the joint is viewed from the inside or the outside of the culvert. The following discusses aspects of the problem and corrective or repair action that may be taken.

Reverse lap joint - For some culverts it may be possible to disassemble the seam joints and reverse the lay of the plates so that they are properly assembled to prevent cracking of the plates.

Reinforcing bars - Numerous State highway agencies repair cracked seams in corrugated metal structural plate culverts by welding #5 reinforcing bars across the lap joint. Details of the procedure are described in appendix B-32.

Shotcrete beams - The Alberta (Canada) Ministry of Transportation has developed a procedure for strengthening culverts that have cracked longitudinal seams. The procedure involves constructing lateral steel fiber reinforced shotcrete beams around the periphery of the culvert, across the cracked seam. The procedure is described in appendix B-38.

Joint Defects

The circumferential seams, like joints in factory pipe, do not carry ring compression. They do make the culvert one continuous structure. Distress in these seams is rare and will ordinarily be the result of a severe differential deflection or distortion problem or some manifestation of soil failure. Circumferential seam distress can also be a result of foundation failure, but in such cases should be clearly evident by displacement in the vertical alignment.

Repairs for such seam or joint defects will depend on the type and severity of the problem. Several repair procedures are described in appendix B-26.

Invert Durability

The inverts of corrugated metal structural plate culverts suffer from deterioration due to corrosion and abrasion, just as corrugated metal pipes and pipe arches do. Left to continue, such deterioration can lead to loss of the invert, severe scour and undermining, and eventual distortion and possible collapse of the culvert. The primary methods of repair and restoration are essentially the same as for corrugated metal pipe and pipe arch culverts. Guidelines for paving the inverts are provided in appendix B-11 and B-29.

Shape Distortion

As noted previously, corrugated metal culverts are flexible structures that maintain their shape by support from the surrounding soil. Thus, distortion of the shape of a corrugated metal structural plate culvert is an indication of uneven or unsymmetrical soil pressures that are being exerted around the periphery of the culvert. This distortion may occur during construction because of improper construction practices or it may occur during the service life of the culvert. If the latter is the case it is indicative of a developing problem. The rate at which the problem will worsen and the solutions to the problem will depend on site specific details of the design, the location, and the cause of the problems.

Depending upon the nature and the severity of the distortion problems it may be possible to take corrective action that will stop further distortion or some other type of repair work may be necessary. Procedures for doing such repair work are described in appendix B-34.

CORRUGATED METAL ARCHES AND BOXES

Corrugated metal arches and boxes are routinely used in some portions of the United States. Although they are made of corrugated metal these forms of culverts are more structurally rigid than their counterpart pipe or structural plate culverts. However, since they are made of corrugated metal they are still considered to be flexible type structures.

Arch and box type culverts are generally quite large and wide with respect to their height. The arches rely upon rigid footings to develop the arch action and to resist horizontal and vertical thrust forces. Box culverts are complete structures that resist structural loads by frame action. Box culverts may be either single or multiple cell. Single cell boxes structures are generally strong in torsion but somewhat weak in flexure and lateral (or unsymmetrical) bending. Multiple cell boxes are more rigid than single cell boxes.

Since these types of culverts are made of metal, they suffer from many of the same types of problems as do corrugated metal pipe and pipe arch and structural plate culverts. In addition, they also suffer from problems that are unique to their style of construction. Corrective action for many of their types of problems have already been discussed. The following describes problems that are unique to these forms of construction and presents corrective actions that may be taken.

Underpinning Footings

In general, the footings of arch culverts are made of plain, unreinforced concrete. Normally such footings have a sufficiently large cross section that they will not crack or become structurally inadequate by themselves. However, the footings of arch culverts may be undermined by scour action if they are not founded deep enough to be below a potential scour line. Undermining of the footings of an arch culvert will frequently cause settlement, rotation, distortion, and possible failure of the culvert.

Thus, detection of scour problems and underpinning of the footings of arch culverts should have a high priority. Guidelines and procedures for underpinning footings are provided in appendix B-20.

Streambed Repair

One of the primary purposes for building an arch culvert is to span the stream and leave it undisturbed. This facilitates the passage of fish and eliminates the need to repair the invert of culverts that have been corroded or abraded away. However, use of the natural streambed as the invert presents the possibility that the elevation of the streambed may be raised by the deposit of rock or debris as well as the possibility that it may be scoured away by fast moving floodwater.

In either case corrective action should be taken to minimize the potential for the development of more serious problems. In many cases a buildup of rocks or debris may be cleaned out with a small bucket loader or a dragline. Scour action and a lowering of the streambed should be repaired by replacement of the streambed material, installation of riprap stone, or by paving the streambed under the culvert. Guidelines and procedures for doing such work are provided in appendix B-13, B-15, and B-29.

Shape Distortions

As noted previously, corrugated metal culverts are flexible structures that maintain their shape by support from the surrounding soil. In addition, corrugated metal arches and boxes are subject to additional problems that may cause distortion. Regardless, distortion of corrugated metal culverts is an indication that problems exist that must be corrected. Many of these problems, and solutions to them have already been discussed.

Depending upon the nature and the severity of the distortion problems it may be possible to take corrective action that will stop further distortion or some other type of repair work may be necessary. Procedures for doing such repair work are described in appendix B-34. In addition, if the problems are due to scour of the footings of an arch culvert it may be necessary to include vertical jacking of the side(s) to raise the level of the footing to its original elevation or ,conversely, to excavate under a portion of the footing so that it will settle and be at the same elevation along its entire length.

GENERAL CULVERT BARREL REHABILITATION

The preceding discussion has addressed specific types of distress or damage, and techniques for repairing them have been presented. When the extent or type of distress severely limits the structural strength or the functional adequacy of an existing culvert barrel and it cannot be effectively repaired, other procedures should be considered to restore the structural strength and the serviceability of the culvert. The following discussion presents techniques that may be considered. The viability of these techniques will depend upon site-specific conditions, the cost of materials and labor, and the type and extent of the inadequacy.

Most of the following techniques for restoring the structural strength and serviceability of culverts also reduce the internal cross sectional area of the culvert, which may accordingly reduce the hydraulic capacity of the culvert. The actual reduction in hydraulic capacity will depend upon many factors; including the size, type and condition of the existing culvert as well as upon details of the corrective action.

Decisions regarding the corrective action, and justification for downsizing, must be done as the result of analysis of site-specific conditions by a hydraulic engineer. Current hydrology design and analysis practices may show that older culverts are oversized, and in fact, could be downsized without adversely affecting existing upstream conditions. By flood routing a hydrograph through a culvert system designed for only the flood peak, it is frequently possible to justify downsizing of an existing culvert, provided that there is some temporary storage caused by roadway embankments. It may also be helpful to note that modern culverts are almost always constructed with headwalls, endwalls and wingwalls, but that many older (and some modern) culverts are not constructed with these features. Thus, under certain hydraulic related, site-specific, circumstances replacement of an older style culvert inlet with an improved inlet can dramatically increase the capacity of the culvert or justify downsizing the culvert barrel.[4],[5]

Flood hazard related problems due to culvert downsizing or inadequate capacity might be solved with upstream detention or retention ponds. Another possibility is for the hydraulics engineer to consider risk analysis that may permit justification of a lower flood design frequency.

Sliplining

One of the more effective ways to restore a culvert to a functional condition is by sliplining, which is the process of lining the culvert with either conventional or new types of prefabricated culvert products. In a sense, almost any type of culvert can be sliplined with almost any kind of culvert material. The proper selection of the most appropriate material will depend upon many factors, including:

- Type, kind and size of the existing culvert;
- Structural and functional (hydraulic) conditions and adequacy of the existing culvert;
- Site-specific conditions
  - Urban or rural location
  - Flat or mountainous terrain
  - Amount and velocity of water passing through the culvert at the time of the work;
- Effluent characteristics;
- Design life requirements;
- Service life assigned;
- Economic factors including the cost of materials, labor and equipment; and
- Expected maintenance.

Depending on the materials and techniques used for the sliplining, it may be possible to restore the structural strength of deteriorated culverts and to minimize the loss in hydraulic capacity. It may also be possible to eliminate the influence of environmental conditions that led to the deterioration of the existing culvert, such as the effects of acid mine runoff or caustic water, by selecting a lining or interior coating material that is resistant to such conditions. Although the lining process may reduce the internal cross-sectional area of the existing culvert, some plastic, precast concrete and lined corrugated metal pipe have a lower Manning's roughness coefficient than that of the existing culvert.

Procedures - There are a wide variety of individual techniques that may be used to slipline a culvert, that depend upon the above factors as well as the contractor's knowledge and experience with this type of work and the equipment that must, or can, be used for the work. The following steps are normally required for the sliplining process:

1. Divert and/or control water passing through the culvert.
2. Clean and make any repairs in the existing culvert that may be necessary prior to sliplining. Repair embankment as well by identifying voids and grouting behind and culvert.
3. Construct a guideway on the invert of the culvert, to facilitate the sliplining of sections into the existing culvert.
4. Install segments of the liner in the culvert, by sliplining, and connect them together.
5. Grout or seal the space between the liner and the existing culvert. Perform a check to ensure complete grouting of annular space after sliplining.
6. As necessary, complete the project by constructing or modifying head- and wing-walls on the ends of the culvert.

There are many technical details that must be worked out for the actual construction project, including: (1) how the liner sections will be moved into place in front of the culvert, (2) how the sections will be slid into the culvert, and (3) if and how structural interaction will be established between the liner and the existing culvert. Although there are some procedures that are relatively simple and straightforward, others are much more complex. In some cases it may be possible to stipulate standard construction procedures while at other times the procedures should be left open for contractor innovation, which may permit a contractor to use special equipment or techniques that may reduce the cost of the work.

The Minnesota Department of Transportation has recently completed a project to investigate alternative means of culvert renewal in lieu of removal and replacement. Seven different reliners were placed in concrete and metal pipe, and five joint repair options were placed in concrete pipe. Reliners include:

- smooth polyethylene with mechanical joints;
- smooth polyethylene with fused joints;
- corrugated polyethylene
- spiral ribbed polyvinyl chloride;
- fiberglass;

- spiral ribbed coated steel arch; and
- cured resin impregnated felt tube.

The final report on the project, *Culvert Renewal*[6], Report Number MN/RD-92/02, is available through the National Technical Information Services, Springfield, Virginia, 22161. More detailed information on the sliplining process and techniques that have been used are provided in appendix B-39 and B-40 on sliplining and grouting sliplined culverts.

Products - The range of prefabricated or modular culvert products that may be used for sliplining existing culverts is almost limitless. Basically any type of product that is used to construct new culverts may be used to line existing ones. Moreover, concrete culverts may be lined with corrugated metal and corrugated metal culverts may be lined with precast concrete sections. In addition, structurally strong but deteriorated culverts may also be lined with such products as unreinforced plastic pipe that may have relatively little structural strength by itself. Structurally weak culverts may also be lined with filament-wound fiberglass pipe or with fiberglass-polymer concrete sections. To a large extent the procedures for assembling or connecting and grouting slipliners are based on industry guidelines for the construction of new culverts. Information on the sizes and shapes of culvert and culvert lining products is provided in appendix A. The following comments deal with special aspects for use of these materials and products for sliplining.

<u>Corrugated metal</u> - Many sizes of corrugated pipe, pipe arch and structural plate products are available. In general the pipe and pipe arch shapes must be prefabricated to the desired length or assembled by connecting them together at the jobsite. If multiple sections are needed, they may be connected together outside of the culvert and pulled or pushed into the existing structure. As an alternative if conditions permit, individual sections may be pulled through and assembled inside the existing culvert using tabs for alignment and grout to hold position. If structural plate pipe is used, the outside dimensions of the liner will have to be sufficiently smaller than the existing culvert so that workmen may handle fastening the bolts from both the inside and the outside. Clips can also be used so that the bolts can be tightened from the outside. A Spiral Rib (internal rib) CMP is available that has a low Manning's "n" factor, that minimizes the reduction in flow capacity. Concrete-lined corrugated metal pipe is available. As with the use of Spiral-Rib CMP, a low "n" factor is obtained.

If corrugated pipe or pipe arch sections are to be used to line an existing corrugated metal culvert it may be necessary that either timber skids or a concrete "sidewalk" be installed in the invert so that the liner may be slid into position. They may not be needed for 36" and smaller CMP if the culvert is less than 150 feet long. On some jobs special endguides and temporary internal bands are used until the structure is grouted.

Precast Concrete - A wide range of precast concrete shapes may be used to slipline culverts. One particular advantage of using precast concrete sections is that the sections are shorter in length than corrugated metal sections and they may (in some ways) be handled somewhat easier. They may also be connected inside of the culvert, which minimizes the amount of working space that is needed outside of the culvert. They are frequently pulled into the culvert by using a pulley system that is attached to a strongback frame that spans one end of the existing culvert.

Plastic pipe - A wide range of polyethylene, high density polyethylene and polyvinyl chloride (PVC) plastic pipes are available for lining culverts. Some of them have a corrugated outer surface or corrugations on both the inner and outer surfaces and others are smooth on the inside or on both sides.

Others are folded for insertion and then expanded into shape with hot water, such as Nu-Pipe and U-Liner. Plastic pipe may be connected in several ways, but the most common are either by snapping them together or by fusion bonding them together. Normally sections of plastic pipe are connected together prior to their installation in a culvert. The Pipe Liners Incorporated system is manufactured in a circle. It is deformed to a U-shaped while it is still hot and, at the site, is expanded with steam after insertion.

Fiberglass pipe - There are basically two types of fiberglass pipe that can be used to slipline culverts. However, they are generally more expensive than the plain unreinforced plastic pipe and they are more routinely used to line pipelines. The largest, and strongest, of such pipe is filament wound with glass fibers in a polyester resin. The connections of fiberglass pipe include O-ring seals, with one being used for low pressure applications and two being used for high pressure applications. The other type of pipe is made with a combination of glass fibers and a sand-resin mixture, that produces a strong, but somewhat heavier and less expensive pipe.

Grout - A variety of grouting materials may be used to fill the void between the sliplined conduit and the existing culvert. The types of materials that are typically used range from Portland cement-based mortar to a controlled low strength material (CLSM),which is a title that has been established for this class of materials by the American Concrete Institute technical committee 229. It should be noted that the grout may not need to have the strength of structural concrete but rather only the strength of well compacted soil.

CLSM mixes are routinely used for highway-related construction in many states including the following: Ohio, Illinois, Iowa, North Carolina, and Texas. This class of materials may have a variety of other names throughout the U.S. including: controlled low density fill, flowable mortar, lean mix backfill, and flowable fill. The National Ready Mixed Concrete Association published guidelines with the title of *Ready Mixed*

Flowable Fill. The American Concrete Pavement Association uses the term "flowable low-strength mortar backfill."

A CLSM is usually a mixture of cement, fly ash, fine sand, and water. A typical mix may have three times more fly ash (a pozzolanic cementiceous material) than cement. Hydration of the cement and slow hydration of the fly ash produces a material that may have a 28-day compressive strength of only 100 psi or 14,400 psf, which is about six times stronger than many soils that have a strength in the range of only 2,500 psf. Lower strength CLSM mixes may be used. Particular advantages of CLSM mixes are they are easy to place, they are self-leveling and their installed cost is less than for many other comparable materials. The state of New York typically uses CLSM for trench excavation fill.

More detailed information on grouts and procedures for grouting sliplined culverts is provided in appendix B-40.

Design considerations - There are a number of design-related factors that should be recognized when considering sliplining. These relate to the hydraulic capacity and the structural strength of the existing culvert, with and without the liner, and the clearance and access for installing the liner. Some agencies design a sliplined culvert as if the existing culvert is providing no additional structural support.

<u>Hydraulics</u> - One of the biggest functional concerns about sliplining culverts is the loss in hydraulic capacity because of the reduction in the cross-sectional area taken up by the liner. Although the area is reduced, the influence of a size reduction is dependent upon (1) the change of usable cross-sectional area, (2) the roughness of the existing culvert and the roughness of the liner and (3) whether the inlet characteristics may be improved to enhance the flow of water and maintain or reduce the existing headwater depth. The tolerance for a reduction in cross sectional area is dependent upon whether the existing culvert was initially over-designed or oversized and the current and future hydraulic requirements. Many culverts are oversized to allow for an increase in future flow requirements, to minimize problems with debris buildup, or because of certain economic factors at the time of construction.

It is well recognized that the hydraulic capacity of culverts is a function of the roughness of the barrel. Each of the existing types of culvert sections have a characteristic roughness including those of corrugated steel, stone masonry, and reinforced concrete. Similarly, liners also may be made of plain or reinforced plastic, which may have a very smooth surface that will reduce friction losses through the culvert. Culverts also are made in a variety of shapes including boxes, which are not as hydraulically as efficient as circular or elliptical shapes. Thus, sliplining with a hydraulically efficient shape may not reduce the hydraulic capacity of the existing culvert.

