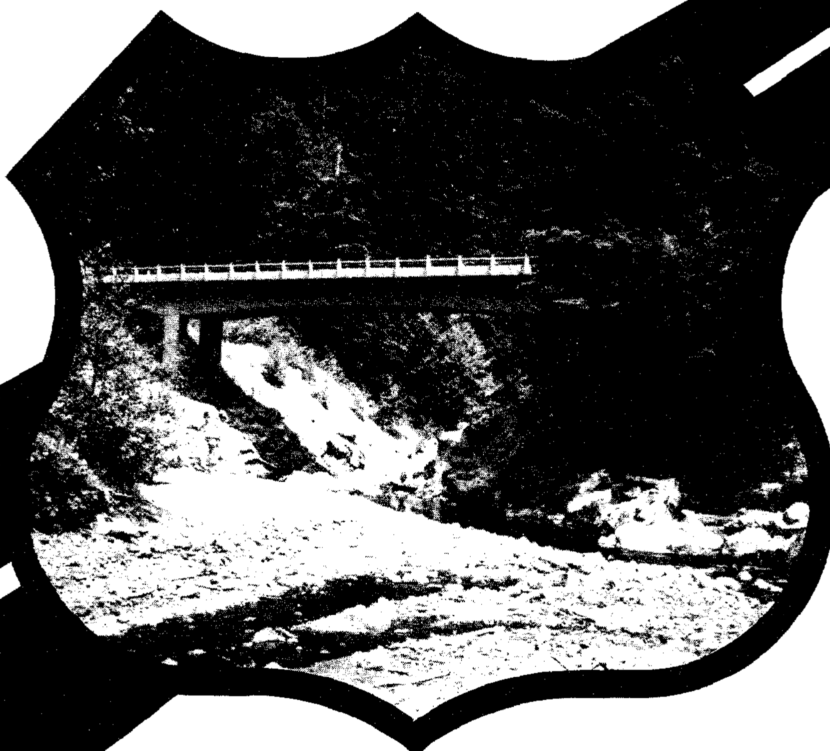
Report No. FHWA/RD-80/038

STREAM CHANNEL DEGRADATION AND AGGRADATION: CAUSES AND CONSEQUENCES TO HIGHWAYS

June 1980
Interim Report



Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Environmental Division
Washington, D.C. 20590

FOREWORD

This interim report describes the first phase of a research effort on stream-channel aggradation and degradation. Gradation changes are long-term channel bed elevation changes which extend for long distances along the streambed. This interim report describes the extent of problems nationwide, examines the causes of gradation changes, documents case studies where highway crossings have been affected, and summarizes methods available for recognizing the potential for bed level changes. During the second phase, better methods will be investigated for predicting the change in bed level, the rate of change and the stream length affected.

Research in highway drainage and stream crossing design is included in Federally Coordinated Program of Highway Research and Development in Project 5H "Protection of the Highway System from Hazards Attributed to Flooding." Roy E. Trent is the Project Manager and Stephen A. Gilje is the Contract Manager.

Sufficient copies of the report are being distributed to provide a minimum of one copy to each FHWA regional office, division office, and State highway agency. Direct distribution is being made to the division offices.

Richard E. Hay / for
Charles F. Scheffey
Director, Office of Research

NOTICE

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16. Abstract

Aggradation and degradation are long-term changes in stream channel elevation. The effects of gradation changes are not the same as local scour or erosion because they extend greater distances along the stream-bed. Degradation is a more common problem than aggradation and in general, has a more severe impact on highway crossings. Although gradation changes do occur naturally, human activities are responsible for the most severe cases. Channel alteration, stream-bed mining, and the construction of dams and control structures are the major causes of gradation problems. Virtually every river in the U.S., which flows on an alluvial bed, has a potential for gradation change. The prevalence of human activities as chief cause of gradation changes means many rivers suffer to some degree. The best regional indicator of degradation or aggradation potential is a sediment yield map for the U.S. or areas of interest because high sediment yields correlate with erodability. To aid in the anticipation of gradation changes the highway engineer should be aware of the principles of geomorphology. The simplest hydraulic analysis procedures predict the limiting slope of a gradient change based on critical shear stress of the bed material. The methods can be applied to any site where degradation or aggradation are suspected. The most complex techniques use a computer solution of differential equations. These techniques are more expensive and are probably applicable only for a new bridge where gradation problems are anticipated using simple hydraulic and geomorphic methods.

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The cooperation of many individuals and agencies in the preparation of this report is gratefully acknowledged. The authors are particularly appreciative of the efforts of all state and district engineers, who not only identified sites and supplied general information but also furnished bridge and countermeasure plans, maintenance records, and photographs for specific sites.

The authors also wish to acknowledge the help of Water and Environmental Consultants, Inc., of Fort Collins, Colorado, which documented thirty case histories in the western United States.

CONTENTS

(Note: A copy of Appendix A has been submitted to the Contract Manager; Appendix B will be available with the Phase 2 final report.)

CHAPTER I
INTRODUCTION

Aggradation and degradation are long-term changes in streambed elevation caused by natural factors or man's activities. A recent study of countermeasures for hydraulic problems at bridges by Brice, Blodgett, and others (1978) considered 224 sites.* Of these, 39 or 17.4 percent were experiencing hydraulic problems related to gradation changes. This significant incidence of gradation-related problems indicates that research is needed to further determine their extent and courses.

This interim report describes the first phase of an extensive investigation of aggradation and degradation. A data base is presented containing 110 case histories of bridge crossings where gradation problems exist. The data base is analyzed to determine the geographic extent, nature, and causes of gradation problems. The data base also contains information on remedial measures and their success or failure. Preliminary consideration is given to the recognition of gradation problems at existing bridge crossings. An appraisal of current technology for calculating gradation changes is included.

DEFINITION OF AGGRADATION AND DEGRADATION

Point of View

Understanding the aggradation-degradation problem and its relationship to highway river crossings requires a shift in point of view from the immediate vicinity of the crossing to a broad perspective of the river. Traditionally, bridge design is focused at the crossing site. Historical records are examined and flood flows determined. A bridge opening capable of passing the flood flows is designed. The stream channels are occasionally straightened or modified in some way to accommodate the required structure. In streams flowing over bedrock this is an adequate approach. In alluvial streams this approach may prove inadequate.

Streambeds composed of erodible material are in delicate states of equilibrium with the flowing water. The channel moves slowly and persistently from side to side, and, more important to this study, vertically in response to changing discharge and sediment load. Fixing the channel at a point in space by placing approach abutments and piers in the floodplain and channel often results in undesirable side effects such as deep scour channel widening as the stream tries to balance the discharge and sediment load. The sometimes disasterous consequences of these side effects have now been recognized and research undertaken to allow for their consideration in design and in the protection of existing structures.

A complete description of the relationships of highways to the alluvial river environment is presented by Richardson, Simons, and others (1974). The report clearly indicates that successful hydraulic design on an alluvial river requires a broad spatial perspective. For example, the width of a meandering river may only be several hundred meters. However, over the life of a typical bridge it may be necessary to consider the width of the stream meanders. The meander width may be three to twenty times the river width (Leopold, Wolman and Miller, 1964). Meanders migrate slowly downstream and, upon encountering a highway crossing, can cause a variety of problems. The slow downstream movement of meanders emphasizes that design in alluvial rivers requires a broad perspective in time as well as space. Similarly, vertical movement of a channel is slow and extends for long distances. In the late 1800s a huge natural log jam called the Great Red River Raft was removed by the U.S. Army Corps of Engineers from the Red River below Shreveport, Louisiana. The raft had retarded flow in the river for decades. Its removal accelerated the flow and resulted in over 5.8 m of degradation taking place at Shreveport over 50 years. The degradation extended upstream over 161 km along the river. Vertical stream morphology changes take place slowly but well within 30- to 50-year life of a bridge. It is necessary to look at where the river or channel bed has been and where it is now and anticipate its position in the future. Aggradation and degradation are phenomena that require a very broad perspective in both space and time. Many gradation changes can take place on an historically stable channel because of man's activities. It therefore becomes important to conduct research on proposed man-made modifications to the hydrologic system.

Definitions

The terms *aggradation* and *degradation* are not defined in precisely the same way by engineers, geologists, and geomorphologists. The differences in the definitions come from defining the limits of the perspective used to view the river in time and space. The purpose of this section is to define the terms as they are used in this report and contrast the definitions with terms often used to describe vertical stream changes.

*References are presented on page 89.

Leopold et al. (1964) provide a definition of aggradation and degradation from the viewpoint of the geomorphologist. They also introduce into the definition the terms *scour* and *fill*. These are the two terms most likely to be confused with aggradation and degradation.

> "With the rise in stage accompanying flood passage through a river reach, there is an increase in velocity and shear stress on the bed. As a result the channel bed tends to scour during high flow. Because sediment is being contributed from upstream, as the shear decreases with the fall of stage the sediment tends to be deposited on the bed or the bed fills. Channel scour and fill are words used to define sedimentation during relatively short periods of time, whereas the terms degradation and aggradation apply to similar processes that occur over a longer period of time. Scour and fill involve times measured in minutes, hours, days, perhaps even seasons, whereas aggradation and degradation apply to persistent mean changes over periods of time measured in years."

Contrast this with Simons and Senturk (1977) in an engineering text where the following is provided: "A river is stable when the geometry of a cross section is constant in time. If the bottom level increases in elevation the stream bed is aggrading. If the bottom level decreases, the stream bed is subject to degradation." Simons and Senturk leave out the important consideration of the time frame.

For the purposes of this report the Leopold et al. (1964) definitions will be adopted. All bed level changes which occur over time periods less than one or two years will be referred to as *scour* or *fill*. Aggradation and degradation require long time spans. For example, if after a single flood event a channel bed moves downward, scour has occurred. If after three years and several flood events the channel bed consistently moves downward, degradation has occurred.

Spatial perspective also enters into the definition. For the purpose of this report the terms *scour* and *fill* will be associated with changes in bed elevation which take place over distances no greater than one to three channel widths. *Degradation* and *aggradation* will be associated with changes occurring over many channel widths. The perspective in viewing problems will often extend for kilometers both upstream and downstream of a bridge crossing.

The large spatial perspective will minimize discussions of ripples, dunes and other alluvial forms of roughness elements. The roughness elements must be considered when assessing computational methods but will not play a major role in the discussions.

OBJECTIVES AND SCOPE

Objectives

This study has three major objectives. The first objective is to create a data base which is national in scope containing case histories of highway bridge crossings impacted by gradation changes. The second objective is to analyze the data base to determine: (a) the regional extent of any gradation problems, (b) causes of gradation problems; (c) national impact of gradation problems on highway crossings; and (d) mitigative measures and their degree of success or failure. The third objective is to assess the technology available to highway engineers for evaluating gradation problems. The assessment includes ways to recognize gradation problems, to analyze them to take possible mitigative measures at existing structures, and to account for gradation changes in newly designed structures.

Accomplishment of the three objectives has been broken into two phases. The first phase is designed to accomplish the first two objectives and conduct preliminary research for accomplishing the third objective. The second phase completes the study. This interim report is a result of the first phase activity.

Scope

The general scope of the research presented in this report was implied in the definitions of aggradation and degradation. Specifically, the study will concentrate on changes in river gradation which occurs over several years time and which takes place over distances many times the stream width. Local and general scour due to passage of single flood events will not be considered. Likewise the passage of small scale alluvial bed forms such as ripples, dunes, or bars will not be considered (except as required for analytical purposes). Rivers with histories of gradation change will only be considered if they have significantly impacted highway river crossings or have the potential to do so.

Several research items are included in the scope of Phase I. Most important of these items is creation of a case history data base. This data base is developed from records kept by highway engineers throughout the United States. The second item is an analysis of the data base. The analysis is designed to determine the regional extent of gradation problems and their impact on highway crossings. An important aspect of the analysis is to determine the cause of problems. Specifically, the relative magnitude of man-related versus natural problems is determined. Damming and gravel mining are examples of man's impacts. Fault shifts and base level changes on alluvial fans are examples of natural causes.

The final item included in Phase I is an appraisal of the technology related to gradation problems. A complete, annotated bibliography of past and current research is developed. Methods for (a) recognizing gradation problems, (b) calculating rates and limits of gradation changes, and (c) determining design and effectiveness of remedial measures are reviewed and evaluated. The evaluation completed as part of Phase I is designed to identify potentially useful methodology. Documentation of the techniques and specific application to highway problems are deferred to Phase II.

Phase II of the research effort is not covered in this interim report. Included in the scope of Phase II are research activities designed to provide highway engineers with means to include gradation changes in design considerations. Also included are means for recognizing and selecting remedial measures for gradation problems at existing bridge sites.

The design portion of Phase II will include consideration of the effect of gradation changes on water surface profiles, local and general scour, debris loads, and potential for lateral movement. Analytic tools will be presented for computing rates and limits of gradation changes. Example applications will be made using the data base from Phase I.

The remedial measures portion of Phase II will be based on the data base from Phase I. Various methods used to control gradation will be evaluated for use in different circumstances. Cost-effectiveness will be an important factor.

METHOD OF STUDY

The two major research efforts in Phase I were the development of the case history data base and the collection of a bibliography and references for the assessment of technology. The general research procedures used will be described at this time.

Case History Data Base

Sutron worked closely with the Contract Manager to develop the case history data base. The research method was based somewhat on the experience of Brice, Blodgett et al. (1978). The initial search for suitable data was initiated through a letter from the Contract Manager to Regional Federal Highway Administration officials. The regional offices, in turn, requested state highway offices to forward data on bridge sites with gradation problems. These responses were forwarded to the Contract Manager and jointly reviewed with Sutron. States with large numbers of gradation problems were selected for visits. Sutron met with local highway engineers and viewed the sites while collecting all available information on the history, effect, and remedial measures related to the gradation changes. Special forms were used to ensure a uniform level of information from each site. The information from the site visits was catalogued to form the data base.

Assessment of Technology

Assessment of technology required gathering and reviewing a large number of published abstracts and papers. A variety of methods were used to locate information.

A major source of information was the Office of Water Research and Technology's Water Resources Scientific Information Center. A computer search was conducted of all keywords related to gradation problems. These keywords included *scour, fill, aggradation, degradation, erosion*, and a number of others. Over 500 pages of annotated bibliography related to sediment transport were obtained by this method.

A second major source of information was personal libraries. Mr. Stephen Gilje, Contract Manager, provided many useful documents. Drs. Daryl Simons and Stanley Schumm of Colorado State University contributed many references. The principal investigator also provided papers and data.

Several data sources were also used. State highway engineers were quite helpful in providing reference manuals and papers. The principal investigator obtained a number of useful references from other highway researchers through contact at technical meetings. A National Technical Information Service (NTIS) information search similar to that at the Office of Water Research and Technology's Water Resources

Scientific Information Center above also yielded useful references. The U.S. Geological Survey's National Headquarters Library was a valuable source of reference documents.

ORGANIZATION OF REPORT

The remainder of this interim report is divided into five sections. These are *Case Histories, Highway Problems Due To Gradation Changes, Appraisal of Technology, Summary and Conclusions, and Recommendations.* The latter two are self explanatory. The general content of the first three will be described here.

Case Histories

This section of the report summarizes the contents of the case history data base. A complete description of the research procedures and the organization of the data base are provided. The case histories themselves are presented in Appendix A. The regional limits of the gradation problem are defined here.

Highway Problems Due To Gradation Changes

This section of the report presents the analysis of the case history data base. Four major subsections discuss the general analysis approach, man's effects, natural effects, and combined effects. Specific examples from the case history data base as well as tables of sites with similar problems are provided.

Appraisal of Technology

The appraisal of technology section presents a brief summary of the more promising methods for recognizing, analyzing, and solving gradation problems. A three level approach is taken. The first level addresses the question of whether a gradation problem exists. Regional problems are discussed along with techniques to identify degrading and aggrading streams. The second level addresses analysis methods. These range from simple calculations to complex math model studies. The final level presents remedial measures for gradation problems. This portion is based largely on the data base.

CHAPTER II
CASE HISTORY DATA BASE

GENERAL DESCRIPTION

The usefulness and validity of this study depends in large degree on the detailed evaluation of specific aggradation/degradation sites reported as case histories in Appendix A and selected case histories from other reports. Examples of such other reports are Brice, Bloggett and others (1978), Keeley (1967 and 1971), URS/Ken White Company (1975), and the Sulphur River Degradation Study (1976).

RESEARCH PROCEDURES

The request for bridge sites with gradation problems from the state highway departments provided over 200 possible sites. Unfortunately not all states responded. Published reports provided approximately another 75 possible sites that required verification and additional updated historical data. From these 275 possible sites, 110 sites were selected for documentation to accomplish the objectives of the study. Specifically the sites were selected to

- determine the probable causes of gradation changes,
- establish the relative significance of man's activities on river gradation,
- provide a regional description of degrading and aggrading streams,
- determine the highway problems related to gradation changes,
- establish and evaluate guidelines and methods to recognize gradation problems,
- determine and evaluate mitigative measures that have been used by state highway agencies, and
- provide a data base to examine and evaluate methods for prediction of gradation changes required in Phase II.

Very few sites provided all the items listed above. Some sites were selected only to illustrate specific causes of gradation changes both natural and man induced, others were selected because of excellent historical data, and others to illustrate various types of mitigative measures.

All physiographic regions of the United States are represented in the case histories. Consideration of 200 possible sites plus information obtained during the field site visits were necessary to provide a better regional description of degrading and aggrading streams.

Organization of Data Base

The objectives of documenting the case histories involved a consideration of many factors. To standardize data collection and analysis, a standard format for the case histories was used. This is done to ensure all of the relevant factors were considered by each of the several investigators involved in data collection, field site visits, and analysis. The case history format was divided into the following four sections and basically follows the format used by Brice, Blodgett, and others (1978).

Description – Each case history title includes the name of the river being crossed, the designated highway number, and the name of the nearest city or town. A brief description of the geomorphic and river characteristics includes the channel pattern, if it is perennial or an ephemeral stream, the streambed slope, the bed material, the bank shape, the bank material, the channel width, and a statement about the overbank channel and/or floodplain. A brief description of the bridge characteristics includes the year constructed, its length, the angle of skew to the river, its structural foundation, the abutment type, and the type of deck construction. The hydrologic characteristics are briefly described by designating the drainage area above the highway crossing and the bankfull discharge when such information was available.

Gradation Problem – Each case history contains a chronological sequence of events related to the gradation changes. Also listed are the probable cause or causes such as natural changes, man's activities, or a combination of both. The hydrologic and geomorphic implications are discussed by documenting the bed elevation changes. Documentation includes historical data collected at or near the bridge site, photographs, and streambed profile information upstream and downstream of the highway crossing when available.

Countermeasures – Where possible, a chronological summary of mitigative measures is described and their effectiveness evaluated. Photographs were included when available to better illustrate and visualize the problems at highway crossings due to gradation changes. In many cases countermeasures were applied at highway crossings to mitigate other problems. These countermeasures are described in order to evaluate their impact on the gradation problem. (In cases in which no countermeasures were applied at a site, this section is omitted in this report.)

Discussion – This section provides an assessment of the gradation problem in both time and space. An evaluation of the mitigation measures is presented or if no mitigative measures were implemented, recommendations are made. Because many factors are involved at each highway crossing, it was sometimes necessary to discuss other stream problems and other mitigative measures applied at the site along with their impact on the gradation problem.

Sources of Information

Information on the chronological sequence of gradation changes, the bridge characteristics, and mitigative measures was generally obtained from the agency responsible for the bridge. Construction plans, maps and aerial photographs were obtained when available at each site. In several cases useful maintenance information was obtained from district highway offices, but in most districts maintenance records were not adequate to provide the detailed information necessary. Hydrologic and geomorphic information was obtained from publications and files of the U.S. Geological Survey. To fully assess man's activities it was often necessary to obtain supplemental information from other state and federal agencies responsible for the design, construction, and or operation of facilities that have had an impact and influence on gradation or bed elevation changes (dams, gravel mines, etc.).

EXAMPLES OF CASE HISTORIES

Case History 82 is included as an example of the standard format used in documenting the case histories. This is an example of a case in which little information was available from either state or federal agencies. The Highway District Maintenance Section did provide the photograph and had an inspection program that required a determination of the distance between the average streambed and the bridge deck. This information is sufficient to indicate that a serious degradation problem exists and that some mitigative measures should be used to protect the bridge foundation.

Case History 82: North Fork of Walnut Creek at U.S. Highway 62 Near Blanchard, Oklahoma

Description

The North Fork of Walnut Creek is located in McClain County and is a tributary to the South Canadian River. The bridge is 55 m long, concrete piers in channel, wood pile foundations, spill-through abutments, and concrete wingwalls.

The drainage area is 120 km^2. The stream is ephemeral, alluvial with a sand bed. The channel is fairly straight, cut banks, with silt sand banks.

Gradation Problem

Figure 1 illustrates the degradation problem at U.S. Highway 62. Information from maintenance records can be summarized as follows:

Date	Distance Below Deck to Average Streambed (m)
1938	6.4
1950	8.1
4-06-61	8.6
2-10-67	8.9
10-27-69	9.1
3-04-70	9.3
2-11-71	9.3
7-09-73	9.6
7-16-75	9.5
8-24-77	9.6

The degradation problem at this site is due to channel modifications and straightening, as well as a significant change in land use to more productive agricultural land. The degradation is not only impacting this highway crossing but is primarily responsible for caving banks, loss of productive farm land, and debris problems. The channel is 3 to 4 m deeper, 100 to 200 m wider, and unstable laterally as the channel seeks to adjust its slope.

Discussion

The highway department has no plans to protect the bridge from additional degradation.

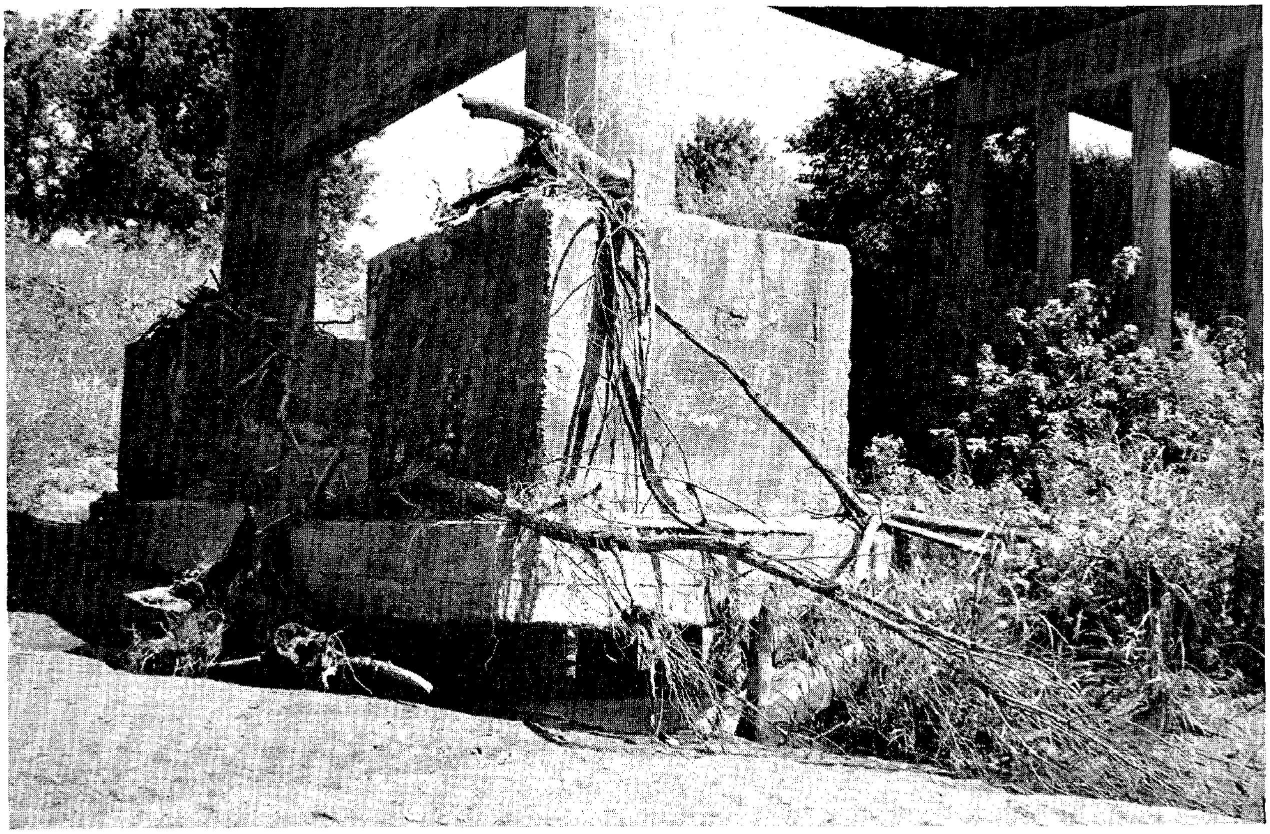


Figure 1. DEGRADATION PROBLEM AT U.S. HIGHWAY 62 NEAR BLANCHARD, OKLAHOMA

Very little information and data exist at this site. The U.S. Geological Survey does have a gaging station downstream just before Walnut Creek joins the South Canadian River.

Case History 68: Niobrara River Near Niobrara, Nebraska

Case History 68 is included as another example of a documented case history. There was so much information available at this site that it was necessary to eliminate much of the data and details for this presentation as a case history. This aggradation problem is not uncommon in backwater situations although this specific case is a rather extreme example. Both state and federal agencies had detailed information available.

This gradation problem not only resulted in moving the highway crossing, but the moving of the City of Niobrara, Nebraska.

Description

The reach of the Niobrara River of interest is in Knox County. The highway crossing of the Niobrara River is State Road 12 Bridge about 1.6 km south of Niobrara. It is of equal importance to discuss in detail the Missouri River. Its confluence with the Niobrara River is only about 2.4 km downstream of SR-12.

The natural state of the Missouri River near its confluence with the Niobrara is best described by its serpentine channel alignment that meanders at random across an alluvial floodplain that is entrenched between steep valley bluffs. The bankfull flow channel averaged about 610 m in width but was generally divided into several channels by large islands or lower elevation sandbars (Figure 2). The channel's general shape was rectangular. The floodplain bank heights averaged between 3.7 and 4.6 m, with a channel capacity of about 4249 m^3/sec. At normal stages, the water surface slopes generally varied between 0.00815 and 0.0002; channel widths, from 210 to 460 m; and mean depths, between 1.2 and 3.4 m. The greater widths and shallower depths occurred in the diagonal crossings where the channel meandered between bluff contacts. Channel bed forms were constantly in a state of change due to the shifting movements of ripples, dunes, and bars. Although this movement would produce characteristic, seasonal shifts in the stage-discharge relationship, the long-term rating at

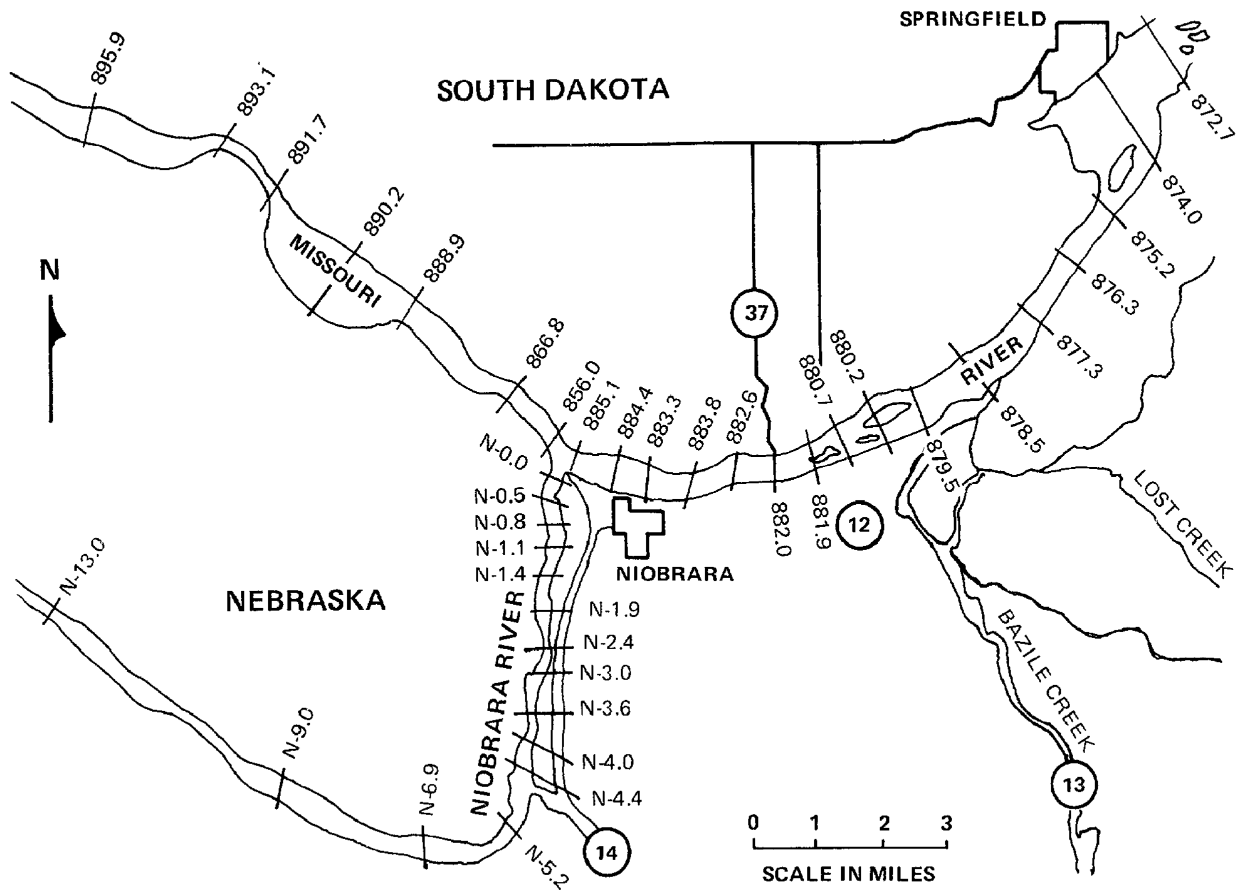


Figure 2. CONFLUENCE OF MISSOURI AND NIOBRARA RIVERS

station locations remained relatively consistent. The natural sediment transport capability of Missouri River flows was both great and variable. Annual sediment load volumes for the Missouri River near Niobrara probably ranged between 72.7 and 218.2 million MT with an average near 134.5 million MT. The particle size distribution of the suspended sediments averaged about 30 percent sand, 30 percent silts and 40 percent clays. The bed material sediments generally ranged within the very fine to fine sand sizes. A normal D_{50} size was 0.20 mm with D_{10} and D_{90} being 0.08 and 0.30 mm, respectively.