The hydraulic capacity of a culvert is also a function of the inlet design and construction features. Depending upon the circumstances, it may even be possible to increase the hydraulic capacity of existing culverts during the time of sliplining with the addition of a headwall and wingwalls.

Clearance - An additional concern when sliplining is the amount of clearance that must be provided between the inside of the existing culvert and the outside of the liner. The overall approach is usually to match the existing culvert shape and to install as large a section as possible to minimize the reduction in cross-sectional area of the existing culvert. Three major factors that affect the decision on the final size of the liner are (1) the actual internal shape and alignment of the existing culvert, (2) the amount of clearance that is needed by the contractor for the sliplining operation, and (3) the space needed for grout flow. The actual internal shape and alignment of the existing culvert can be a major factor in selecting and sizing the liner, particularly if the existing culvert is of corrugated steel or aluminum. Corrugated metal culverts are termed "flexible" culverts. They may be moderately or severely distorted because of variations in the surrounding soil pressures to the point that the largest liner that may be inserted into it is considerably smaller than the existing culvert. Similarly, disjointed or misaligned precast concrete pipe may also reduce the effective area of a culvert. It should also be recognized that it is not sufficient to determine the size and shape of the inlet and outlet ends but to consider the dimensions along the length of the existing culvert barrel, both on a section basis and a length-of-the-culvert basis. That is, is the longitudinal alignment constant or changing. When determining the available clearance, the need for a paved "sidewalk" invert in the existing culvert to facilitate sliding in the liner sections should also be considered. Thus, the reduction in cross-sectional area caused by lining the culvert is a function of how closely the interior surface of the existing culvert can be matched with the outside surface of the liner. For medium sized culverts, 36 inches to 72 inches, it is not unusual to have a 6 inch minimum clearance.

Structural - Consideration of the structural design and adequacy of the existing culvert to be sliplined is a major factor in selecting the allowable types of slipliners. If the existing culvert has a serious structural problem, then the liner must provide sufficient strength to support the overhead embankment and the projected traffic. The basic differences in the design philosophy for rigid and flexible types of culverts must be recognized, both for the existing culvert and for the liner. If there are existing structural problems, the cause of those problems should be determined and considered when selecting the liner type. It is not sufficient to merely correct the symptoms, but rather the soil-structure interaction problem must be recognized and corrected. Thus, if the existing culvert is of the flexible type and uneven support and soil pressures are causing deformation, then the liner may have to be of the rigid type. Conversely, if the existing culvert is rigid and there are no significant structural problems, then the liner may be either flexible or rigid. The solution to the problem may also require the proper selection of the grout to be used between the existing culvert and the liner. A higher strength grout than 100 psi may be necessary.

Access - The amount of working space inside of the existing culvert and also inside the liner is of concern from the standpoint of the contractor and the need for proper installation and alignment of the liner. This may be particularly critical for smaller size culverts and liners that will limit the amount or space for workmen to operate. The lack of working room will, in turn, limit the options for liners and the manner in which they are installed. Similarly, the amount of available space will influence the options for type and size of equipment that may be used for the sliplining operation. However, it has been found that some contractors are quite innovative with regard to the methods and equipment that may be used for sliplining. Nonetheless, access related questions and problems should be taken into account when considering and planning a sliplining operation.

Inversion Lining

Inversion lining is a process by which a culvert is lined with a resin-impregnated polyester felt tube that provides a continuous lining of the existing culvert. The felt liner is impregnated with thermosetting polyester resin and the interior surface is coated with a layer of polyurethane provide corrosion and abrasion resistance and some reduction in roughness for increased hydraulic efficiency. The thermosetting resin is cured in place by the heating and recirculation of the water that is used in the inversion of the polyester felt tube. The continuous lining eliminates problems due to both exfiltration and infiltration of water that may have been passing through the walls and joints of the existing culvert. Depending on the thickness of the liner and the type of resin used, some structural strength may be provided to enhance the strength of the existing culvert.

The process may be used with all types of culvert materials including the following: brick, concrete, corrugated metal, stone masonry, terra cotta, and timber. It provides a close fitting liner for all shapes including: round, oval, trapezoidal, elliptical and arched in sizes from 6 inches to over 72 inches. A particular advantage of this type of liner is that it will bridge all joints and irregularities in the interior surface of the existing culvert. Because of its initial flexibility, the liner will conform to barrels that are longitudinally curved or sections that are displaced, with open joints between them.

The liner is custom-made to the exact diameter, thickness, and length of the culvert to be lined. The liner may be pre-impregnated with the thermosetting polyester and polyurethane resins and shipped to the jobsite in a refrigerated truck or it may be impregnated at the jobsite. The latter method is frequently used when the culvert is long and over 48 inches in diameter, because of the weight of the resin-saturated liner and difficulty in handling it in the uncured state. Precautions must be exercised that the impregnated liner is kept cold until the culvert is properly prepared and the lining operation can proceed without stop.

Consideration should be given to the requirement for sufficient water to invert the liner and to completely fill the culvert. If the culvert is in a municipal area it may be filled with water from a fire hydrant. In rural areas it may be necessary to truck water to the site.

Procedure - The following describes the steps that are involved with the inversion lining process. The process takes a four-person crew approximately one day to line a culvert.

Cleaning and inspection - The existing culvert must be blocked off and cleaned of debris. The cleaning operation is often done with a high velocity water jet; however, major amounts of debris may need to be removed with a dragline bucket. Small diameter culverts may be cleaned with a rotary cleaner. Following cleaning, the culvert should be inspected to identify unanticipated problems that must be corrected prior to continuation of the inversion lining process. One somewhat unusual aspect of this process is that frequently a videotape is made of the culvert after it is cleaned.

Preparation work - It may be necessary to do some repair or preparation work on the culvert prior to initiation of the inversion lining process, particularly to correct the following problems:

- Loose or missing plates of corrugated metal culverts may have to be secured or replaced.
- Severely eroded or missing inverts with large voids in the soil may have to be filled with either rock or concrete.
- Culverts with a bituminous coating will have to be lined with a plastic barrier that will prevent chemical interaction with the liner resins. The culvert may be lined with a thin polyethylene preliner tube or coated with an epoxy paint. When a plastic tube is used it is often inflated with a large capacity fan so that the liner can be inverted within it. For larger size culverts it may be more feasible to use an epoxy paint, provided that the culvert can be dried and cleaned before application of the paint.

Equipment setup - This process involves the setup of an inversion tube and the boiler heat exchanger and its suction and discharge lines. The vertical inversion tube is needed to create the hydraulic head for water to invert the lining and to completely fill the culvert. It is set up by attaching it to a tower of construction scaffolding. The tower height will vary with the diameter and depth of the culvert below grade, as well as the thickness of the liner. The inversion head may vary from a maximum of 38 feet for a 6 millimeter thick, 8 inch diameter liner to as little as 12 feet on a 9 millimeter, thick 24 inch diameter liner.

The upper end of the tube is attached to a metal ring on the scaffold and the lower end is attached to a metal 1/4 round "elbow" pipe section. The liner is subsequently attached to this elbow for the inversion process. If there is a clearance problem, it may be necessary to eliminate the conventional inversion tube and, instead, attach the inversion liner directly to the ring on the scaffold platform. This will require additional expense for the additional liner material.

Inversion - The liner is inserted into the inversion tube with the polyurethane side out. The end of the liner is then turned inside out and clamped to the outside of the bottom of the inversion tube. This places the resin side of the lining against the inside of the culvert. After the liner is clamped and the bottom of the inversion tube is positioned in the damaged culvert, cold water is pumped into the top of the inversion tube. As water is added the static pressure created by the tall inversion tube causes the liner to turn inside out and move through the culvert, conforming to the shape of the culvert. The rate at which the liner moves through the culvert is controlled by the static pressure head and by a rope that is attached to the trailing end of the pre-measured liner. A perforated hot water tube is also attached to the trailing end of the liner.

Curing - Once the liner has been fully extended through the culvert, the cold water inside the liner is skimmed off at the top of the inversion tube, recirculated through a truck mounted boiler-heat exchanger, heated, and pumped deep into the pipe through the perforated hot water tube. The 150° to 200F° water causes the thermosetting polyester and polyurethane resins to cure and harden and become permanently set against the inside of the culvert. The water temperature is monitored throughout the curing process by wire thermocouples that are inserted in the ends of the culvert. It should be recognized that the heat-sink characteristics of the culvert and the ground can vary greatly and cause differences between the temperatures of the recirculating water and the liner bag outer surface. Thus, the temperature of the circulating water should not be used as the only criteria for determining the extent to which the curing process has proceeded. After the resin has cured, the hot water is slowly cooled down and drained through a small hole that is cut in the outlet end of the liner. As a safety measure personnel should not be allowed downstream of the culvert, particularly during the curing period.

Cutting ends - After the curing water is drained, the protruding stiffened ends of the liner are cut off with a carbide tipped rotary saw and work on the ends of the culvert is completed.

Reinspection - The final step in the process is to reinspect the culvert to ensure that the liner has been properly installed. Problems that are detected should be corrected at that time. It is also not uncommon for the contractor to: (1) make a videotape of the final installation and (2) make special specimens or take samples of the completed work for subsequent testing and acceptance of the work. This may include lining of an additional short length of culvert material that is then removed so that measurements can be taken and testing can be done. Core samples may be taken from the barrel of the culvert for measurement of the lining thickness.

Materials and products - The base material for the inversion liner is a densely needled polyester fiber felt. The liner bag is made by sewing together 1/8 inch thick layers of felt to provide the desired thickness. The thickness may vary from 1/8 to 3/4 inch in the prelining state. The primary function of the felt is to act as a medium to hold the resin prior to curing.

The polyester felt liner may be pre-impregnated with the polyester resin and shipped to the jobsite in a refrigerated condition, or the liner and the resins may be shipped separated in an uncombined state. The latter practice is commonly used for large diameter liners.

Design Considerations - There are a number of design-related factors that should be recognized when considering rehabilitating culverts by the inversion lining process. These relate to the functional hydraulic capacity and the structural strength and condition of the existing line, with and without the liner, and access for installing the inversion liner.

Hydraulics - The inversion process provides a lining that closely conforms to the inside of the existing culvert. Because it is less than an inch thick and it has a smooth polyurethane resin coating on the inner surface, the lining will normally not reduce the hydraulic capacity of the existing culvert, and it may even be increased somewhat for larger diameter culverts.

Structural - For certain situations, with properly selected resins and thickness the inversion lining may provide some additional strength to the existing culvert. However, if the existing culvert is deformed from its original shape and/or adequate soil restraint is not provided, the inversion liner will not increase the strength of such culverts.

Access - The primary concern is to provide sufficient access for proper cleaning of the existing culvert and inspection before and after the inversion lining process. There must also be sufficient space at one of the ends of the culvert to set up the construction scaffolding and the inversion tube.

Cement Mortar Lining

Cement mortar lining is a concept that is routinely used to line water mains and other types of commercial and public pipelines, and recently it has also been used to line some culverts for repair and to provide corrosion protection. These methods have been used to line cast iron, steel, concrete, brick, and smooth and corrugated steel pipelines in sizes from 4 inches to 22 feet in diameter. Benefits of the process include elimination of leakage, reduced surface roughness and improved flow capacity, and improved corrosion resistance. One of the reasons it is used for new steel pipelines is that the corrosion protection liner may be installed after the pipe sections are assembled, thereby reducing the need to ship and assemble heavy pipe sections with a pre-installed cement mortar liner. This rationale could also apply to metal culverts.

Thus, cement mortar lining may be used to protect, repair, and rehabilitate culverts. The lining provides a relatively smooth interior surface layer that spans joints and repairs damaged or corroded inverts. Within limits, the process will also fill voids under eroded inverts and open joints between segments of a culvert. It should be noted, however, that the success and benefit of this process for culvert repair is questioned by some highway agencies. Some agencies have found that the liner does not bond to the existing culvert and there have been problems of cracking and loss of function as the liner may crack and separate from the existing culvert periphery. The likelihood of problems will depend upon many factors including: the types and degrees of distress, the choice of materials and methods, and the quality of workmanship.

The cement mortar lining may be applied with mechanized equipment or pneumatically by the shotcrete technique. Both methods use a cement mortar that is quite dry (it has a very low water/cement ratio) so that it will remain on vertical and overhead surfaces without sagging or sloughing. The dry mix type of shotcrete is called "gunite." The mechanized process involves applying a layer of cement mortar against the inside periphery of the pipe with equipment that has either a rotating spray head or rotating trowels. The gunite method involves a workman spraying the mortar against the inside surface with compressed air and then finishing the surface by hand. There is a minimum size for using the gunite method, which is in the range of 5 foot diameter.

Procedure - The process of cement mortar lining a culvert involves the following steps, which must be undertaken with diligence, to ensure the best possible durability and benefits of the lining:

<u>Cleaning and inspection</u> - A requirement for cement mortar lining is that the existing culvert must be completely cleaned and dry before it is lined. All dirt, tubercles, scale, loose or deteriorated remnants of old lining materials, and all other foreign materials must be removed prior to lining. For some culverts the cleaning

process may only involve flushing with high pressure water or waterjet. However, more aggressive cleaning is normally required. Several companies that have developed mechanized equipment for this lining process have also developed special rotary equipment for cleaning small diameter pipelines and culverts. This type cleaning equipment has several steel scraper elements that rotate around the culvert to remove loose and unwanted materials. Larger diameter culverts will normally be cleaned by workmen with hand tools.

Prior to initiation of the lining process it may also be necessary to do some other preparation work, such as spot patching or repairs needed to restore or maintain structural integrity and to fill large voids under deteriorated inverts. The culvert should then be inspected to ensure that it is ready for application of the cement mortar lining.

Equipment setup - The equipment setups basically include equipment for mixing the mortar, a method for transporting the mortar to the culvert, and a machine that applies the mortar to the inside surface of the pipeline or culvert. For the smaller lines the mortar is mixed and pumped to the application head. For larger lines the mortar may either be pumped to the machine or it may be dumped and transported to the machine in a wheeled buggy.

It should be noted that neither of these types of equipment are small, and a certain amount of space is required for staging and equipment setup on one or both ends of the culvert. Depending on the specific site, it may be necessary to acquire a temporary easement and possibly even necessary to excavate adjacent land to provide adequate space for setup and deployment of the equipment.

Lining operation - The mortar lining method used for culverts should be a continuous process that does not be stop until the entire culvert has been lined. For lines up to 36 inches in diameter the mortar is applied by a spinning spray-type head that centrifugally casts the mortar against the inside wall of the culvert. The distribution head is pulled through the line by a cable and winch system. After it is applied, the mortar is compacted and its surface is smoothed by a special flexible conical-shaped trowel that is pulled through the line with the mortar placement machine. Larger diameter, or size, culverts are lined with a larger machine that places, compacts, and smoothes the mortar with two or more rotating trowels or by the gunite method.

Inspection - Following completion of the process and after the necessary time for curing of the mortar, the lining should be inspected for cracks, loss of bond with the existing culvert, and other types of gross imperfection. The thickness of the lining may be determined by taking small diameter cores at selected locations. For the smaller diameter culverts it may not be feasible for them to be personally inspected by an inspector. For such culverts the inspection may have to be done remotely with a special television camera assembly that is pulled through the culvert on wheels or skids.

Mortar material - The material used for the lining may be a conventional cement/sand mortar or the mortar may contain special admixtures to facilitate placement, minimize drying and shrinkage cracks, and improve durability, including the use of air entrainment for freeze-thaw resistance. A latex-modified mortar is commonly used for some types of work. The water/cement ratio of the mortar mixes is quite low to ensure that it will remain in place around the periphery of the culvert. In addition to having a low water/cement ratio, the cement factor for gunite mortar is quite high, with the result that a very high strength concrete is provided that may have a strength in excess of 10,000 psi.

Design considerations - There are a number of design-related factors that should be recognized when considering rehabilitating culverts with a cement mortar lining. These relate to the functional hydraulic capacity and the structural strength and condition of the existing line, with and without the liner, and access for the equipment needed to install the liner.

Hydraulics - The cement mortar lining process provides a lining that closely conforms to the inside of the existing culvert. Because it is less than an inch thick the lining will normally not reduce the hydraulic capacity of the existing culvert, particularly for the larger diameter culverts. The inside surface of the lining will be somewhat smooth, but it will also tend to conform to the substrait surface profile. However, there is a significant reduction in roughness when this process is used to line a corrugated metal culvert.

Structural - For certain situations a plain cement mortar lining may provide some increase in strength for the culvert; however, it primarily fills voids and provides improved durability and protection against corrosion. On the other hand, the gunite method allows the option of creating a structural reinforced concrete/mortar lining. For such cases steel mesh or reinforcing bars are installed on the inside surface of the culvert before placement of the gunite lining. Such linings that must carry loads should be designed by a structural engineer.

Access - A primary concern for mortar lining is for proper cleaning of the existing culvert and inspection before and after the inversion lining process. There must also be sufficient space on or adjacent to the roadway above the culvert for setting up the mortar mixing equipment and setup of the lining equipment at one end or both ends of the culvert.

Other Techniques

In addition to the above commonly used techniques for general repair of culvert barrels there are a few concepts that are routinely used for repair and restoration of utility pipelines that may have application for culverts. The following are two such concepts:

LINK-PIPE™ - Link Pipe Technologies of Ontario, Canada, has developed two different types of systems that may be used to repair certain types of culvert problems. Both systems are normally used to repair relatively short sections of long culverts or pipelines that are otherwise in reasonably good condition, although two or more sections of these liners may be installed adjacent to each other. They are particularly applicable for localized problems such as localized cracking, distortion and infiltration and exfiltration. They may be installed without excavation and normally without dewatering. Both systems are available in the United States.

XPANDIT™ - It may be possible and economically feasible to replace small diameter vitrified clay and unreinforced concrete culverts by the XPANDIT™ trenchless construction method that has been developed by the Miller Pipeline Corporation. Although it is a proprietary system, it does provide unique features that may warrant its use for some types of culverts.

The method involves the use of a special head unit that is pulled through the pipeline and successively expanded and retracted (by hydraulic jacks) to break the existing line and push it radially outward into the surrounding soil. The pipeline is immediately relined with a high density polyethylene pipe that is pulled into the pipeline behind the XPANDIT™ head. At the present time this method is limited to a maximum size of about 12 inch diameter lines. The sections of the polyethylene pipe may be connected together by either planing and butt-fusing the mating ends or with a proprietary matching milled groove joint that snaps together. To ensure a watertight connection an "o-ring" seal is built into the joint.

SikaRobot® - The Swiss company has developed a robotic type of equipment that may be used to inspect and repair inaccessible sections of 6 to 32 inch (150 to 800 mm) pipelines and culverts.[7] For sewer inspection and repair the robot is inserted into the line at a manhole. It is controlled by an operator who watches a television monitor and controls the robot from a control panel that is connected to the robot by a multiple-hose cable. A 20,000 rpm pneumatic motor powers the robot and its tools. Pneumatic cutters and grinders attach to the robot's tool holder, to do a variety of types of cleaning and preparation work for subsequent repair work. One of the important elements of the system is a small, shock-resistant television camera, that permits the operator to see and record the condition of the pipeline.

The process of repairing cracks starts with grinding and cleaning the damaged area. The operator controls the robot as it thoroughly mills the damaged area with a diamond studded grinding tool. After the surface is prepared the robot is removed from the pipeline, so that the grinding tool may be replaced with a grout injection shoe. The robot is then re-inserted into the pipeline and moved to the location of the crack. An epoxy grout is then applied to the crack area and smoothed by the grout shoe. Information on this equipment is available from the Aquatech company, whose address is provided in appendix D.

Field Manufactured Liner - The Montana company is currently developing a process for field manufacturing and installing a fiberglass, polyurethane or other type of liner in pipelines and culverts.[8] The process involves use of a specially made machine to mix and spray a plastic resin onto the liner that is wet wrapped around an inflatable bladder that is pulled into the pipe or culvert. The bladder is then inflated to press the liner against the pipe or culvert until the resin cures. Multiple layers of the liner may be installed to build up the thickness and the strength of the liner. Information on this process is available from the Innovative Process Corporation whose address is provided in appendix D.

REPAIRS TO OTHER BARREL MATERIALS

The preceding portion of this chapter dealt with repairs to the more common types of culverts that are made with modern construction materials. Although they are now quite rare, there are culverts still in existence that are made with less modern materials, notably stone masonry, vitrified clay and timber. There are also some culverts that are made with plastic pipe. The following will provide some guidance on repair of these latter types of culverts.

Masonry

Stone masonry culverts are probably the oldest form of construction that may still be found. The fact that they are still in existence, in itself, tells the story that they are quite durable, particularly the stones themselves. The primary problem is often that such culverts are not well maintained and over the years moisture and freeze-thaw action causes degradation and loss of the cement based mortar that holds the stone together. Continued loss of mortar from around the stones can lead to loss of the stones themselves. This then permits unrestrained exfiltration and infiltration of water and soil through the walls of the culvert. Procedures for repair of stone masonry is provided in appendix B-41. Other procedures provided in appendix B may also be considered for additional types of repair and/or protection of masonry culverts. For example, such culverts may readily be sliplined, or even mortar lined.

Vitrified Clay

Vitrified clay (or Terra Cotta) pipe culverts are generally rare, and of small size. Because they are small and made of a brittle clay-based material it is difficult, and generally not cost effective, to repair them. One of the most viable ways to "repair" them is to use the XPANDIT™ system to enlarge them (by radial expansion) and line them with a high density polyethylene pipe, that is pulled into the pipeline behind the XPANDIT™ head.

Another aspect of the problem of deteriorating vitrified clay culverts is that they may have been installed, even in modern times, because of their unique durability against aggressive chemicals. If this is the case, the above procedure may still be the most viable, or to simply slipline them without using the XPANDIT™ equipment.

Wood

There are still a number of wooden culverts in service and the State of Ohio is building more in areas with highly corrosive runoff. Wood, particularly treated wood, is an excellent construction material that will last many years. Appendix B-10 provides information on repair of timber structures.

Cast Iron

In years past cast iron pipe was sometimes used for culverts, because they were available in modular sections and the material has good resistance to corrosion. However, as with vitrified clay, cast iron culverts are generally small and difficult to repair. They crack more easily than steel and they are not weldable. One of the most viable procedures for "repairing" cast iron culverts may be to break them up and line them with the XPANDIT™ system equipment. This will line them with a plastic pipe that has at least the same diameter, and less friction loss. Larger size cast iron pipe culverts may also be sliplined.

Plastic

Plastic pipe culverts are a new form of culvert that are used primarily in small sizes. Because of their size, and material, it is difficult to repair them. Options for "repair" would be to slipline them or to excavate and replace them.

Larger size plain pipes are now frequently used to slipline almost all types of culverts that are exhibiting many types of distress. The size of such plastic liners may be as large as 120 inches in diameter. Since their use is quite new, there is very little information available on their durability, their forms of damage or deterioration, and particularly, how they may be repaired. Depending upon the type and severity of damage or distress of large diameter plastic culvert liners, it may be possible to make some repairs, or they may have to be sliplined to provide an integral interior lining.

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CHAPTER 7. CULVERT REPAIR OR REPLACEMENT

SCOPE

Under some circumstances it may not be possible or practical to repair a deteriorated culvert. Replacement may be required. This chapter presents factors to consider when making the decision whether to repair or replace. These factors should also be considered when deciding between repair alternatives. This is especially true of larger, more significant culverts. The chapter also discusses the analysis of maintenance, repair, and rehabilitation options.

GENERAL

There are literally thousands of culverts in use today that are showing signs of wear. While some types of deterioration may not, for the present, endanger the traveling public or affect the capacity of the culvert to perform, many of these culverts may need to be either repaired or replaced.

REPAIR VERSUS REPLACEMENT

The rehabilitation or replacement of a culvert, particularly a large one, can be an item of great significance in the budget of a local agency. County or state agencies, which are responsible for the construction and maintenance of many culverts, can be faced with enormous costs, especially as culverts in place begin to reach their life expectancy.

It is, therefore, important that all pertinent facts are considered and evaluated before decisions are made as to whether to rehabilitate, repair, or replace and how the work is to be performed. The development of available alternatives should include consideration of the following elements:

- The condition of the existing culvert and its suitability for rehabilitation;
- The current and future needs of the area served by the culvert;
- The capacity, alignment, and other characteristics of the culvert to meet present and anticipated needs;
- The cost of repair versus the cost of replacement;
- Site conditions;

- Effluent characteristics;
- Other considerations:

  - Life-cycle costs;

  - Funding availability;

  - Availability and expertise of in-house forces;

  - Availability and expertise of local contractors;

  - Availability and cost of materials and specialized equipment;

  - User costs or time out of service; and

  - Aesthetics.

Condition of Existing Structures

The first step in the process to determine whether a culvert should be replaced or rehabilitated is a thorough inspection and evaluation of the existing structure. The inspection should be conducted in a systematic, organized manner. This will enable the culvert inspector to detect and identify common types of culvert distress or deficiencies, and analyze the severity and significance of defects found. Additionally the streambed and approach roadway should be reviewed.

Whereas bridges with spans over 20 feet in length are inspected on a two-year cycle in accordance with the National Bridge Inspection Standards (NBIS), no such requirement governs the inspection of culverts (those with spans under 20 feet in length). However, the Federal Highway Administration has published the *Culvert Inspection Manual*[1] as a supplement to the *Bridge Inspector's Training Manual*. This manual details inspection procedures for each type of culvert. It also contains a form, modified from the Structure Inventory and Appraisal Sheet (SI&A), for the inspection of culverts. This form is shown in figure 7.1.

Ideally, all culverts should be inventoried and their condition assessed at regular intervals. Small culverts may not warrant the same rigorous level of inspection as large culverts. The types and amount of condition information gathered should be based on the purposes for which it will be used.

LOCATION

County______________ Division______________ District______________

On Route______________ at Milepost______________ or Miles From______________

IDENTIFICATION	TYPE OF CULVERT	BARRELS
Culvert No.__________	Shape__________	Size__________
Over__________	Material__________	Number__________

CONDITION

	Condition Rating	Remarks	
61 Channel & Channel Protection			
Channel Scour	[ ]		
Embankment Erosion	[ ]		
Drift	[ ]		
Silt	[ ]		
Vegetation	[ ]	General Rating	[ ]
62 Culvert & Retaining Walls			
Barrel	[ ]		
Headwall	[ ]		
Wingwall	[ ]		
Settlement	[ ]		
Adequacy of Cover	[ ]	General Rating	[ ]
63 Estimated Remaining Life			
Inspectors Appraisal of Structural Condition (years)			[ ]
65 Roadway			
Shoulders	[ ]		
Embankment	[ ]		
Pavement	[ ]	General Rating	[ ]
71 APPRAISAL Waterway Adequacy			
Opening	[ ]		
Alignment	[ ]		
Scour	[ ]	General Rating	[ ]
72 Roadway Alignment			
Appraisors Estimate of General Rating			[ ]

Recommendations and Miscellaneous Comments

Figure 7.1. Culvert inspection report.[1]

Table 7.1 shows the kinds of information that generally should be reviewed for each type of culvert. When considering the advantages of repair versus replacement, the information gathered during the inspection can assist in determining the remaining service life of the culvert as well as its suitability for rehabilitation, especially if the results of inspections have been recorded over several years.

Remaining service life - The information gathered as a result of a consistent culvert inspection program, such as that described in the *Culvert Inspection Manual*, is an excellent basis for determining the condition of the culvert. Item 63 of the suggested inspection form shown in figure 7.1 is to record the remaining service life of the culvert.

The remaining service life of the culvert is the estimated remaining life in years based on related and appropriate factors, such as the type of material from which the culvert is constructed and its condition, projected traffic volumes, and the age of the structure. The estimate, which should be made using the best judgement of a knowledgeable individual, should reflect the remaining life without major rehabilitation.

Another method of predicting the remaining service life is to gather information on culverts under comparable conditions installed at various times by plotting the condition of these culverts over time. A curve of age versus condition can be developed that can be of used in predicting the years left for a particular type of culvert under similar circumstances.

Service life of a culvert, however, should be considered in terms of the overall requirements of the roadway of which it is an integral part. If the highway is to be rebuilt in a relatively short time, a culvert with a shorter remaining service life may be tolerable. There is no need to pay for extended service life for a replacement or rehabilitated culvert if general maintenance procedures would extend the life of the culvert to be equal to the projected service life of the road.

Suitability for rehabilitation - A number of factors need to be considered to determine whether the culvert can be repaired or rehabilitated. Rehabilitation, rather than replacement, should be considered if a combination of the following circumstances exist:

- The culvert is under a roadway that carries a large amount of traffic and interruption would represent substantial costs to users in terms of delay and additional fuel costs;
- The culvert is under an excessive amount of fill;
- The barrel, even if lined, is hydraulically adequate to carry projected flow;

Table 7.1. Information to be reviewed for each type of culvert.

	ALIGNMENT	SCOUR	OBSTRUCTION	OPENING	GEN. CONDITION	SHAPES: GENERAL SHAPE	SHAPES: TOP ARC-MID ORD.	SHAPES: HORIZONTAL SPAN	SHAPES: RISE	SHAPES: SIDES	SHAPES: BOTTOM ARC	SEAMS OR JOINTS	FOOTINGS	METAL	CONCRETE	MASONRY	MORTAR
Channel & Channel Protection	●	●	●														
Waterway Adequacy	●	●		●													
CMP-Round & Vertically Elongated					●	●		●				●		●			
CM Pipe Arch					●	●		●				●		●			
Structural Plate Arch					●	●			●			●	●	●			
CM Box Culvert					●	●	●	●		●		●	●	●			
Low-Profile Arch - Long Span					●	●	●	●				●	●	●			
High-Profile Arch - Long Span					●	●	●	●		●		●	●	●			
Pear-Shaped Long Span					●	●	●	●		●		●		●			
Horizontal Ellipse Long Span					●	●	●	●			●	●	●	●			
Precast Concrete Pipe					●							●			●		
Cast-In-place Concrete Pipe					●							●	●		●		
Masonry					●								●			●	●

- Concrete endwalls and wingwalls are basically sound and any deterioration in the concrete is related to factors other than lack of air or bad aggregate and is not progressive;

- The existing culvert is structurally adequate to carry traffic volumes and types of traffic projected; or

- The present alignment of the culvert does not cause irreparable scour and erosion or excessive lowering of the streambed.

In addition, consideration should be given to the timing of any expected major rehabilitation of the roadway. If there are plans to change the vertical or horizontal realignment of a roadway or if major rehabilitation or reconstruction of the roadway is being considered, rehabilitation or construction of the culvert should be coordinated with these plans.

Current and Future Requirements

A culvert rehabilitation or reconstruction project should be conceived and designed to meet the needs of the area in which it is to be constructed. Culvert projects of any type can be costly and the maximum benefits must be attained from the funds expended. A completed project that becomes obsolete in five years because it should have been constructed to higher standards is a costly error. A complicated project that is far more elaborate than required can also be expensive, although it is better, as a general rule, to err on the side of over-design and construct a project to higher than minimum standards. Traffic volumes and loads are more likely to be higher than expected rather than lower. Hydrologic requirements generally increase with future development rather than decrease. Additionally, structures are often required to serve beyond their originally conceived design life.

Traffic - Establishing the amount of traffic presently passing over the culvert is important to determine the inconvenience to the traveling public should this section of roadway be taken out of service if the culvert is replaced. In addition, the volume and type of future traffic may affect the structural characteristics of the structure.

If truck traffic is expected to increase, the structure may need to be rehabilitated to provide for the heavier loads. Since culverts are usually covered by embankment material, they must be designed to support the dead load of the soil over the culvert as well as the live loads of the traffic. Either live loads or dead loads may be the most significant load element, depending on the type of culvert, type and thickness of cover, and the amount of live load. Live loads are generally not as significant as dead loads except where the cover is shallow. For example, live loads are important on box culverts with shallow cover.

Safety considerations - The minimum width of the roadway or the proximity of the endwalls to the edge of the pavement may also influence whether the structure should be modified. Guardrails may be used to protect the traffic rather than extending the culvert. In some cases, full-height headwalls can be replaced with half-height headwalls, end sections installed and slopes reduced, or safety grates may be installed. Use of the roadway as a school bus route or the potential for industrial development that will increase heavy truck traffic may also affect the decision.

Hydrologic changes - There are many individual factors that affect storm water runoff, but they are essentially those that affect the runoff coefficient, the intensity of the rainfall, and the size of the drainage area. Local changes in land use as a result of development can greatly affect the amount of runoff that must be handled by a particular drainage structure. The hydrology of a stream changes in response to initial site clearing and grading. The cleared and graded site loses its ability to prevent rainfall from being rapidly converted into runoff. The situation worsens as construction is completed. Rooftops, roads, parking lots, sidewalks, and driveways make much of the site impervious to rainfall. As a result, the capacity of a culvert may not be adequate to handle the flow.