The Niobrara River is, in contrast, a shallow braided stream. The total channel width generally varies from 300 to 460 m but the flow is divided into numerous separate channels by barren or sparsely vegetated sandbars and higher elevation islands. Note the braided conditions in Figure 3. The heights of sandbars above low flow stages are usually less than 0.3 to 0.46 m. The height of the channel bank, floodplain and island elevations range between 1.2 and 1.8 m above low flow stages; however, the floodplain contains many remnants of old flow channel chutes which are, at times, subject to inundation of less than bankfull stages. Natural levees of slightly higher elevation along both the active and older chutes are also common. The average slope of the lower Niobrara River over long reaches appears to be quite uniform at about 0.0015, but short reach slopes can vary quickly over a wide range as shifts in the flow channel shape or alignment occur.

The sands which comprise the streambed of the Niobrara are, like the Missouri River, quite uniform in size but slightly coarser. Their range from fine to coarse sand makes them easily transportable even under the energy gradient of low flows. This characteristic is, of course, associated with a braided stream and accounts for the lack of any stable stage-discharge

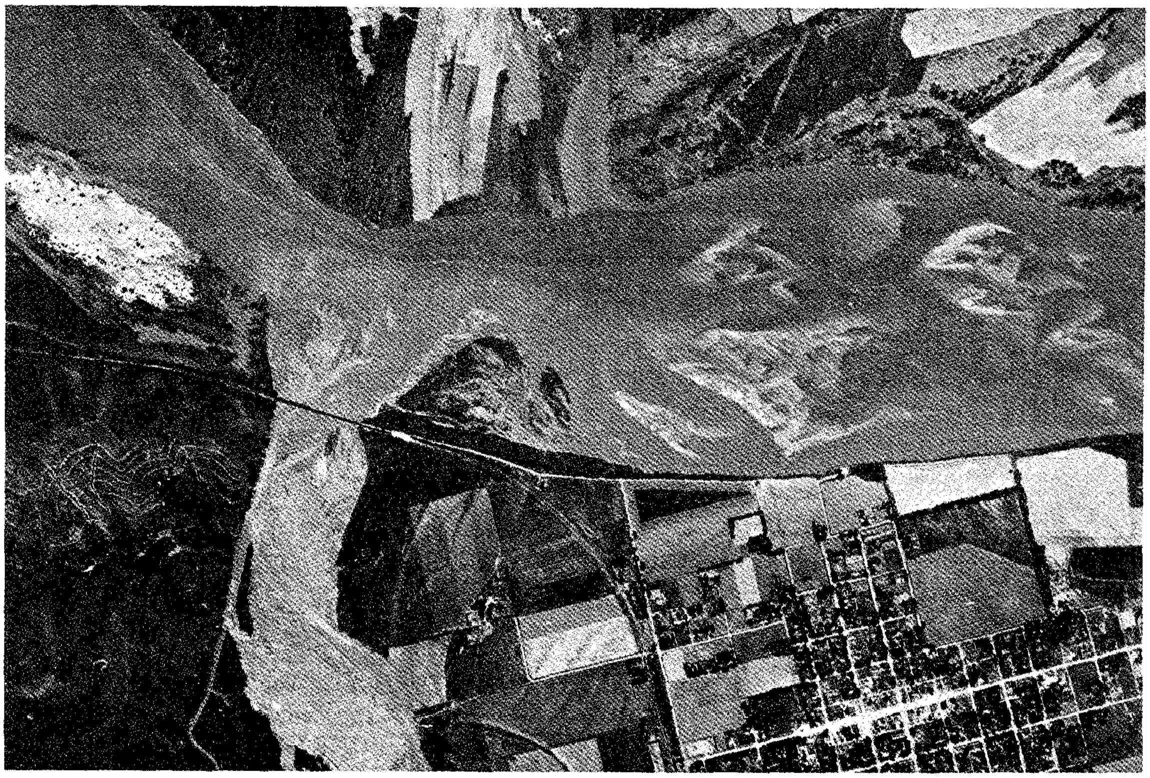


Figure 3. EXAMPLE OF ACTIVE DELTA GROWTH (JUNE 1961)

relationship over the range of base flows. Year round, this base flow varies between 28.3 and 56.6 m^3/sec. Spring snowmelt runoff in March, combined with ice jams, accounts for maximum stages and peak flows, but the greater volume is sometimes produced during late spring and early summer. Table 1 presents a summary of experienced discharge variations for the Niobrara River near Verdel, Nebraska, for the 20-year period 1953-1973. (The time increments shown will remain consistent in later tables to permit a comparative assessment of variations in stream and sediment discharge, channel dimensions, and deposition volumes).

The long-term, average annual sediment load of the Niobrara River is estimated at 2,636,363 MT. This estimate is based upon a limited record of sampling measurements where total suspended sediment load computations provided a relationship with annual runoff volumes and permitted an extrapolation for a 41-year flow record. It correlates very well with the volume of deposited sediments measured by hydrographic surveys in the Missouri River channel and Lewis and Clark Lake. Unlike the relatively constant annual runoff volumes, the annual sediment volumes vary by a factor of two or more. The peak flood discharges account for some of this variance, but high transport rates during periods when moderate flows produce sustaining scour capability may be an equal or greater influence. During normal flow periods, the transport rates during periods when moderate flows produce sustaining scour capability may be an equal or greater influence. During normal flow periods, the transport rate of sand is near 75-80 percent, silt ranges from 10 to 20 percent, and clays usually less than 10 percent. However, during peak flows the wash load will at times dominate with the sand contribution dropping to 25 percent or less. The bed material sizes probably increase with discharge, but the average D_{50} size is about 0.25 mm with the D_{10} and D_{90} percent finer being 0.15 and 0.4 mm, respectively. Gravel size particles or larger are very uncommon. Table 2 presents a summary of estimated suspended sediment discharges for the Niobrara River near Verdel, Nebraska, for the period 1953-1973.

The first step toward regulation of the Missouri River started with construction and closure of Fort Peck Dam in Montana in 1937. Although it provided regulation of the extreme upper basin, its influence on the flow duration trends of the Missouri near Niobrara were insignificant. The next two quick steps, the closure of Fort Randall in 1952 and Garrison in 1953, produced a decisive and positive change in the flow regime to complete regulation. Later, closure of Oahe in 1958 and Big Bend in 1963 completed a regulation

Table 1. VARIATIONS IN STREAM DISCHARGE

Stream	Stream Location	Period (Water Year)	Total Runoff Volume (millions of m^3)	Mean Annual Discharge (m^3/sec)	Maximum Mean Daily Discharge (m^3/sec)
Missouri	Below Fort Randall Dam	1953-1955	60,679	649	2,975
		1956-1960	79,755	510	1,431
		1961-1965	74,605	479	1,088
		1966-1970	115,905	744	1,473
		1971-1973	84,560	904	1,431
Niobrara	Verdel	1953-1955	4,981	48	445
		1956-1960	7,523	49	711
		1961-1965	7,850	50	470
		1966-1970	6,595	42	283
		1971-1973	4,080	44	184

capability for storage of over 92,695 million m^3 of water. With the closure of Fort Randall and Garrison, an immediate need developed for the initial filling of almost 26,833 million m^3 of operational storage from an anticipated mean annual supply of about 29,272 million m^3. Under normal hydrologic conditions this filling aspect would induce some minor downstream flow restrictions but an orderly accumulation of operational storage in the system was probably within a few years. But coincident with this need, in 1954 there began a 7-year drought over the upper basin which effectively extended the filling period to 1968. Abnormally low inflow rates occurred in 1954, 1955, 1958, and 1961.

Releases from the reservoir system via Fort Randall were held to a minimum during these years. Peak discharges range up to 1275 m^3/sec during periods of maximum power demands but nighttime releases were frequently zero. During the March-to-November open-water season, the mean daily flow of the Missouri River passing the confluence of the

Table 2. ESTIMATED VARIATIONS IN SUSPENDED SEDIMENT DISCHARGE

Stream	Stream Location	Period (Water Year)	Total Suspended Sediment Discharge (MT)	Annual Variations (MT)		
				Mean	Maximum	Minimum
Missouri	Range 893.1	1953-1955	2,750,515	907,185	1,456,939	635,936
		1956-1960	2,168,172	435,449	830,981	198,673
		1961-1965	1,784,432	353,802	459,943	96,162
		1966-1970	7,086,020	1,415,208	2,052,959	927,142
		1971-1973	8,145,612	2,721,554	3,642,347	1,424,280
Niobrara	Verdel	1953-1955	8,119,303	2,703,411	3,356,584	1,814,369
		1956-1960	11,394,240	2,277,034	3,039,068	1,460,567
		1961-1965	13,535,196	2,703,411	4,989,516	1,678,292
		1966-1970	9,298,644	1,859,729	2,104,669	1,632,933
		1971-1973	5,996,491	1,995,806	2,394,968	1,723,651

Niobrara River seldom exceeded 992 m^3/sec. Winter flows were consistently less than 283 m^3/sec. It was not until 1969, when it became necessary to evacuate flood control storage in the upstream system, that releases exceeded the 1415 m^3/sec level, or about an expected 5-year flow event. The magnitude of these discharges plus the need demonstrated the influence of the Niobrara delta growth on the main stem channel capacity.

Gradation Problem

The regulated flow regime of the upstream reservoir system and the start of the Niobrara aggradation or delta growth began one year after the historic 1952 flood of record flushed the Missouri River channel clean at the confluence. For the next 17 years, until 1969, the mean daily flow of the Missouri passing Niobrara was usually 849 m^3/sec or less. However, during the first decade of this period, above-normal flows from the Niobrara Basin, including the flood of record, continued to add sediments to the delta at an average growth rate of about 0.55 million m^3 per year. This produced a deltaic blockage of the Missouri River channel for several kilometers downstream from the Missouri-Niobrara confluence. The Figure 3 photo depicts typical conditions during an active delta growth period. The resultant effect of the shallow, weir-like delta produced (1) a progressive upward shift of at least 1.5 m in the Missouri River rating curve at Niobrara; (2) a reduction in the channel capacity from about 3396 to 1698 m^3/sec at this same point; and (3) significant backwater influences at upstream points along both the Missouri and Niobrara Rivers. The first consequence of this delta became apparent after the mid-1960's when adverse groundwater levels were experienced within the town of Niobrara and at the nearby Niobrara State Park. The next impact occurred during the late summer and through the fall of 1969 when it became necessary, for the first time, to evacuate water from upstream reservoir flood control storage zones prior to winter in preparation for the next flood season's runoff. Sustained releases in the 1415 m^3/sec range produced near bankfull stages and the inundation of some 7.1 km^2 of lower elevation flood plain lands. Similar inundations occurred again in 1971 and 1972 for the same reasons.

The most sensitive indicators for assessing the delta growth have been shifts in the Missouri River stage-discharge relationship at Gage 884.2. This gage is strategically located just downstream of the Missouri-Niobrara confluence near the apex of any delta growth.

The changes in channel dimensions which account for such stage-discharge trends have been documented by periodic surveys of channel ranges. These cross-sectional measurements provide the basic means for assessing variations in hydraulic parameters and sediment deposition volumes. Tables 3 and 4 present comparisons of such measurements.

Assessment of the data presented in Tables 1 through 4 provides several interesting insights related to the rate of growth, attainment of a stability level and the sensitivity of this equilibrium to change. Reference is made to a composite summary on Table 5 for the following interim evaluation on these items. It is intended that final study assessments, to be presented in a comprehensive manner in a future paper, will amplify this discussion and produce quantitative conclusions.

(1) The combination of greater than normal sediment contributions from the Niobrara drainage and less than normal releases from the Missouri reservoir system strongly influenced the rate of early delta growth. During the periods when the Niobrara produced from 85 to 90 percent of the total sediment inflow, the growth rate of the delta remained relatively constant at about 550 thousand m^3/sec per year. However, this rate accounts for only 25 percent of the available sediment supply. These values probably establish near maximum rates for expected delta growth and its trap efficiency.

(2) The relatively stable channel widths observed on both the Missouri and Niobrara while deposition depleted the channel capacity were were not anticipated. A much greater degree of change was expected. A cursory review of additional data indicates that the average channel-forming velocities immediately downstream of the confluence were significantly higher. This could account for the coarsening of the D_{50} bed material sizes noted at range 884.4 in Table 4. The higher width-depth ratios indicate an expected increase in bed material transport but total load computations are not sufficiently complete to isolate the significance of this bed coarsening.

(3) The delta equilibrium appears to be most sensitive to variances in Missouri River discharges. Stage-discharge trends during the higher flow periods after 1969 indicate the possiblity of delta scour or at least more efficient channel conditions. Lower deposition rates also tend to confirm this even though the upstream Missouri

Table 3. VARIATIONS IN CHANNEL DIMENSIONS

Range	Date	Bank Top Elev. (MSL) (m)	Cross-Section			Width-Depth Ratio
			Area (m^2)	Width (m)	Depth (m)	
M-885.6	Oct 1955	372	2700	835	3.23	258
	Jul 1960		2478	849	2.91	291
	Aug 1965		2338	850	2.74	309
	May 1970		2346	859	2.73	314
	Sep 1973		2311	890	2.60	343
M-884.4	May 1955	372	3427	900	3.80	237
	Jul 1960		2802	946	2.96	319
	Aug 1965		2286	978	2.34	418
	Aug 1970		2185	986	2.22	445
	Sep 1973		1986	984	2.02	487
M-882.0	May 1955	370	2221	716	3.10	231
	Jul 1960		1968	718	2.74	262
	Aug 1965		1339	718	1.87	385
	Aug 1970		1368	720	1.89	379
	Sep 1973		1351	717	1.88	381
N-0.0	Sep 1956	373	1086	388	2.80	138
	Jul 1960		935	389	2.40	162
	Aug 1965		838	389	2.15	181
	Aug 1970		727	390	1.87	209
N-0.8	Sep 1956	373	1656	702	2.36	298
	Jul 1960		1487	707	2.10	336
	Aug 1965		1207	715	1.69	424
	Aug 1970		1027	718	1.43	502

River channel is transporting significantly greater sediment loads. Defining the hydraulic combinations that trigger a shift in the bed material transport capability from deposition to scour will provide the much needed key to predicting the degree of future delta growth.

Discussion

The dynamic balance in sediment transport that occurred under a natural regime at the confluence of the Missouri and Niobrara Rivers was dependent on the frequency, magnitude, and duration of main stream flows. Regulation of these flows after 1952 by a system of upstream reservoirs interrupted this equilibrium and permitted the tributary sediment contributions to accumulate in the Missouri River channel. The growth of this Niobrara delta was accelerated due to two concurrent factors; first, below normal runoff from the upper Missouri River basin during the "filling" of operational reservoir storage and second, above normal sediment yield from the Niobrara drainage. The resultant effect has been a significant reduction in channel capacity with attendent consequences of operational restrictions, frequent low land inundation and higher groundwater levels.

Table 4. VARIATIONS IN CHANNEL DEPOSITION

Stream Reach	Period	Deposition Volume (millions of m^3)	Deposition Rate (millions of m^3/sec/yr)	Bed Material Size D_{50} (mm)
M-885.6 to M-884.4	1955-1960	0.81	0.15	0.26
	1960-1965	0.63	0.12	0.27
	1965-1970	0.09	0.02	0.20
	1970-1973	0.22	0.07	0.26
M-884.4 to M-882.0	1955-1960	1.68	0.31	0.31
	1960-1965	2.19	0.40	0.31
	1965-1970	0.13	0.03	0.30
	1970-1973	0.41	0.13	0.32
N-0.0 to N-0.8	1955-1960	0.20	0.05	0.27
	1960-1965	0.24	0.04	0.25
	1965-1970	0.19	0.03	0.29
	1970-1973	0.11	0.03	0.23

Field measurements of sediment and hydraulic parameters have documented the growth of this delta over a 20-year period. Study assessments of this data are not complete but preliminary results indicate (a) the probable maximum growth rate to be expected would be 550,000 and m^3 per year with a trap efficiency factor of 25 percent; (b) surprisingly, relatively stable channel widths have prevailed, while the channel capacity has been reduced by at least 50 percent; and (c) delta scour has probably occurred due to high releases from the reservoir system, but the accompanying variances in bed material transport have not, as yet, been quantified. It is planned that a comprehensive report of study findings, including the complete documentation of field data, will appear in a future addition to the Missouri River Division Sediment Series publications.

Table 5. RELATIONSHIP OF STREAMFLOW AND SEDIMENT DISCHARGES TO DELTA GROWTH

Period	Average Annual Missouri River Discharge (m^3/sec)	Total Sediment Discharge (millions of m^3/sec)	Delta Growth: Volume Change (millions of m^3/sec)	Delta Growth: Deposition Rate (millions of m^3/sec/yr)	Sediment Inflow Deposited (%)
1953-1955	697	8.3	1.0	0.5	11.8
1955-1960	558	10.3	2.7	0.5	26.0
1960-1965	530	11.7	3.0	0.6	26.1
1965-1970	785	12.5	0.4	0.08	3.3
1970-1973	946	10.8	0.7	0.2	6.9
Total	683	53.6	7.8	0.4	14.7

LIST OF CASE HISTORIES IN THIS REPORT

Table 6 is a complete list of the case histories documented in Appendix A. Each case history title includes the name of each river being crossed, the designated highway number and the name of the nearest city or town.

These 110 case histories are a significant portion of the existing data base on gradation problems and their impact on highway crossings.

There was not sufficient time or funds to document and visit all the potential case histories provided by the state highway departments. However, these data are an important part of the data base, and were valuable in making an assessment of the regional extent of gradation problems. This unpublished information is summarized by state in the following sections.

OTHER AVAILABLE DATA

Alaska

Numerous streams in Alaska are subject to rapid changes in bed elevation. In fact most streams are aggrading in one part of the reach and degrading in another. The majority of the active streams are of glacial origin, and many have been subject to glacial lake breakouts. Documentation in most cases will probably be somewhat meager and consist of maintenance records for removal of excess bed material or for supplying rip-rap to protect the local structure.

The following list consists of streams that have been the most troublesome and have come to the attention of the state headquarters. A cause has been included in cases in which a cause was known.

- *Jack River at Cantwell* – aggrading
- *Cathedral Rapids* – Alaska Highway – aggrading
- *Sheep Creek on Richardson Highway* – landslides and glacial lake breakouts
- *Lemon Creek* – Glacial Highway in Juneau – degradation caused by aggregate removal up and downstream
- *American Creek 1 and 2 on Taylor Highway* – degradation caused by human activity constricting the stream (probably no records)
- *Chena River* – degradation – rapid channel shifts. This stream has caused considerable problems to the highway and to structures.

The major streams systems, Matanuska River, Knik River, and Copper River, could also be included. They are used extensively as a seemingly inexhaustible aggregate source. This removal, frequently in the vicinity of bridges, has caused undermining of footings and channel shifts.

California

There is continuing aggregate mining in many California streams. Although public agencies are gaining some control over it, there are sites that have had degradation problems and sites that need watching. Some examples of these are

- Cache Creek in Yolo County at Interstate 5
- Big Tujunga Wash in Los Angeles County at Interstate 210
- Lytle Creek in San Bernardino County at Interstate 15.

Some of the following sites have more than one stream-related problem but are listed here to provide examples of streams with changing or shifting alignment and resultant profile changes:

- Santa Clara River in Ventura County at Highway 118
- Myers Creek in Imperial County at Interstate 8.

The following are examples of locations where recent events have changed the stream characteristics (burned watershed, washed out stabilizer, watershed damaged by heavy rainfall):

- Mejico Creek in Ventura County at Highway 118
- Whitewater River in Riverside County at Interstate 10
- Castaic Creek in Los Angeles County at Interstate 5.

Table 6. DOCUMENTED CASE HISTORIES

Case History	Location
1	Rattlesnake Wash at I-40 Kingman, Arizona
2	Oraibi Wash at SR-264 near Old Oraibi, Arizona
3	Little Colorado River at U.S.-666 near St. Johns, Arizona
4	Little Colorado River at SR-77 near Holbrook, Arizona
5	Fries Wash at I-40 near Kingman, Arizona
6	Quartzite Canyon at U.S.-60 Arizona
7	Santa Cruz River at I-19 near Sahuarita, Arizona
8	Rillito Creek at I-10 near Tucson, Arizona
9	Rillito Creek at U.S.-89 near Tucson, Arizona
10	Avondale Wash at SR-85 near Phoenix, Arizona
11	Holy Moses Wash at U.S.-66 near Kingman, Arizona
12	Walker Creek at U.S.-160 near Mexican Water, Arizona
13	St. Francis River Floodway (Ditches 60 & 61) at U.S.-63 near Marked Tree, Arizona
14	Red River at SH-41 between Forman and Fulton, Arkansas
15	Burnt Cane Lake at S.H.-38-50 near Widener, Arkansas
16	Crow Creek at I-30 near Forest City, Arkansas
17	Sulphur River at U.S.-71 near Fort Lynn, Arkansas
18	Boeuf River at S.H.-144 near Lake Village, Arkansas
19	Stillwater Creek at S.R.-299 near Redding, California
20	Smith River at U.S.-101 near Crescent City, California
21	San Diego River at S.R.-67 near Lakeside, California
22	Cuyama River at S.R.-166 near Santa Maria, California
23	Kelsey Creek at S.R.-89 near Kelseyville, California
24	Mad River at S.R.-299 near Blue Lake, California
25	Hosler Creek at S.R.-96 near Hoopa, California
26	Broaddus Creek at S.R.-20 near Willits, California
27	Wildcat Creek near Ft. Morgan in Morgan County, Colorado
28	15th Street Bridge over the South Platte River, Denver, Colorado
29	Cruz Gulch at U.S.-24 near Colorado Springs, Colorado
30	Little Missouri River at U.S.-22 north of Killdeer, North Dakota
31	Small stream at S.R.-24 south of Fort Yates, North Dakota
32	Tributary to East Fork of the Nishnabotna River at S.H.-37 near Defiance, Iowa
33	Culver Creek Tributary to Boyer River at S.H.-37 near Dunlap, Iowa
34	Mosquito Creek at S.H.-191 near Portsmouth, Iowa
35	Silver Creek at I-80 near Shelby, Iowa
36	Big Whiskey Creek at U.S.-20 near Lawton, Iowa
37	Iowa River at S.H.-14 near Marshalltown, Iowa
38	Allen Creek at S.H.-127 near Manolia, Iowa
39	Graybill Creek at S.H.-92 near Carson, Iowa
40	One Hundred and Two River near Gravity, Iowa
41	Floyd River near Jame, Iowa
42	Kansas River near Bonner Springs, Kansas
43	Stone House Creek, U.S.-24 and U.S.-59 at Williamstown, Kansas

Table 6. DOCUMENTED CASE HISTORIES (Continued)

Case History	Location
44	Middle Fork of Beargrass Creek at I-64, Jefferson County, Kentucky
45	Poor Fork of the Cumberland River at U.S.-119, Harlan County, Kentucky
46	Chadwick Creek at I-64, Boyd County, Kentucky
47	Taylor Creek I-471, Campbell County, Kentucky
48	Pond Creek at U.S.-119, Pike County, Kentucky
49	Amite River at S.H.-37 near Grangeville, Louisiana
50	Cool Creek at I-55 near Kentwood, Louisiana
51	Whitten Creek at S.R.-37 at Baywood, Louisiana
52	Lawrence Creek at S.R.-16 near Franklinton, Louisiana
53	Comite River at S.H.-64, East Baton Rouge Parish, Louisiana
54	West Pearl River at I-59, St. Tammany Parish, Louisiana
65	East Pearl River at I-10, St. Tammany Parish, Louisiana
56	Mississippi River at I-494, South St. Paul, Minnesota
57	Yalobusha River at S.H.-9 near Calhoun City, Mississippi
58	Perry Creek at I-55 near Grenada, Mississippi
59	Batupan Bogue at S.H.-8 at Grenada, Mississippi
60	Black Creek at S.R.-7 near Avalon, Mississippi
61	Pigeon Roost Creek at S.R.-305 near Lewisburg, Mississippi
62	Homochitto River at S.R.-33 at Rosetta, Mississippi
63	Tillatoba Creek at S.H.-35 at Charleston, Mississippi
64	Kimsey Creek at I-29 near Mound City, Missouri
65	Middle Fork Grand River S.H.-46 near Grant City, Missouri
66	Davis Creek at I-70 near Sweet Springs, Missouri
67	West Gallatin River at I-90 near Bozeman, Montana
68	Niobrara River at S.R.-12 near Niobrara, Nebraska
69	Muddy Creek at S.R.-50 in Otoe County, Nebraska
70	South Fork Little Nemaha River at S.R.-50 near Cook, Nebraska
71	Logan Creek at S.R.-9 near Pender, Nebraska
72	Elk Creek at S.R.-15 near Jackson, Nebraska
73	Little Nemaha River County Road near Unadilla, Nebraska
74	Small Creek at U.S.-73 south of Decatur, Nebraska
75	Papillion Creek at S.R.-64, U.S.-6, S.R.-92, I-50, S.R.-370 near Omaha, Nebraska
76	East Branch Pemiqewasset River near Lincoln, New Hampshire
77	Arroyo Seco at U.S.-84 near Espanola, New Mexico
78	Chupaderos Arroyo at S.R.-30 near Espanola, New Mexico
79	Washes at S.R.-78 near Velarde, New Mexico
80	White Water Creek at U.S.-180 near Glenwood, New Mexico
81	Caddo Creek at S.H.-53 west of Milo, Oklahoma
82	North Fork of Walnut Creek at U.S.-62 near Blanchard, Oklahoma
83	Wallowa Lake Bridge over Grande Ronde River near Island City, Oregon
84	Pacific Highway West Bridge over the Willamette River near Harrisburg, Oregon
85	Mt. Hood Highway Bridge over White River, Oregon
86	South Fork Forked Deer River at U.S.-51 near Halls, Tennessee

Table 6. DOCUMENTED CASE HISTORIES (Continued)

Case History	Location
87	Cane Creek at U.S.-51, S.R.-19, CR-8044, near Ripley, Lauderdale County, Tennessee
88	North Sulphur River at F.M-68 near Paris, Texas
89	Rowdy Creek at F.M.-38 near Paris, Texas
90	Merrill Creek at S.R.-34 near Ladonia, Texas
91	Merrill Creek at F.M-1550 near Ladonia, Texas
92	Baker Creek at F.M-1550 near Ladonia, Texas
93	Mallory Creek at F.M.-137 near Howland, Texas
94	Cherry Creek at F.M-1184 near Howland, Texas
95	Weber River at I-80 N between Echo and Riverdale, Utah
96	Salina Creek at I-70 near Salina, Utah
97	Virgin River at I-15 near Bloomington, Utah
98	East Fork of the Virgin River at U.S.-89 near Mt. Carmel, Utah
99	Boxelder Creek at I-25 near Glenrock, Wyoming
100	Carpenter Creek at S.R.-192 near Sussex, Wyoming
101	Cole Creek at S.R.-192 near Sussex, Wyoming
102	Unnamed Draw on Kaycee - Mayoworth Road near Kaycee, Wyoming
103	Elk Creek at S.R.-789 near Basin, Wyoming
104	Alkali Creek at Ralston-Badger Basin Road near Powell, Wyoming
105	Old Badwater Bridge over Badwater Creek near Shoshone, Wyoming
106	Tenmile Draw Creek at I-80 near Point of Rocks, Wyoming
107	Cheyenne River at S.R.-63 south of Eagle Butte, South Dakota
108	Big Elk Creek Bridge #47-080-535 at I-90 South Dakota
109	Polo Creek Bridge #41-162-082 at I-90 South Dakota
110	Bear Butte River Bridge #47-015-427 at I-90 South Dakota

The following are locations either where aggradation has been a problem or where it is expected to become one:

- Bluff Creek in Humboldt County at Highway 96
- Cache Creek in Kern County at Highway 58
- Indian Creek in Trinity County at Highway 299
- Canyon Creek in Trinity County at Highway 299.

Colorado

In addition to the sites reported in the case histories, three other aggradation sites were reported in Colorado. They are

- Sand Creek at I-270 parallel to Frontage Road in the City and County of Denver;
- Wash at I-70 four miles northwest of Debeque in Mesa County; and
- State Draw Bridge Crossing S.H. 139 20.9 km south of Rangely in Rio Blanco County.

The drainage area of the Sand Creek at I-270 site is 414 km^2, and the estimated 100-year flood is 1133 m^3/sec. This channel has been constricted by the highway on the right bank and by development on the left. Extensive gravel and sand mining has lowered the channel bottom as much as 6 m. The cost of remedial repair of retaining walls, cross sewer lines and bridge piers, exceeded $1,000,000 in 1974. Five check dams were placed across the channel in 1974. The channel material is sand, overlying clay.

The drainage area of Wash at I-70 is 6.7 km^2, and the estimated 50- and 100-year floods are 24.4 m^3/sec and 28.3 m^3/sec, respectively. This channel was straightened and constricted by the highway in 1951. The channel has degraded about 2 m. It has a slope of 0.02. The bed material consists of some 45 cm rocks and considerable fines. The channel will be reworked, including placement of check dams during the proposed I-70 construction. Numerous other channels in the vicinity are degrading or aggrading, depending upon their location within the basin.

The drainage area for State Draw Bridge south of Rangely is 14 km^2, and the estimated 25- and 100-year floods are 45.3 m^3/sec and 93.5 m^3/sec, respectively. This wash is in a transition reach from steep rock outcrop terrain to the well-defined degrading valley of Douglas Creek. The country is arid with peak flows resulting from rainfall. Very little degradation is observed at the highway bridge. However, approximately 90 m downstream a headcut in excess of 6 m is occurring. Surface bed material ranges from gravel to fine.

Delaware

The following four highway crossings in Delaware were identified as having minor gradation problems:

- Shellpot Creek at Philadelphia Pike
- Matson Run at I-95
- Christina River at the I-95, I-495, and I-295 interchange
- White Clay Creek at Harmony Road.

Iowa

Degradation of some Iowa streams is severe and has resulted in the expenditure of a substantial amount of highway funds. The degradation is a result of extensive channel straightening which took place in the 1920s and before. A partial listing of the streams where degradation has occurred at numerous highway crossings would include

- Soldier River,
- Willow River,
- East and West Boyer Rivers,
- Mosquito Creek, and
- Silver Creek.

Degradation of up to 6 m has been experienced on some streams.

Aggradation is a less common problem, but it has occurred at the base of the Loess Bluffs in western Iowa and on flat reaches of some of the small streams that are tributary to the Missouri River. It has also been experienced on some tributary streams to the 102 River in Taylor County.

Kentucky

Numerous sites in Kentucky have gradation problems. Aggradation and degradation problems are primarily due to man's activities such as dredging, channel straightening, strip mining, and in-stream mining. The sites of interest are as follows:

County	*Road*	*Stream*
Barren	Cumberland Parkway	So. Fork of Beaver Creek
Carroll	I-71	Mill Creek
Carter	KY-7	So. of Grayson
Clark	I-64	Little Stoner Creek
Clark	I-64	Stoner Creek
Franklin	I-64	So. Benson Creek
Fulton	Purchase Parkway	Bayou de Chien
Hardin	Bluegrass Parkway	Younger Creek
Harlan	US-421	Clover Fork & Martins Fork
Jefferson	I-64	Floyds Fork
Jefferson	I-264	Glenview Ditch
Kenton	KY-17	Horse Branch
Magoffin	KY-1090	Licking River
Pike	US-23	Shelby Creek
Powell	Mountain Parkway	Red River
Pulaski	KY-80	Flat Lick Creek
Rockcastle	I-75	Long Branch
Rowan	I-64	Triplett Creek
Shelby	I-64	Guist Creek
Whitley	I-75	Clear Creek
Whitley	I-75	Jellico Creek
Woodford	I-64	Elkhorn Creek

Maryland

In Maryland, major degradation problems occurred at:

- Little Paint Branch at I-95;
- Manokin River at U.S. 13; and
- Gwynns Falls at I-695.