There are many factors that influence the quantity of storm water runoff. Most of these factors, listed below, are subject to change, especially in areas under development:

- Drainage area size, shape, and slope;
- Ground cover;
- Type of soil exposed to surface drainage;
- Antecedent moisture condition;
- Storage or ponding potential; and
- Development potential.

Some local jurisdictions now have development restrictions that require Best Management Practices (BMPs) that dictate that runoff from newly developed areas not exceed the quantity of stormwater runoff produced by the drainage area before development. Detention ponds are sometimes used to detain the excess runoff until it can be routed to the stormsewer system at the rate previous to development.

Alignment - Culvert installations should conform as much as possible to the natural stream in alignment, grade, and width to limit the hydraulic and environmental stress placed on the stream. When the culvert barrel is placed on an alignment and grade that conforms to the existing stream channel, the advantages include reduction of head loss, equal depths of scour at the footings, less sedimentation in multibarrel culverts, and less excavation. The disadvantages are that the inlet may be skewed with respect to the culvert barrel and the culvert will be longer.

Sudden changes in stream flow direction can result in turbulence and erosion of the streambank. When stream meanders are substantially cut off by culvert installations, the slope of the culvert and resulting stream velocities will be greater than the original velocities. Such conditions are conducive to scour at the culvert outlet.

Construction Costs and Economic Analysis

There are several types of maintenance and repair that will extend the service life of culverts. Each of these types has different implications for the cost that must be borne by the agency and the service that will be received by the public. These alternatives should be carefully documented and the costs analyzed so that the best value can be received for the dollar.

Routine maintenance - The objective of routine maintenance is to keep a culvert in a uniformly good and safe condition by repairing specific defects as they occur. Routine maintenance is often reactive as opposed to scheduled. Typical activities may include debris or sediment removal in response to heavy rainfall, thereby preventing flooding of the adjacent roadway or scour or undermining due to increased velocities caused by a decreased culvert cross section. It may also include thawing frozen culverts.

Preventive maintenance - Preventive maintenance is a more extensive strategy than routine maintenance and is intended to arrest light deterioration that has occurred and to prevent progressive deterioration. Preventive maintenance is cyclic in nature and can be scheduled. Typical activities include joint sealing, concrete patching, mortar repair, invert paving, scour prevention, and ditch cleaning and repair. Preventive maintenance does not improve the load-carrying capacity of a culvert but does alleviate conditions that can eventually lead to such conditions as deterioration of joints or inverts, bolt hole tears, or undermining of footings that would affect the structural integrity of the culvert.

Rehabilitation - The strategy of rehabilitation takes maximum advantage of the remaining usable structure in a culvert to build a reconditioned culvert. Rehabilitation is most appropriate for culverts that have deteriorated beyond the point of effective preventive maintenance but have not deteriorated to the point where all structural integrity has been lost. The barrel is still hydraulically adequate in terms of size and the appurtenant structures remain basically sound. This means that the deterioration in the concrete is related to something other than lack of air or bad aggregate and is not progressive. Rehabilitation may include repair of basically sound endwalls and wingwalls, invert paving, repair of scour, slope stabilization, streambed paving, addition of an apron or cut-off wall, improving the inlet configuration to enhance culvert performance, or installing debris collectors.

Upgrade to equal replacement - Upgrading to equal replacement means that once upgraded, the structure will provide service that is equal to that provided by a new structure. The upgraded structure must be hydraulically sufficient to carry the design flow, based on climatic and current watershed characteristics. The upgraded installation should be structurally adequate. Culvert material used to upgrade the barrel should be chosen to provide longevity and protect against abrasion and corrosion as required. Upgrading may include such procedures as the addition, repair, or replacement of appurtenant structures; lining of the barrel; or providing safety improvements such as safety grates or safety barriers. It may include lengthening of the culvert.

Replacement - When the culvert condition has deteriorated to the point that there is very little structural value left, the pavement over the culvert has deteriorated, or the alignment of the present culvert is causing insurmountable problems with scour and erosion of the streambed, the culvert may need to be replaced in its entirety. Reconstruction projects may be accompanied by realignment of the culvert, traffic control, and hydraulic and safety improvements. It may require the placement of a culvert of another shape or material so that the same type of deterioration is not repeated. Replacement projects normally require long lead times because of the expense involved. Replacement of the culvert results in a completely new culvert with a new service life.

Types of work options are shown in tabular form in table 7.2. The decision to chose one of these options over the other should be accompanied by an economic analysis. Economic analysis is a decision-making tool having two basic applications. First, it provides for an analysis of relative costs in relation to returns (benefits). Second, economic analysis provides a method of evaluating alternatives using a common unit of measurement. It allows independent solutions to be compared for the purpose of aiding in the allocation of resources.

Since public agencies do not have profitability as a primary mission, economic analysis should be used only as a tool. It does not, by itself, determine the final decision. There may be any number of other factors to consider when evaluating alternatives that cannot be quantified in terms of dollars.

Table 7.2. Types of work options for each strategy.

STRATEGY	OBJECTIVE	WORK OPTIONS
Routine Maintenance	To keep a culvert in a uniform and safe condition by repairing specific defects as they occur.	• Debris & sediment removal • Thawing frozen culverts
Preventive Maintenance	A more extensive strategy than routine maintenance intended to arrest light deterioration and prevent progressive deterioration.	• Joint sealing • Concrete patching • Mortar repair • Invert paving • Scour prevention • Ditch cleaning & repair
Rehabilitation	Takes maximum advantage of the remaining unusable structure in a culvert to build a reconditioned culvert.	• Repair of basically sound endwalls & wingwalls • Invert paving • Repair of scour • Slope stabilization • Streambed paving • Addition of apron or cutoff wall • Improving inlet configuration • Installing debris collector
Upgrade to Equal Replacement	Upgrade to provide service that is equal to that provided by a new structure.	• Addition, repair or replacement of appurtenant structures. • Lining of the barrel. • Provision of safety grates or safety barriers • Lengthening of the culvert
Replacement	Provide a completely new culvert with a new service life.	Can be accompanied by: • Realignment • Hydraulic structural and safety improvements • Change in culvert shape or material

There are many factors that enter into the life-time cost of a structure in addition to the initial cost of rehabilitation or replacement. Table 7.3 illustrates the types of factors that might be considered in an economic analysis.

Table 7.3. Economic analysis factors.[2]

Agency Costs	User Costs
Initial capital cost of construction.	Travel time.
Future capital cost of construction or rehabilitation.	Vehicle operation and maintenance.
Future maintenance costs.	Accident costs.
Residual or salvage value at the end of the analysis period (may be a "negative cost").	Discomfort.
Engineering and administrative costs.	Time delay and vehicle cost during construction and maintenance operations.
Cost of investments, or discount rates.	

There are three primary methods of economic analyses that can be helpful in selecting or prioritizing culvert projects: first-cost analysis, life-cycle cost analysis, and benefit-cost analysis. Each of these methods differ in terms of information considered. The life-cycle cost analysis builds upon first-cost analysis and benefit-cost builds upon life-cycle analysis. Table 7.4 illustrates this concept.

Table 7.4. Methods of economic analysis.[2]

Consideration	Method
Initial Costs	First-cost analysis
Future costs, discount rates, and analysis period	Life-cycle cost analysis
User costs	Benefit-cost analysis

First-cost analysis - The most common type of economic analysis is the least sophisticated. This is a first-cost analysis, which normally includes only the initial capital costs. First-cost analyses can be performed on a regular basis when considering routine decisions. When performing first-cost analysis, every effort should be made to include all costs. Administrative costs; design fees; in-house equipment, labor, and materials; and estimated contract costs are all appropriate for a first-cost analysis.

First-cost analyses should not ignore life-cycle costs. Attempts should be made to ensure that alternatives selected for analysis will perform equally. If equal performance is not expected, that fact should be made known to the decision maker as another factor to consider in addition to the first-cost analysis. One approach might be to list all the foreseeable differences in life expectancy, maintenance costs, and future rehabilitation needs, with a discussion on each item. Even though a first-cost analysis does not attempt to place a dollar estimate on the effects current decisions will have on future expenditures, these effects should be made known to a decision maker.

Life-cycle costs - Life-cycle cost analysis considers the costs to the agency throughout the life of the project under consideration. It allows an alternative having different expenditures over its life to be compared with others by converting these costs to their present worth.

The costs of investment, or discount rate, must be used in life-cycle cost analysis to combine future costs with first costs and be restated in terms of today's costs. Economic analysis is independent of how a project is to be financed, by whom, and when. The discount rate is simply a device used to allow present and future costs to be compared.

Primary factors to be considered in a life-cycle cost analysis are:

- Present costs for replacement or rehabilitation;
- Annual maintenance costs;
- Future increases to maintenance costs due to deterioration;
- Future rehabilitation costs;
- Salvage value;
- Analysis period; and
- Discount rate.

The National Corrugated Steel Pipe Association (NCSPA)[3] emphasizes the basic difficulty in making this method of comparing costs work: the assumptions that produce fair comparison of competing products or methodologies must be unbiased. The assumptions that must be made about each alternative are as follows:

- Project design life;
- Length of maintenance-free life;
- Rehabilitation costs;
- Inflation rate;
- Interest rate;
- Discount rate;
- Project residual value, if any, at the end of the design life.

Project design life - The project design life is independent of and not related to the service life of the different alternatives being considered. However, the least cost analysis is affected by the project design. Even though the design life of a product may be 100 years, the use of a 100-year design life is incorrect due to two reasons: design obsolescence and the availability of money. Site conditions change and the functional capacity requirement of the culvert may also change. In addition, in a population that is growing older, a 100-year design life may be difficult to sell to taxpayers. Therefore, both politically and practically, design life is about 50 years.

Length of maintenance-free life - The end of the average service life of a particular culvert does not mean that the culvert must be replaced. However, it does mean that some funds must be spent at that time for maintenance. The life of culverts vary and an objective evaluation must be made for life-cycle analysis to work. Published reports and local experience can assist in estimating a realistic service life.

Rehabilitation costs - The service life of a culvert can be effectively extended with rehabilitation. The NCSPA states that if a culvert is routinely and properly inspected and maintained, rehabilitation costs should be no more than 25% of the original cost of the culvert. This assumes that the culvert is new when the procedure is begun and that funds are always available for proper maintenance.

Inflation - Inflation is a rise in the general price levels, caused usually by an increase in the volume of money and credit relative to available goods.

Interest rate - The interest rate is a ratio of the amount paid for using resources for a given period of time to the total investment. It is a term generally associated with borrowing money.

Discount rate - The discount rate is a value, expressed as a percentage, that is used as the means for comparing the alternate uses for funds by reducing the future expected costs or benefits to present day terms. Discount rates are used to reduce various costs or benefits to their present worth or to uniform annual costs so that the economics of the different alternatives can be compared. An extensive discussion of discount rates can be found in the National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 122: *Life-Cycle Cost Analysis of Pavements.*[5]

According to the research undertaken in NCHRP Synthesis 122, "there is general agreement that the discount rate or real discount rate should be the difference between the market interest rate and inflation rate using constant dollars." The AASHTO Manual on User Benefit Analysis states that "if future benefits and costs are in constant dollars, only the real cost of capital should be represented in the discount rate used. The real cost of capital has been estimated at about 4 percent in recent years for low risk investments." For an explanation of how the results are affected over range of discount rates, refer to the booklet *Life Cycle Cost Analysis: Key Assumptions and Sensitivity of Results* [4], which states that, in general, greater significance is given to future spending at low discount rates, and less significance at high discount rates.

Salvage value - It is unlikely that there will be any salvage value remaining in a culvert that can be counted against the cost of a replacement. Most drainage products are not considered to be salvageable as prime, reusable materials and have little, if any, cash value.

Life-cycle costs can be evaluated in terms of either present worth or annual costs. Either method is equivalent in terms of evaluation alternatives and relative differences in alternatives. The decision to use present worth or annual costs should be based upon ease of calculations and meaningful presentation of results.

Example: Life-Cycle Cost Analysis

This example has been developed to illustrate the use of life-cycle cost analysis to arrive at a comparison of present worth. Assume that two alternatives have been developed for the rehabilitation of a 215 foot section of a 64" x 43" pipe arch that requires providing a new invert throughout the length of the pipe. At this time the pipe is not structurally deficient nor will it be for future traffic conditions. However, the pipe is showing evidence of infiltration at the joints, which must also be repaired.

The engineer has determined that the pipe can either be (1) sliplined or (2) the invert can be paved with a concrete pad of 4 inches, covering 25 percent of the pipe wall periphery and reinforced with wire mesh. For the purpose of this analysis, it is assumed that both solutions will perform satisfactorily for 30 years.

Either of these alternatives will provide adequate hydraulic capacity. Since the streambed is generally low or dry, no dewatering process will be required.

The sliplining procedure can be performed with in-house forces for $87 per linear foot for pipe, sliplining and grouting or $18,705. Yearly maintenance will be $100 per year for the first 20 years and $300 per year for the last 10 years. The sliplined culvert will have a life expectancy of 30 years.

The concrete invert can be placed by in-house forces at a cost per linear foot of $28 or $6020. Surface preparation of the existing culvert will cost $7 per linear foot or $1505. Joint sealing will be required at a lump sum cost of $5000. It is expected that the concrete invert will require repair every 5 years at $4 per linear foot and must be replaced at the end of 15 years. Joints must also be resealed. Additional maintenance will be $350 per year. (Several repairs, required at different times during the life of the culvert, have been included in this alternative to illustrate how these costs are brought back to present worth.)

Assuming a discount rate of 4%, the alternatives can be evaluated as follows:

<u>Solution</u>:

1. The first step toward obtaining a solution in economic analysis is to construct a cash flow diagram. The cash flow diagram shows all expenditures and the point in time in which they are made. All annual expenditures such as annual maintenance costs are assumed to be end of year payments. The cash flow diagrams for alternative A and B is shown below in figures 7.2 and 7.3:

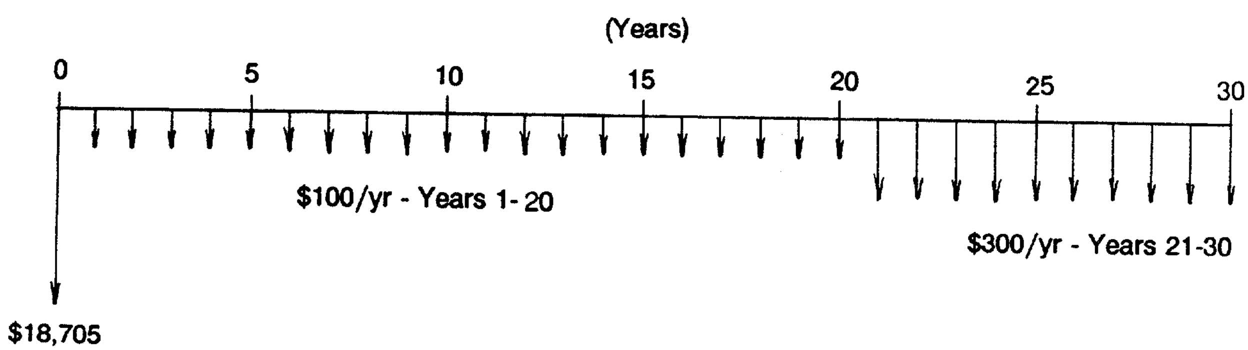


Figure 7.2. Alternative A cash flow diagram.

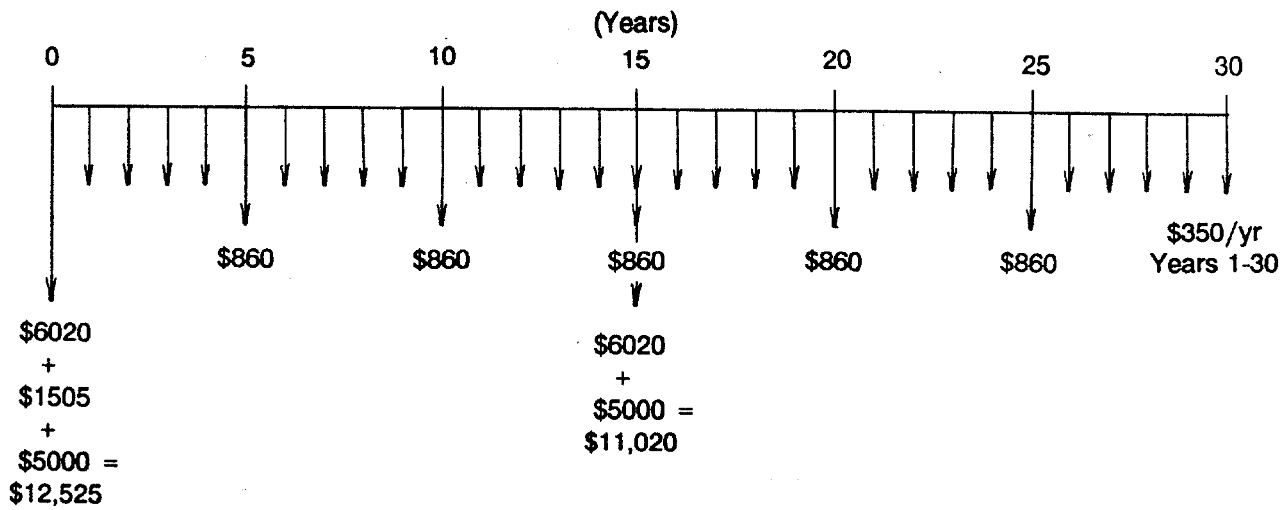


Figure 7.3. Alternative B cash flow diagram.

2. Next all expenditures must be converted to the same type payments at the same point in time. In this example all annual expenditures and future single payments will be converted to single payments at year zero. The sum of these single payments is the present worth and represents the dollar amount that must be invested at the chosen discount rate to pay all estimated expenditures and have zero balance at the end of the analysis period. Engineering economy textbooks contain tables of these factors for particular interest rates. Table 7.5 contains tables for 4 percent discount rate.

3. Calculate the percent worth of Alternative A:

   a. The $18,705 for the sliplining is a single payment at year zero and needs no conversion. Therefore,

      PW_{A1} = $18,705

   b. The $100 maintenance cost in the years 0 through 20 and $300 for years 21 through 30 must be converted to present worth. This is a two-part procedure. To find the present worth of $200 per year over a period of 20 years, multiply the $200/year by the Uniform Series Present Worth Factor for 20 years at 4%:

      PW_{A2} = $100 (13.59033) = $1359

Table 7.5. Four percent (4%) discount rate.

YEAR	SINGLE PAYMENT PRESENT WORTH	UNIFORM SERIES PRESENT WORTH	EQUIVALENT UNIFORM ANNUAL COST
1	0.96154	0.96154	1.04000
2	0.92456	1.88609	0.53020
3	0.88900	2.77509	0.36035
4	0.85480	3.62990	0.27549
5	0.82193	4.45182	0.22463
6	0.79031	5.24214	0.19076
7	0.75992	6.00205	0.16661
8	0.73069	6.73275	0.14853
9	0.70259	7.43533	0.13449
10	0.67556	8.11090	0.12329
11	0.64958	8.76048	0.11415
12	0.62460	9.38507	0.10655
13	0.60057	9.98565	0.10014
14	0.57748	10.56312	0.09467
15	0.55526	11.11839	0.08994
16	0.53391	11.65230	0.08582
17	0.51337	12.16567	0.08220
18	0.49363	12.65930	0.07899
19	0.47464	13.13394	0.07614
20	0.45639	13.59033	0.07358
21	0.43883	14.02916	0.07128
22	0.42196	14.45112	0.06920
23	0.40573	14.85684	0.06731
24	0.39012	15.24696	0.06559
25	0.37512	15.62208	0.06401
26	0.36069	15.98277	0.06257
27	0.34682	16.32959	0.06124
28	0.33348	16.66306	0.06001
29	0.32065	16.98372	0.05888
30	0.30832	17.29203	0.05783
35	0.25342	18.66461	0.05358
40	0.20829	19,79277	0.05052
45	0.17120	20.72004	0.04826
50	0.14071	21.48218	0.04655
55	0.11566	22.10861	0.04523
60	0.09506	22.62349	0.04420

To calculate the present worth of the \$300/year for 10 years, multiply the \$300/year by the Uniform Series Present Worth Factor for 10 years at 4% to convert the value of these payments to a single payment at the end of 20 years; then multiply by the Single Payment Present Worth Factor for 20 years at 4% to get the value of this money at the present time:

$$PW_{A3} = \$300\ (8.11090)\ (.45639) = \$1110$$

c. The present worth of alternative A is the sum of the individual present worth values:

$$PW_{A} = PW_{A1} + PW_{A2} + PW_{A3}$$

$$PW_{A} = \$18705 + \$1359 + \$1110$$

$$PW_{A} = \$21,174$$

The present worth of Alternative B is calculated as follows:

a. The original costs for the invert paving will be \$6020 plus the surface preparation at \$1505, and the joint sealing at \$5000 for a total of \$12,525. Since this cost is a single payment at year zero, it needs no conversion. Therefore,

$$PW_{B1} = \$12,525$$

b. At the end of 15 years, the invert must be replaced at a cost of \$6020 and the joints must be sealed again at a cost of \$5000, a single payment at the end of 15 years. Therefore, multiply the single payment by the Single Present Worth Factor for 4% at the end of 15 years to convert to present worth:

$$PW_{B2} = (\$6020 + \$5000)(0.55526)$$

$$PW_{B2} = \$6119$$

c. The sum of the repairs made at the end of years 5, 10, 20, and 25 is equal to the sum of $860 times the Single Payment Present Worth Factors at the end of years 5, 10, 20, and 25:

$$PW_{B3} = \$860\ (0.82193) + \$860\ (0.67556) + \$860\ (0.45639) + \$860\ (0.37512) =$$

$$PW_{B3} = \$707 + \$581 + \$392 + \$323$$

$$PW_{B3} = \$2003$$

d. The last cost is the present worth of $350/year maintenance for 30 years. This uniform payment made annually for 30 years must be converted to the present worth of a single payment made at year 0. Use the Uniform Series Present Worth Factor for 30 years:

$$PW_{B4} = \$350\ (17.29203) = \$6052$$

e. The present worth of Alternative B is

$$PW_B = PW_{B1} + PW_{B2} + PW_{B3} + PW_{B4}$$

$$PW_B = \$12{,}525 + \$6119 + \$2003 + \$6052$$

$$PW_B = \$26{,}699$$

A comparison of the two alternatives shows that alternative A has the lower present worth and thus is the preferred choice using a discount rate of 4%. The discount rate is mentioned to stress the fact that the preferred alternative is dependent upon the assumed discount rate.

This example has been given because it illustrates how to convert expenditures occurring at several different times during the life of the structure. There are other reasons why alternative A is the best solution. Although the present worth of the two alternatives is close, alternative B requires extensive repairs to extend the life of the culvert to 30 years. It is difficult to project whether other types of deterioration may occur that is not accounted for during this period. However, there are times when the life of a structure can effectively be extended for a shorter period of time until funds for rehabilitation are available.

Example: Life Cycle Cost Analysis - Equivalent Uniform Annual Cost

To accommodate the analysis of structures that have different life expectancies, the results of life cycle cost analysis may also be presented as equivalent uniform annual cost (EUAC). The EUAC is an equal year-end payment for each year of the analysis period that will finance all costs of the alternative. In other words, year-end payments equal to the EUAC and invested at the assumed interest rate will finance the proposed alternative with zero balance at the end of the analysis period.

For example, compare the sliplining procedure, alternative A, to the first 15 years of life of alternative B before the invert has to be paved for the second time. The cash flow diagrams for the two alternatives based on a 30 year life for alternative A and a 15 year life for alternative C are shown below in figures 7.4 and 7.5:

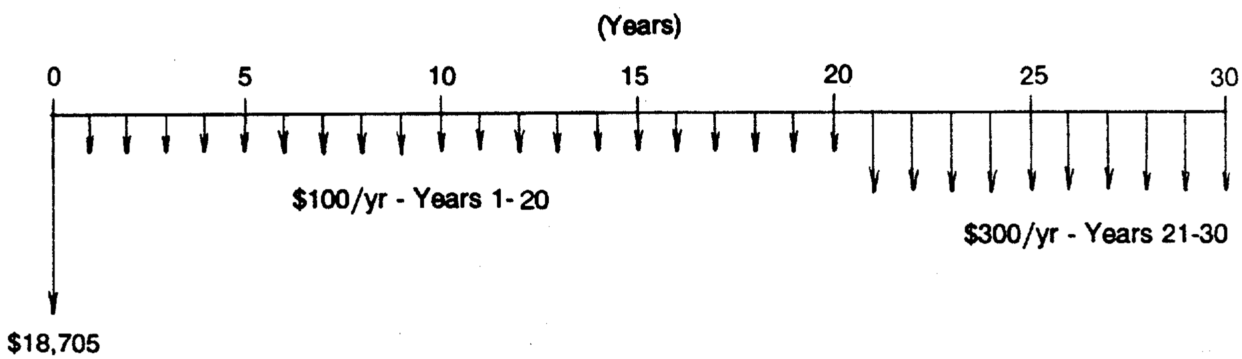


Figure 7.4. Alternative A cash flow diagram.

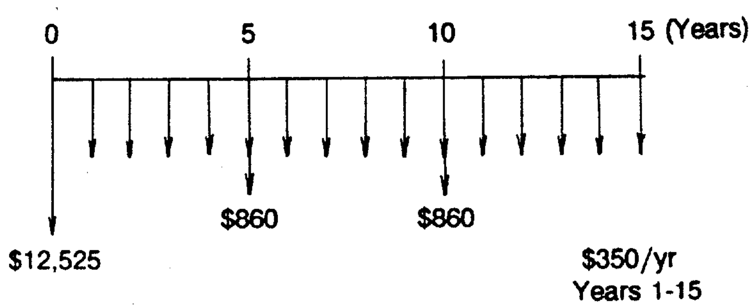


Figure 7.5. Alternative C cash flow diagram.

Solution:

1. Calculate the equivalent uniform annual cost of alternative A:

   a. The $18,705 for the sliplining is to be annualized over a period of 30 years. Therefore, it should be multiplied by the Equivalent Uniform Annual Cost Factor for 30 years at 4% from Table 7.6:

   $EUAC_{A1}$ = $18,705 (0.05783) = $1082 per year for 30 years

   b. One hundred dollars per year will be expended for maintenance for the entire 30 years of the life of alternative A. However, for the last 10 years of the project, maintenance costs will increase by $150 per year.

   $EUAC_{A2}$ = $100 per year for 30 years

   To calculate the yearly cost over a period of 30 years of $150 at 4% for the last 10 years of the life of the culvert:

   - first reduce the additional $150 per year for 10 years to a single payment at the end of 20 years by multiplying it by the Uniform Series Present-Worth Factor for 10 years:

   $EUAC_{A3}$ = $150 (8.11090) = $1217 (single payment at year 20)

   - then convert this amount to a single payment at present worth by multiplying by the Single Payment Present-Worth Factor for 20 years:

     = $1217 (.45639) = $555 (single payment at year 0)

   - then distribute this single payment at year 0 over the 30 year period by multiplying by the Equivalent Uniform Annual Cost Factor for 30 years:

     = $555 (0.05783)

     = $32

   c. $EUAC_A = EUAC_{A1} + EUAC_{A2} + EUAC_{A3}$

      = $1082 + $100 + $32 =

      $EUAC_A$ = $1214 annual cost

2. To calculate the equivalent uniform annual cost for alternative C:

   a. Distribute the initial cost of $12,525 over 15 years by multiplying by the Equivalent Uniform Annual Cost Factor:

      $EUAC_{C1}$ = $12,525 (0.08994) = $1126 per year for 15 years

   b. Reduce both of the $860 repair costs at 5 and 10 years to a single present worth at year zero:

      $EUAC_{C2}$ =$860 (0.82193) + $860 (0.67556)

      = $707 + $581 = $1288

      and distribute over 15 years:

      $EUAC_{C2}$ = $1288 (0.08994) = $116

   c. Add the yearly cost of maintenance: $EUAC_{C3}$ = $350

   d. $EUAC_{C}$ = $EUAC_{C1}$ + $EUAC_{C2}$ + $EUAC_{C3}$

      = $1126 + $116 + $350

      $EUAC_{C}$ = $1592

This method makes the point again that it is more economical in this case to proceed with the rehabilitation and slipline if funds are available.

If, however, costs for joint sealing and the additional repairs at the end of 5 and 10 years were not necessary (i.e., if the culvert needed ONLY invert paving) it would be more economical to only pave the invert. The additional repairs caused by the overall poor condition of the culvert, in addition to the invert perforations, make the alternative too costly. However, if funds are not available to slipline or if this example represents 20 culverts rather than one, the agency may be forced to rehabilitate rather than upgrade to equal replacement, until the money is available.

Benefit-cost analysis - The most complete analysis method is a benefit-cost study that considers changes in user costs as the return or benefit on agency costs. Future user costs are discounted just as agency costs are. A benefit-cost analysis expands the framework of decision-making factors to include all costs to the public, rather than just agency costs.

Benefit-cost can be calculated in two ways. One way to obtain the benefit-cost ratio is simply to divide the sum of the life-cycle benefits by the life-cycle costs. If the ratio is greater than one, the public will realize benefits greater than the cost of the project. A ratio smaller than one indicates a project that will not "pay for itself" in public benefits.

Another approach to benefit-cost analysis is to add or subtract all user costs to/from the agency costs of each alternative to arrive at a total cost. This total cost analysis is helpful when the magnitude of the differences in user costs and agency costs is needed. It can also ease the calculations because usually only the differences in alternatives are needed.

Funding availability - In many instances the amount of funds available to an agency will determine the type of repairs and the amount of work that can be done. When funding dictates the available options, the agency should consider all alternative sources of money. On Federal-aid highways, the possibility of receiving Federal funds for improvement projects can be an additional source of funding. For local agencies, the same may be true of State-aid roads.

In some circumstances, the private sector may be another source. Direct payment of funds is generally not made by developers to public agencies for drainage facility improvements required because of new development. The improvements may be made as a part of the development and discharge to existing storm water facilities usually limited to the amount prior to development.

Other Considerations

There are other practical considerations to be taken into account. These factors are important to both the agency and the user.

Availability and expertise of in-house forces - The selection of a repair or rehabilitation process or alternative could be determined by the ability of the in-house work force to perform the work. Some alternatives require considerable specific experience while others require only a reasonable amount of construction experience. In-house personnel should not be expected to perform work beyond their ability or capacity to perform it in a reasonable amount of time. It may, of course, be possible to supplement in-house personnel with local vendors from the private sector to perform specific functions or tasks.

Availability and expertise of local contractors - The choice of a particular repair or rehabilitation alternative method could conceivably rest partly on the suitability of local contractors to perform the work. If the project is fairly small but beyond the capabilities of in-house personnel, it may be necessary to perform the work under contract. If the contractors must travel a considerable distance to the work site, the cost of the work can become prohibitively high. The process that originally appears the most economical when compared with others may then become the most expensive. Additionally, rehabilitation or repair procedures that can be performed by only one firm because of proprietary rights should generally be used only after careful review and when quantities are large enough to offset the contractor's expense of traveling to the work site.

Availability and cost of materials and specialized equipment - When preparing alternative plans for repair or rehabilitation, a review should be made of the materials that are required for the work. Some materials are very expensive and difficult to obtain in small quantities, particularly if special sizes or types are required. The availability and cost of materials for the project should be investigated before a final decision is made as to the rehabilitation procedure that is to be followed.

Similarly, the requirements for specialized equipment should be evaluated when alternatives are being considered. One procedure that appears the most economical may require specialized equipment not readily available in the area and may become more costly than others.

Time out of service - When a considerable amount of traffic uses the roadway crossing a structure and the only possible detour is long, the time that a structure repair puts a road or travel lane out of service can be a vital concern. A choice may be possible between the least expensive method of rehabilitation that requires the temporary closing of a structure and a somewhat more costly alternative that permits the maintenance of traffic. Other choices may involve closing the road during part of the day, temporary bridges, or maintaining light traffic only. All possible choices should be considered following the concepts described under benefit-cost, and professional advice should be obtained for complex cases. Normally, however, the best choice will become obvious when the problem is considered carefully and all the available facts are evaluated.

Aesthetics - Structures at some locations can be a very prominent part of the local landscape. Old structures in some locations have become very important to those who live near them. In such instances, the appearance of a completed project should be a consideration when comparing various alternatives. A perfectly utilitarian structure can also be an eyesore, which might not matter in some areas but be very important in others. An attempt should be made to visualize what the project will look like when it is completed and whether its appearance will be acceptable to those most affected.

Comparison of Alternatives

There is no single best way or magical method to select the best strategy and work option. The local government official must decide whether the standard referred to is that needed by the locality for its purpose or whether it is that which must be used to meet Federal or State requirements for participation. Also, whether the cost is just the cost of construction, life-cycle cost, or the total cost as used in a benefit-cost analysis must also be evaluated. Further questions can arise as cost could be considered to be the sum of the costs to every agency involved or just the community's share to match Federal and/or State participation.