Additional sites with minor aggradation problems are as follows:

District 3:

- Booze Creek at I-495, Box Culvert.
- Booze Creek at Maryland Route 190, Box Culvert.
- Cabin John Branch at Maryland Route 190, Box Culvert.
- Tributary Little Falls Creek at Maryland Route 190, Box Culvert.
- Rock Creek at Cedar Lane, part of I-495.
- Rock Creek at Maryland Route 185 Bridge.
- Tributary Rock Creek at Maryland Route 185, Box Culvert.
- Hensen Creek at I-95, Box Culvert.
- Indian Creek at Maryland Route 434, Berwyn Road Bridge.
- Northwest Branch at Maryland Route 500 Bridge.
- Northwest Branch at Maryland Route 410 Bridge.
- Northwest Branch at Maryland Route 193 Bridge.
- Paint Branch at Maryland Route 193 Bridge.
- Paint Branch at I-95/I-495, various box culverts within the interchange.
- Paint Branch at I-95, Box Culvert.
- Paint Branch at Cherry Hill Road, County Box Culvert.

District 6

Garrett County

- Youghiogheny River – in the area where U.S. 48 and Maryland 42 cross the Youghiogheny.
- Casselman River – in the area of the U.S. 48 and U.S. 40 crossing.

Washington County

- Antietam Creek
- Conococheague Creek

District 7

- Maryland Route 75 over Linganore Creek in Frederick County.

Montana

The following sites are submitted for possible study of aggradation/degradation under the research study as requested:

- *Madison River.* Until three or four years ago serious maintenance and flooding problems were encountered along the Madison River immediately below Quake Lake due to aggradation and degradation. The problems are supposed to have been minimized by structural changes made at the highway crossing and by controlling discharges in the river.
- *Spring Creek.* Degradation has been a problem in Spring Creek at the highway crossing just north of Lewistown. The Soil Conservation Service is now working on a project to control the degradation.

Aggradation has also created problems at the Kennedy Creek crossing on U.S. 89 near Babb, the Landers Fork crossing on Montana 200 near Lincoln, and the Teton River crossing on Secondary 223 near Fort Benton. Two failures have occurred at the Kennedy Creek Crossing.

Oregon

The State Department of Transportation office in Portland, Oregon, identified two stream crossings where degradation or aggradation has caused problems:

- *Small Creek* – North Shore Road Crossing, Olympic National Park.
- *Ipsut Creek* – Carbon River Road Crossing.

The State Department of Transportation office in Salem, Oregon, indicated significant bed elevation changes at the following sites:

- Columbia River Bridge at Astoria
- Deschutes River Bridge on I-80N
- Homestead Bridge on the Rogue River, I-5
- McKenzie River Bridge, I-5
- Siuslaw River Bridge at Florence, Coast Highway
- Oregon Slough Bridge at Portland, I-5
- Marquam Bridge on Willamette River (Portland), I-5.

Washington

In general terms, Washington's rivers suffer from the following conditions:

- The upper reaches of the glacier-fed streams are degrading.
- The lower reaches of the coastal rivers are aggrading. Consequently, the Corps of Engineers is having to maintain navigable channels by dredging.

The following rivers have streambed elevation changes that impact highway crossings:

- Palouse River
- Yakima River
- Chehalis River
- Walla Walla River
- Snohomish River
- Upper Columbia River
- Deschutes and Nisqually Rivers.

DATA OBTAINED FROM OTHER REPORTS

The remaining portion of the data base was obtained from published reports. Brice, Blodgett and others (1978) documented 39 case histories of gradation problems. Table 7 is a list of the sites documented in *Countermeasures for Hydraulic Problems at Bridges,* Volume II, "Case Histories for Sites I-283." These documented case histories provided additional information about the impact and extent of streambed elevation changes on highway crossings.

Four additional publications provided detail documentation on gradation problems. These included two reports by Joe W. Keeley (1967) and (1971), where 28 case histories of general highway problems in Oklahoma are documented. Several of these case histories are highway crossing problems resulting from streambed elevation changes.

A third report was entitled *The Sulphur River Degradation Survey, District 1, Fannin Delta and Lamar Counties, Texas.* The report was prepared by the State Department of Highways and Public Transportation, Paris, Texas (1976). The report documents several case histories of degradation from 1930 to 1976.

The fourth report is entitled *Bridge Foundation Investigation and Scour Study – South Platt River and Cherry Creek at Denver Colorado.* The report was prepared by URS/Ken R. White Company, Denver, Colorado (1975).

Several other reports provided documentation on an aggradation and degradation site and are listed in the Annotated Bibliography, Appendix B.

Table 7. DOCUMENTED CASE HISTORIES OF GRADATION PROBLEMS FROM BRICE, BLODGETT AND OTHERS (1978)

Site No.	Location
1	Cache Creek at I-505 near Madison, California
7	Stony Creek at I-5 near Orland, California
24	Yuba River at S.R.-20 near Smartville, California
27	Fishing Creek at L.R.-19026 at Light Street, Pennsylvania
39	Trinity River at AT and SF Railroad Bridge near Lavon, Texas
42	Fishing Creek at S.R.-487 at Orangeville, Pennsylvania
52	Pigeon Roost Creek at S.R.-305 near Lewisburg, Mississippi
85	Sand Creek at Quebec Street Bridge and I-270 at Denver, Colorado
88	Henrys Fork at S.R.-88 near Rexburg, Idaho
90	Boise River at Fairview Avenue at Boise, Idaho
123	Grande Ronde River at S.R.-82 at Island City, Oregon
125	Cow Creek at I-5 near Azalea, Oregon
148	Merrill Creek at F.M.-1550 near Ladonia, Texas
159	Boeuf River at U.S.-82 near Lake Village, Arkansas
168	Pfeiffer Creek at S.R.-25 near Batesville, Arkansas
170	Red River at S.R.-41 near Forman, Arkansas
1731	Sulphur River at U.S.-71 near Fort Lynn, Arkansas
174	Homochitto River at S.R.-33 at Rosetta, Mississippi
176	West Fork Crooked Creek at S.R.-206 near Gaither, Arkansas
178	Soldier River at S.R.-37 at Soldier, Iowa
179	Soldier River at Monona County Bridge near S.R.-183 1.5 miles north of Soldier, Iowa
180	East Nishnabotna River at U.S.-34 near Red Oak, Iowa
181	East Nishnabotna River at S.R.-48 near Red Oak, Iowa
193	Lawrence Creek at S.R.-16 near Franklinton, Louisiana
198	Whitten Creek at S.R.-37 at Baywood, Louisiana
205	Mississippi River at I-494 at South St. Paul, Minnesota
212	Tuscolameta Creek (North Canal) at S.R.-35 at Walnut Grove, Mississippi
218	Tallahatchie River (Fort Pemberton cutoff) at U.S.-82 at Greenwood, Mississippi
227	Middle Fork Grand River at S.R.-46 near Grant City, Missouri
239	Elkhorn River at U.S.-30 at Arlington, Nebraska
242	Logan Creek at S.R.-9 near Pender, Nebraska
246	South Fork Little Nemaha River at S.R.-50 near Cook, Nebraska
247	South Platte River at U.S.-83 at North Platte, Nebraska
261	South Fork Forked Deer River at U.S.-51 near Halls, Tennessee
266	Boulder Creek at Bridge 394-2.4, Mt. Baker-Snoqualmie National Forest, Washington
282	Homochitto River at U.S.-61 near Doloroso, Mississippi

CHAPTER III

REGIONALIZATION OF GRADATION PROBLEMS

GENERAL DISCUSSION

Regionalization of gradation problems proved to be a difficult task. Even though more than 100 case histories were considered, not all parts of the country are uniformly represented. Man's interference with natural processes proved to be the biggest cause of gradation problems. (The causes of gradation problems will be discussed further in Chapter IV.) Thus, a knowledge of impacting activities is probably more important than regional considerations. Nevertheless, certain areas of the country contributed an above average share of case histories. Some general conclusions could be drawn concerning their location.

Two short discussions are presented here. First, gradation problems are identified with regions known to have high sediment runoff. Next, gradation problems are identified with specific major river basins. These two general groupings may prove of some use to highway engineers.

REGIONS OF HIGH SEDIMENT YIELD

Figure 4 illustrates the location over the U.S. of the case histories presented in Appendix A. Also identified on the figure are concentrations of sediment in the major U.S. streams.

With few exceptions the sites with gradation problems lie in areas of the country with high sediment yields. These areas are mostly along or west of the Mississippi River. The western and central portion of the country from a line along the western borders of Arizona and Montana to the Mississippi River seems to be particularly prone to gradation problems. A fair number of sites are located in northwest California.

The correlation between sites with gradation problems and streams with high sediment loads is intuitively sensible. High sediment loads imply easily

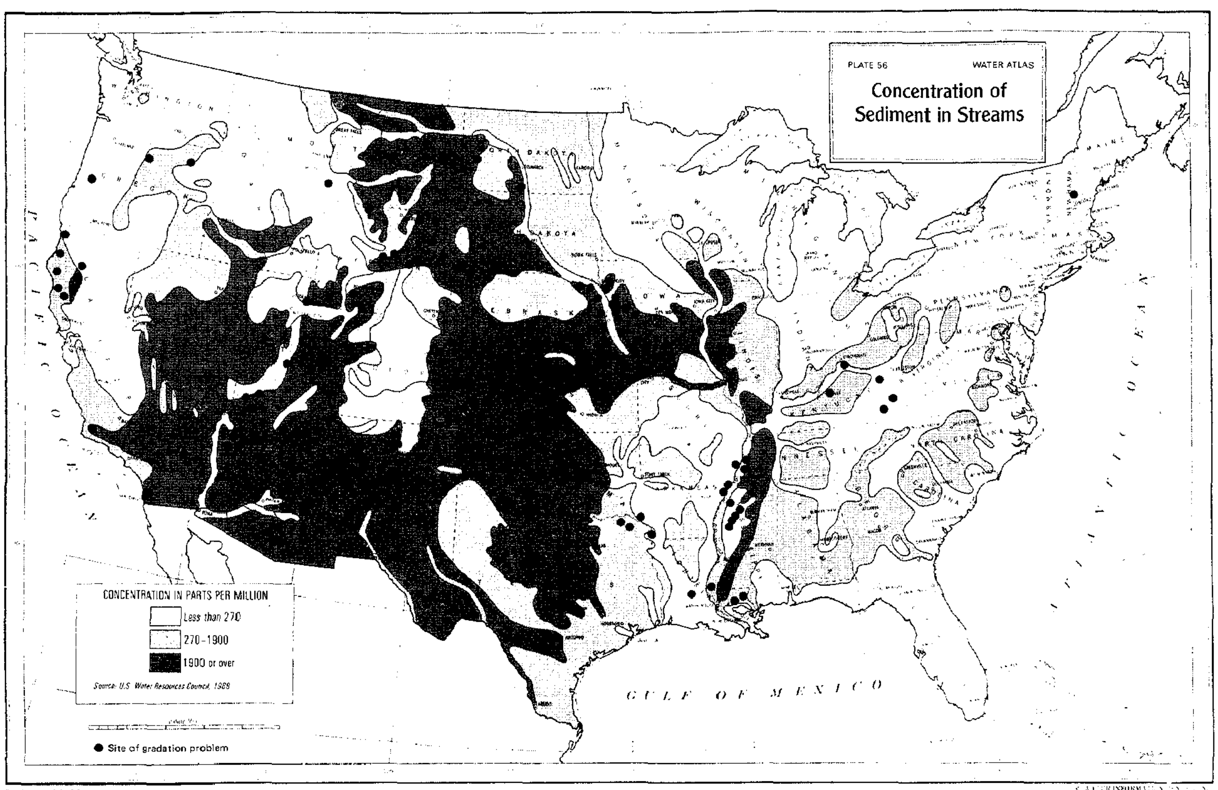


Figure 4. LOCATION OF CASE HISTORIES AND CONCENTRATIONS OF SEDIMENT IN STREAMS

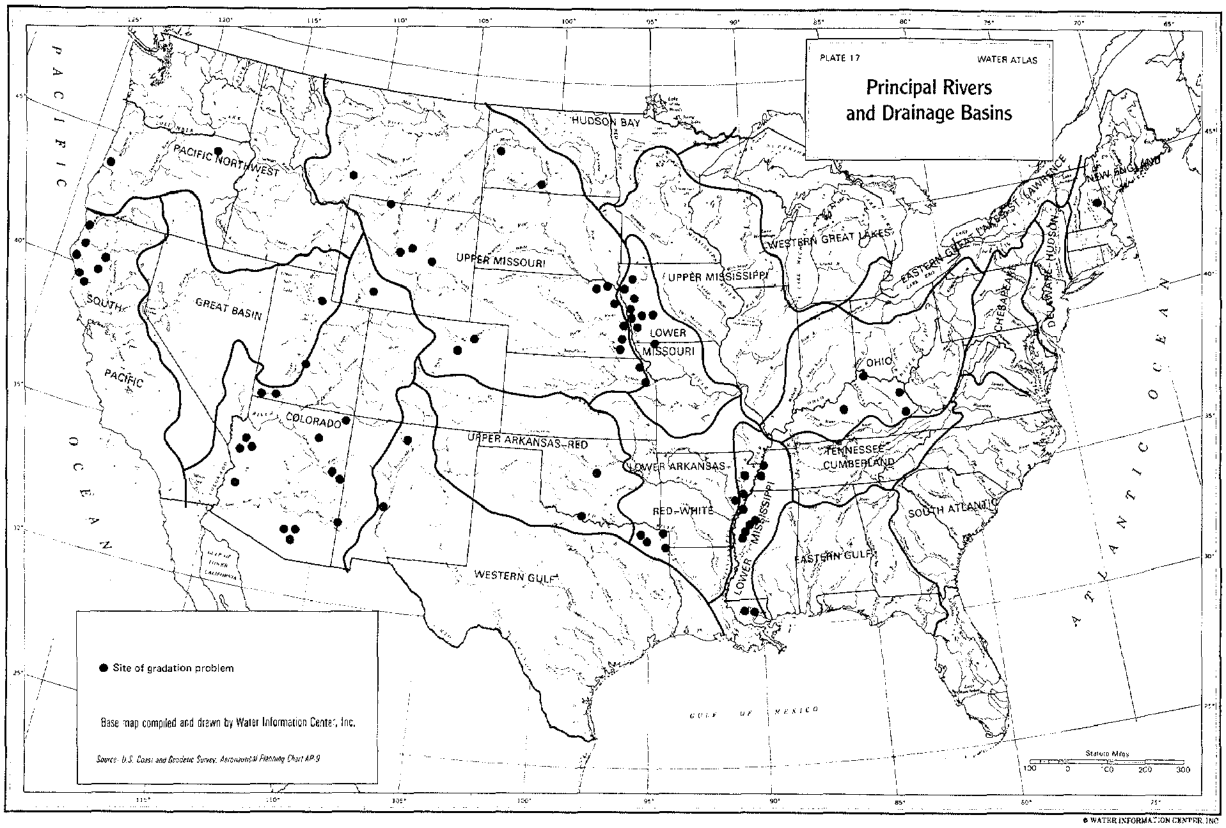


Figure 5. LOCATION OF CASE HISTORIES NEAR PRINCIPAL RIVERS AND DRAINAGE BASINS

erodable soil and streams with sand beds. Such streams are more likely to change course or shape than streams flowing in bedrock channels or channels with very large sediment. Note that almost no case histories are located in the Appalachian Mountains or in the mountainous regions of the West.

The absence of streams with high sediment yield does not rule out an area for gradation problems. The sediment yield does provide a rough guide, however.

MAJOR DRAINAGE BASINS

Figure 5 identifies the major river drainage basins of the U.S. and locates the case histories used in this study. Most of the case histories lie in three of the drainage basins. These basins are the Upper Missouri, the lower Mississippi, and the Colorado. The Red-White and Lower Missouri basins also contain significant numbers of case history sites.

Missouri Basin

The nature of the problems in the various basins varies widely. The great number of sites along the Missouri River are near the lower portion of its drainage. The extensive reservoir regulation on the Missouri has cut off its sediment load (Figure 4). In the absence of this load, the river is degrading rapidly. The tributaries of the river are also degrading rapidly.

Lower Mississippi Basin

The gradation problem sites which lie in the lower Mississippi basin have come about largely from channelization. Many stream changes made to improve navigation have increased stream gradients and resulted in degradation.

Red-White Basin

The Red River basin is a unique case of widespread degradation. For many centuries the flow of the Red River was restricted below Shreveport, Louisiana, by a large natural log jam called the Great Red River Raft. The Raft was removed by the Army Corps of Engineers over an extended period of time in the late 1800s. Removal of the Raft greatly accelerated the flow and resulted in massive degradation over a 20 to 30 year time span. Over 5.8 m occurred at Shreveport. The lowering of the Red River accelerate degradation on many of its tributaries. Dams along the Texas-Oklahoma border (notably Denison Dam, Denison, Texas) have also contributed to degradation of the Red River.

Colorado Basin

No readily identifiable cause is associated with the case history sites in the Colorado basin. The locations are widely scattered and usually associated with local channel straightening, dams, or other more related impacts.

SUMMARY

Regionalization of gradation changes is not a complete answer for the highway engineers. It is, rather, one of several methods which provide clues as to the presence of or potential for such problems. Bridge engineers in all areas with high sediment yield should consider the possibility of gradation problems. Highway engineers should be particularly vigilant of bridges near the lower reaches of the Missouri, Red, and Mississippi Rivers. Bridges in the other areas of the country should be evaluated on a case-by-case basis.

CHAPTER IV

HIGHWAY PROBLEMS RELATED TO GRADATION CHANGES

GENERAL DESCRIPTION AND APPROACH

Purpose and Organization

Chapter II presented the extensive case history data base developed as part of this study. The purpose of this chapter is to present a preliminary analysis of gradation problems. First, a description of the types of gradation problems is presented. Next, a discussion of the causes of gradation problems is presented. Finally, a number of tables which summarize the problem categories are presented. Supporting case histories are included at the end of this chapter.

Types of Gradation Problems

The typical effects of aggradation are illustrated in Figure 6, and typical effects of degradation are illustrated in Figure 7.

Aggradation Problems

The highway crossing problem most associated with aggradation, as illustrated in Figure 6, is reduction of flow area. This reduction in flow area results in possible flow over the bridge deck. Traffic is immediately or potentially disrupted. Not only is there a potential disruption of traffic, there is a potential to have the bridge swept away due to an increase in horizontal force and turning movement. Aggradation at bridge crossing also results in expensive maintenance costs. It becomes necessary to excavate the deposited material in the flow area upstream and downstream of the bridge to provide necessary flow area to pass the design flow.

Degradation Problems

As illustrated in Figure 7, the highway crossing problems associated with degradation are the exposure of footings, the exposure of pile bents, and the erosion of the abutments. Degradation also undermines bank protection, results in instability of channel banks, and increases debris problems. Ultimately, the degradation can result in the loss of a bridge and, in fact, is responsible for the loss of many bridges throughout the United States.

Degradation changes crossing conditions such that other stream hazards (which under original stream conditions caused no problems) are more dangerous to the structure. For example, a local scour of 2 m would be no problem under design conditions; it could, however, cause bridge failure when degradation has lowered the general streambed a few meters. In such a case, although local scour might be stated as the cause of failure, degradation is the major problem.

Summary of Problems

Aggradation and degradation problems may range in degree from rather trival, requiring only routine maintenance for correction, to partial or complete failure of the structure; and it is difficult to set definite limits within these extremes. However, most of the problems documented in this report lie in a middle range between the extremes, in that they present a definite hazard to the bridge and are subject to corrective action less drastic than partial or complete replacement of the structure. For bridges that have been swept away in catastrophic floods, it is usually difficult to decide which part failed first, what exactly caused the failure, and what practical countermeasures might have been taken to prevent the loss.

ANALYSIS OF CASE HISTORY DATA BASE

Description of Analysis

This section of the report identifies the case histories in Appendix A by category. First, the cases are simply classified on aggradation or degradation. Next, the case histories are classified by specific causes. These causes include natural causes, man's effects, and combinations of both.

Classification by Aggradation and Degradation

The case histories classified as either aggradation or degradation are listed in Table 8. Of the 110 gradation problems documented, 81 may be classified

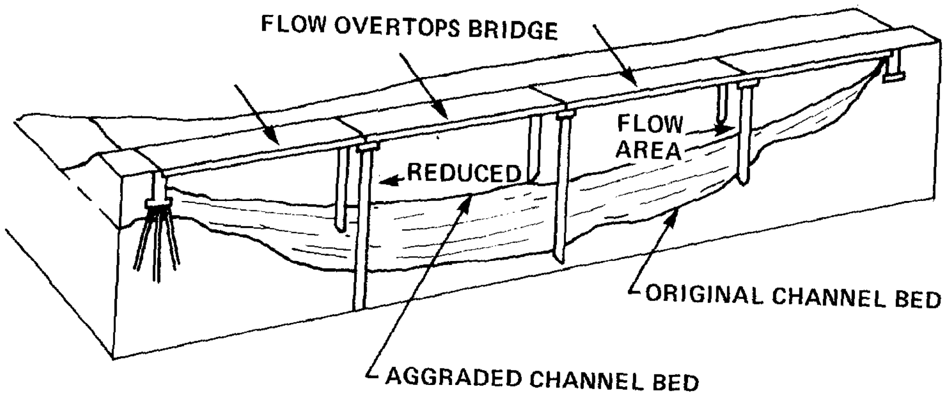


Figure 6. PROBLEMS OF HIGHWAY CROSSINGS RELATED TO AGGRADATION CHANGES

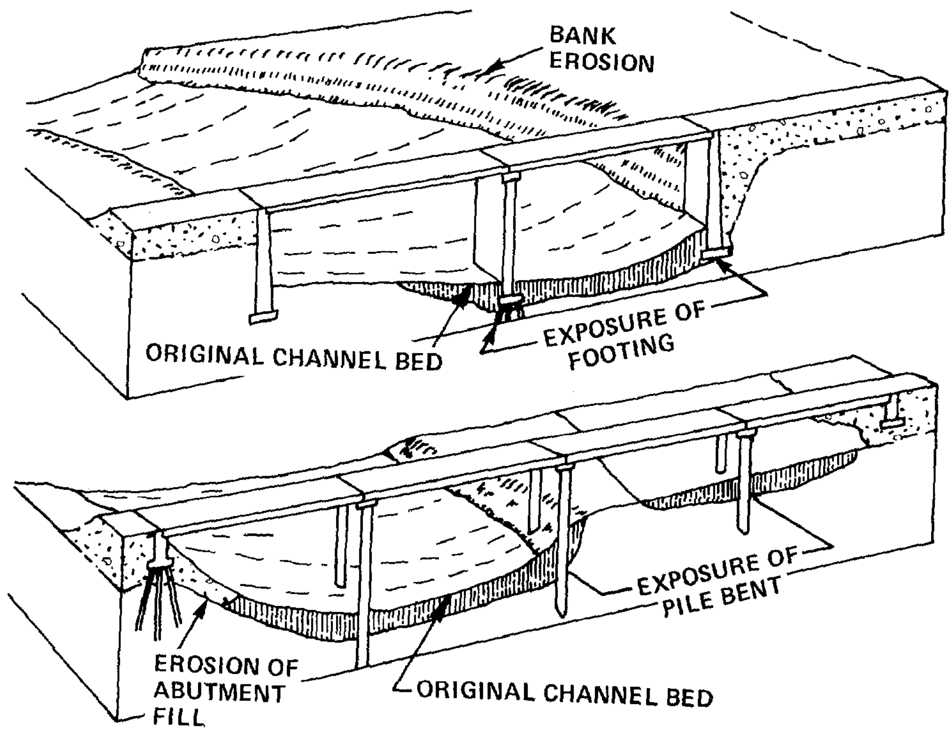


Figure 7. PROBLEMS OF HIGHWAY CROSSINGS RELATED TO DEGRADATION CHANGES AND SCOUR

Table 8. TYPES OF GRADATION PROBLEMS

Gradation Problem	Case History Number
Aggradation	3, 4, 8, 10, 12, 22, 25, 30, 37, 40, 44, 45, 47 48, 60, 66, 67, 68, 77, 78, 79, 80, 85, 101, 105, 106, 107, 108, 109
Degradation	1, 2, 5, 6, 7, 9, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 31, 32, 33, 34, 35, 36, 38, 39, 41, 42, 43, 46, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 61, 62, 63, 64, 65, 69, 70, 71, 72, 73, 74, 75, 76, 81, 82, 83, 84, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 102, 103, 104, 110

as degrading cases and 29 as aggrading cases. Channel aggradation is apparently not as common a problem as degradation. Also, aggradation in a bridge waterway does not reduce the stability of foundations or become a problem until the waterway area or bridge clearance is reduced below the minimum value needed to convey the design flood.

Degradation is among the more common causes of hydraulic problems at bridges. Brice, Blodgett, and others (1978) reported only one aggradation site and 39 degradation sites. The results of this study indicate that there are about three serious degradation sites for every serious aggradation site.

Classification of Causes

Causes of gradation changes that have an impact on highway crossings can be classified into two basic categories: (1) natural causes or factors and (2) the result of man's activities. An analysis of the case histories indicates that very few gradation changes were due to natural factors. Some gradation changes should perhaps be classified as being caused by a combination of both natural and man-induced factors. Their number is so small that a separate category is not warranted. Because man's activities dominate the causes for gradation problems, they will be discussed first.

Man's Activities

The activities of man are literally changing the face of the Earth and, hence, the hydrologic basins. Some activities have had far-reaching consequences on streams and have caused, or contributed to aggradation and degradation problems at bridges. Construction of a bridge and approach embankments may also have consequences, but they are unlikely to be far-reaching. Man's activities were found to be the major cause of streambed elevation changes.

From an analysis of the case histories, man's activities resulting in gradation problems can be classified into the following five categories:

- channel alterations,
- streambed mining,
- damming and reservoir regulation,
- land use changes, and
- construction activities.

Each of the five categories can be described more specifically with subcategories. Table 9 is a summary analysis of causes of gradation problems for the documented case histories in this report.

Each major category will now be discussed in detail with illustrative examples of the consequences of man's activities on highway crossings.

Channel Alterations

Straightening, dredging, clearing and snagging, artifical contrictions, and other alterations of natural channels are the major causes of streambed elevation changes. Channel straightening is the dominant activity. Examples of straightening and several others will now be presented.

Table 9. SIGNIFICANCE OF MAN'S ACTIVITIES ON RIVER GRADATION

Activity	Cause	Case History Number
Channel Alteration	Drainage/Dredging	51, 53, 56
	Channelization/Straightening/ Cutoffs	2, 15, 16, 18, 27, 32, 33, 34, 35, 36, 37, 38, 39, 41, 46, 50, 53, 57, 58, 61, 62, 64, 65, 69, 70, 71, 72, 73, 75, 81, 82, 84, 86, 87, 88, 95, 96, 98, 99, 102, 106
	Clearing/Snagging	87
	Constrictions	3, 4, 19, 25, 26, 27, 44, 61, 79, 84, 102
	Structure Alignment/Design	8, 10, 22, 29, 54, 102, 109, 110
	Tributary Gradation As a Result of Mainstream Gradation	59, 64, 72, 74, 89, 90, 91, 92, 93, 94
Land Use Changes	Urbanization	29, 44, 47, 75
	Agriculture	40, 62, 82
	Strip Mining	45, 48
	Logging/Clearing	25, 86
Streambed Mining/ Excavation	Sand and Gravel	7, 8, 11, 19, 20, 21, 23, 24, 26, 42, 43, 49, 51, 53, 83, 84
	Borrow Pit	1, 5, 9
Construction Activities		47, 48, 106
Damming and Reservoir Regulation	Clear Water Releases	13, 14, 17, 41, 42, 43, 57, 72, 74, 84
	High Sustained Regulated Flows	13, 14, 17
	Backwater	12, 30, 101, 105, 107
	Low Sustained Regulated Flows	68, 84
	Dam Breach or Removal	74
	High Controlled Irrigation Canal Releases	104

Straightening of natural channels, principally to improve drainage for agricultural purposes, has been widely practiced in the United States since about 1900. The documented case histories indicate that this practice has had an impact on many streams and highway crossings in the states of Nebraska, Iowa, Texas, Tennessee, and Mississippi, and to a lesser degree, the states of Kansas, Oklahoma, Missouri, and Arkansas. Table 9 indicates that there were 41 case histories documented with gradation problems at highway crossings due to channel straightening. Data exist to document another 50-100 case histories with gradation problems as the direct result of channel straightening. Channelization of streambeds for highway crossings is currently done on a small scale, and an attempt is made to keep stream slopes similar. In addition, highway engineers are cautious about stabilizing the reaches that are changed. Although there are some examples of streambed channelization that have resulted in degradation, highway engineers have been generally successful in preventing gradation problems (Brice, Blodgett, and others, 1978).

Many of the straightened channels have degraded, and degradation is usually accompanied by widening of the channel, unstable banks and serious debris problems. The degradation is attributed to an increase in channel slope that results from shortening of channel length. The increase in channel slope increases the velocity and the shear stress on the bed. As a result, the channel bed degrades until the bed becomes armored or the channel widens and begins to meander to reduce the channel slope back to an equilibrium, a stable condition. Some degradation has resulted from the abandonment of channels that have been adjusted to the stream regime and the cutting of new channels and failure to stabilize them. In this case, an armored channel is moved to freshly cut alluvium that has less capacity and erosion resistance (i.e., it is poorly vegetated, is not armored, is of a different material, has higher banks, etc.). The mechanics of degradation are discussed further in Chapter V.

Many examples of channelization, straightening, and cutoffs exist. Case History 62, the Homochitto River at SR-33 at Rosetta, Mississippi, is a classic example of degradation and the impact on highway crossings (Appendix A). A fairly complete historical background exists on the problem and the various mitigative measures employed to arrest the problem over many years.

Another example is Case History 86, the South Fork of Forked Deer River at US-51 near Halls, Tennessee. This case history, in its entirety, is presented at the end of this chapter because of the completeness of the data to document the causes, impact, and mitigative measures.

Other important channel alterations include constrictions (11 case histories), structure alignment/design (8 case histories), tributary gradation as result of mainstream gradation (10 case histories), drainage/dredging (3 case histories), and clearing/snagging operations.