Advantages/Disadvantages - Probably the best general procedure to follow is to completely describe each alternative and list the advantages and disadvantages of each in terms of the issues previously discussed with the exception of cost. Assuming that the structure is suitable for rehabilitation and will or can be modified to meet the future needs of the area, preliminary sketches of possible plans that will fulfill the minimum requirements should be developed. These do not need to be elaborate, but they should be sufficiently detailed so that the various elements of the structure needing attention are identified and alternatives for their improvement can be presented. If future needs of the area cannot be met by improvement to the existing structure, sketches of possible replacement schemes should be prepared.

Costs - The costs should be listed for each alternative in terms of cost to the community and total cost to all agencies concerned. The development of life-cycle costs for each alternative is a good starting point although this should not be considered the only or ultimate answer.

Estimated costs should be prepared for performing the work to correct the defects discovered and to make the improvements indicated in the plans and sketches previously prepared. Too much emphasis on exact costs is neither warranted not necessary at this stage since a comparison between different rehabilitation plans is desired rather than costs for exact budgeting purposes. The method chosen should be consistent between plans.

The first category of costs that should be estimated are those required to restore the existing structure to a satisfactory condition. The cost of necessary repair to all of those items that will be kept as part of the rehabilitated structure for the minimum design should be included. When some items must be replaced, the cost of a new installation should be calculated. It is advisable to keep estimated costs broken down into structural elements so that the cost of different combinations of materials and techniques can be reviewed. It may be that such items as diversion of the water in the stream, which may be common to all alternatives, may not need to be estimated at this point. It will, however, need to be included in the final estimated cost of the project.

When estimating this category of costs, it should be realized that the unit costs are likely to be high in comparison with usual construction costs. Much of the work tends to be labor-intensive and does not lend itself to production-type processes. The removal of deteriorated concrete with chipping hammers while ensuring that adjacent should concrete is not damaged is a task that must be done carefully and cautiously.

The second category of costs that should be estimated is the cost of all of those items necessary to upgrade the structure. Obviously a different estimate should be developed for each plan. The costs added to those developed for the first category will provide a means of cost comparison between plans and will also provide a total cost range is all required items, such as diversion of the stream, are included. In most instances, only the differences in cost are required.

If replacement is a feasible option, the third category of costs that should be estimated is the cost of a new replacement structure using only those parts of the existing structure that will provide service equal to that provided by new parts. Additionally, if a replacement option is being considered, relocation of the structure may also be under consideration.

Table 7.6 is a work sheet for recording the data collected on each culvert. It is suggested that this tabulation be utilized as a summary sheet and placed at the front of calculations and sketches prepared for each culvert on which a decision is required.

Decision - At this point, the alternatives will have been developed, life-cycle costs comparisons will have been made, and the alternatives reviewed in terms of all the other factors such as availability of expertise, materials, and specialized materials, as well as current and future needs and aesthetics. In practically all cases the best solution will be obvious when all the facts are considered.

Economic analysis is a helpful decision-making tool, but it is only a tool. Its usefulness is in the consideration of a number of factors in terms of a common unit of measurement. There are limitations to economic analysis because it involves many assumptions about the future, not to mention estimates of immediate expenditures, and not all factors bearing on a decision can be reduced to dollars. Perhaps the greatest limitation is the lack of understanding about economic analysis on the part of decision-makers, politicians, and the public. Despite these limitations, however, well-done economic analysis will help ensure that the most cost-effective projects are advanced.

Transportation Research Record 1315, *Culverts and Pipelines: Design, Monitoring, Evaluation, and Repair, 1991*,[6] presents a discussion of the development of a ranking system for culverts found on local agency systems. Cost models are developed to identify major contributors to user and agency costs. On the basis of the cost models, a working dBase III Plus™ microcomputer software package was developed to evaluate culvert systems of local agencies.

Table 7.6. Worksheet for recording culvert data for strategies and work options.

GENERAL INFORMATION

- Location of culvert ______________________
- Type material ______________ • Size & length ______________
- Age of structure ______________ • Depth of cover ______________
- Roadway classification ______________________
- Urban or rural ______________________
- Roadway scheduled for repair? ☐Yes ☐No
- Hydraulically adequate/future ☐Yes ☐No
- Structurally adequate/future ☐Yes ☐No
- Alignment adequate ☐Yes ☐No
- Safety adequate/future traffic ☐Yes ☐No
- Deterioration:
  - Light ☐Yes ☐No
  - Usable structure remaining ☐Yes ☐No
  - Can be upgraded to equal replacement ☐Yes ☐No
  - Little structural value remains ☐Yes ☐No

STRATEGIES AND WORK OPTIONS (Refer to Table 7.2)

Routine Maintenance
☐ Remove debris & sediment
☐ Thaw frozen culvert
☐ Control vegetation

Preventive Maintenance
☐ Clean & repair ditches
☐ Seal joints
☐ Patch concrete
☐ Repair mortar
☐ Pave invert (limited)
☐ Prevent scour

Replace (May include the following:)
☐ Realignment
☐ Hydraulic, structural and safety improvements
☐ Change in culvert shape or material
Alternate 1 ______________

Rehabilitation
☐ Repair scour damage
☐ Repair endwalls and wingwalls
☐ Stabilize slopes
☐ Pave streambed
☐ Add apron or cutoff wall
☐ Improve inlet configuration
☐ Install debris collector

Upgrade to Equal Replacement
☐ Add, repair or replace appurtenant structures
☐ Line the barrel
☐ Provide safety grates or safety barriers
☐ Lengthen the culvert
Other ______________
Alternate 2 ______________
Alternate 3 ______________

REFINEMENT OF OPTIONS

	Alternative 1	Alternative 2	Alternative 3
• Expertise available?	☐Yes ☐No	☐Yes ☐No	☐Yes ☐No
• Equipment available?	☐Yes ☐No	☐Yes ☐No	☐Yes ☐No
• Estimated costs			
Present:	________	________	________
Annual:	________	________	________
Future:	________	________	________
Year applied:	________	________	________
Estimated life:	________	________	________
Present worth:	________	________	________
Annual cost:	________	________	________

REPLACEMENT SYSTEMS

Not all culverts should be repaired or rehabilitated. Some should be replaced if they cannot be repaired or rehabilitated to meet the present and future needs of the area in which it is located. Therefore, if the physical requirements have changed, careful analysis and design should precede the selection of the type, size, and installation characteristics of the replacement culvert.

Design Considerations

Seldom should a culvert that has failed be replaced with an identical structure. In order to avoid the same type of failure in the future or continue the circumstances that caused failure, the total design process should be followed for the selection of a replacement system. Design considerations of the replacement culvert may include the a review of the hydrology of the watershed, effluent characteristics, seasonal changes in effluent, the hydraulic capacity and structural capacity of the culvert, erosion control and other environmental requirements, safety and legal aspects, and the need for appurtenant structures such as debris control structures. Of primary importance are hydraulic, structural, durability, and cost considerations. These design considerations are discussed at length in chapter 2.

Hydraulic - When a culvert is being replaced, there is an opportunity to correct deficiencies that may have led to the failure of the culvert. For instance, the new design should take into account changes in the watershed that produce more runoff. The culvert can be realigned to eliminate abrupt changes in direction of flow that contribute to scour and undermining. The slope of the culvert can be changed to more closely follow the slope of the natural streambed. The culvert can be designed to operate under inlet control, except for those on flat terrain. The hydraulic capacity of the culvert, of course, should be adequate to accommodate present and future anticipated peak flows. The culvert should be designed to accommodate the minimum flood frequency that corresponds to the classification of the roadway.

Structural - The structural design of the culvert must ensure that the culvert is strong enough to resist the live and dead loads that will be imposed upon it in the future. Structural requirements will influence both the material that is selected and the shape of the culvert.

Durability - Although structural condition is a very important element in the performance of culverts, durability problems are probably the most frequent cause of replacement. Culvert are more likely to "wear away" than fail structurally. Durability is affected by both corrosion and abrasion. If the culvert has failed due lack of durability, a material should be selected that will resist the type of deterioration that has affected the previous structure.

Costs - Cost have been discussed extensively in this chapter. It should be reiterated that cost analysis of alternative systems involve more factors than the first cost. The life-cycle costs as well as user costs should be reviewed.

a. Construction - Besides the cost of labor and materials, construction costs may include the cost of additional right-of-way, traffic control, and temporary detours.

b. Maintenance - The cost of maintenance can include the annual maintenance costs, future increases to maintenance costs due to deterioration, and future rehabilitation costs.

Traditional Materials/Past Performance

Performance of previously used culvert materials in a particular location can give some indication as to the type of material to use and what not to use for replacement. Most State departments of transportation have in their specifications the types of materials that can and cannot be used in parts of the state where the pH of the soil is problematic and/or where runoff may contain mine wastes that cause corrosion. A culvert inspection system that records condition assessments can be most helpful in making decisions about the type of replacement systems to install.

Recent Innovations in Materials, Products, and Procedures

In recent years there have been many innovations in materials, products, and procedures, some of which have been discussed earlier in this manual. The following discussion includes some of the others that are rapidly gaining acceptance.

It should be noted that several of the following are three-sided or arch type culvert concepts that are constructed on footings, which leave the natural channel bottom undisturbed. These types of designs do not necessarily guard against scour that could undermine the footings and cause loss of the culvert.

The three sided bridge system is a rigid frame design that incorporates a flat-top geometry. By providing a flat-top structure, the system allows pavement to be placed directly on top of the structure. When combinations of long spans (more than 16 feet) and shallow earth covers (0 to 2 feet) were encountered, a grouted shear key joint accompanied by shear plates were provided. The effectiveness of this arrangement is explored in Transportation Research Record 1315.[7] In this publication deflection results were presented for various combinations of shear plates and the keyed joint when subjected to simulated live loading. The results indicated that the grouted shear key joint system is an effective means of distributing the load between the precast sections. The addition of shear plates does not enhance the structural response of the grouted structure. Shear plates along are not effective.

Precast Culvert Systems - Several precast concrete culvert systems are presently on the market and are being used by many states. One of the patented culvert systems available is the CON/SPAN™ Culvert System, the components of which are shown in figure 7.6.

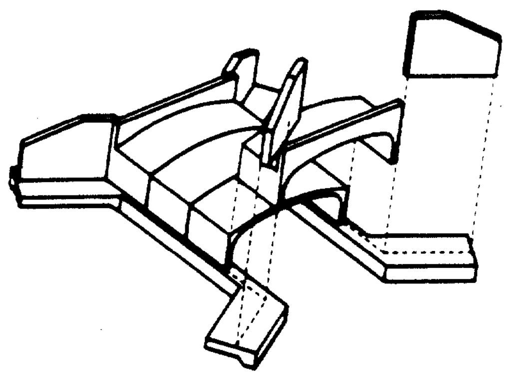


Figure 7.6. CON/SPAN™ culvert system.[8]

The system is available in both a short span series and a long span series. The size of span and rise that are available are included in appendix C. In addition to a single, straight barrel, the system can also be placed as a multicell installation, set on pedestals to increase the rise, and installed on a horizontal radius as shown below in figures 7.7, 7.8, and 7.9.

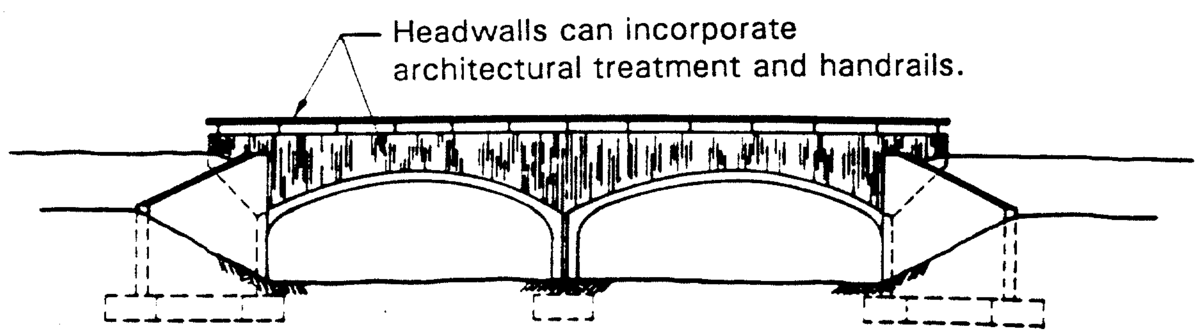


Figure 7.7. Multiple cell installation.[8]

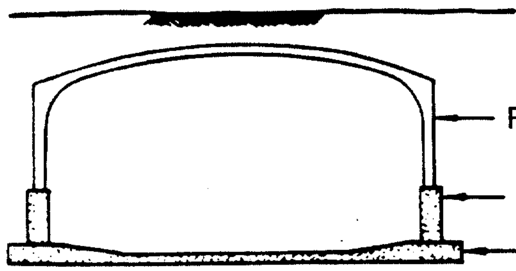


Figure 7.8. Pedestals to increase rise.[8]

The sections are brought in by truck and placed with a crane. The installation can often be completed in a day and backfilled the next day. An additional advantage is that the culvert bottom is the natural streambed material and will not interfere with fish passage.

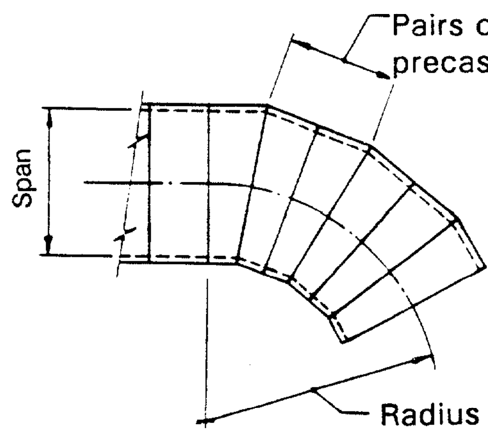


Figure 7.9. Installation on a horizontal radius.[8]

Hy-Span™, licensed and manufactured by the Hyway Concrete Pipe Company, is also a precast modular system that offers clear span units ranging from six feet to forty feet in one foot increments coupled with vertical clearances from two feet to ten feet in one inch increments so that a very wide range of opening configurations can be achieved. Laying lengths also are variable to maintain the weight of individual modular units with workable limits. Therefore, there are no standard sizes of Hy-Span units. Each project is provided with the proper components in the dimensions to meet specific requirements. Other systems include 3-S Bridge™, manufactured by Price Brothers and TriSpan™, from Cincinnati Concrete Pipes.

A third system is the BEBO™ precast concrete arch, manufactured by The Rotondo Companies, is shown in figure 7.10. Arch components are six feet wide and ten inches thick.

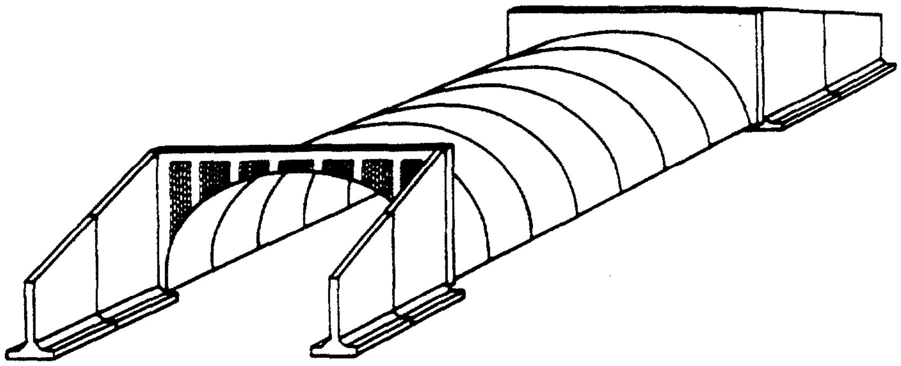


Figure 7.10. BEBO™ precast concrete arch.[9]

TechSpan™ is a precast concrete arch system from The Reinforced Earth Company that is custom designed and is another alternative for conventional culverts. A typical structure is shown in figure 7.11.

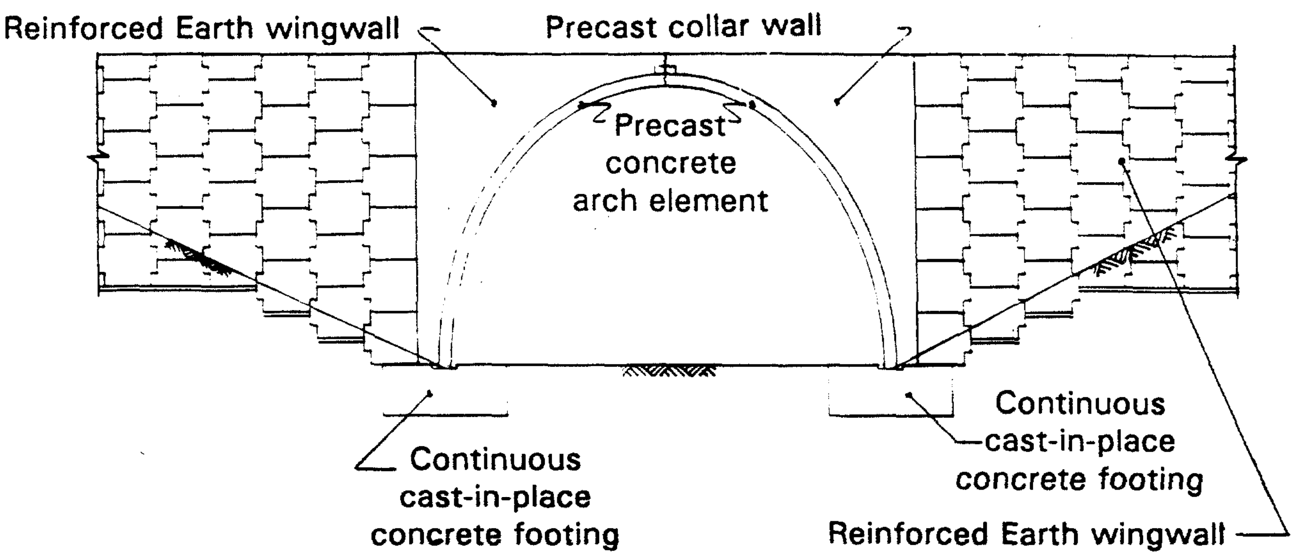


Figure 7.11. Typical TechSpan™ structure with Reinforced Earth wingwalls.[10]

Air-inflated forming system - At least one company has developed a concept for forming culverts by using an air-inflated tubular bag over which steel reinforcing is placed and then covered with shotcrete.[11] AIR-O-FORMS™ is the patented system of Concepts in Concrete (CIC, Inc.) in which reusable inflated forms are the basis of a system for building small bridges and culverts. The method involves the following procedure:

1. Cast a reinforced bottom slab or footing, with dowels or another provision for tying the arch and footing together. In some locations precast footings are feasible, and in other areas, rock layers are available to support the arches.

2. Inflate a closed-end, cylindrical fabric form and shape the form as required with metal tie-down straps. Flexible steel straps spaced at 1- to 2-foot intervals are used to tie the inflated forms down and restrict the size and shape of the arch to be built. The straps are hooked onto hairpin-shaped wickets of bent #3 reinforcing bars that are set in the foundation slab during casting, or crimped onto short sections of strapping embedded in the slab.

3. Place reinforcing steel, as required, on bar supports over the inflated form. Set plastic-tipped bar support chairs or bolsters over the straps to support the necessary longitudinal reinforcing bars. Then vertical bars are curved over the top of the form to provide crosswise reinforcement. Steel is tied as required.

4. Adjust air pressure inside the form once the reinforcement is in place.

5. Apply 6-inches of shotcrete, all in one layer. This creates an arched reinforced concrete structure with a flat bottom.

6. Deflate the form after the concrete has gained the necessary strength. Remove the form.

The forms can be used as many as 40 or 50 times, and one form can be adjusted to build many sizes of culvert arches. A single standard size inflatable form can be used to build 180-degree arch culverts from the 14-foot-wide, 7-foot-high maximum on down to 2-feet in diameter. Various arches less than 180 degrees, for example 4 feet high by 18 feet wide, can also be made. Arches up to 20 feet high and spanning over 50 feet are also achievable with special sizes of the forms. No shoring is needed and the form requires no cleaning or surface preparation.

The system has a flexibility that is extremely useful in some situations:

- Since the shape of the form is regulated by the placement of metal bands, the size of the inlet can be increased in diameter and can be flared to improve the hydraulic performance of the culvert.

- The ends of the culvert can be mitered to eliminate headwalls. Riprap can be placed around the inlet and outlet end or a shotcrete collar can be constructed if erosion of the embankment slope is a problem.

- Since the form is flexible, any kind of bend can be formed into the barrel or,if it advantageous, the streambed can be followed to avoid abrupt changes in direction at the inlet or outlet end.

- Transitions can be formed to go from different sizes of boxes, arches, or round section. Shapes can be transitioned to increase or decrease sizes with a distance of a few feet.

- Junctions can be formed in the culvert barrel.

- At low-water crossings, headwalls can be mitered to as much as a 3:1 slope to assist flood water to pass over the low-water crossing rather than wash away the structure.

These types of structures have been constructed by the Arizona, Kentucky, and Pennsylvania Departments of Transportation as well at the U. S. Bureau of Mines.

Controlled low-strength material (CLSM) - Controlled low-strength material is the name assigned by the American Concrete Institute Technical Committee 229 to a variety of products that are commonly a blend of cement, fly ask, sand, and water. Typically it is designed as a low-strength, flowable material requiring no subsequent vibration or tamping to achieve consolidation. It is called by several names in different areas depending on it use, such as controlled low-density fill, flowable mortar, flowable fill, and lean-mix backfill. The Transportation Research Board's *TRR 1234, Concrete and Construction - New Developments and Management*[(12)] contains several articles on different types of CLSM with applications for culvert repair and replacement.

CLSM is not considered concrete, but is a class of low-strength cementitious material having a compressive strength of less than 1200 psi. If it is anticipated that the material may be excavated at some point in the future, the late-age strength of removable CLSM may be specified to be in the range of 30 to 150 psi. Slumps measured in the ordinary way are generally 8 inches or higher.

CLSM can be used as a low-cement-content material for the replacement of unsuitable soils. Flowable fill can be used for backfilling voids behind culvert wingwalls where erosion is a significant problem or in locations where usual compaction methods are difficult.

It can also be used to fill culverts abandoned in place. The culvert is filled with the flowable mortar after sealing off both ends of the culvert. It can be used to fill large areas from a single entry point. It does, however, exert significant pressure on the bulkheading placed to block the ends of the culvert. Care should also be taken to vent the area to be filled so that entrapped air or water can escape as the void is filled.

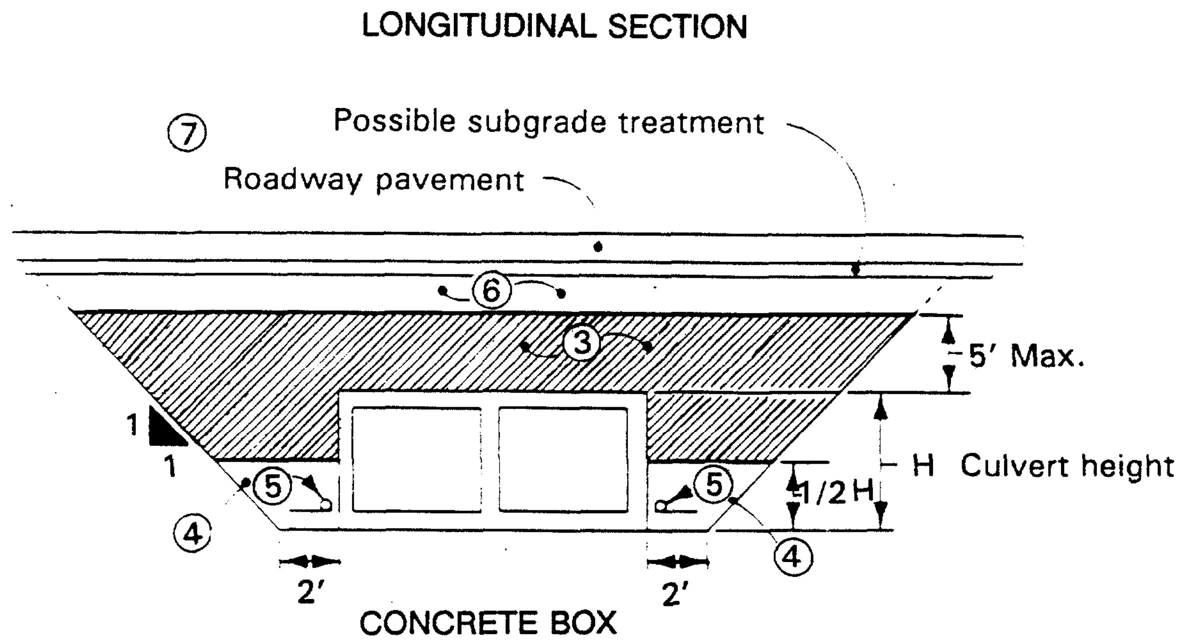
Flowable fill can be used to grout the annular space in sliplined culverts. Although care must be taken in placing the fill so as not to cause the liner to float and incur damage, grouting can prevent failure in four ways:

- Grouting provides support for the existing pipe;
- It slows or stops corrosion of the existing pipe;
- It blocks the flow of water from infiltration; and
- It helps prevent long-term damage or collapse of the new liner pipe.

Unshrinkable fill, another form of CLSM, is a controlled density backfill material used in utility cuts and trenches to eliminate settlement of trench backfill and prolong the service life of the street or highway. It is usually a mixture of Portland cement, water, fine and coarse aggregates and may contain an air-entraining admixture. It is an extremely low-strength concrete with a maximum strength usually specified, rather than a minimum strength as for normal concrete so that the trench can be reopened at some future date using normal excavation tools and equipment. It is generally ordered from a ready-mixed concrete supplier, mixed at the plant and delivered to the job site in a ready-mix truck.

Since the CLSM flows freely into the trench and there is no need to ensure proper lift heights or the compactive effort to be applied to granular fill, the amount of inspection required is greatly reduced. The flowable property of unshrinkable fill is especially beneficial when the subgrade material has fallen away from the sides of the trench and from under the pavement, creating voids that are difficult to fill and compact if granular backfill is used.

Flowable mortar is being used by the Iowa Department of Transportation for culvert backfill with the following requirements: granular backfill for half the height of the culvert and flowable mortar for a maximum of 5 feet above the culvert. The granular backfill ensures that the culvert does not float and acts as a filter to keep from plugging the drainage system. The required subgrade treatment must be between the pavement and the flowable mortar. The sand and flowable mortar are contained by soil as shown in figures 7.12 and 7.13.



1	1:1 Slope	4	Granular backfill	6	Possible Class 10 or embankment
2	Earth fill	5	4" Subdrain at flowline	7	Non-reinforced pavement
3	Flowable mortar				

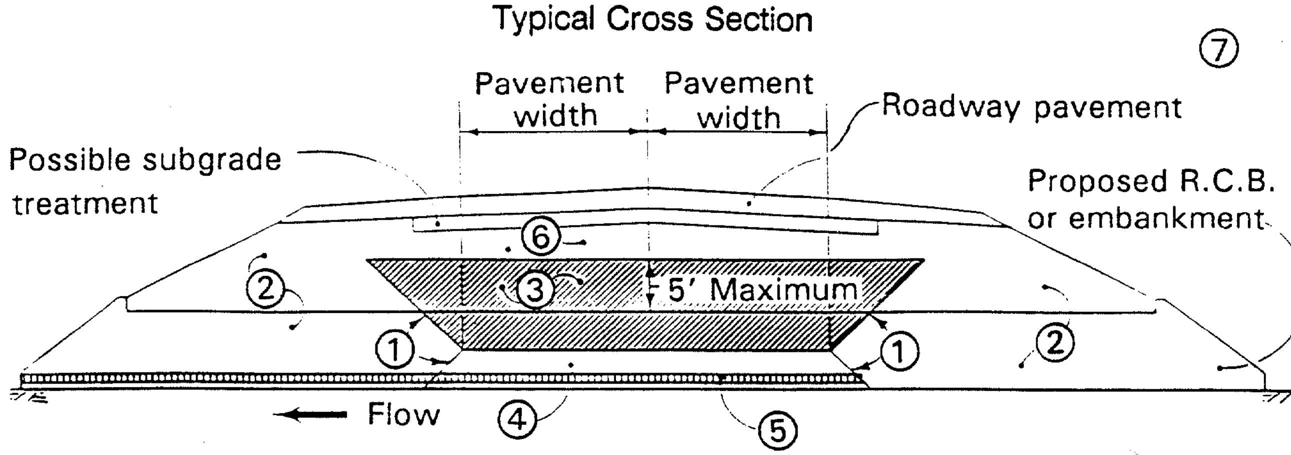
Figure 7.12. Side view of culvert backfilled with flowable mortar.[13]

Another type of CLSM that may be useful for culvert repair or replacement is flowable fly ash, also described in the TRR 1234[14] publication mentioned earlier. It has several unique characteristics. These characteristics include its resistance in both a fresh plastic and a hardened state to erosion from flowing water. This resistance to erosion from water normally allows the material to be placed directly into water without the need for tremies. In addition, flowable fly ash can normally support the weight of a loaded truck within the first 24 hours after it is poured.

FLOWABLE MORTAR

BACKFILL OVER CULVERT

Typical Cross Section



1	1:1 Slope	4	Granular backfill: when crushed limestone is used, it shall meet the durability of granular subbase.	6	Possible Class 10 or embankment
2	Earth fill	5	4" Subdrain at flowline elevation of culvert	7	Non-reinforced pavement
8	Flowable mortar				

Figure 7.13. Cross section of culvert backfill using flowable mortar.[13]

In hot weather, it has supported trucks and construction loads in a matter of a few hours. Flowable fly ash consists of Type F fly ash, water, and a small amount of Portland cement. It has also been used to fill abandoned tanks, tunnels, pits, and sewers and could be used to fill culverts abandoned in place.

Figure 7.14 shows the material as used to fill an abandoned storm sewer under a new automotive plant. The fill points were drilled about 250 feet apart. After flowable fly ash was placed in one point, the air was vented at the next point 250 feet away. That point, in turn, became the next fill point. Drilling after placement of the flowable fly ash served to check that the method was successful. The same procedure can be used to fill a culvert abandoned in place.

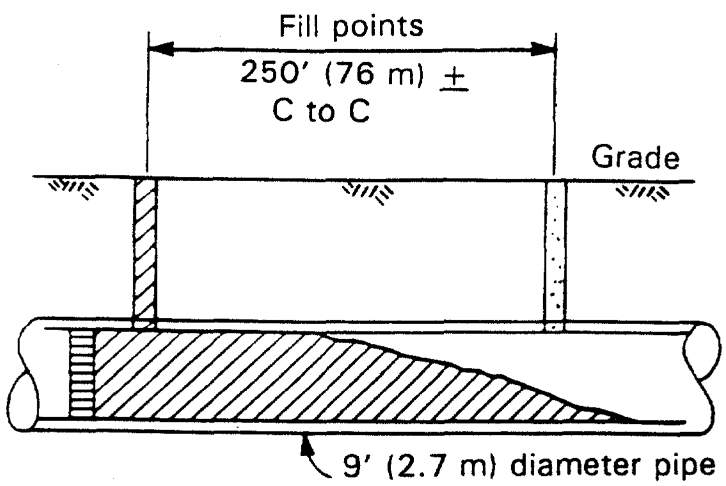


Figure 7.14. Structural fill of underground enclosures.[14]

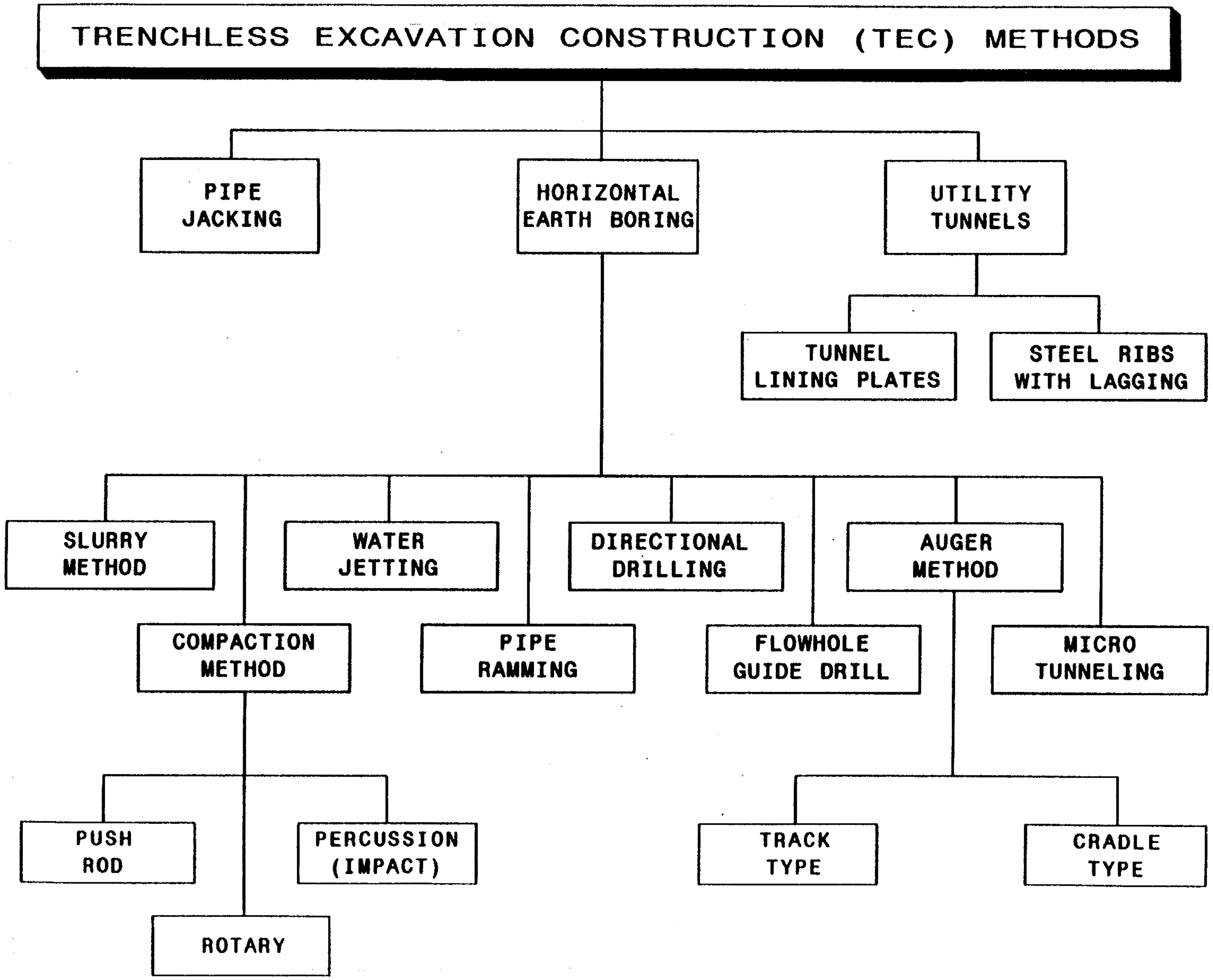
The use of a controlled low-strength material can be extremely advantageous in the repair and replacement of culverts because of its ease of placement, reduction in inspection, ready availability, resistance in both fresh plastic and hardened state to erosion, resistance to freeze and thaw, and its ability to be removed by a small backhoe. or even handtools.