Degradation of a main channel often leads to degradation of tributaries, whether these have been altered or not. Another example, straightening and consequent degradation on the North Sulphur River in Texas led to degradation and hydraulic problems at a bridge on Merrill Creek, a tributary to the North Sulphur River (Case History 91) (Appendix A).

An excellent example of tributary degradation as a result of mainstream gradation change is Case History 72, Elk Creek at SR-15 near Jackson, Nebraska. This case history illustrates the impact of the degradation of the Missouri River below Gavins Point Dam. This case history is presented in its entirety at the end of the chapter.

There is some evidence that degradation, if it is to occur as a consequence of channel alteration, will be most rapid during a period shortly following the alteration and will thereafter occur at a decreasing rate. For example, Yearke (1971) measured degradation following channel straightening on the Peabody River in New Hampshire. He found that the major degradation occurred in the first year after straightening and that successively smaller amounts occurred in subsequent years. On the Homochitto River at Doloroso, Mississippi (Brice, Blodgett and others, 1978), the river course to the Mississippi River (downstream from the US-61 bridge) was shortened from about 28 km to about 15 km in 1938. Degradation began at the bridge in 1944, reached 5 m by 1945, and increased an additional 1.3 m during the period 1945-57. Between 1957 and 1975, the channel aggraded about 0.6 m. But degradation that begins in the lower reaches of a stream may require a substantial length of time to progress upstream. For example, the main wave of degradation on the Homochitto River did not reach Rosetta, Mississippi (Case History 62), which is about 26 km upstream, until the period 1949-66.

With documented evidence that channel alterations are the major causes of gradation problems (74 case histories), it is important for highway engineers to recognize the impact to highway crossings. For new bridges this may require a modification in the design or for existing bridges this may require a mitigative measure to protect the bridge. There is also a definite need to develop some technical tools or methods to predict degradation resulting from channel alterations. The analysis of gradation problems is discussed in Chapter V.

Land Use Changes

Urbanization, agriculture, strip mining, and logging/clearing are other activities of man that cause gradation problems. Eleven case histories have been documented that can be directly related to land use changes.

Cruz Gulch at US-24 near Colorado Springs, Colorado (Case History 29), is an example of the impact from urbanization on a highway crossing.

Natural vegetation is extremely important in maintaining channel stability. The lateral stability of most streams in the United States, particularly in regions where agriculture or lumbering is practiced, has very probably been affected by the clearing of natural vegetation. Because this clearing has occurred more or less gradually over the past hundred years, the magnitude of the effect at a particular crossing site is sometimes difficult to assess.

Mining in an upland area may cause aggradation of channels, which are then subject to degradation after the mining ceases. Although only two case histories were documented, many more known examples could have been documented.

Although only about 10 percent of the case histories documented show gradation problems from land use changes, it is a significant problem. Highway engineers should be aware of land use changes in design of new bridges and the maintenance of existing bridges.

Streambed Mining/Excavation

If sand or gravel is removed from an alluvial channel in quantities that represent a substantial percentage of the bedload in transport, the channel will probably degrade. In addition, removal of gravel from pits or trenches in or along the stream may result in a change in flow alignment at the bridge. Nineteen case histories illustrating these consequences of removal are listed in Table 9. In some states, operators may legally continue to remove sand or gravel despite clear evidence of the consequent damage at a bridge.

Case History 52, Lawrence Creek at SR-16 near Franklin, Louisiana, is presented in its entirety at the end of this chapter as an example of the impact of streambed mining on highway crossing. In 20 percent of the case histories documented streambed mining was the major cause of a lowering of the streambed elevation.

Highway engineers should, as a minimum, conduct annual inspections of bridges upstream and downstream for gradation problems.

Dams and Reservoirs

The effects of dams and reservoirs on a stream are complex and have not been thoroughly investigated. Twenty-two case histories illustrate the consequences on dams and reservoirs. These consequences include clear water releases; high, sustained, regulated flows; backwater; low, sustained, regulated flows; dam breach or removal; and high, controlled, irrigation canal releases. The twenty-two case histories are listed in Table 9. Many more examples could have been documented.

Downstream from a reservoir, channel degradation is to be expected because of removal of sediment load. This effect has been documented for many streams. The total amount of degradation is difficult to predict; if a sand-bed channel becomes armored with gravel, the amount may be small. On gravel-bed streams aggradation may occur downstream from the dam because the flow releases are insufficient to transport gravel brought in by tributary streams. As pointed out by Kellerhals, Church, and Bray (1976), channel avulsions, which can present a serious threat to many engineering structures, are associated with most aggrading situations. Rapid lowering of river stage may result in severe bank slumping from pore-water pressures in the banks. However, the more general effect of reservoirs is probably to lessen hydraulic problems at bridges, both by reduction of flood peaks and a reduction of lateral erosion rates. An increase in stream stability has been attributed to reservoirs by Keeley (1971) for the North Canadian River in Oklahoma and by Brice (1977) for the Sacramento River in California.

An example of a problem downstream of a dam is the Missouri River below Gavins Point Reservoir. Case History 72 included at the end of this chapter summarizes the degradation at several locations as illustrated by the continual changing of stream stage for a given discharge.

Summary

Man's activities are definitely an important factor in causing gradation problems to highway crossings. More than 80 percent of gradation problems are directly related to man's activities. Highway engineers should evaluate the impact of man's activities on each highway crossing for both design and maintenance considerations.

Natural Causes

It was difficult to isolate case histories with gradation problems solely caused by natural factors because of the extensive activities of man. Less than 20 percent of the case histories documented could be related totally or partially to natural causes. Table 10 lists the natural causes of gradation problems. The associated case histories are listed across from each category. In several of these cases both natural factors and man's activities are involved. No attempt was made to isolate which factors started the gradation problem or which factors were dominant.

Alluvial Fans

Case History 108, the Elk River at I-90 near Piedmont, South Dakota, is an excellent example of natural causes. The case history is included to illustrate the impact of locating a highway crossing on an alluvial fan.

Other Factors

Other identified natural causes and complications from gradation problems included natural armoring, braiding, debris, meandering/migration (natural cut-offs), recurrent flooding/high stream velocity, channel bed and bank material erodibility and fire.

Although problems resulting from natural causes are not as frequent as those resulting from man's activities, it is important to recognize natural causes in both design and maintenance of highway crossings.

Table 10. **SIGNIFICANCE OF NATURAL EFFECTS ON GRADATION CHANGES**

Causes	Case History Number
Alluvial Fans	60, 85, 108, 109
Armoring	67
Braiding	67, 108
Debris	57, 58, 60, 61, 108
Meandering/Migration	8, 14, 22, 28, 62
Recurrent Flooding/High Stream Velocity	62
Delta Growth	68
Channel Bed and Bank Material Erodibility	97

Summary

The case history data base provides ample evidence that gradation changes are a significant cause of problems at highway bridges. Approximately three times as many problems related to degradation (81 cases) have been documented as have those related to aggradation (29 cases).

Man's activities are the dominant cause of gradation problems. Channel alteration, principally straightening, is the primary cause. Degradation below dams is also a frequent cause of problems, as is stream-bed mining. Natural factors seldom cause gradation changes. Aggradation of channels under bridges built on alluvial fans is the most common problem occurring naturally.

Chapter V of the report examines the technology used in analyzing gradation changes. Empirical methods from the field of geomorphology as well as theoretical hydraulic calculations are presented.

Case History 86

SOUTH FORK OF FORKED DEER RIVER AT US-51 NEAR HALLS, TENNESSEE

Description

The location of interest is near the Dyer and Lauderdale County line as seen in Figure 8 (lat. 35°57′, long. 89°24′). Dual bridges were built in 1963, with a 16 m main span supported by wall-type piers in the main channel, and thirty 8 m approach spans supported by concrete pile bents. In 1975, both bridges over the main channel were rebuilt, with a main span of 22.5 m supported by hammerhead piers. Spill-through abutments, set back from the main channel, were protected with sacked concrete in 1963 and have remained stable.

The drainage area is 2,688 km^2; the bankfull discharge is 28 m^3/s, and the width where bordered by natural vegetation is 24 m. The stream is perennial, alluvial, sand bed, in a valley of moderate relief and in a wide floodplain. The natural channel has a sinuosity of about 2.5 but the channel has been straightened; it is equiwidth, not incised, cut banks are rare, with silt-sand banks.

Gradation Problem

The channel was first straightened and enlarged in the 1920's by local drainage districts; but, probably because the natural floodplain forest was not cleared, the banks remained stable. In 1969, the Corps of Engineers straightened and enlarged a reach about 4.8 km in length downstream from the bridge, reducing the length about 20 percent. During the past few decades, and particularly in recent years, the floodplain has been cleared of trees for agricultural purposes.

Figure 9 illustrates the Corps of Engineers channel modifications that reduced the channel length and increased the channel slope. Figure 9 also provides an accurate profile of the channel before any modifications were made and in 1975. Several cross-sections are illustrated at various longitudinal stationings showing the extent of the channel modifications.

Between 1970 and 1971 the left bank receded an average distance of 4 m. The peak discharge during this period was 215 m^3/s (R.I. of flood, 1.5 year). Timber pile retards were built at the left bank near bent 7 and a single row of pile with wood face planks, extending from the downstream end of bent 7 for a distance of 37.5 m upstream.

Between 1971 and 1973 the peak discharge during this period was 751 m^3/s (Q_{17} frequency). Bankfull stage occurred several times, high flows sustained for periods of weeks. The left bank continued to erode behind retard, average distance of recession was about 2 m for the 3-year period. Bent 7 became exposed below the ground line. Concrete was poured at base to prevent further erosion. Slumping from the left bank deflected flow toward the right bank, causing rapid erosion and failure of bent 8. The south lane of the bridge was closed. A detailed inspection was made in 1973, but little field data were collected. What data were collected, indicated a large local scour problem at the bridge. No profile data were collected to evaluate the gradation problem.

Countermeasures

In 1975 both lanes of the bridge were rebuilt, with new piers having deeper footings and less area normal to flow (Figure 10). Single-row, timber pile retards were built along both banks in the vicinity of the bridge (Figure 11). A large scour hole in the center of the channel downstream from the bridge, attributed to flow constriction during bridge construction, was filled with gravel. In 1975 a detailed inspection was made and the 1975 profile is plotted in Figure 9 to indicate the extent of the degradation problem.

In 1977 a detailed inspection was made and cross-section data at the bridge indicated that the local scour problem was somewhat corrected and the gradation problem was fairly stable. Effectiveness of timber-pile retard has not yet been tested, and the area between the retard and the bank is not accumulating sediment. The lowermost face plank on the retard is about 1.5 m above the streambed. From experience in Oklahoma, Keeley (1971) recommends that face planks be extended to, or below, streambed elevation. In addition, the upstream end of the retard seems to be keyed into the bank for an insufficient distance. Vegetation is becoming re-established on the banks, which appear more stable now than in the recent past.

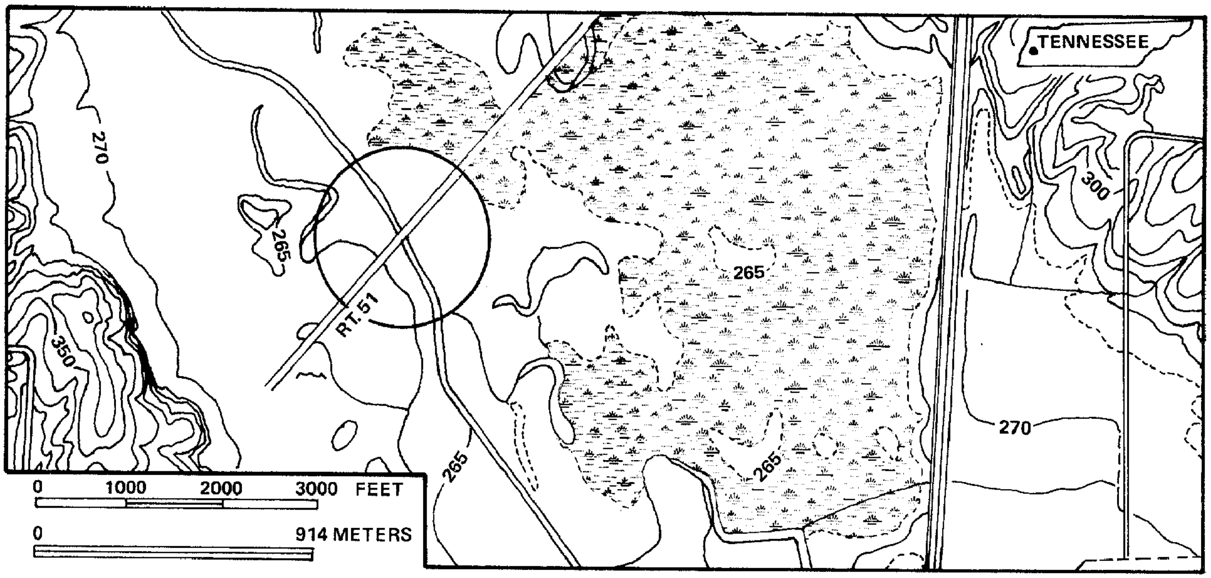


Figure 8. MAP SHOWING SOUTH FORK OF FORKED DEER RIVER AT U.S. HIGHWAY 51 CROSSING

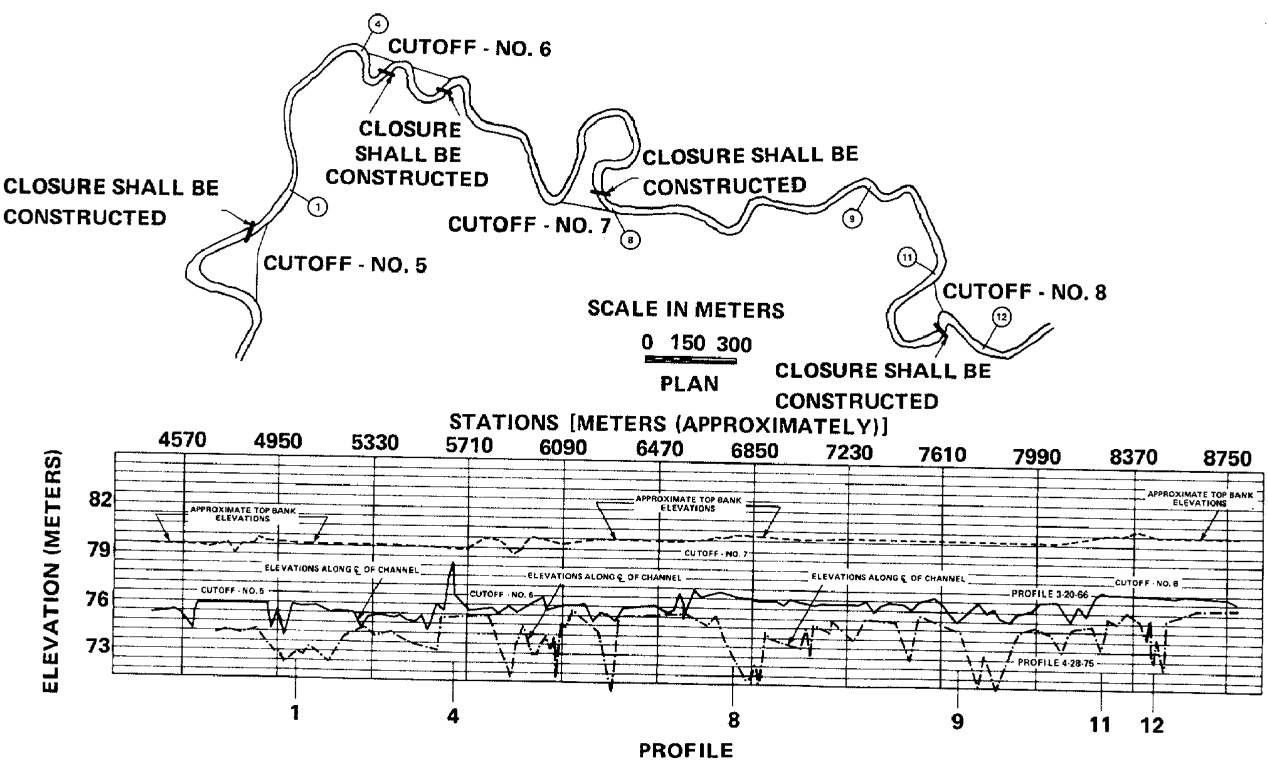


Figure 9. CHANNEL MODIFICATIONS TO SOUTH FORK OF DEER RIVER AT U.S. HIGHWAY 51 NEAR HALLS, TENNESSEE

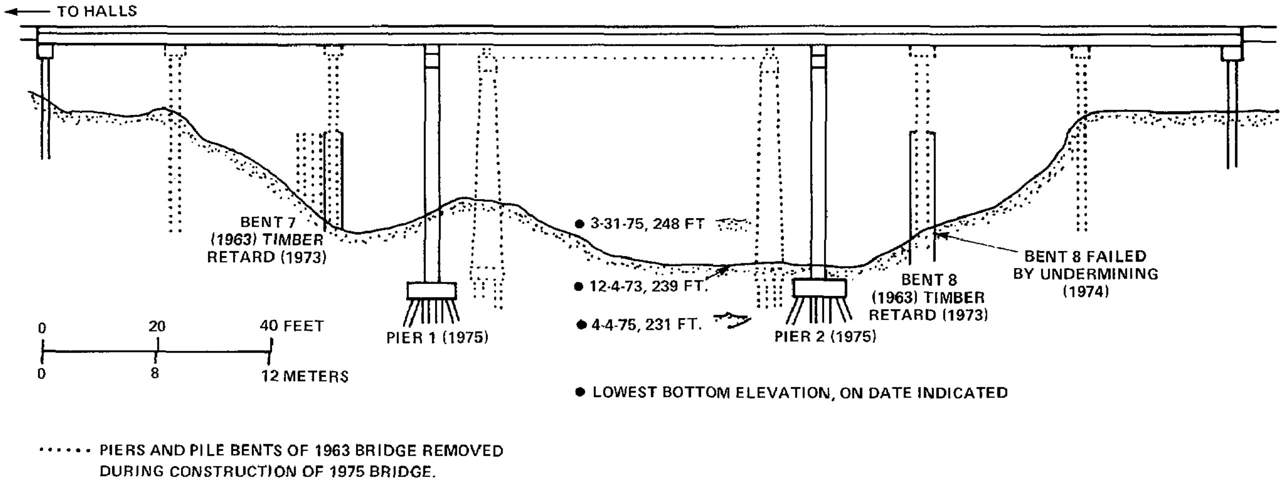


Figure 10. ELEVATION SKETCH OF U.S. HIGHWAY 51 BRIDGE

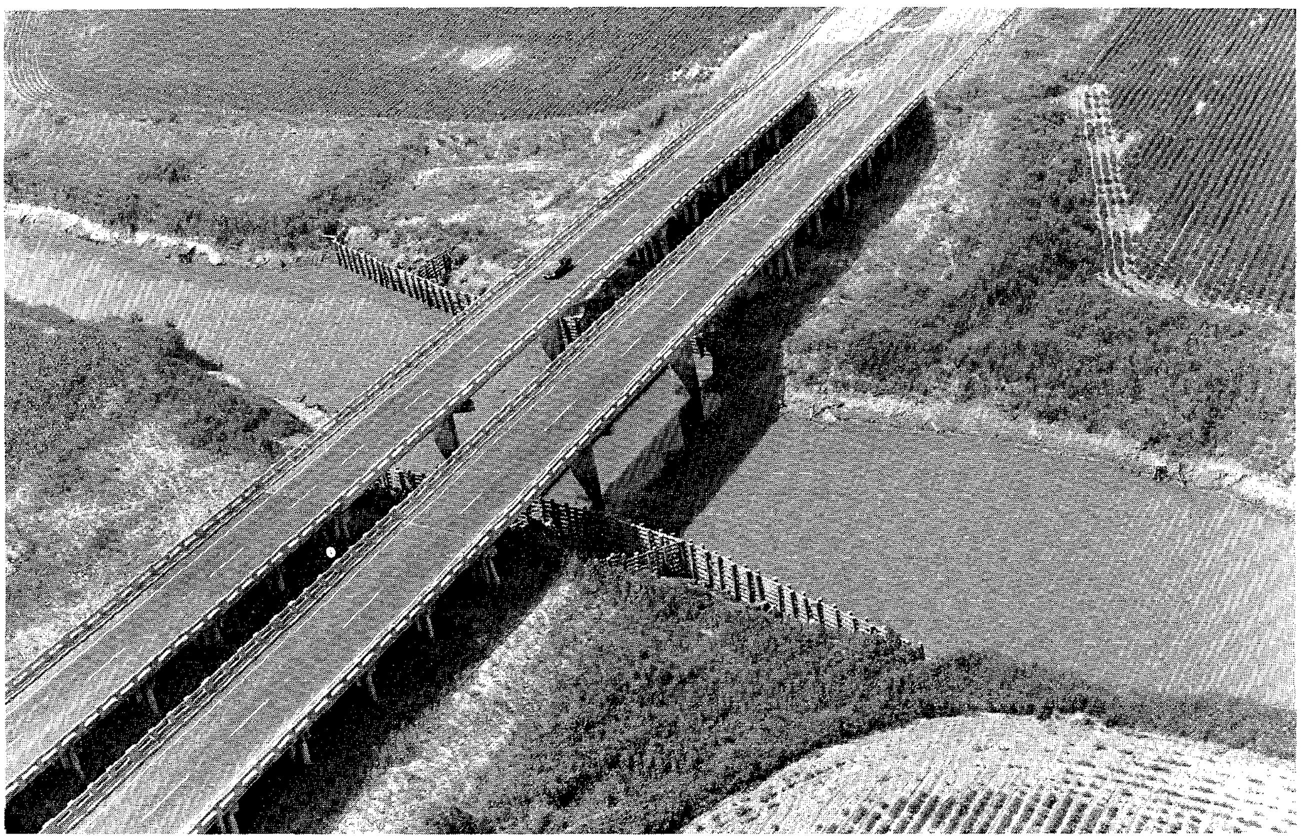


Figure 11. U.S. HIGHWAY 51 BRIDGE SHOWING TIMBER PILE RETARDS

Discussion

The 1973 bridge failed because of channel degradation and concurrent bank recession, which are directly attributable to straightening of the channel for drainage purposes and clearing of the banks and floodplain for agricultural purposes. Channel width increased by a factor of 2, approximately, between 1969 and 1976. The clearing of vegetation is apparently one of the most critical factors, because channel straightening in the 1920's, which was not accompanied by extensive clearing, did not result in significant bank instability. The timber pile retard installed in 1971 was of inadequate design, in view of the seriousness of the problem. Bank recession might have been controlled by an adequate retard or other countermeasure, but channel degradation is more difficult to control.

The site was inspected in 1973, 1974, four times in 1975, and in 1976 by numerous federal and state agency employees. It should be pointed out that little actual field data were collected to document the progressive channel changes. All inspectors have concluded that the channel changes were responsible for the gradation problems and other related hydraulic problems.

Case History 72

ELK CREEK AT SR-15 NEAR JACKSON, NEBRASKA

Description

Elk Creek is located in Dakota County and is a tributary of the Missouri River. It flows into the Missouri River just upstream of Sioux City, Iowa. The State Road 15 Bridge just west of Jackson is of interest. The stream is perennial but flashy, alluvial, sand-silt bed and in a valley of low relief with a wide floodplain. The channel is sinuous, incised by degradation, and has silt-clay banks

Gradation Problems

The stream bed has degraded at least 3 m since 1955. There are two primary reasons for this degradation. First, channel modifications have been made to improve and maximize agricultural production. As a result, the channel has been straightened and changed at isolated locations. Second, and probably more important, is the general degradation below Gavins Point Dam. Missouri River Stage Trends, for almost 100 years for eight of the key main stream gaging stations below Sioux City, indicated at least 3 m of degradation at Sioux City, as indicated in Figure 12. This degradation is probably due to three main reasons as follows:

- Between 1890 and 1960 the Missouri River length from Sioux City to Omaha has been reduced 21 percent by the Corps of Engineers. As a result the stream bed slope was increased accordingly.
- The sediment-free water released at Gavin's Point Dam is transporting the bed sediment that is available.
- The rather high sustained flows of the regulated Missouri River System do not allow for any aggradation or filling.

The degradation is primarily responsible for lateral instability as the channel has almost doubled in width. The degradation has exposed the pier footing.

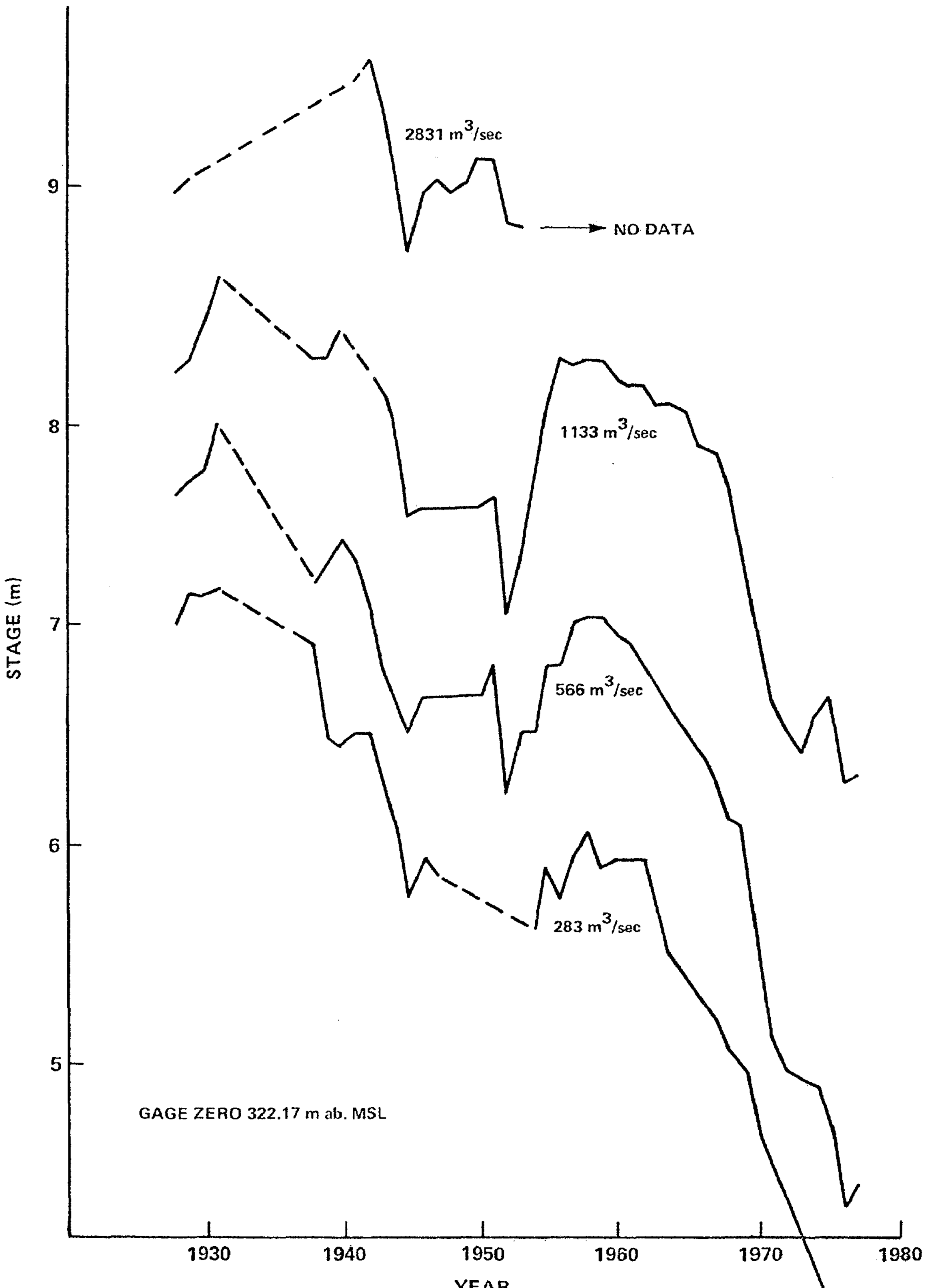
Countermeasures

No countermeasures have been applied at this time.

Discussion

Tributary degradation, resulting from degradation on the mainstream of the Missouri River is to be expected. The Missouri River has historically degraded, as indicated in the Missouri River stage trends. This condition should be evaluated on an annual basis and bridges inspected that are subject to this headcutting that is experienced by each tributary that is not protected by a grade control structure.

Failure of this bridge due to degradation is not likely because of the great depth to which bridge foundations have been placed.



SOURCE: SAYRE AND KENNEDY (1978).

Figure 12. STAGE TRENDS AT SIOUX CITY, IOWA, ON THE MISSOURI RIVER

Case History 29

CRUZ GULCH AT US-24 NEAR COLORADO SPRINGS, COLORADO

Description

The crossing is a triple reinforced concrete box (RCB) culvert: 4.57 x 2.44 m, 5.49 x 2.44 m, and 4.57 x 2.44 m. The length is 66 m including an inlet and outlet.

The channel is 15 to 23 m wide, is straight upstream, and is sinuous downstream. The upstream banks are 1.2 to 1.5 m, sloping, and grass-covered. The downstream bed at present is 3 to 4 m below the outlet, with the channel having sidecut 5 to 6 m near vertical banks. Both the bed and the bank materials are sand, clay, and loam. The downstream channel continues to degrade with each heavy runoff. An interceptor outlet approximately 91 m east of this crossing experiences similar problems on a smaller scale.

Gradation Problem

The original culvert (built in the mid-1960's) was 1.83 x 1.22 x 35.36 m RCB. This crossing was adequate at the time, as upstream pastureland tended to attentuate peaks. The mid-1960's brought suburban development upstream of the site. By 1968, the increased runoff from the housing development caused the single RCB to be inadequate. It was replaced by a double RCB.

As building continued upstream, the double RCB became inadequate. The present structure was installed in 1970.

The downstream channel started to headcut in the late 1960's and degradation has continued since that time. The present triple box is adequate to pass an annual spring runoff, and sometimes flows within 0.6 m of the top. The outlet protection is undermined and is considered marginal at present. There are no current plans to repair the outlet or to stabilize the downstream channel.

Countermeasures

The single RCB was replaced with first a double and then a triple RCB, which exists at present. However, no headcutting countermeasures have been conducted.

Discussion

Upstream development activity has caused overloading of the two successive installations at this site. The present crossing, while hydraulically adequate, has created downstream degradation. This site is considered typical of Colorado culverts, where the channel is grass-covered and stable upstream of the crossing.

Case History 52

LAWRENCE CREEK AT SR-16 NEAR FRANKLINTON, LOUISIANA

Description

Lawrence Creek is located in Washington Parish (lat. 30° 19′, long. 90° 19′). The bridge is 13 m in length, pile bents with square concrete piles and spill-through abutments revetted with sacked concrete. The drainage area above SR-16 is 130 km^2, and the channel slope is 0.003. The stream is perennial, alluvial, sand bed, in a valley of low relief and has a wide flood-plain. The stream is sinuous, not incised, and has sand banks.

Gradation Problem

Sand and gravel mining downstream from the bridge has caused serious channel degradation. Head-cutting moved upstream causing banks to cave along with large trees and debris. The trees partially blocked the main channel upstream of the bridge, such that at high flows the main flow was diverted to an old channel that flows almost parallel to SR-16 and then makes a 90° bend to flow under the bridge.

The channel has been lowered by an estimated 3 m at the bridge.

The degradation, bank caving, and debris problems resulted in extensive lateral erosion of banks at the bridge.

Countermeasures

As a countermeasure, the bridge was lengthened by the addition of span to the right end in 1967. In 1973, the approach embankment was raised and a curved spur dike of earth, revetted with broken concrete rip rap, was built at the right abutment to protect the embankment (Figure 13). Timber cleared during construction of the spur dike was to be placed along the embankment but was placed too far from embankment. During a flood in 1974, flow was diverted against the spur dike, eroding the tip and upstream side of the dike and impinging against the approach embankment.

Discussion

Lateral instability of the channel is directly attributed to sand and gravel mining. Although the spur dike serves to direct flow through the bridge waterway, it does not seem to be an effective measure for protection of the approach embankment, which is subject to erosion or breaching during major floods. The main channel of Lawrence Creek is apparently too nearly parallel to the right approach embankment for the spur dike to function properly.

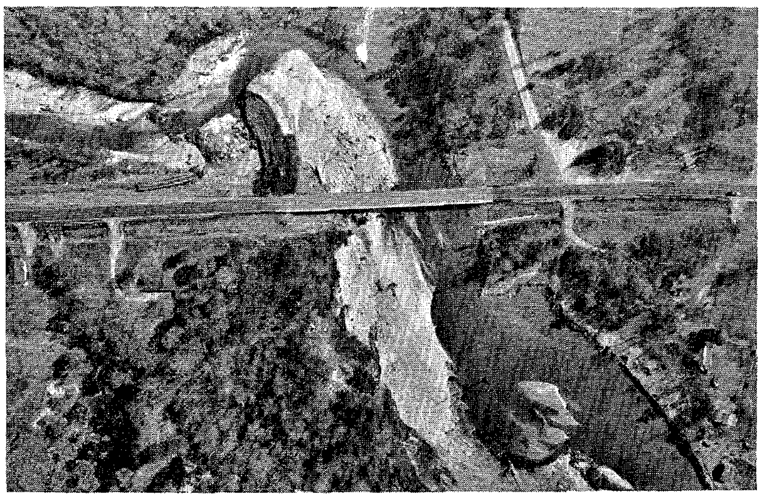


Figure 13. SR-16 BRIDGE OVER LAWRENCE CREEK NEAR FRANKLINTON, LOUISANA

Case History 108

BIG ELK CREEK AT I-90 NEAR PIEDMONT, SOUTH DAKOTA

Description

Big Elk Creek is located in Meade and Lawrence counties and is a tributary of the Cheyenne River. The headwaters of Big Elk Creek originate in the Black Hills National Forest. I-90 crosses the Big Elk Creek on an alluvial fan just outside of the National Forest, where there is a significant reduction in channel slope. The bridge, built in 1964, is 54 m long, has pile bents with square piles, spillthrough abutments, and a concrete deck. The creek is intermittent, flashy and alluvial with cobble and gravel bed. The drainage area above I-90 is 1300 km^2 and the design discharge was 85 m^3/sec.

Gradation Problem

The highway crossing is located on an alluvial fan. At this location there is insufficient slope (energy) to transport the cobble and gravel material. Since 1964, it has been necessary to excavate about 20,000 m^3 of deposited bed material on three occasions at an expense of hundreds of thousands of dollars. The excavation was necessary to pass the flow from the spring snowmelt runoff. The primary aggradation problem is insufficient flow area and is aggravated by too many piers in the channel as well as a bad alignment with a 67 degree skew.

Countermeasures

In 1966 several rock and wire basket flow deflectors were installed for several hundred meters upstream of the bridge to constrict the flow and increase the transport characteristics. Figure 14 illustrates the deflector arrangement as well as the alignment problem. The deflectors were not very effective. They did constrict the flow and increase the velocity to transport the gravel sizes, but the cobble bed material still deposited upstream of the bridge. The constriction was not enough compensation for the reduction in slope as the creek comes out of the Black Hills.

Discussion

The channel is not well defined as it flows onto the alluvial fan. As a result, it is difficult to locate a bridge to take into account both significant lateral channel migrations and bed elevation changes. A possible solution to the problem would be to build a debris basin upstream of the bridge to trap the large-sized bed material. This would then provide a great source of gravel which is in demand in that area.

This might be a site where a simple bedload transport model may be helpful in determining the solution to the aggradation problem.

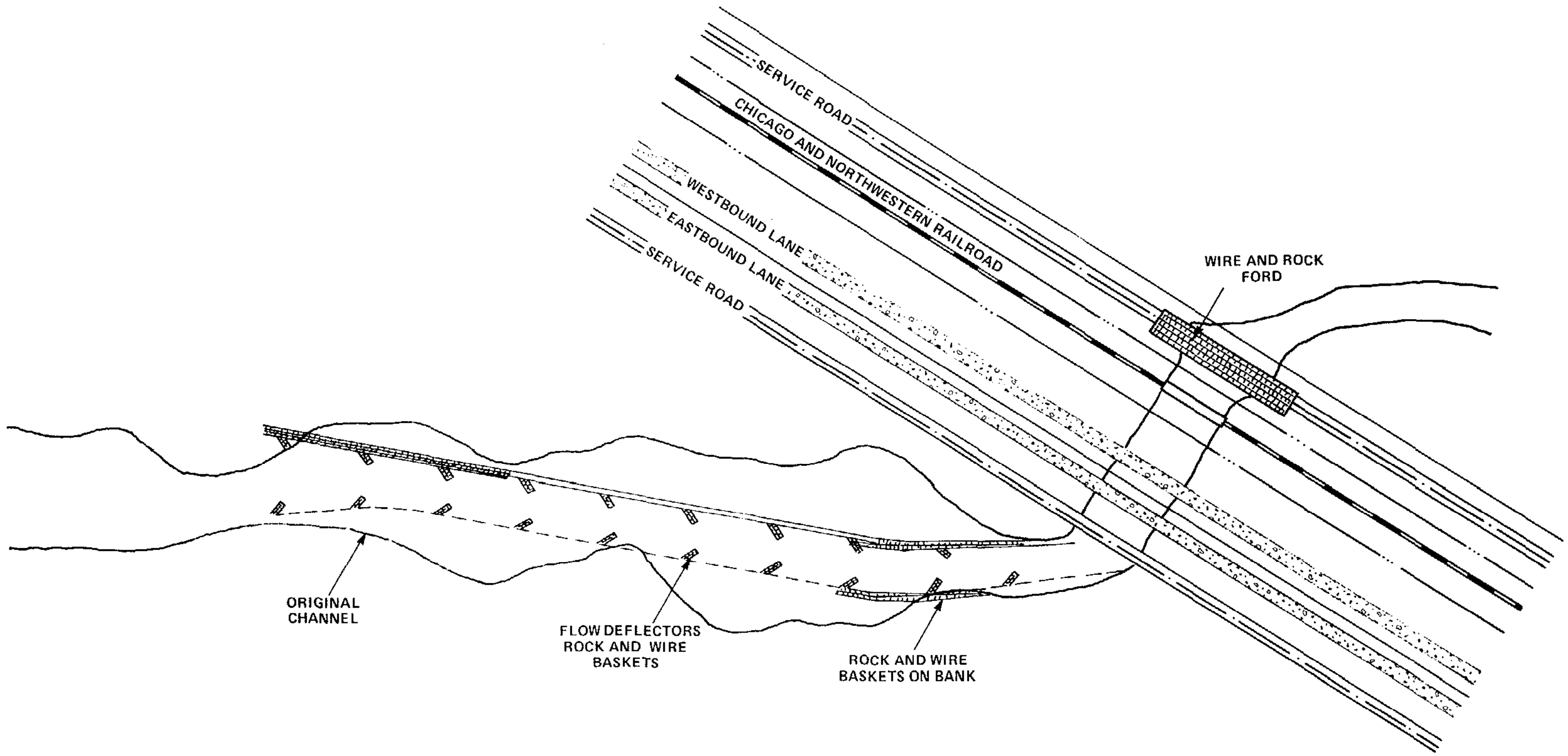


Figure 14. DEFLECTOR ARRANGEMENT AND ALIGNMENT PROBLEM ON I-90 BRIDGE ACROSS BIG ELK CREEK NEAR PIEDMONT' NORTH DAKOTA

CHAPTER V
APPRAISAL OF TECHNOLOGY

GENERAL DESCRIPTION AND APPROACH

Relationship to Overall Research Effort

This interim report is designed primarily to satisfy the first two purposes of the overall research study of aggradation and degradation. These two purposes are: (1) to identify streams with gradation problems including effects on highways, causes, and success or failure of remedial measures, and (2) to provide a regional description of degrading and aggrading streams along with reasons for the gradation changes. Chapters II and III of this report have addressed these two purposes.

The third overall purpose of the gradation research study is to evaluate the technology available for recognizing gradation problems and computing their extent. The background research necessary for meeting the purposes was accomplished as part of Phase I. This was done by reviewing pertinent literature. This section of the report provides an extensive review of the techniques for studying gradation changes which appear to be useful or which could be modified for use by highway engineers. Recommendations are made for research in the second phase of the gradation study.

Role of Annotated Bibliography and Case Histories

The annotated bibliography was discussed briefly in the Introduction. Several thousand bibliography entries were gathered on virtually every aspect of sediment transport. Many were obtained from computerized key word searches. A number of other useful references were obtained through personal contact, the U.S. Geological Survey National Library, and personal libraries of the investigators and Contract Manager. The entire annotated bibliography is presented as Appendix B of this report.

Technical references within the bibliography were broken into three basic categories. These deal specifically with aggradation, degradation, or both. Five subcategories were identified within each of the three basic categories. These are (a) case histories, (b) control methods, (c) prediction/theory, (d) models (laboratory/mathematical), and (e) general.

From several thousand references, more than 150 were identified as having information of potential use to this study. The breakdown by subcategory was 27 included case histories, 10 on control methods, 9 on prediction/theoretical, 41 dealing with laboratory or math models, and 62 general references.

Efforts were made to obtain or view as many of the references as possible. Each was evaluated as to its potential for use in Phase II of this research. Where possible computational methods were identified with specific problems from the case history data base. The remainder of this section describes in general the state of technology as determined from the literature review. An organizational philosophy for the information is presented first.

Organization of Technology Assessment

The writers have chosen to view the aggradation-degradation problem as one having three steps to solution. The first step is to recognize the existence of a problem or the potential for one. The second step is to choose a suitable method with which to analyze the problem. The final step is to select a suitable remedial measure.

It was not within the scope of Phase I to provide a technical manual for identification, analysis, and solution of gradation problems. However, the above organization was chosen so that the capability could be established to produce such a reference under Phase II. The three step framework provides a means of quickly categorizing and evaluating technical material.

The technology evaluation is organized strictly into the three step framework. First, a discussion of methods for recognizing gradation problems or the potential for them is presented. Regionalization, data collection, and analysis of available data are discussed. Second, problem analysis methods are presented. Two subsections are included in problem analysis. These are for geomorphic methods and hydraulic methods. Under hydraulic methods a range from simple to complex is identified. Third, the available remedial method and selection criteria are discussed.

RECOGNITION OF GRADATION PROBLEMS

New Design Versus Existing Structures

There are two somewhat different categories of effort under recognition of gradation problems. The first is anticipating or recognizing the potential for gradation changes when designing new structures. The second is recognizing a problem at an existing structure. The first case obviously allows the bridge engineers the opportunity to avoid problems altogether. The second case is more likely to call for selection of a remedial measure.

This part of the report is concerned strictly with identifying streams which are undergoing or are likely to undergo gradation change. Many of the techniques discussed are applicable for both new design and existing structures. If a particular method applies only to one or the other, it is identified as such.

No computation techniques will be considered here. That is, no methods for computing the extent and magnitude of gradation are included. Computational methods are the subject of the final portion of this section.

The most promising methods for recognizing gradation problems are regional awareness, awareness of impacting activities, and data collection/analysis methods. Awareness of impacting activities requires some knowledge of geomorphology. All three methods are presented here.

Regional Awareness

Regional awareness is important both for new design and existing structures. It is probably of more importance, however, to new design. If a designer is aware that he is not in an area prone to gradation problems, he is relieved of one additional responsibility. Conversely, if the bridge crossing is located in an area with known problems, the designer is forewarned and can act accordingly.

Chapter II of this report has identified a number of regions of the U.S. which are very prone to gradation problems. With few exceptions these are areas where streams flow through valleys or regions composed of fine alluvial material. It is safe to say that most bridge crossings near the lower Mississippi River suffer from some type of gradation problem. Likewise western Tennessee is a problem area. The Missouri River and its tributaries have many documented problems (see, for example, Sayre and Kennedy, 1978). Numerous other localities are identified in Chapter II and in the Annotated Bibliography, Appendix B (U.S. Bureau of Reclamation, 1978; Emmett, 1974; USGS, 1978).

At the very minimum, then, before any new design is undertaken, the designer should become aware, through Chapter II of this report and publications specific to his area, of the potential for gradation problems. The bridge engineer faced with repeated or prolonged scour or fill problems should also be aware of regional tendencies for gradation change.

Awareness of Impacting Activities

Awareness of impacting activities is equally important to both new designs and existing structures. The case histories analyzed in Chapter II illustrate the overriding influence of man's activities in gradation problems. With only two exceptions, all the case histories were caused by or heavily influenced by attempts to change some aspect of a river's natural morphology.

Chief among the causes of gradation problems are channel realignment, streambed mining, and dams. In the case of an existing structure, identification of such impacting activities merely requires a broad viewpoint on the river. The river should be examined not only at the crossing site but upstream and down to determine what activities take place. Chapter III identifies those that are most common and which have the biggest impact on gradation.

In the case of a new structure it is still important to examine the proposed site from a broad viewpoint. In addition, it is desirable to communicate with organizations likely to cause impacts. Government agencies such as the Corps of Engineers plan projects well in advance. Impacts of their activities can easily be anticipated and accounted for. Private impacts such as gravel mining or changes in land use may be harder to anticipate. Past use is often a good guide.

The second important step, then, in new design or problem analysis at an existing bridge is to become aware of impacting activities. This is easily done, and has considerable value. By comparing the activities present near a crossing to those described in Section III, a good idea can be obtained concerning the presence or absence of gradation-related problems.

Awareness of Local Geology/Geomorphology

Definition and Organization

The term geomorphology, as used here, means modification of land forms by flowing water, wind, or other natural processes. Geology refers to structural features such as mountains, faults, glacial moraines, and rock types.

At this point, no detailed discussion of geomorphology will be given. Much of the qualitative understanding of impacting activities comes from geomorphological analysis. A detailed discussion will be given under analysis techniques. The purpose here is to briefly define the role of geology-geomorphology in problem identification.

Examples from Case History Data Base

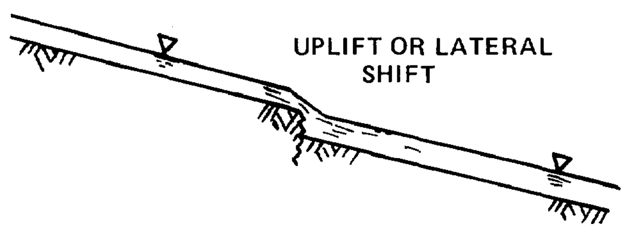
Although most of the problems described in the case histories were caused by man's activities, several were not. Awareness of geology-geomorphology would have avoided the problems or been useful in their solution.

Black Creek near Avalon, Mississippi, is a good example of a gradation problem caused by natural geologic change. A bridge was constructed near the mouth of a narrow valley where Black Creek flows out of hills onto the Yalobusha River floodplain. A sharp change in gradient occurs, going from steep to flat. A natural alluvial fan exists at this point and is continually aggrading. An examination of the site with an awareness of geology/geomorphology would have resulted in a higher deck for the bridge.

A second similar site is Big Elk Creek at Mile Post 42.83 near Rapid City, South Dakota. Again the bridge is built along the edge of a major floodplain. The sudden decrease in gradient as Big Elk Creek leaves the hills causes reduced transport capacity, leaving large quantities of material deposit in the channel beneath the bridge. Again geologic/geomorphologic awareness could have avoided the problems.

Other Examples of Gradation Problems

Other natural changes may cause gradation problems. Simons et al. (1975) describe some of the consequences of such changes. Among the natural phenomena that can have an impact on the river environment are earthquakes, fault movement, and other tectonic (movement of the plates making up the Earth's crust) activity (Figure 15). Large portions of the United States are subjected to at least infrequent earthquakes. Associated with earthquake activity are severe landslides, mud flows, uplifts in the terrain, and liquefaction of otherwise semistable materials, all of which can have a profound effect upon channels and structures located within the earthquake area. Several of the possible changes due to a shift in a channel bed are listed in Figure 15. Historically, several rivers have completely changed their course as a consequence of earthquakes. For example, the Brahmaputra River in Bangladesh and India shifted its course laterally a distance of some 322 km as a result of earthquakes that occurred approximately 200 years ago. The region of Yellowstone Park, Wyoming, contains a number of lakes formed by landslides associated with earthquakes. An awareness of geologic events is at least desirable in anticipating gradation changes.



Local Effects	Upstream Effects	Downstream Effects
1- Channel changes	1- See local effects	1- See local effects
2- Scour or deposition	2- Slide lakes	2- Slide lakes
3- Head cutting		
4- Decrease in bank stability		
5- Landslides		
6- Rockslides		
7- Mudflows		

Figure 15. TECTONIC ACTIVITY

Types of Streams

An important aspect of geomorphologic consideration is stream type. After a bridge designer or hydrologist has satisfied himself that an impacting activity exists near a crossing or that a geologic impact may be present, it is necessary to begin gaging the magnitude. Certain types of streams are more susceptible to changes in gradient than others. The problem is complicated by the fact that changes in gradient are often accompanied by changes in lateral movement. Detailed discussion is again postponed until the next part of the report. However, a brief discussion of stream types and their behavior is in order here.

Definitions

Numerous classification schemes for rivers are available. Simons et al. (1975) and Richardson et al. (1974) provide lengthy discussions of channel properties and classification. Brice and Blodgett (1978) develop a detailed classification scheme oriented primarily toward lateral stability of rivers. Relevant information from all three sources is included below.

Figure 26 in Brice and Blodgett (1978) is reproduced here as Figure 16. It provides an excellent quick-reference guide to the types of alluvial channels. The common geomorphic terms for the various types of streams (meandering, braided, incised, etc.) are shown in the figure. Each term is well defined by the small sketches.

Various methods are used to classify rivers. One of the methods used by geomorphologists classifies streams as youthful, mature and old. Youthful implies the initial state of streams. They are generally V-shaped, very irregular, and consist of fractured erosive and nonerosive materials. Examples of youthful streams are mountain streams and their tributaries developed by overland flow. In mature streams, the streambed has achieved a graded condition; that is, the slope and the energy of the stream are just sufficient to transport the material delivered to it. With mature channels, narrow floodplains and meanders have formed. The valley bottoms are sufficiently wide to accommodate agricultural and urban developments, and where development has occurred, usually channel stabilization works and other improvements have been made to prevent lateral migration of the river.

River channels classified as old develop such that their characteristics include greater width and low relief, the stream gradient has flattened further, and meanders and meander belts that have developed are not as wide as the river valley. Natural levees have formed along the stream banks. Because of the more-sophisticated development of the river valley, channel stabilization and contraction work, such as revetments and dikes, are generally present.

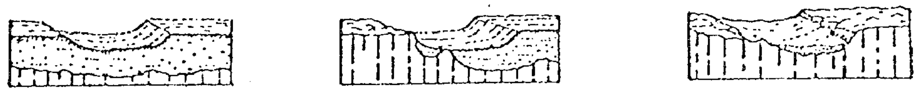
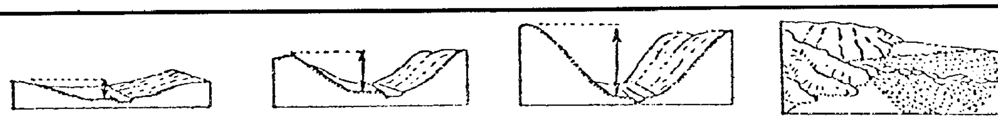
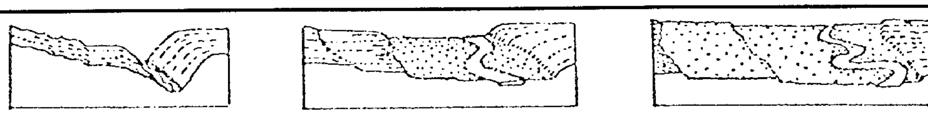
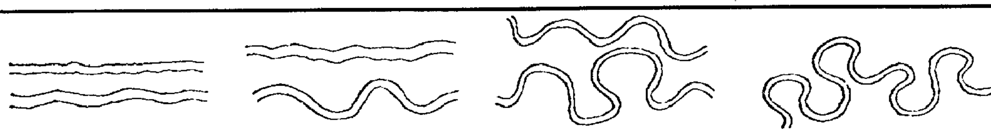
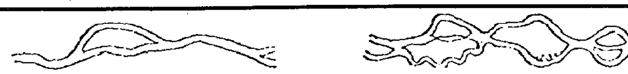
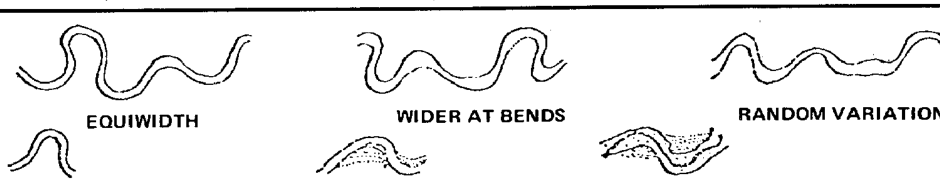
Some geomorphologists define old age as a condition when the entire river system is graded. This concept can only be applied as an average condition extending over a period of years. No stream is continuously graded. A poised stream refers to one that neither aggrades or degrades its channel over time. Both graded and poised streams are delicately balanced. Any change imposed on the river system will alter the balance and lead to actions by the stream to reestablish balance. For example, a graded or poised stream may be subjected locally to the development of a cutoff (or one may be man-made). The development of the cutoff increases the channel slope, increases velocity, and increases transport at least locally. Changes in these variables cause changes in the channel and deposition downstream. The locally steepened slope gradually extends itself upstream attempting to reestablish equilibrium. When such a gradation change encounters a bridge crossing, a problem may develop. In terms of overall potential for gradation problems, the highway engineer should be able to recognize the mature and old streams. Young streams are often not alluvial in nature and gradation changes occur over the spans so long as to be of no concern to highway bridges.

A brief discussion will now be presented concerning the nature and stability of straight, braided, and meandering channels. Each behaves in a slightly different way when subject to man-related or natural impacts. A knowledge of this behavior is important in anticipating and understanding gradation problems.

Straight Streams

Leopold and Wolman (1960) have pointed out that truly straight channels in alluvial material are rare in nature. Although a stream may have relatively straight banks, the thalweg, or path of greatest depths along the channel, is usually sinuous. As a result, there is no simple distinction between straight and meandering channels. If a straight channel is observed, it should be a warning to the bridge engineer to anticipate problems. The channel will probably be trying to move vertically and/or laterally.

The sinuousity of a river, the ratio between thalweg length to down valley distance, is most often used to distinguish between straight and meandering channels. Sinuosity varies from a value of unity to a value of three or more. Leopold, Wolman, and Miller (1964) took a sinuosity of 1.5 as the division between mean-

CHANNEL WIDTH	SMALL (30 M WIDE)		MEDIUM (30-150 M)		WIDE (150 M)
FLOW HABIT	EPHEMERAL	(INTERMITTENT)	PERENNIAL BUT FLASHY		PERENNIAL
CHANNEL BOUNDARIES	 ALLUVIAL		SEMI- ALLUVIAL		NON- ALLUVIAL
BED MATERIAL	SILT- CLAY	SILT	SAND	GRAVEL	COBBLE OR BOULDER
VALLEY; OR OTHER SETTING	 LOW RELIEF VALLEY (< 100 FT. OR 30 M DEEP)	MODERATE RELIEF (100-1000 FT. OR 30-300 M)	HIGH RELIEF (> 1000 FT. OR 300 M)		NO VALLEY; ALLUVIAL FAN
FLOOD PLAIN	 LITTLE OR NONE (< 2x CHANNEL WIDTH)		NARROW (2-10x CHANNEL WIDTH)		WIDE (> 10x CHANNEL WIDTH)
DEGREE OF SINUOSITY	 STRAIGHT (SINUOSITY 1-1.05)	SINUOUS (1.06-1.25)	MEANDERING (1.26-2.0)		HIGHLY MEANDERING (> 2)
DEGREE OF BRAIDING	 NOT BRAIDED (< 5 PERCENT)		LOCALLY BRAIDED (5-35 PERCENT)		GENERALLY BRAIDED (> 35 PERCENT)
DEGREE OF ANABRANCHING	 NOT ANABRANCHED (< 5 PERCENT)		LOCALLY ANABRANCHED (5-35 PERCENT)		GENERALLY ANABRANCHED (> 35 PERCENT)
VARIABILITY OF WIDTH AND DEVELOPMENT OF BARS	 EQUIWIDTH NARROW POINT BARS		WIDER AT BENDS WIDE POINT BARS		RANDOM VARIATION IRREGULAR POINT AND LATERAL BARS
APPARENT INCISION	 NOT INCISED				PROBABLY INCISED
CUT BANKS	RARE		LOCAL		GENERAL
BANK MATERIAL	COHERENT RESISTANT BEDROCK NON-RESISTANT BEDROCK ALLUVIUM				NON-COHERENT SILT; SAND GRAVEL; COBBLE BOULDER
TREE COVER ON BANKS	50 PERCENT OF BANKLINE		50-90 PERCENT		> 90 PERCENT

Source: BRICE AND BLODGETT (1978).

Figure 16. STREAM PROPERTIES FOR CLASSIFICATION AND STABILITY ASSESSMENT

dering and straight channels. It should be noted that in a straight reach with a sinuous thalweg developed between alternate bars a sequence of shallow crossings and deep pools is established along the channel.

Reaches of a river that are relatively straight over a long distance are generally classed as unstable, as are divided flow reaches and those in which bends are migrating rapidly. Long straight reaches can be created by natural or man-made cutoff of meander loops where long reaches of sinuous meandering channels with relatively flat slopes are converted to shorter reaches with much steeper slopes. Straight reaches can also be man-induced by placing of contraction works such as dikes and revetment to reduce or control sinuosity. As noted, even where the channel is straight, it is normal for the thalweg to wander back and forth from one bank to the other. Opposite the point of greatest depth there is usually a bar or accumulation of sediment along the bank, and these bars tend to alternate from one side of the channel to the other. The alternate bars control channel pattern and, thus, their stability determines the stability of the reach.

Braided Streams

A braided river is generally wide with poorly defined and unstable banks and is characterized by a steep, shallow course with multiple channel divisions around alluvial islands (Figure 16). Braiding was studied by Leopold and Wolman (1960) in a laboratory flume. They concluded that braiding is one of many patterns which can maintain quasi-equilibrium among the variables of discharge, sediment load, and transporting ability. Lane (1957) concluded that, generally, the two primary causes that may be responsible for the braided condition are: (1) overloading, that is, the stream may be supplied with more sediment than it can carry, resulting in deposition of part of the load, and (2) steep slopes, which produce a wide, shallow channel where bars and islands form readily.

Either of these factors alone, or both in concert, could be responsible for a braided pattern. If the channel is overloaded with sediment, deposition occurs, the bed aggrades, and the slope of the channel increases in an effort to maintain a graded condition. As the channel steepens, the velocity increases and multiple channels develop and cause the overall channel system to widen. The multiple channels, which form when bars of sediment accumulate within the main channel, are generally unstable and change position with both time and stage.

Braiding is often associated with alluvial fans. The importance of alluvial fans was mentioned earlier when discussing the case histories.

Another cause of braiding is easily eroded banks. If the banks are easily eroded, the stream widens at high flow and at low flow bars form which become stabilized, forming islands. In general, then, a braided channel has a steep slope, a large bed-material load in comparison with its suspended load, and relatively small amounts of silts and clay in the bed and banks. Figure 17 summarizes the various conditions for multiple-channel streams. The braided stream is difficult to work with in that it is unstable, changes its alignment rapidly, carries large quantities of sediment, is very wide and shallow even at flood flow, and is in general unpredictable. Again, the presence of grading should be a tipoff to the highway engineer to expect problems.

Meandering Streams

A meandering channel is one that consists of alternating bends, given an S-shape appearance to the plan view of the river (Figure 16). More precisely, Lane (1957) concluded that for a meandering stream channel alignment consists principally of pronounced bends, the shapes of which have *not* been determined predominantly by the varying nature of the terrain through which the channel passes. The meandering river consists of a series of deep pools in the bends and shallow crossings in the short, straight reach connecting the bends. The thalweg flows from a pool through a crossing to the next pool forming the typical S-curve of a single meander loop. At low flows the local slope is steeper and velocities are larger in the crossing than in the pool. At low stages that thalweg is located very close to the outside of the bend. At higher stages, the thalweg tends to straighten. More specifically the thalweg moves away from the outside of the bend, encroaching on the point bar to some degree. In the extreme case, the shifting of the current causes chute channels to develop across the point bar at high stages.

Alluvial channels of all types deviate from a straight alignment. The thalweg oscillates transversely and initiates the formation of bends. In general, the river engineer concerned with channel stabilization should not attempt to develop straight channels. Again, a straight channel, particularly an artifically straightened one, is a tipoff of instability. The river will attempt to return to a meandering pattern either by changing its gradient or by widening or both.