Although CLSMs have been in use for a number of years, confusion about their construction benefits and economic savings remains. In Transportation Research Record 1315, *Culverts and Pipelines: Design Monitoring, Evaluation, and Repair, 1991*,[15] a method for determining the cost of CLSM-CDF and how it can affect a contractor's total construction costs is described.

Construction Methods

The methods that are used to replace or add a culvert to a highway may be classified under two general headings: (1) trench construction and (2) trenchless construction, depending on whether a trench is cut down through the roadway to below the level of the culvert. Trench-type construction methods are well established and commonly used for the construction of new culverts as well as for new sewer, water, and utility lines. Trenchless excavation construction (TEC) methods include all methods of installing utility systems below grade without direct installation into an open-cut trench. Trenchless construction includes jacking, boring, and tunneling methods concepts. Table 7.7 illustrates the variety of ways that trenchless construction may be undertaken.

Table 7.7. Trenchless excavation construction (TEC) classification system.[16]



The selection of any of these construction methods over the others depends on many factors including: depth of cover, length and size of culvert, type of embankment material, amount of traffic, safety, and, certainly, cost. It should be noted that all TEC methods are not equivalent or applicable to all locations. Moreover, it is not reasonable or prudent to allow open competitive bidding of all options at all times in the name of promoting competition and contractor flexibility. At critical locations that may involve public health and safety, it is the responsibility of the designer and/or the public agency to limit the acceptable methods to those that are compatible with the site conditions.

Trenching - The open trench concept is the most commonly used method for replacing a culvert. Contractors and highway agency personnel are familiar with the procedures for doing this type of work, and it may be done quickly and well by them. The general procedure is to excavate a trench and remove the existing culvert, prepare the appropriate bedding for the new culvert, install the new culvert and then build up the embankment, roadbed, and pavement around and above it with materials that are similar to those that were removed. Detailed guidelines for installing culverts in a trench are provided in many industry and highway agency handbooks.

The biggest drawback to replacing culverts by the trenching method is that at least a portion of the roadway must be closed while the work is underway. The cost and inconvenience to users may not be defensible if there is another way to install the replacement. It is also more difficult to replace a culvert by this method if there is a flow of water through the culvert. However, water can be channelized through a temporary pipeline by building a temporary catch basin and pumping the water across the roadway or by diverting the water to an adjacent drainage area. An additional disadvantage to the open trench method is the possibility of damage to the pavement due to improper backfilling, compaction, and patching. As the pavement settles and cracks develop, water can get into the base, causing the pavement to deteriorate further. Piping, which can affect the culvert installation, can ensue.

However, jacking does have some requirements that may not be met by every site. A certain amount of right-of-way is required to install the mechanical equipment or an easement may be required. The site may have trees, shrubs, or various types of structural installations that must be removed in order to locate the equipment in the precise position needed for boring or jacking. This is not always possible.

Jacking - As shown in Table 7.7, there is a wide range of methods that may be used for pipe and culvert trenchless excavation construction. Each has advantages and disadvantages, depending on the specific site conditions and the size and length of the culvert to be installed. There is some effort in the industry to subdivide the classification of basic jacking methods into (1) Pipe Jacking (PJ) and (2) Horizontal Earth Boring (HEB), depending on whether workers are required inside the borehole. Borehole excavation is accomplished entirely by mechanical equipment for the HEB process whereas workers are required inside of the borehole for the PJ concepts. For the PJ methods, the excavation procedure may vary from the basic manual process to those of the highly sophisticated tunnel boring machines (TBM). However, the excavation is normally conducted inside a shield, to provide maximum worker safety. The shield is normally articulated and guided by individually controlled hydraulic steering jacks. The most common type of jacking material is reinforced concrete or steel pipe. The jacking equipment is quite similar for all of the PJ and HEB jacking methods. Additional information on jacking is provided in appendix B-42.

The following is a definition and brief description of each of the methods that may be used for horizontal earth boring (HEB) that have been excerpted from reference 9, *Construction Specifications for Highway Projects Requiring Horizontal Earth Boring and/or Pipe Jacking Techniques,*[16] a product of an Indiana Department of Transportation research project.

a. Auger method - This method involves the process of simultaneously jacking a casing through the earth while removing the spoil (soil) inside the encasement by means of a continuous rotating flight auger. The auger HEB method is traditionally classified as : (1) track-type or (2) cradle-type. The major components of the track-type system include the track system, machine, casing pipe, cutting head and the augers. The cradle-type machine is supported by the trailing end of the casing pipe, eliminating the need for the track system. However, hoisting equipment are required to support the casing pipe as the TEC proceeds. Optional additional components of the system include a bentonite lubrication system, a steerable (grade control) head, a casing leading edge band, a water internal injection system and a dutch water level indicator. Four major factors of concern include (1) minimizing torque, (2) minimizing thrust, (3) locating the leading end of casing, and (4) being able to control the direction of the leading end of the casing. The steerable (grade control) head and the dutch water level system are not applicable to the cradle-type methods.

b. Compaction method - This method forms the borehole by compressing the earth that immediately surrounds the compacting device. The soil is not removed, it is displaced. This method is only applicable to small diameter lines (i.e. less than 6 inches) in compressible soil conditions. This method is divided into three sub-classifications which are: (1) push rod method, (2) rotary method and (3) percussion (impact) method. These methods are commonly referred to as expansive installation techniques, which mean that the volume of the installed pipe exceeds the volume of the excavated soil. Although these techniques have been used for many years, their use has been limited because of their inherent unpredictable degree of accuracy. Improved location and steering systems have been developed within the past few years that have reduced the risk and extended the allowable distance that may be accomplished with these methods.

c. Slurry horizontal rotary drilling (SRD) method - This method is distinguished from horizontal auger boring in that it uses drill bits and drill tubing in lieu of augers and cutting heads. A drilling fluid (such as a bentonite slurry, water, or air) is used to facilitate the drilling process by keeping the bit clean and aiding in spoil removal. Because a drilling fluid is used, this method is often confused with the jetting method; however, unlike the jetting method, the SRD method does not use the drill fluid to cut the face or to wash out a hole. The face is mechanically cut with a drill bit and wash-outs are prevented by controlling the drill fluid rate of flow and pressure. SRD offers the distinct advantage of being able to install a small diameter pilot hole before the main bore hole is developed. This ensures the accuracy of line and grade. The SRD method is primarily suited for small diameter (up to 6 inches) sizes, although larger sizes are installed where soil conditions permit. The recommended bore length is a function of soil conditions but it should be limited to approximately 40 feet unless drill bit location and directional control systems are used.

d. Water jetting method - This method uses the principle of soil liquefaction to create a borehole. Water pressure and flow rate create a jetting action that places the soil in a quick (liquid) condition for the purpose of eroding the borehole. This method requires a minimum investment in equipment. The equipment includes a source of pressurized water, a flexible hose, a probe, and a nozzle. The probe is usually a rigid small diameter pipe that is used to direct the water as it cuts or washes out a borehole. Although this method is simple and economical, it has serious adverse long term effects associated with significant subsidence problems. Many organizations have banned its use.

e. Pipe ramming method - This method uses a percussion (impact) tool as a driving hammer to force direct burial of pipe. The two basic methods are closed face and open face. The closed face method utilizes the soil expansion principle, which does not require removal of the soil. The open face method uses the same equipment but the spoil is removed from within the pipe. Bentonite may be used to reduce skin friction. Accuracy is a function of soil conditions and the presence of obstructions. Directional control is dependent upon the degree of accuracy established during the initial set up. Casing leading edge detection systems have been used with success, but they are not commonly used.

f. Directional drilling method - This method is an outgrowth of the technology and methods that have been developed for the directional drilling of oil wells. Use of these techniques, which have revolutionized complicated pipeline river crossings, are also viable for highway and railroad crossings. The two-stage directional drilling process consists of: (1) drilling a small diameter pilot hole along the desired centerline of the proposed pipeline, (2) enlarging the pilot hole to the desired diameter to accommodate the pipeline. The pilot hole is drilled with a specially built drill rig that allows the drill string to enter the ground at an angle of entry that can vary from 5 to 30 degrees; however the optimum angle is 12 degrees. The drill rig forces the drill stem into the ground, and bentonite drilling mud is pumped through the drill stem to a down hole motor located behind the bit. The drill mud operates the down hole motor, functions as a coolant and facilitates spoil removal by washing the cuttings to the surface where they settle out in a retention pit. The drill stem is approximately 3 inches in diameter, nonrotating, and contains a slightly bent section which is called a bent housing. The bent housing is used to create a steering bias. A curved or a straight profile is achieved by steering the drill rod as it is being pushed into the ground. The steering is controlled by positioning the bent housing. The pilot hole path is monitored by a down hole survey system that is located behind the bent housing and provides data on the inclination, orientation and azimuth of the leading end. This data is transmitted to the surface where it is interpreted and plotted. During the drilling operation a 5-inch diameter steel washover pipe is rotated over the pilot drill stem to relieve friction, resist pressure caused by the cuttings mixed with the drill mud, and provide rigidity to the pilot drill stem. Bentonite slurry is pumped between the washover pipe and the pilot drill stem. The rotation of the washover pipe allows the diameter of the borehole to be increased to approximately 11 inches. The pilot drill stem is withdrawn through the washover pipe after the pilot hole has been constructed. Reaming devices are attached to the washover pipe and pulled back through the pilot hole to enlarge it to the desired diameter for the pipeline.

g. FlowMole guidedrill method - This is a proprietary method that was developed by the FlowMole Corporation of Kent, Washington. The method offers a unique steering capability for small diameter lines that are installed at depths that extend to 15 feet and are up to 600 feet long. The patented SoftBor process is characterized as a low flow (1 to 2 GPM) and high pressure (1,000 to 4,000 psi) soil cutting system. Although the cutting action is performed by a bentonite slurry, this process is differentiated from the water jetting and the slurry rotary drill methods because of the pressure and flow rates that create the cutting action. Soil erosion and over cutting do not occur with the FlowMole system because the small diameter jets that produce the required type of flow are designed so that the energy of the cutting fluid is rapidly dissipated. This also eliminates the risk of cutting existing utility lines. A computerized electronic remote control steering system is used to control the direction of cutting at the nose of the bore tool. The position of the tool can be determined within one inch laterally and vertically.

h. Micro-tunneling method - These methods of horizontal earth boring employ the use of highly sophisticated, laser-guided and remotely controlled equipment that can be monitored and accurately adjusted for alignment and grade. This classification group applies to sizes of lines up to 36 inches that are too small for workers to work inside of efficiently. Larger machines of this type are also used for jacking larger size pipe, which may employ workmen to remove the spoil material, but the term Micro-tunneling does not apply. The state-of-the-art technology of this equipment permits it to be used to install small diameter pipelines in soft, unstable, water-bearing soils. This is accomplished automatically and continuously by the mechanical earth pressure counter-balance (MEPCB) system that coordinates excavation speed, cutting face pressure and thrust force. This permits operation in water saturated sands, silts, clays, and gravels without dewatering or compressed air. The system utilizes a slurry pumping system to transport the excavated material from the cutting face to the disposal process. All systems are electronically monitored and controlled from a single operation panel.

Tunneling - The tunneling industry refers to the type of work of concern here as "utility tunneling" (UT) to differentiate it from the major type of tunneling that is used to create passageways for vehicles. Identical excavation methods may be used for both pipe jacking and utility tunneling work. The major difference between these methods is in the lining system. With PJ prefabricated pipe is the lining system whereas with UT the lining system is constructed inside of the tunnel. The most popular UT lining systems are steel tunnel liner plates, steel ribs, and wood lagging and box tunneling.

In summary, it is recommended that when these methods are to be considered that detailed specifications should be developed for each specific TEC project. A large number of types of field problems can occur as the result of faulty, inaccurate, and incomplete specifications. Incomplete specifications require inspectors to apply judgement in areas in which they may have no real knowledge or experience.

It is recommended that TEC projects should be segmented into at least three categories according to their degree of difficulty. The degree of difficulty should be a function of desired length, depth, size, groundwater conditions, soil conditions, surface and subsurface congestion, required accuracy, casing/carrier pipe, and other factors that are applicable. Methods permitted would be a function of the category selected for the project. The topics that should be considered for each TEC project are requirements for are shown in table 7.8.

Table 7.8. Considerations for each Trenchless Excavation construction project.

- Subsurface investigations
- Access pits and vertical shafts
- Materials
- Horizontal earth boring
- Utility tunneling
- Lighting
- Casing/carrier void filler
- Obstruction/changed conditions
- Measurements
- Groundwater control
- Right-of-way or easements
- Accuracy
- Pipe jacking
- Ventilation
- Grouting
- Bulkheading
- Abandonment
- Payment
- Information that should be submitted by the design engineer and the contractor prior to execution of the work.

It is also important to recognize that simply modifying specifications for this type of work will accomplish little without proper training and educational programs for designers, permit reviewers, and inspectors.

On occasion existing culverts may be relocated or abandoned and new culverts placed by TEC methods to meet new hydraulic or structural requirements. Disposition of old and no longer used culverts should be a planned activity that gives due consideration to public safety and the possibilities that a major roadway hazard could develop if the abandoned culvert would collapse, sometime in the future. Abandoned open culverts may become a place for undesirable animals to live or in which curious people could be injured. It should be kept in mind that the agency may have legal responsibility for events that occur within the highway right-of-way.

It is for these reasons that many highway agencies have adopted the practice of filling culverts that are taken out of service, although on some occasions they are merely blocked off at the two ends. Several types of material may be used to fill abandoned culverts, including:

- Rock, crushed stone, or pieces of broken concrete;
- Sand; and
- Controlled low strength material (CLSM), as shown in figure 7.15.

Depending on the materials and approach that is selected, it may be necessary to consider forces that may be developed at the ends on the design of closure walls that would first be constructed at the ends of the culvert.

CONCLUSION

Because of the many culverts in use today, some as major structures, State and local agencies are faced with a major expense in repairing, rehabilitating, and replacing culverts as they reach the end of their design life. However, many new products and techniques have been developed that often make complete replacement unnecessary. This manual is furnished in a loose-leaf format so that agencies can continue to build a collection of procedures that are cost-effective for their location and that will meet the needs of their particular area.

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