In general, the behavior of a stream is defined in terms of changes in its position or its form properties with time. Form properties include channel width, sinuosity, meander form, bars, and islands. Aggradation

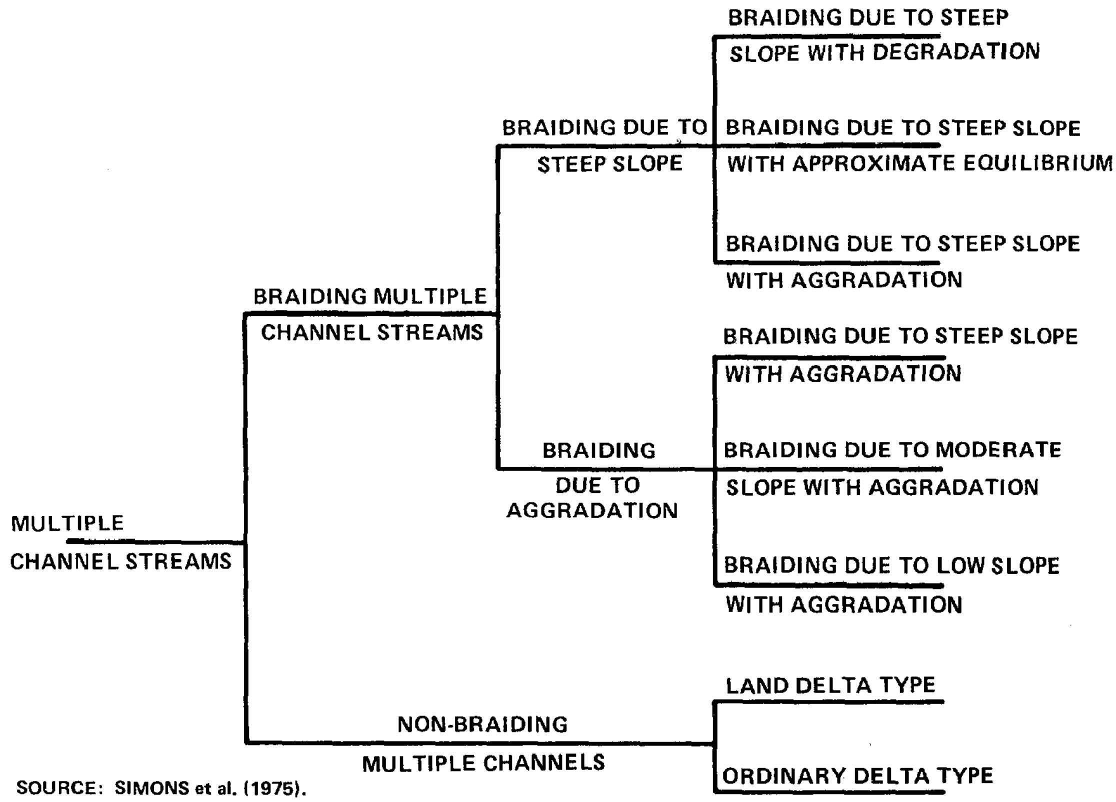


Figure 17. TYPES OF MULTICHANNEL STREAMS

and degradation are difficult to assess from the physical appearance of a stream except in rather obvious cases, such as migrating scarps ("headcuts") in the channel. They are best assessed from historical changes of bed elevation in relation to fixed structures or datum planes (Brice and Blodgett, 1978).

Alluvial Fans

Some additional discussion of alluvial fans is in order. These have been mentioned in connection with braided channels. Alluvial fans are one of the few natural causes of aggradation problems at bridge crossings. Fans occur wherever there is a change from a steep to a flat gradient. Typical examples are steep creeks entering the floodplain of a large river. As the bed material and water reaches the flatter section of the stream, the coarser bed material can no longer be transported because of the sudden reduction in both slope and velocity. Consequently, a cone or fan builds out as the material is dropped. The steep side of the fan faces the floodplain. There is considerable similarity between a delta and an alluvial fan. Both result from reductions in slope and velocity. Both have steep slopes at their outer edges. Both tend to reduce upstream slopes. Alluvial fans, like deltas, are also characterized by unstable channel geometries and rapid lateral movement. If the lateral movement is constrained by a bridge crossing, a gradation problem will result.

Direct Identification of Gradation Problems

General Discussion

Geomorphic and geologic observations, as well as awareness of impacting activities will provide the highway engineer with valuable clues as to the presence of gradation problems. However, not all engineers are comfortable with geomorphic techniques. In any case, even if a gradation problem is anticipated due to impacting activities or geomorphic reasons, a direct verification is necessary. Several fairly simple ways to identify gradation changes are now presented.

Verification of a gradation problem is difficult from two standpoints. First, the time span involved is long. The gradation problems concerned with here take place over times measured in years. Second, the changes occur in the channel bottom. In many parts of the country the channel bottom is perennially covered with water. Natural flow variations and regulation vary the depth frequently. Casual observation is not an adequate way to detect problems. Trouble is often not evident until the pilings erode out of the channel bed, and even then the problem may not be seen if the bridge is visited at high flow.

Examples from Case History Data Base

Detection of gradation problems requires either collection of or analysis of data taken over periods of several years. By some means it is necessary to determine the change in water surface elevation for a given discharge as a function of time, or the elevation of the channel bottom as a function of time. In some instances analysis of the longitudinal profile of the stream or analysis of changing sediment load may be desirable. Examples of each of these techniques applied to case histories will now be presented.

Long-Term Observations of Streambed

Figure 18 illustrates progressive degradation as determined by long-term observations of the streambed. The data are from Caddo Creek at State Highway 53 west of Milo, Oklahoma, and North Fork of Walnut Creek at U.S.-62 near Blanchard, Oklahoma. Both sites degraded roughly 3 m. Degradation of Walnut Creek appears to be slowly lessening while at Caddo Creek it appears to be accelerating. Both sites are on rivers which have been artifically straightened. Analysis of this type takes very little time and provides an accurate picture of gradation changes at a crossing. It is highly recommended that once a year measurements be made from bridge decks to streambed. These data should be kept as part of bridge inspections in grada-

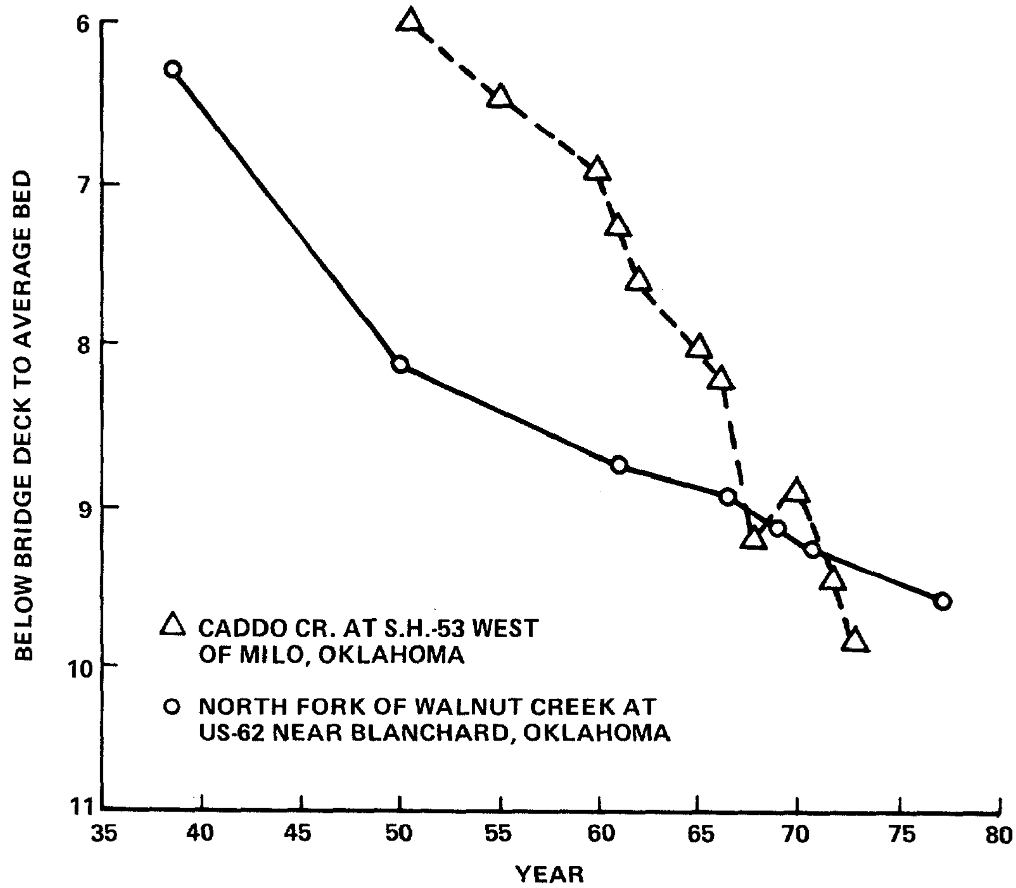


Figure 18. OBSERVATIONS OF PROGRESSIVE DEGRADATION

tion problem areas. Data of this type would be helpful in new design as well as in evaluating the need for and success of remedial measures.

Observations of Changes in Stage-Discharge Relations

In many cases data on the changing bed level may not be available. Occasionally information can be gained from series of maps which have been prepared at different times. Data from railroad and pipeline crossing surveys upstream or downstream of a highway bridge may also be helpful at determining bed elevation as a function of time. In the absence of such data other methods are required.

On many streams of reasonable size long-term data or streamflow are available at the gaging stations of the U.S. Geological Survey (USGS) and the U.S. Corps of Engineers. Shifts in the rating curves that relate river stage to discharge are often good clues to gradation changes.

The Missouri River and its tributaries near Omaha, Nebraska, provided a number of excellent sites for the case history data base. Changes in the rating curves at gaging stations along the river are documented by Sayre and Kennedy (1978). Figures 19 and 20, from Sayre and Kennedy, illustrate the rather dramatic changes which have taken place as a channel degrades. The degradation is due primarily to closure of large reservoirs on the river and efforts to maintain a navigation channel.

An additional example of a drastic shift in a rating curve can be seen at the Yalobusha River near Calhoun City, Mississippi, site. The channel underwent significant degradation due to channelization by the Soil Conservation Service. Figure 21 shows the rating curve for the USGS gaging station Yalobusha River at State Highway 9 at Calhoun City, Mississippi, before and after the channelization. Stage shifts of 1 to 1.5 m took place for any given discharge.

Analysis of gaging station stage trends is, again, easily done and yields useful information on long term trends. On many occasions the USGS and Corps of Engineers have already performed the analysis. Gaging station records are excellent because many have been in existence for 30 years or longer.

Observation of Changes in Sediment Load

Another type of useful information from gaging stations is sediment load. Although not many stations have continuous sediment data, when available it can provide clues to the presence of gradation problems. By definition, aggradation takes place when sediment inflow to a river exceeds sediment outflow. Degradation occurs when outflow exceeds inflow. Any change in the long-term sediment load signals an imbalance in the stream system. Such imbalances lead to lateral movement, bank sloughing, and gradation problems.

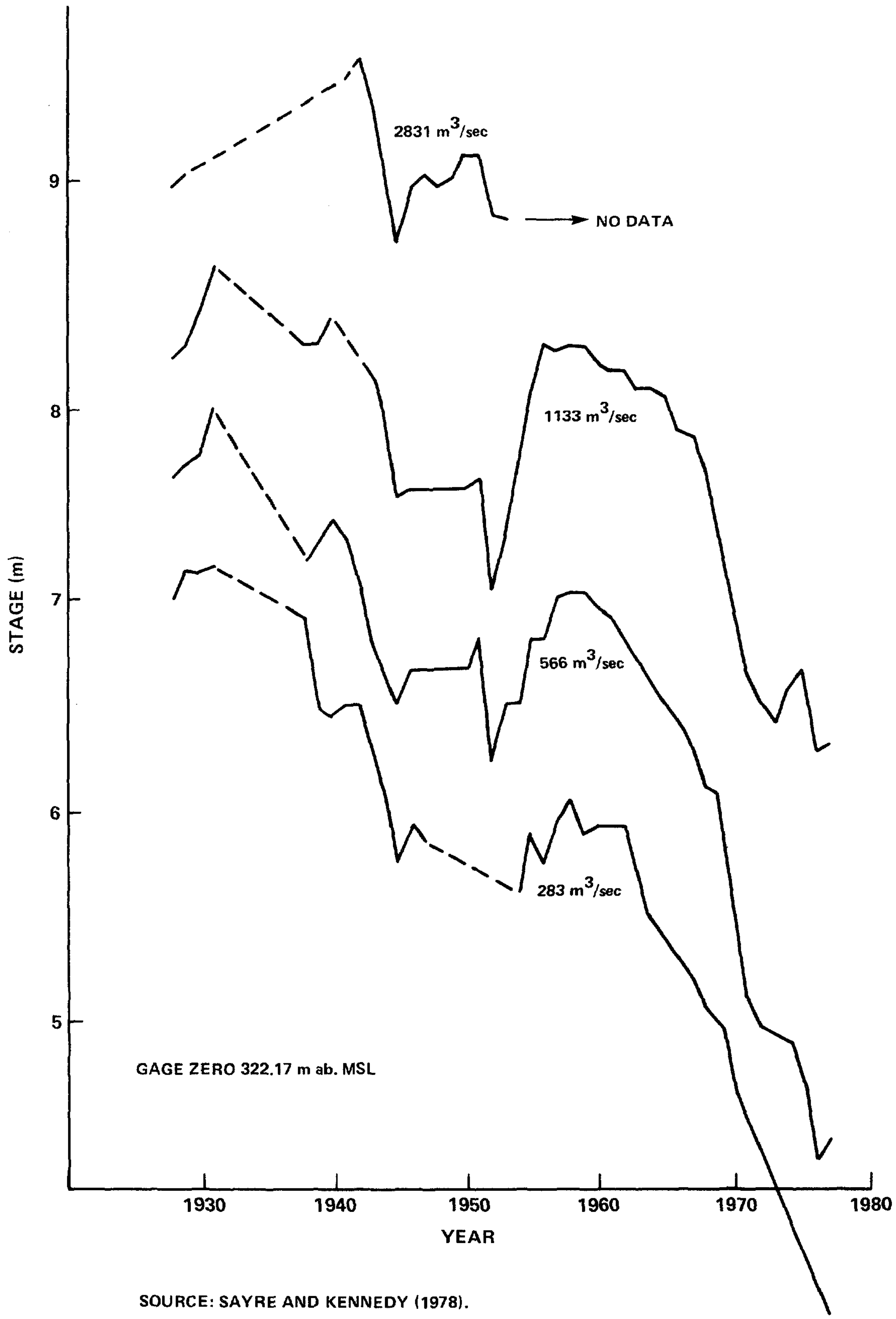
The Missouri River has a number of long-term sediment stations. Data from Sayre and Kennedy (1978) illustrate the changes which take place in sediment load at the time of gradation problems. Figure 22 illustrates the 100-fold change in sand, silt, and clay load which took place in the early 1950's when the dams above Omaha were closed. This time period coincides with the beginning of major gradation changes along the river.

Streambed Profile Analysis

Another method for verifying the presence of gradation changes is stream profile evaluation. This method requires considerable surveying effort. The idea is similar to measuring the change in bed elevation from the bridge deck. Instead, a longitudinal profile of the thalweg is surveyed and compared to a historic profile.

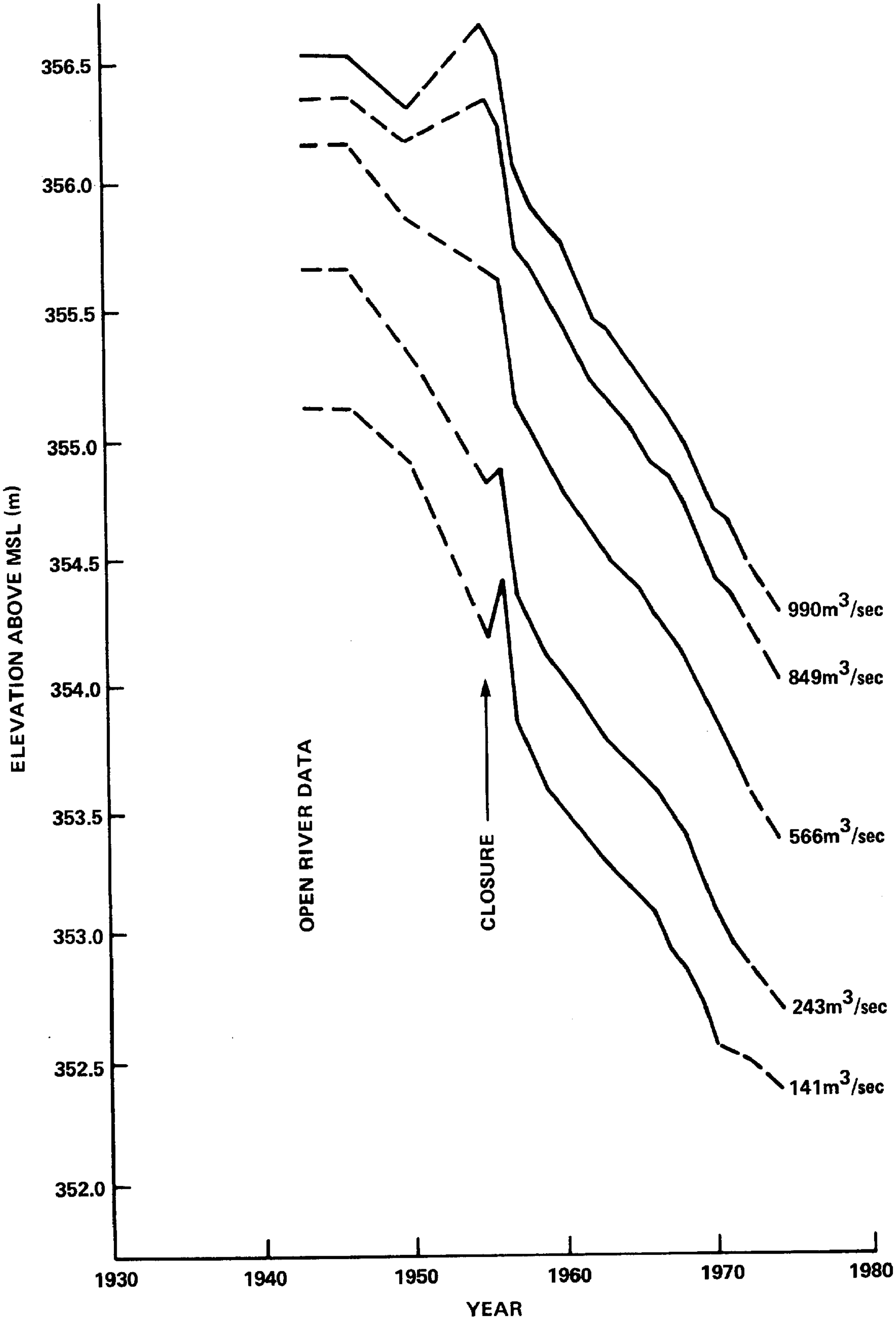
A good example of such analysis is given in the case history data base under South Fork of Deer Creek near Halls, Tennessee. The channel was straightened and enlarged in the 1920's by local flood control districts. In 1969 the Corps of Engineers straightened and enlarged a 4.8 km reach of the river below the highway bridge. Figure 23 illustrates the change in streambed profile which occurred in the 6 years subsequent to the channel changes. A degradation of 2.5 to 3 m has taken place.

Profile analysis requires considerable effort if it is necessary to perform the actual survey. Rough profile analysis can occasionally be performed by plotting the elevations of cross-sections at pipeline crossings and railroad bridges and other similar data as a function of time. This may be required when gaging



SOURCE: SAYRE AND KENNEDY (1978).

Figure 19. STAGE TRENDS AT SIOUX CITY, IOWA, ON THE MISSOURI RIVER



SOURCE: SAYRE AND KENNEDY (1978).

Figure 20. TAILWATER TRENDS AT GAVINS POINT DAM ON THE MISSOURI RIVER

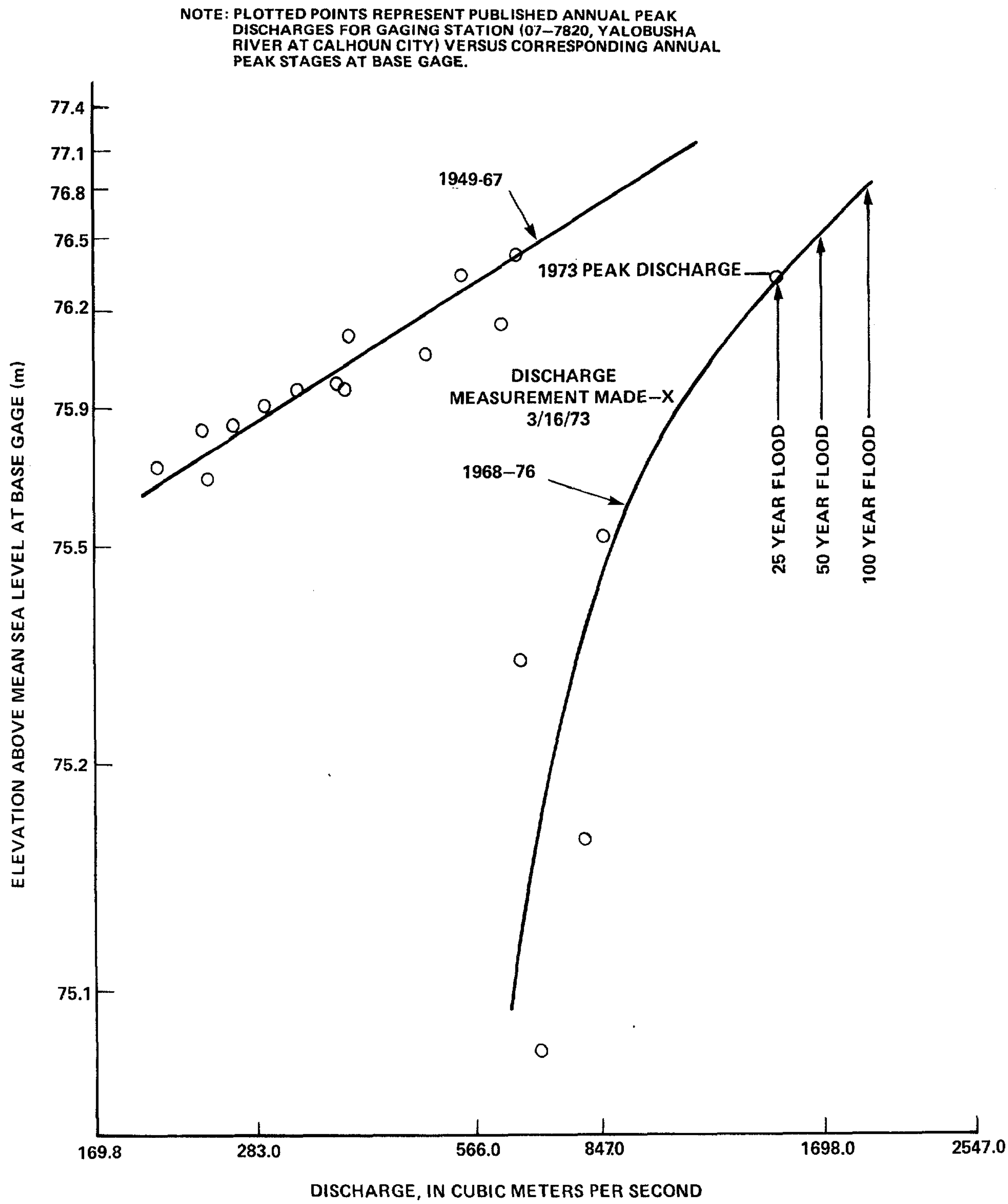


Figure 21. STAGE-DISCHARGE RELATIONSHIP AT YALOBUSHA RIVER AT STATE HIGHWAY 9 AT CALHOUN CITY, MISSISSIPPI

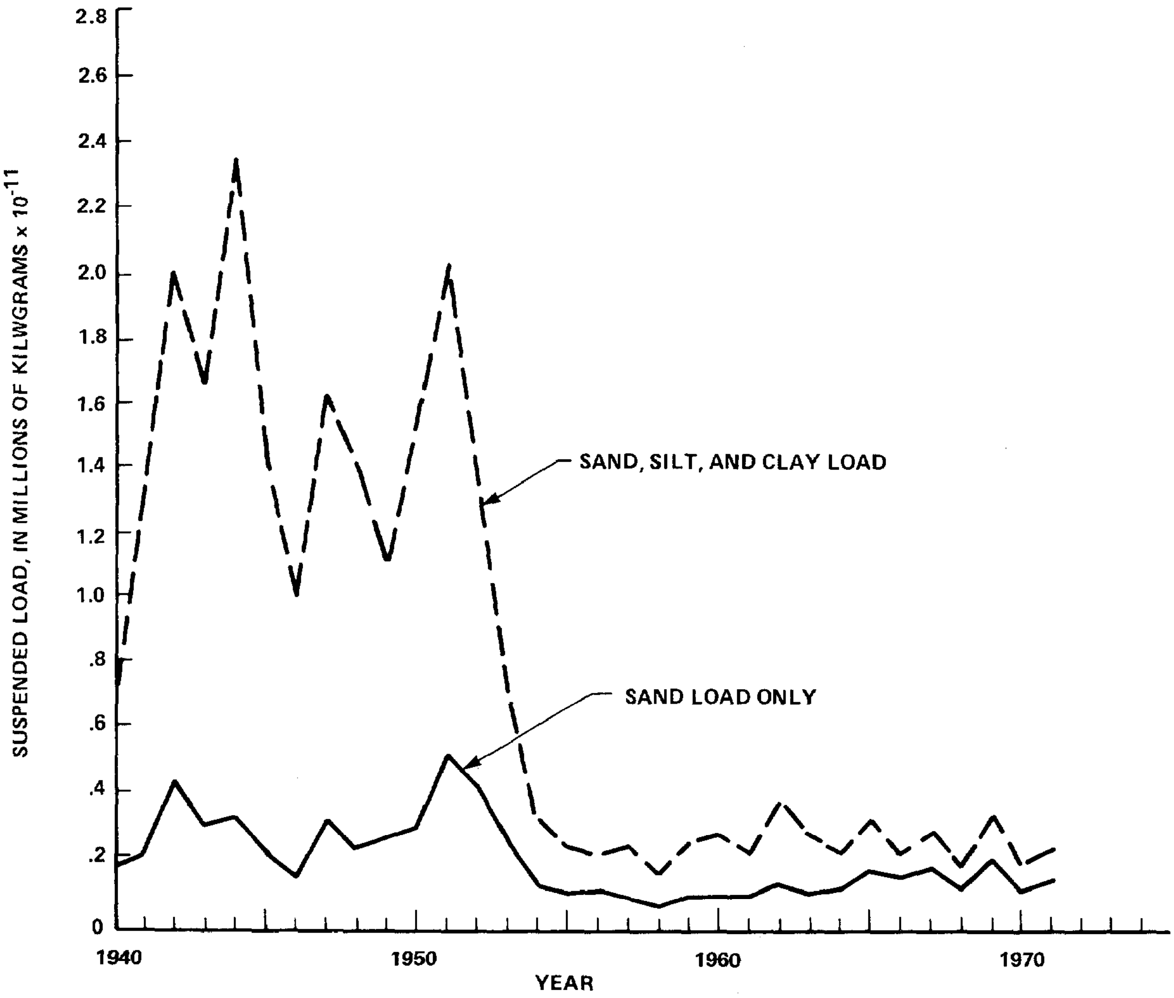


Figure 22. COMPARISON OF ANNUAL AVERAGE DAILY SUSPENDED SEDIMENT LOAD AT OMAHA, NEBRASKA, BEFORE AND AFTER DAM CLOSURES ON THE MISSOURI RIVER

stations or other more readily available data are absent. The U.S. Corps of Engineers conducts potamology surveys and maintains sediment ranges on many major streams. Data from these sources may be useful in determining bed level changes with time.

Summary

To this point the first step of the three-step approach to aggradation-degradation problems has been discussed. Clues to the presence of gradation problems have been presented. These include geomorphic/geologic clues such as location on an alluvial fan or on a straightened river. Also included are clues such as location in certain geographic areas or near major impacting activities.

Several methods for verifying a gradation problem have been discussed. These methods include direct observation, stream stage analysis, sediment flow analysis, and stream profile analysis.

By looking for clues and by performing simple analysis, the bridge engineer can identify the presence of a gradation problem. The second step is to determine the extent of the problem. This requires more sophisticated analysis. The following section discusses means for computing the rate and amount of a gradation change.

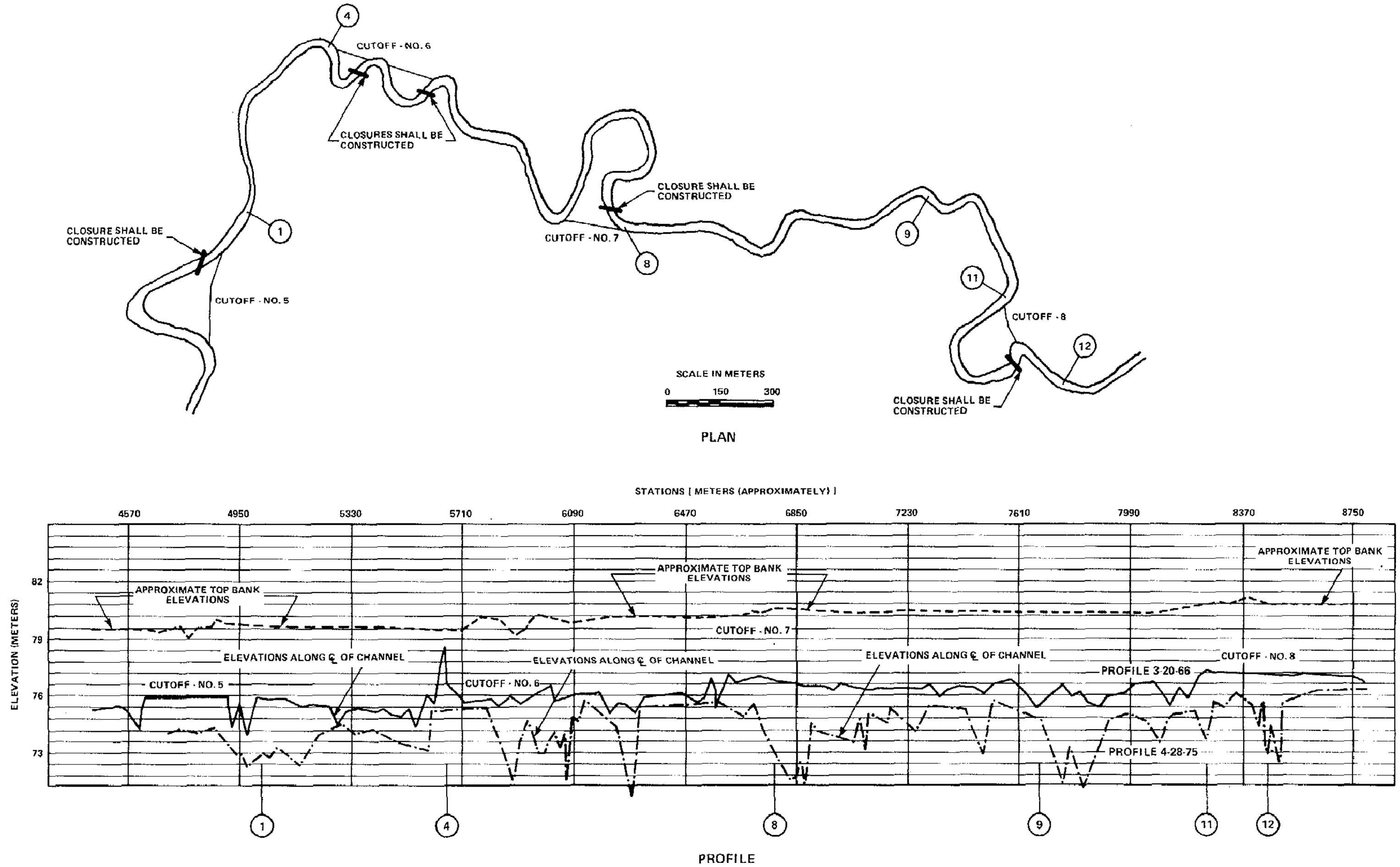


Figure 23. PROFILE ANALYSIS OF DEGRADATION AT SOUTH FORK OF DEER CREEK NEAR HALLS, TENNESSEE

PROBLEM ANALYSIS

General Approach

After the potential for or the presence of a gradation problem is confirmed, the bridge engineer must determine the extent of the problem. In new design, sufficient pile depth or deck height must be included. At existing sites suitable remedial measures must be taken. These actions require methods of analysis which will predict the long-term extent of the gradation change.

It was not within the scope of work of Phase I to develop design procedures to account for gradation changes. That is part of Phase II. Instead, useful or potentially useful computational methods have been identified from the technology assessment of the annotated bibliography. Reasonably detailed descriptions are given of the data required, computational effort, and results of each technique. Where possible examples are identified from the case history data base where a particular technique might be useful. Recommendations for testing or modification of techniques as part of Phase II are given.

The discussion of analysis methods is divided into three parts. Data requirements are similar for most detailed computations. Therefore, data are discussed first. Geomorphic techniques, discussed next, are generally qualitative in nature and of medium complexity, halfway between direct observations and more advanced hydraulic computations. Hydraulic methods involving computation of sediment transport are discussed last.

Data Requirements for Gradation Analysis

Richardson et al. (1974) provides an excellent summary of the data requirements for hydraulic analysis of bridge crossings (Table 11). Although not all of the data required for a hydraulic analysis are required for gradation changes, the summary is worth reproducing here. Much of the data may be available from bridge design or previous studies.

Maps and Photographs

Two of the most basic data needs are maps and photographs. These data are used to evaluate stream type, identify impacting activites and land use, and measure distance for computation techniques.

An area map is needed to identify the location of the entire highway project and all streams and river crossings involved. The purpose of the map is to orient the highway project geographically with other area features. The map may be very small scale showing towns, cities, mountain ranges, railroads, and other highways and roads. The area map should be large enough to identify river systems and tributaries.

Vicinity maps for each river crossing are needed to aid in geomorphic analysis and identification of impacting activities. There should be sufficient length of river reach included on the vicinity map to enable identification of stream type and to locate river meanders, sandbars, and braided channels. Other highways and railroads should be identified. The maps should show coarse contours and relief. The direction of river flow should, of course, be clearly indicated.

Site maps are needed to determine details for hydraulic and structural designs. The site map should show detailed contours with 0.3 to 0.6 m intervals, vegetation distribution and type, and other structures. The site map is used to locate highway approach embankments, piers and alignment of piers, channel changes, and protection works. If data are available, high water lines should be indicated on the site maps for the purpose of estimating flood flows and distributions across the river cross-section.

It is highly desirable in preparing vicinity and site maps that aerial photographs be obtained. Modern multi-image cameras use different ranges of the light spectrum to assist in identifying various features such as sewer outfalls, groundwater inflows, types of vegetation, sizes and heights of sandbars, river thalwegs, river controls and geologic formations, existing bank protection works, old meander channels, and other features. Detailed contours can be developed from aerial photographs for vicinity and site maps where such information is not readily available.

Land photographs (as opposed to aerial photos) of existing structures are always helpful in documentation and evaluation of potential effects of highway construction. Series of photographs from the same location over a period of years are useful in making visual identification of gradation changes. Conditions of the river channel in the river reach of concern are easy to record photographically, and such pictures can be very helpful in analysis of the river reach. Vegetation on floodplains and seasonal variations of vegetation should be recorded photographically. Notable

Table 11. LIST OF DATA SOURCES FOR HYDROLOGIC AND GRADATION STUDIES

Topographic Maps:

(1) Quadrangle maps — U.S. Department of the Interior, Geological Survey, Topographic Division; and U.S. Department of the Army, Army Map Service.
(2) River plans and profiles — U.S. Department of the Interior, Geological Survey, Conservation Division.
(3) National parks and monuments — U.S. Department of the Interior, National Park Service.
(4) Federal reclamation project maps — U.S. Department of the Interior, Bureau of Reclamation.
(5) Local areas — commercial aerial mapping firms.
(6) American Society of Photogrammetry.

Planimetric Maps:

(1) Plats of public land surveys — U.S. Department of the Interior, Bureau of Land Management.
(2) National forest maps — U.S. Department of Agriculture, Forest Service.
(3) County maps — State Highway Agency.
(4) City plats — city or county recorder.
(5) Federal reclamation project maps — U.S. Department of the Interior, Bureau of Reclamation.
(6) American Society of Photogrammetry.
(7) ASCE Journal — Surveying and Mapping Division.

Aerial Photographs:

(1) The following agencies have aerial photographs of portions of the United States: U.S. Department of the Interior, Geological Survey, Topographic Division; U.S. Department of Agriculture, Commodity Stabilization Service, Soil Conservation Service and Forest Service; U.S. Air Force; various state agencies; commercial aerial survey; National Oceanic and Atmospheric Administration; and mapping firms.
(2) American Society of Photogrammetry.
(3) Photogrammetric Engineering.
(4) Earth Resources Observation System (EROS)
    Photographs from Gemini, Apollo, Earth Resources Technology Satellite (ERTS) and Skylab.

Transportation Maps:

(1) State Highway Agency.

Triangulation and Benchmarks:

(1) State Engineer.
(2) State Highway Agency.

Geologic Maps:

(1) U.S. Department of the Interior, Geologic Survey, Geologic Division; and state geological surveys or departments. (Note—some regular quadrangle maps show geological data also.)

Soils Data:

(1) County soil survey reports — U.S. Department of Agriculture, Soil Conservation Service.
(2) Land use capability surveys — U.S. Department of Agriculture, Soil Conservation Service.
(3) Land classification reports — U.S. Department of the Interior, Bureau of Reclamation.
(4) Hydraulic laboratory reports — U.S. Department of the Interior, Bureau of Reclamation.

Source: Richardson et al. (1974).

Table 11. LIST OF DATA SOURCES FOR HYDROLOGIC AND GRADATION STUDIES (Continued)

Climatological Data:

(1) National Weather Service Data Center.

(2) Hydrologic bulletin – U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

(3) Technical papers – U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

(4) Hydrometeorological reports – U.S. Department of Commerce, National Oceanic and Atmospheric Administration; and U.S. Department of the Army, Corps of Engineers.

(5) Cooperative study reports – U.S. Department of Commerce, National Oceanic and Atmospheric Administration; and U.S. Department of the Interior, Bureau of Reclamation.

Stream Flow Data:

(1) Water supply papers – U.S. Department of the Interior; Geological Survey, Water Resources Division.

(2) Reports of state engineers.

(3) Annual reports – International Boundary and Water Commission, United States and Mexico.

(4) Annual reports – various interstate compact commissions.

(5) Hydraulic laboratory reports – U.S. Department of the Interior, Bureau of Reclamation.

(6) Owners of Reclamation.

(7) Corp of Engineers, U.S. Army, Flood control studies.

Sedimentation Data:

(1) Water supply papers – U.S. Department of the Interior, Geological Survey, Quality of Water Branch.

(2) Reports – U.S. Department of the Interior, Bureau of Reclamation; and U.S. Department of Agriculture, Soil Conservation Service.

(3) Geological Survey Circulars – U.S. Department of the Interior, Geological Survey.

Quality of Water Reports:

(1) Water supply papers – U.S. Department of the Interior, Geological Survey, Quality of Water Branch.

(2) Reports – U.S. Department of Health, Education, and Welfare, Public Health Service.

(3) Reports – state public health departments.

(4) Water resources publications – U.S. Department of the Interior, Bureau of Reclamation.

(5) Environmental Protection Agency, regional offices.

(6) State water quality agency.

Irrigation and Drainage Data:

(1) Agriculture census reports – U.S. Department of Commerce, Bureau of the Census.

(2) Agricultural statistics – U.S. Department of Agriculture, Agricultural Marketing Service.

(3) Federal reclamation projects – U.S. Department of the Interior, Bureau of Reclamation.

(4) Reports and progress reports – U.S. Department of the Interior, Bureau of Reclamation.

Power Data:

(1) Directory of Electric Utilities – McGraw Hill Publishing Co.

(2) Directory of Electric and Gas Utilities in the United States – Federal Power Commission.

(3) Reports – various power companies, public utilities, state power commissions, etc.

Basin and Project Reports and Special Reports:

(1) U.S. Department of the Army, Corps of Engineers.

(2) U.S. Department of the Interior, Bureau of Land Management, Bureau of Mines, Bureau of Reclamation, Fish and Wildlife Service, and National Park Service.

Table 11. LIST OF DATA SOURCES FOR HYDROLOGIC AND GRADATION STUDIES (Continued)

Basin and Project Reports and Special Reports (Continued):

(3) U.S. Department of Agriculture, Soil Conservation Service.

(4) U.S. Department of Health, Education, and Welfare, Public Health Service.

(5) State departments of water resources, departments of public works, power authorities, and planning commissions.

Environmental Data:

(1) Sanitation and public health — U.S. Department of Health, Education, and Welfare, Public Health Service; state departments of public health.

(2) Fish and wildlife — U.S. Department of the Interior, Fish and Wildlife Service; state game and fish departments.

(3) Municipal and industrial water supplies — city water departments; state universities; Bureau of Business Research; state water conservation boards of state public works departments, state health agencies, Environmental Protection Agency, Public Health Service.

(4) Watershed management — U.S. Department of Agriculture, Soil Conservation Service, Forest Service; U.S. Department of the Interior, Bureau of Land Management, Bureau of Indian Affairs.

geologic formations should be photographed as well and supplemented with adequate notes. This information can be quite helpful in geomorphic analysis such as identification of alluvial fans or headcuts.

The basic data needed are on stream discharge at the nearest gaging station, historical floods, and high-water marks. It is also desirable to prepare a drainage map for the region upstream of the proposed highway project, with delineation of size, shape, slope, land use, and water resource facilities such as storage reservoirs for irrigation and power and flood control projects. These are major impacting activities and are likely to cause gradation changes.

A geologic vicinity map on which physiographic features are indicated is a basic need. The basic rock formations, rock exposures, and glacial and river deposits which form control points on rivers are valuable in analysis of rivers. Soil type has important effects on sediment transport material, infiltration rates, and groundwater flows. Channel geometry and roughness are important factors in river mechanics.

Soil survey maps with engineering interpretations are available for a significant proportion of the United States. They may be helpful in determining transport properties of sediments.

The importance of simply visiting a bridge site and inspecting it in person should not be overlooked. This has been implied in the foregoing paragraphs but is emphasized again because of the underlying importance of making first-hand appraisals of specific sites before conclusions and recommendations are advanced concerning gradation problems. Geologic relief and other features are easier to see in nature than in photographs and maps.

Streamflow Records

While maps and photos serve a useful role in gradation studies, particularly for geomorphic analysis, streamflow and sediment data are of equal importance.

Stream gaging stations have been established on many streams throughout the United States. However, there are some streams where either a gaging station does not exist near the project site or a gaging station does not exist at all. In such cases it is necessary to estimate streamflows. These estimates may be based on regionalized estimating procedures or other prediction models using meteorological and watershed data inputs. These meteorological data are available from the National Weather Service (NWS) Data Center of the National Oceanic and Atmospheric Administration (NOAA), and estimates of average conditions can be made from rainfall data published by the NWS.

Sediment Records

Sediment load data are an integral part of gradation analysis. Bed-material load, suspended load, and wash load data may be obtained for some rivers in the water supply papers published by the USGS, state engineers' reports, and flood control and other water resources investigation reports. Information may also be obtained by direct sampling of the river. Size distributions of bed and bank material as well as the suspended load are required for many analyses. These may be obtained from government agencies or collected by the highway engineer.

Channel Cross-Sections and Streambed Profiles

Channel cross-sections and streambed profiles are required for some gradation calculations. In flowing rivers these may be obtained with sonic depth sounding equipment. In small streams conventional surveying methods may be used.

Flood Frequency Data

Flood frequency information may be required for computing frequency and volumes of sediment flow. At existing gages the USGS often has flood-frequency studies available. At other sites estimation may be required. Several methods ranging from sophisticated stochastic analysis to simple methods have been developed. The greatest difficulty in constructing a flood-frequency curve is lack of sufficient data. Approximate methods for extrapolating the range of flood-frequency curves are available but are not discussed in detail here. (See "Guidelines for Hydrology," published by the Task Force on Hydrology and Hydraulics, listed in references.)

Geomorphic Analysis Methods

General Discussion

Geomorphologic techniques are generally qualitative in nature. After a highway engineer has determined that a number of impacting activities exist near a bridge such methods may be used to determine the trend of the problem. Geomorphology theory provides information concerning the direction and extent of gradation problems but generally does not provide numbers useful in exact design. Nevertheless, a knowledge of geomorphology is very important for selecting a more exact hydraulic analysis method.

As stated earlier, the purpose of this interim report is not to provide a final design manual for gradation problems. A brief review of geomorphology theory will be presented. This is followed by an evaluation of methods described in the current literature. Those methods which appear useful for inclusion in Phase II are identified.

Equilibrium Concepts

Qualitative geomorphic analysis of gradation changes is based on the concept of equilibrium. Rivers strive, in the long run, to achieve a balance between the product of water flow and channel slope and the product of sediment discharge and size. The most widely known geomorphic relation embodying the equilibrium concept is known as Lane's principle.

Lane's Principle

Lane (1955) studied the changes in river morphology caused by modifications of water and sediment discharges. Similar but more comprehensive treatments of channel response to changing conditions in rivers have been presented by Leopold and Maddock (1953), Schumm (1971), and Santos-Cayado (1972). All research results support the following general statements:

(1) Depth of flow is directly proportional to water discharge and inversely proportional to sediment discharge.
(2) Width of channel is directly proportional to water discharge and to sediment discharge.
(3) Shape of channel expressed as width-depth ratio is directly related to sediment discharge.
(4) Meander wavelength is directly proportional to water discharge and to sediment discharge.
(5) Slope of stream channel is inversely proportional to water discharge and directly proportional to sediment discharge and grain size.
(6) Sinuosity of stream channel is proportional to valley slope and inversely proportional to sediment discharge.

These relations will help to determine the response of any water conveying channel to change.

A mathematical statement of the above principles may be derived as follows. Sediment bed-material transport (Q_s) can be directly related to stream power ($\tau_0 V$) and inversely related to the fall diameter of bed material (D_{50}).

$$Q_s \sim \frac{\tau_0 V W}{D_{50}/C_f}, \qquad (1)$$

Here τ_0 is the bed shear, V is the cross-sectional average velocity, W is the width of the stream, and C_f is the final material load concentration. Equation (1) can be written as

$$Q_s \sim \frac{\gamma y_0 SWV}{D_{50}/C_f} = \frac{\gamma QS}{D_{50}/C_f} \qquad (2)$$

If specific weight, γ, is considered constant and the concentration of fine material, C_f, can be incorporated in the fall diameter, D_{50}, the relation can be expressed as

$$QS \sim Q_s D_{50}, \qquad (3)$$

which is the relation originally proposed by Lane (1955), except Lane used the median diameter of the bed material as defined by sieving instead of the fall diameter. The fall diameter includes the effect of temperature on the transportability of the bed material and is preferable to the use of sieve diameter.

Application of Equilibrium Concepts

Equation (3) is very useful to qualitatively predict channel response to climatological changes, river development, or both. Two simple example problems are analyzed using Equation (3).

Consider a tributary entering the main river at point C that is relatively small but carries a large sediment load (see Figure 24). This increases the sediment discharge in the main stream from Q_s to Q_s^+. It is seen from Equation (3) that, for a significant increase in sediment discharge (Q_s^+) the channel gradient (S) below C must increase if Q remains constant. The line CA (indicating the original channel gradient) therefore changes with time to position C'A. Upstream of the confluence the slope will adjust over a long period of time to the original channel slope. The riverbed will aggrade from C to C'.

Construction of a dam on a river usually causes a decrease in sediment discharge downstream. Referring to Figure 25 and using Equation (3) and the earlier discussion, it can be concluded that for a

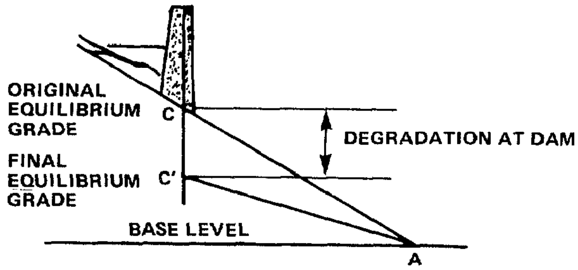


Figure 24. CHANGES IN CHANNEL SLOPE IN RESPONSE TO AN INCREASE IN SEDIMENT LOAD AT POINT C

decrease in bed-material discharge from Q_s to Q_s^-, the slope S decreases downstream of the dam. In Figure 25, the line CA, representing the original channel gradient, changes to C'A, indicating a decrease in bed elevation and slope in the downstream channel with time. Note, however, if the dam fills with sediment so that the incoming sediment discharge passes through, that, except for local scour at the dam, the grade line C'A would return to the line CA. Also, upstream of the dam the grade would return to the original equilibrium grade but would be offset vertically by the height of the dam. Thus, small dams (storage capacity small in relation to annual discharge) may cause degradation and then aggradation over a relatively short period of time.

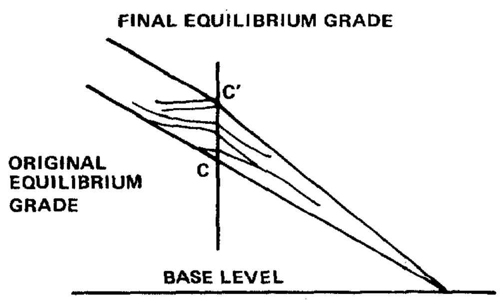


Figure 25. CHANGES IN CHANNEL SLOPE IN RESPONSE TO A DAM AT POINT C

Stream Stability Analysis

The engineer is also interested in quantities in addition to directions of variations. Quantitative methods will be discussed shortly. The geomorphic relation $QS \sim Q_s D_{50}$ is only an initial step in analyzing long-term channel response problems. However, this initial step is useful because it warns of possible future difficulties in designing remedial measures.

In the preceding examples it was shown that changes in water, sediment discharge, or both can cause significant changes in channel slope. The changes in sediment discharge can be in quantity, Q_s, or caliber, D_{50}, or both. Often such changes can alter the plan view in addition to the profile of a river.

Figure 26 illustrates the dependence of river form on channel slope and discharge. It shows that when

$$S\,Q^{1/4} \leqslant .0017\ , \tag{4}$$

a sandbed channel meanders. Similarly, when

$$S\,Q^{1/4} \geqslant .010\ , \tag{5}$$

the river is braided. In these equations, S is the channel slope in meters per meter and Q is the mean discharge in cubic meters per second. Between these values of $S\,Q^{1/4}$ is the transitional range, and the many plots of the U.S. rivers, classified as intermediate sandbed streams, are in this zone between the limiting curves defining meandering and braided rivers (Lane, 1957). If a river is meandering but its discharge and slope borders in the transitional zone a relatively small increase in channel slope may cause it to change, with time, to a transitional or braided river. The importance of Figure 26 to the gradation problem is that vertical instability may result in lateral instability. That is, a dam on a stable meandering stream might cause sufficient aggradation upstream to cause braiding. Artifically constraining the channel to a meandering or straight course may increase the aggradation rate. Many other effects can be analyzed by studying the figure.

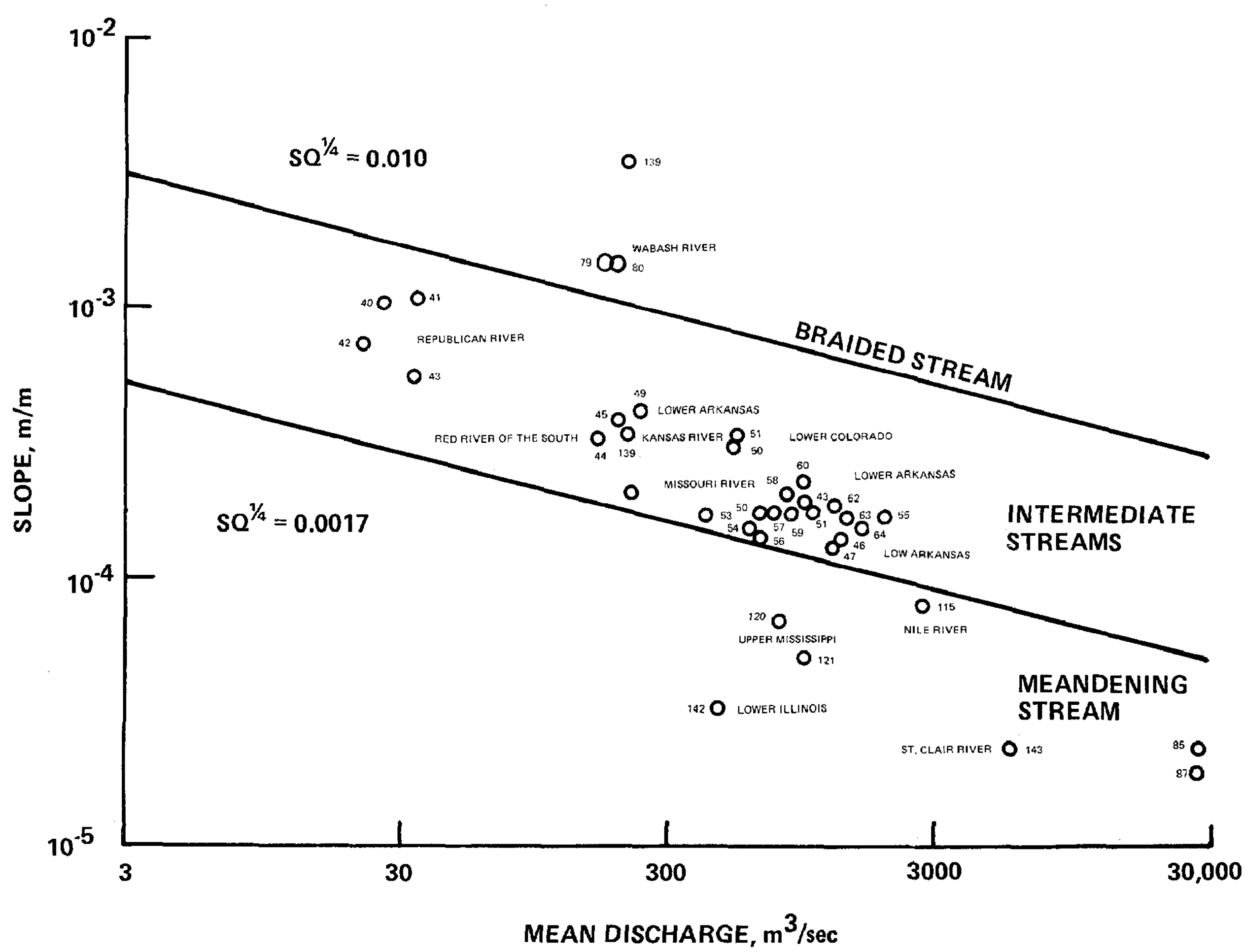


Figure 26. SLOPE-DISCHARGE RELATIONSHIP FOR BRAIDING OR MEANDERING IN SANDBED STREAMS

Application Tables

An an aid to the reader in the application of Lane's principle, Tables 12 and 13 have been prepared. The two tables summarize a number of common conditions, easily observed, and relate them to channel bed response. The tables relate anticipated river response to increases (+) and decreases (-) in key variables.

Use of the tables can be best illustrated by application. Referring to Table 12, consider the effect of an increase in discharge indicated by a plus sign on line (a) opposite discharge. The increase in discharge may affect the river form, energy slope, stability of the channel, cross-sectional area, and river stage. Equations (4) and (5) and Figure 26 show that an increase in discharge could induce a change in the direction of a braided form. Whether or not the channel form changed would depend on the river character prior to the increase in discharge. With the increase in discharge the stability of the channel would be reduced.

With regard to assessing the potential for aggradation and degradation, it is stressed that more quantitative methods are required to determine the rates of aggradation and degradation. This is likewise true for determination of the magnitude of these quantities.

Table 14 relates observed physical conditions such as alluvial fans, construction of dams and reservoirs, etc., to channel stability and to aggradation and degradation. Again, the results are qualitative.

Continuum of Channel Patterns

It is important to reemphasize that gradation problems are closely associated with lateral stability problems. The type of problem which develops depends largely on the relative bank geometry and on the amount of training works and other controls exerted by man. A given reach of river may exhibit both braided and meandering channel patterns, and alteration of the controlling parameters can destroy the balance, causing a rapid shift toward one or the other.

A number of studies have quantified this concept of a continuum of channel patterns. Khan (1971) related sinuosity, slope, and channel pattern (Figure 27). Any natural or artificial change which alters channel slope such as the cutoff of a meander loop, can result in modifications to the existing river pattern. A cutoff in a meandering channel shortens channel lengths and increases slope. As shown in Figure 27, the plotting position of the river shifts to the right. This indicates a tendency to evolve from a relatively tranquil, easy to control, meandering pattern to a braided pattern that varies rapidly with time, has high velocities, is subdivided by sandbars, and carries relatively large quantities of sediment. Conversely, a slight decrease in slope could change an unstable braided river into a more stable meandering pattern.

Two examples will now be discussed to illustrate the use of Lane's and Khan's data on channel stability along with Lane's analysis of the gradation changes. First, a further discussion of the impact of a reservoir on gradation is presented. Next, the effect of channel straightening is presented.

The impact of a reservoir was mentioned briefly earlier. The sketch of degradation which takes place is reproduced in Figure 28. In most instances all of the bed-material load coming into a reservoir drops out within the reservoir. Water released from the reservoir is quite clear. The existing river channel is the result of its interaction with normal water-sediment flows over a long period of time. With the sediment-free flows the channel below the dam is too steep and sediments are entrained from the bed and the banks bringing about significant degradation. The channel banks may become unstable due to degradation, and there is a possibility that the river, as its profile flattens, may change its plan form. A replot of Figure 26 is sketched in Figure 28 (b) to illustrate the possible impact of a significant decrease in slope on channel pattern. Assuming that prior to dam construction the reach below the dam plotted as an intermediate stream (Point 1), the decrease in slope at constant water discharge could move the stream's plotting position to Point 2 in the meandering region of the chart.

Figure 29 illustrates a situation where artificial cutoffs have straightened the channel below a given reach. It is obvious that straightening the channel downstream of Reach A significantly increases the channel slope. In general, this causes higher velocities, increased bed-material transport, degradation and possible headcutting through Reach A. This can result in unstable riverbanks and a braided stream form as shown in the portion of Figure 27 that is included in Figure 29. Here, the original plotting position (Point 1) is moved to Point 2 in the braided region by the

Table 12. QUALITATIVE RESPONSE OF SANDBED CHANNELS

Variable		Change in Magnitude of Variable	Effect on						
			River Form	Resistance to Flow	Area	Stability of Channel	Aggradation	Degradation	Stage
Dis-charge	(a)	+	M→B	±	+	−		√	+
	(b)	−	B→M	+	−	+	√		−
Bed Mater-ial Size	(a)	+	M→B	+	+	±	√		+
	(b)	−	B→M	−	−	±		√	−
Bed Mater-ial	(a)	+	B→M	−	−	+	√		−
	(b)	−	M→B	+	+	−		√	+
Wash Load	(a)	+		−	−	±		√	−
	(b)	−		+	+	±	√		+
Viscos-ity	(a)	+		−	−	±		√	−
	(b)	−		+	+	±	√		+
Seepage Force	(a)	Outflow	B→M	+	+	+		√	+
	(b)	Inflow	M→B	−	−	−	√		−
Vegeta-tion	(a)	+	B→M	+	+	+	√		+
	(b)	−	M→B	−	−	−		√	−
Wind	(a)	Dowmstream	M→B	−	−	−	√		−
	(b)	Upstream	B→M	+	+	−		√	+

Table 13. QUALITATIVE RESPONSE OF GRAVEL- AND COBBLE-BED CHANNELS

Variable		Change in Magnitude of Variable	Effect on						
			River Form	Resistance to Flow	Area	Stability of Channel	Aggradation	Degradation	Stage
Dis-	(a)	+	B	–	+	–		√	+
charge	(b)	–	M	+	–	+	√		–
Bed Mater-	(a)	+	M	+	+	+	√		+
ial Size	(b)	–	B	–	–	–		√	–
Bed Mater-	(a)	+	B	–	–	–	√		±
ial Load	(b)	–	M	+	+	+		√	+
Wash	(a)	+	B	–	–	+		√	–
Load	(b)	–	M	+	+	–	√		+
Viscos-	(a)	+	B	+	+	–		√	+
ity	(b)	–	M	–	–	+	√		–
Seepage	(a)	+	B	+	+	–	√		+
Force	(b)	–	M	–	–	+		√	–
Vegeta-	(b)	+	M	+	+	+		√	+
tion	(b)	–	B	–	–	–	√		–
Wind	(a)	+	B	+	+	–	√		+
	(b)	–	M	–	–	+		√	–

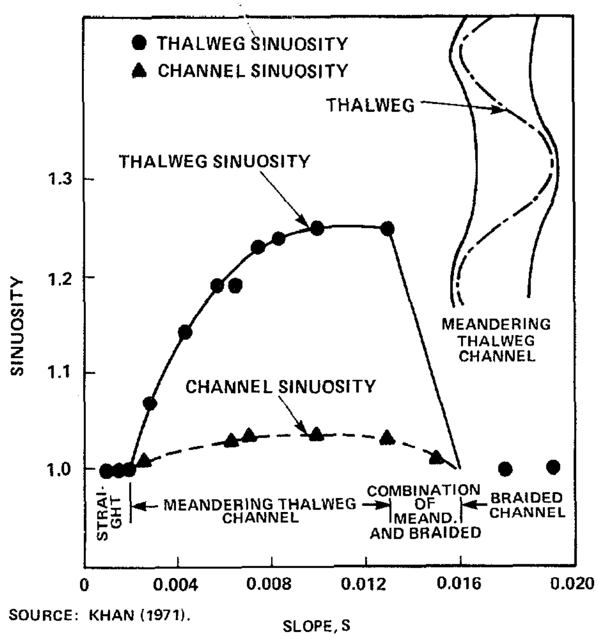
Table 14. INTERPRETATION OF OBSERVED DATA

Observed Condition	Channel Response			
	Stable	Unstable	Degrading	Aggrading
Alluvial Fan				
Upstream		√		√
Downstream		√	√	
Dam and Reservoir				
Upstream		√		√
Downstream		√	√	
River Form				
Meandering	√	√	Unknown	Unknown
Straight		√	Unknown	Unknown
Braided		√	Unknown	Unknown
Bank Erosion		√	Unknown	Unknown
Vegetated Banks	√		Unknown	Unknown
Head Cuts		√	√	
Diversion				
Clear water diversion		√		√
Overloaded with Sediment		√	√	
Channel Straightened		√	√	
Deforest Watershed		√		√
Drought Period	√			√
Wet Period		√	√	
Bed Material Size				
Increase		√		√
Decrease		√	Unknown	

increase in channel slope. In addition, the straightening of the main channel brings about a drop in base level and any tributary streams flowing to the affected reach of the main channel are subject to headcutting or degradation.

On the other hand, if the straightened section is designed to transport the sediment loads that the river is capable of carrying both upstream and downstream of the straightened reach, bank stability may not be endangered. Such a channel should not undergo significant change over either short or long periods of time. It is possible to build modified reaches of main channels that do not introduce major adverse responses due to local steepening of the main channel. In order to design a straightened channel so that it behaves essentially as the natural channel in terms of velocities and magnitude of bed-material transport, it is necessary, in general, to build a wider, shallower section.

Table 15 summarizes the various geomorphic and simple hydraulic analysis methods presented thus



SOURCE: KHAN (1971).

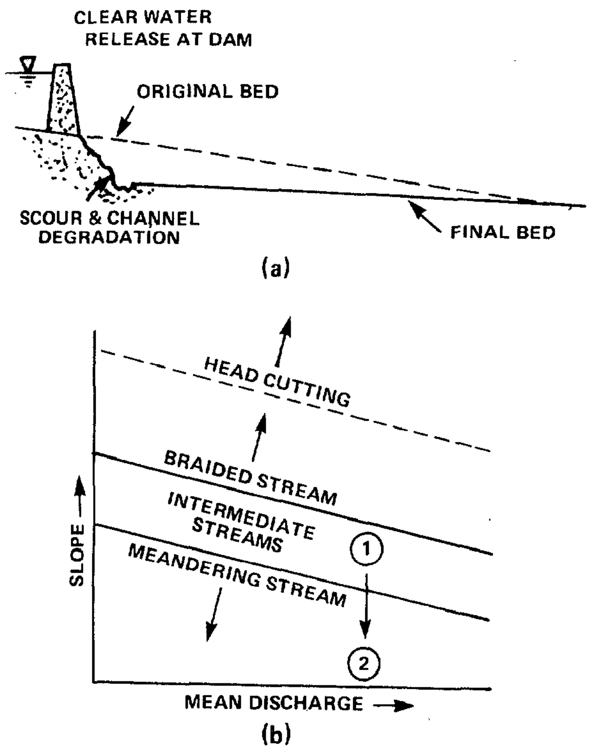
Figure 27. SINUOSITY VERSUS SLOPE FOR A CONSTANT DISCHARGE OF 0.0042 m^3/sec

far. The table may be used as a reference in determining the implication of various analysis results.

Summary

In summary, geomorphology methods are qualitative in nature. It is not possible to predict the exact magnitude of a gradation change without further analytic effort. However, the principles of geomorphology, particularly the balance between stream power and sediment load (as studied by Lane, 1957), are well documented and useful. The highway engineer should be thoroughly familiar with such principles in order to successfully anticipate impacts from dams, channel changes, and other activities. It is recommended that the Phase II report include a summary of geomorphic principles as they relate to analysis of gradation changes, as was done here.

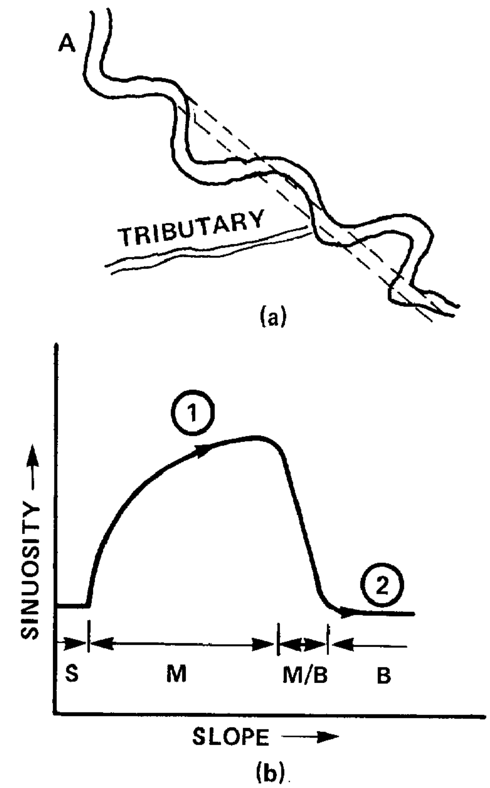
The review of current literature on geomorphology did not yield a great deal of information. Seventeen references in the Annotated Bibliography (Appendix B) dealt in some way with geomorphology. In general the literature can be divided into three categories. One category consists of reference books or papers which mention geomorphology as one aspect of a larger range of subjects. Typical of such references is Leopold, Wolmann and Miller (1964). Only three references were found in this category. Another category consists of case histories of some specific aspect of geo-



Local Effects	Upstream Effects	Downstream Effects
1- Channel degradation	1- See upstream effects, Figure V-4	1- Degradation
2- Possible change in river form		2- Reduced flood stage
3- Local scour		3- Reduced base level for tributaries, increased velocity and reduced channel stability causing increase sediment transport to main channel
4- Possible bank instability		
5- Possible dam failure		

Figure 28. IMPACT OF CLEAR WATER RELEASE BELOW A DAM ON GRADATION AND CHANNEL PATTERN

morphology from which a qualitative relation was developed. Only three references were in this category. Typical of these is Schumm (1969). Schumm demonstrates that channel width, depth, shape, meander wavelength, sinuosity, and gradient are significantly related to the quantity of water and to type of sediment. Some of his results may be used to supplement analysis such as discussed previously. Case histories



Local Effects	Upstream Effects	Downstream Effects
1- Steeper slope	1- See local effects	1- Deposition downstream of straightened channel
2- Higher velocity		2- Increased flood stage
3- Increased transport		3- Loss of channel capacity
4- Degradation and possible headcutting		
5- banks unstable		
6- River may braid		
7- Degradation in tributary		

Figure 29. STRAIGHTENING OF A REACH BY CUTOFFS

of various geomorphic phenomena comprised a third category. Eleven references were found in this category. Several of the case histories may be potentially useful in emphasizing the impact of man on river gradient. Typical of such references are Bull and Scott (1974), who emphasize the impact of gravel mining, and Rzhunitzin et al. (1972), who investigated degradation and channel changes downstream of dams.

It is doubtful that the role of geomorphology will shift from qualitative to quantitative anytime soon. It is recommended that the existing literature be used in Phase II to supplement the case histories and support the regionalization. Several of the case histories may be of local interest or importance to highway engineers (for example, Piest et al., 1977, concerning gradation changes in the Tarkio Basin of Iowa and Missouri).

Hydraulic Analysis Methods

General Approach

This section of the report provides a brief introduction to the quantitative methods for assessing aggradation and degradation. While geomorphic principles will allow the engineer to identify the direction of a gradation change, no estimate of its magnitude can be obtained. Methods for determining the magnitude will be examined here.

The discussion is divided into four parts. First, the potentially useful methods found in the Annotated Bibliography (Appendix B) are identified. Second, an example of a relatively simple computational technique is presented. Third, a computational method of intermediate difficulty is presented. Fourth, an example of an advanced mathematical model study is presented. In each of the four parts recommendations are made concerning modification or application of the technique in Phase II of the research program.

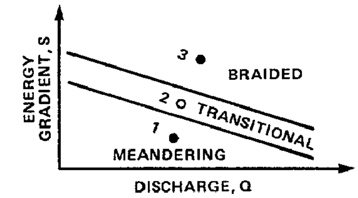
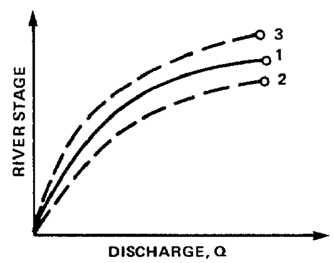
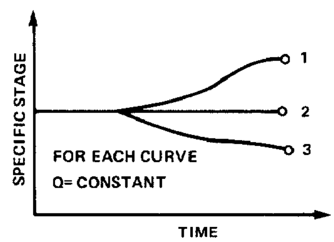
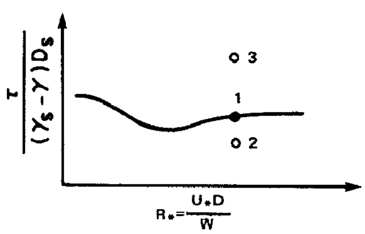
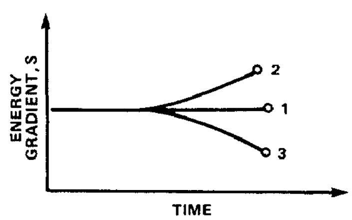
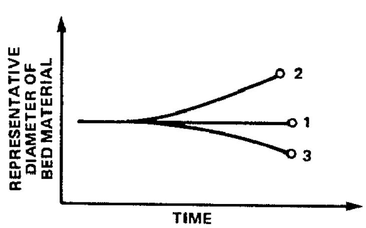
Survey of Current Literature

Considerable information on gradation problems can be found in the literature. Over 50 references in the Annotated Bibliography (Appendix B) deal with some theoretical or practical aspect of gradation change.

The following general categories of reference were found:

- applications of technology to specific problems,
- books which present several computational methods,
- studies of critical shear stress,
- mathematical models,
- specific computational techniques,

Table 15. GEOMORPHIC AND HYDRAULIC ANALYSIS OF RIVERBED LEVEL CHANGES

METHOD OF ANALYSIS	CHANNEL CONDITIONS		RIVER BED RESPONSE		
	STABLE	UNSTABLE	AGGRADING	DEGRADING	UNKNOWN*
	1	2,3			1,2,3
	1	2,3	3	2	
	1	2,3	2	3	
	1,2	3			1,2,3,
	1	2,3	3	2	
	1	2,3			1,2,3

*DETERMINED BY OTHER METHODS OF ANALYSIS.

- methods for computing general scour, and;
- laboratory studies.

The first five categories, which contain the bulk of the published material, are each discussed in this section.

The last two categories require some further explanation. Methods for computing general scour are included because a portion of Phase II will be directed toward the effect of gradation changes or other design parameters. It will be important to consider the additive effects of degradation and scour. Laboratory studies often serve to verify geomorphic concepts as opposed to providing directly useful computational methods. The laboratory studies identified here are used to verify computational methods or theory.

Application of Technology

Very few references deal with specific applications of technology. A number of references present data, but primarily they are from laboratory investigations and used to verify some theoretical relation. The largest study dealing with aggradation and degradation was sponsored by the U.S. Geological Survey. A study was undertaken entitled "Channel Adjustments Downstream from Cochiti Dam on the Rio Grande, New Mexico." The study addresses gradation changes and changes in width, depth, and other variables downstream of the dam caused by loss of sediment flow. No specific publications were listed in the reference, which is apparently a research project description.

Three studies listed actual results of gradation studies along with computational methods. Combs, Thomas, and Russo (1977) present a U.S. Corps of Engineers model for determining areas of aggradation and degradation along a river. Their method also identifies tendencies of rating curves to shift. The model as applied to the Red River in Texas. Simons and Li (1977, 1978) apply a coupled flow-sediment transport model to degradation near a gravel pit in Orange County, California and to degradation below a U.S. Soil Conservation Service (SCS) reservoir in New Mexico. Both the Corps model and Simons-Li model appear to be useful, complex analysis methods. The Simon-Li study of the SCS reservoir will be presented in more detail as an example of an advanced mathematical study. It is recommended that both models be evaluated on the same data set as part of Phase II.

Books

Five valuable books on sediment transport are: American Society of Civil Engineers (ASCE) (1975); Blench (1969); Bogardi (1974); Graf (1971); and Simons and Senturk (1977). ASCE does not consider the gradation problem in any detail. Some information is presented on the legal implication of land created or lost. Blench presents a number of regime formulas which relate flow, sediment transport, channel widths, and slope to one another. These formulas are useful in determining the type of changes which may accompany a change in stream gradient. Bogardi presents a limited discussion of scour below dams. Graf makes no specific mention of gradation problems. Both Boardi and Graf are useful references for formulas and methods for computing sediment transport rates. The best reference is Simons and Senturk. The problem of gradation change is discussed in detail and sample calculations are included. An example from the book is included under the discussion of methods of intermediate difficulty. In general, the books are useful reference material but, with the exception of Simons and Senturk, are not directly useful to the highway engineer concerned with gradation.

Critical Shear Stress Studies

Critical shear stress defines the amount of stress needed to initiate sediment motion. This is an important component of sediment models and is often used as the criterion in computing ultimate degradation or aggradation. The classic work on critical stress is that of Shields (1936). Shields developed this criterion for motion of sand particles.

The research presented in this report identifies works which extend the work performed by Shields to other particle ranges. Of particular interest were studies dealing with coarser particles such as those found in mountain streams. Some work was also found on movement of clays. Typical of the critical stress studies are Miller et al. (1977), Buller and McManus (1973), and Meland and Norman (1969). Miller et al. evaluated Shields criteria and a number of other empirical relations. Buller and McManus investigated the effect of consolidate sediments on the stability of the Tay estuary, Scotland. Meland and Norman investigated critical shear in heterogenious sediment mixtures. The latter work appears quite useful, particularly for incorporation in ultimate degradation computations. The primary use of all the references will be to extend the range of computation techniques outside the sand range if required.

Mathematical Models

A sizable number of mathematical models dealing with sediment transport have been published in recent years. For purposes of this study, those which compute changes in bed level at various cross-sections were identified.

A weakness in all current models is their inability to anticipate lateral as well as vertical channel movement. An important part of Phase II will be to identify the working range of math models and provide guidance to the potential user on when to expect the channel to widen as well as degrade or aggrade.

The large number of models precludes listing all of them here. Brief descriptions of those which appear to be useful for Phase II evaluation are included.

Three math models are representative of the types currently used. These models are by Thomas and Prashuhn (1977), Chong and Hill (1976, 1977), and Chen and Simons (1975). Thomas and Prashuhn present a sediment model coupled to a step backwater calculation. This results in a fairly inexpensive computational procedure and can be used over long periods by assuming a series of steady state discharges (say, mean monthly). Chong and Hill use a similar steady state analysis. The Chen-Simons model was developed at Colorado State University (CSU) and is one of a variety of models available there. The Chen-Simons model consists of a linear, implicit, finite-difference flow model coupled with a sediment transport model. This is an expensive technique, but one which provides a high degree of detail.

The writers feel that the steady-state flow and sediment models would probably be practical for a number of aggradation/degradation studies. The models incorporating unsteady flow would probably be reserved for special problems, ones of large economic importance. It is recommended that Phase II include a side-by-side comparison of several of these models to assess their cost-benefit and accuracy along with data requirements. Variations of the Thomas-Prashuhn model are available from the U.S. Corps of Engineers Hydrologic Engineering Center. Sutron has obtained the CSU model and the Chong-Hill model. Some results from a CSU-developed model will be presented later in this section. A large number of models are available which can be applied to gradation problems.

Specific Computational Techniques

Approximately 20 references in the Annotated Bibliography (Appendix B) deal with computational techniques. Nearly half of these concern degradation downstream of dams. Very few references deal with aggradation, apparently because it is so often connected with reservoir filling and less often with stream channels per se. Several references deal with both types of gradation problems. Typical examples will now be discussed.

Four references are fairly typical of those which describe degradation in general and downstream of dams. These are Witkowska (1947), Gessler (1971), Ashida and Michiue (1971), and Pemberton (1971). Witkowska describes methods for choosing a computational method for riverbed erosion. Included in his evaluation are most of the common bed load formulas such as Meyer-Peter (see Simons and Senturk (1977)). Gessler presents a theoretical analysis of the gradation problem and describes a computational method for use under both aggrading and degrading conditions. Ashida and Michiue investigate the effect of nonuniform grain size distribution on armoring below a dam. A method is proposed to predict the final grain size distribution and the degraded stream profile. Pemberton presents three examples of design and gradation calculations using Einstein's bed load function. All of the methods should be tested as part of Phase II. A number of other references not mentioned here also show promise. For example, a summary of a paper concerning degradation below dams is given in Einstein (1969).

A number of references fill in a category which may be described as quantitative morphology. These are papers which describe the relationship between stream gradient and other variables such as width, hydraulic radius, sinuosity, bank stability, and top width. Such papers serve to bridge the gap between pure hydraulic methods and geomorphology. The classic reference in this area is Blench (1969). His regime formulas have been the basis of countless canal designs. In general these formulas express a parameter such as hydraulic radius as a power function of the discharge (such as $R = AQ^B$, where A&B=const.). Such formulas are useful for determining the overall shape of a degraded or aggraded channel. Sarma (1973) presents a useful analysis of stable channel design in coarse sediments. It is useful in roughly the same way as Blench (1969). One of the most useful new techniques is the unit stream power analysis of Yang and Stall (1974). Yang and Stall postulate that the most stable channel shape is one which minimizes unit stream power. Stream power is roughly equal to the product of discharge and slope. It appears possible to modify the method to compute either an aggraded or degraded stream profile or, given the profile, compute the channel shape. Unit stream power should definitely be studied for application in Phase II.

Two useful references on aggradation are Tsuchiya and Ishizaki (1969) and Garde and Swamee (1973). Both papers describe computational techniques which appear to be applicable to the general gradation problem.

In summary, there is no shortage of computational methods. The difficulty in Phase II will be to evaluate as many as possible of those available and make recommendations as to which can be used by highway engineers.

Two examples will now be presented in order to illustrate the types of calculations which might be performed to determine the limits of a gradation change. The examples are simple calculation of limiting slope and the application of an advanced mathematical model.

Limiting Slope

One of the simplest calculations which can be made in a degrading stream is the limiting slope of the degraded bed. This value is calculated by determining at what slope the bed material could just be moved (critical shear) by the average amount of flow available. An example of such a calculation is provided in Richardson et al. (1974).

The example concerns construction of a 152 m bridge across an alluvial stream. A dam has been constructed 11.57 km upstream from the bridge. Normal daily power releases are 283 m^3/sec from the power plant for the six high-demand hours and nominal releases for the remainder of the day to maintain fish stock. The 100-year design flood is 1133 m^3/sec with the dam in place. The natural flow of sediment in the river has been checked at the dam. The downstream control is 14.48 km downstream where the river in question joins a much larger river.

The effect of the dam is that the time distribution of the flow is changed although the total volume is not. The flood peaks are reduced and the sediment transport is cut off. The average flow has been increased from 198 m^3/sec to about 283 m^3/sec, ignoring the periods when the flows are very low. According to Figure 25, increasing the mean discharge shifts the river toward the braided stream classification. Such a shift is generally a destabilizing trend. The channel will probably widen and this effect may be estimated by one of Blench's (1969) regime equations,

$$W \sim Q^{0.26} \tag{6}$$

The new width is

$$W_n = (152) \left[\frac{(283)}{(198)}\right]^{.26} \tag{7}$$

$$\simeq 168 \text{ m.}$$

The depth of flow at 1133 m^3/sec is computed from Manning's equation, or

$$y_o = \left\{\frac{Vn}{S_f^{1/2}}\right\}^{3/2} \tag{8}$$

but since

$$V = \frac{q}{y_o},$$

$$y_o = \left\{\frac{qn}{S_f^{1/2}}\right\}^{3/5} \tag{9}$$

The unit discharge is

$$q = \frac{Q}{W} = \frac{1133}{168} = 6.75 \text{ m/m.} \tag{10}$$

The n in Manning's equation estimated as 0.028. The friction slope is assumed equal to the bed slope which Richardson et al. gave as 0.00138. Then

$$y_o = \left\{\frac{(6.75)(0.028)}{(0.00138)^{1/2}}\right\}^{3/5} = 2.65 \text{ m.} \tag{11}$$

The average velocity is

$$V = \frac{q}{y_o} = \frac{6.75}{2.65} = 2.56 \text{ m/sec;} \tag{12}$$

the average bed stress is

$$\tau_o = \gamma y_o S_f \tag{13}$$

$$= 1000\,(2.65)\,(.00138) = 3.66 \text{ kg/m}^2.$$

The Froude number for the channel flow is

$$Fr_1 = \frac{2.56}{\sqrt{9.86\,(2.65)}} = 0.50. \qquad (14)$$

The bed level is expected to degrade as a result of a cutoff of sediment by the dam. Degradation starts at the dam and progresses downstream with time and stops only when it reaches a rock or gravel ledge or where the river enters a lake or confluences with a larger river as in this case. The river scours its bed to establish an ultimate gradient such that the shear is below the critical level for transport of sediment. This is not necessarily the critical shear for D_{50} because the large sizes in the bed material tend to remain to armor the bed. The D_{90} size is sometimes considered as appropriate for armoring. Richardson et al. give 15 mm, for example.

The critical tractive force for the D_{90} material is given by Shields (1936). Assume the flow is fully turbulent at the bed. Then

$$\frac{V+D}{\nu} \geqslant 400$$

$$\frac{\tau_c}{(\gamma_s-\gamma)D_{90}} = \frac{\tau_c}{(S_s-1)\gamma D_{90}} = 0.047 \qquad (15)$$

and

$$\tau_c = (0.047)\,(2.65\text{-}1)\,(1000)\,(.015) = 1.174 \text{ kg/m}^2 \qquad (16)$$

It will be the normal daily power release discharge that will degrade the channel. This flow is 283.2 m^3/sec, so

$$q = \frac{Q}{W} = \frac{283.2}{167.6} = 1.69 \text{ m}^3\text{/sec/m}. \qquad (17)$$

Richardson et al. estimate a final n in Manning's equation for the degraded stream as

$$n = 0.028\,. \qquad (18)$$

Manning's equation (given in metric units) states that

$$q = \frac{1.0}{n} y^{5/3} S_f^{\,½} \qquad (19)$$

Here q and n are known because

$$\tau_c = \gamma y S_f = 1.174 \text{ kg/m}^2; \qquad (20)$$

where

$$\gamma = 1000 \text{ kg/m}^3;$$

Then

$$S_f = \frac{1.174}{1000y} = \frac{0.00174}{y}\ . \qquad (21)$$

Put this expression for S in Manning's equation so that

$$1.69 = \frac{1.0}{0.028}\,(.0417)\,y^{7/6}, \qquad (22)$$

or $y = 1.11$ m.

It follows that the limiting slope that the stream may reach is

$$S_f = \frac{.00174}{1.11} = .0016, \qquad (23)$$

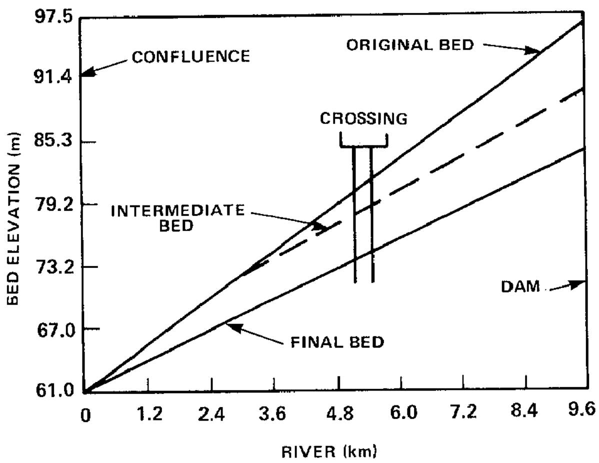
or ~ 1.3 m/km. The slope before degradation was 2.23 m/km.

The existing profile and the ultimate profile as computed by Richardson et al. are shown in Figure 30 along with an intermediate profile during the degradation process. These profiles are ultimately controlled at the larger river, which controls the water surface level of the river at the point of confluence. Degradation at the bridge crossing can be easily estimated from the figure.

The simple analysis method given above may be adequate for a number of gradation problems. More detailed examples based on the case history can be included in Phase II. Similar analysis can be performed in aggrading streams.

Mathematical Model

At the other extreme of calculation methods are the mathematical models. Math models make use of computer solutions of the differential equations governing flow and sediment transport. Many of the models will predict the discharge and bed level changes for each sediment size function. The models developed by Colorado State University [Chen and Simons (1975); Simons, Li, and Stevens (1975)] are good examples. One variation of the various CSU models was applied by Simons and Li (1979) to Boulder Creek at Boulder, Colorado. Their analysis and results will be discussed here.



SOURCE: RICHARDSON et al. (1974).

Figure 30. DEGRADATION CAUSED BY DAM UPSTREAM OF THE CROSSING

The city of Boulder, Colorado, is located at the mouth of Boulder Canyon, which concentrates and discharges the flow from a 337 km^2 drainage basin. This location makes Boulder particularly vulnerable to flash flooding. The Corps of Engineers has been working with the citizens of Boulder to develop flood protection measures that are both hydraulically and economically feasible. The selected plan involves an excavated floodway and related physical improvements along Boulder Creek. An overall view of the study area is shown in Figure 31.

Colorado State University used a mathematical model of sediment movement to analyze the impacts of sediment and debris associated with the 100-year flood on the proposed plan. The model was capable of routing sediment by size fraction and was utilized to estimate erosion and deposition within the proposed floodway subject to the 100-year flood. This model utilized the hydraulic conditions determined by Corps of Engineers' HEC-2 stream surface profile program; thus, the results could be compared to those obtained using the conventional method for determining flood levels.

A number of aggradation-degradation phenomena were analyzed using the sediment model. The following are the general capabilities of the model:

- analyze aggradation and degradation by cross-section, considering the design flood hydrograph with a return period of 100 years;
- determine the potential local scour downstream of the four grade-control structures and twelve bridges for the 100-year event;
- evaluate the potential blockage at bridges and channel restriction as results of sediment aggradation during the 100-year event;
- analyze incipient motion to determine the critical discharge at which each bed material size will start to move;
- evaluate the effect of sediment aggradation on the water surface profile, utilizing the HEC-2 Program;
- determine possible flow diversions from the channel caused by aggradation; and
- recommend possible solutions to adverse impacts associated with aggradation/degradation in the channel.

The CSU sediment model is based on differential equations describing the various physical processes involved in sediment transport, with appropriate simplifying assumptions.

The dominant physical processes include water runoff, sediment transport, sediment routing, degradation, aggradation, and breaking and forming of an armor layer. These processes are unsteady in nature. To simplify the solution and to make the results of the analysis compatible with those of the Corps of Engineers' HEC-2 flood level analysis, a known steady discharge was used. The known discharge solution was considered appropriate in this study because of the short distances involved in the analysis. In addition, to save computer time, the degradation and aggradation analysis was conducted on a reach basis utilizing average hydraulic parameters. The amount of predicted aggradation and degradation was distributed to the verticals of a cross-section according to the channel conveyance to yield a set of new cross-sections.

The developed mathematical model routes the sediment by size fractions. The transporting capacity of each reach is determined through the use of its average hydraulic conditions. The sediment routing procedure is accomplished by applying the sediment continuity equation and considering the size distribution of the upstream sediment supply and the bed material for both the surface and subsurface layers.

Considerable information is required to develop an accurate math model of sediment transport. The

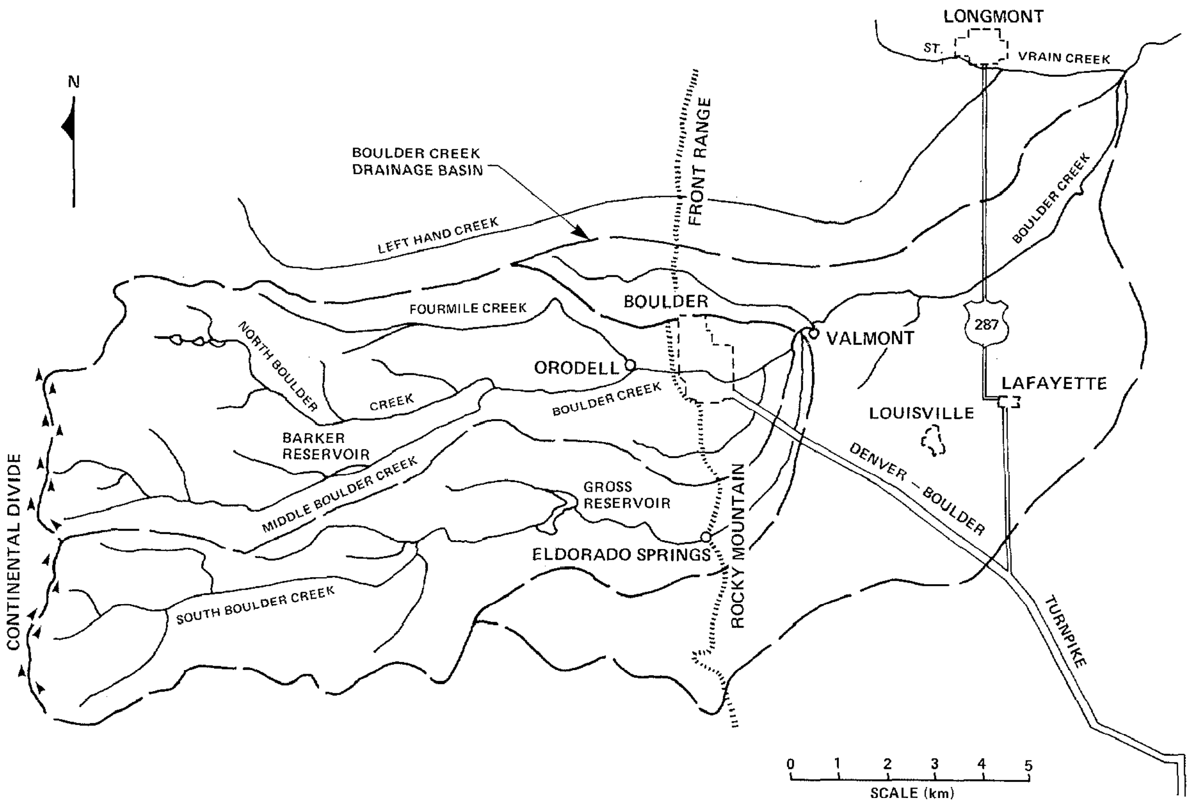


Figure 31. MAP OF BOULDER CREEK DRAINAGE BASIN

following are among the types of historical and current information gathered as part of the Boulder Creek project:

- flood frequency curves for Boulder Creek from U.S. Army Corps of Engineers,
- cross-sectional data for Plan II design HEC-2 computation,
- information relating to the bridge design,
- tree count information within the study reach,
- bed-material samples of both surface and subsurface layers within the study reach,
- profile of the study reach,
- plan view of the study reach, and
- USGS quadrangle map in the vicinity of Boulder.

In addition to the information listed above, USGS streamflow data were required. Stream gaging stations have been maintained on Boulder Creek near Ordell, Colorado, since 1906, and on South Boulder Creek near Eldorado Springs since 1888, with only minor interruptions in the record. In addition to these two stations, there was a short record (1889-1909) available from a former gaging station located in Boulder. Peak discharge estimates were available at this site for the major historical floods (1894, 1914, and 1969). These records were used to estimate flood frequency and to synthesize a 100-year flood hydrograph.

An index map showing the location of cross-sections and reaches for the Boulder Creek study is given in Figure 32. The total number of cross-sections utilized in the water surface profile analysis was 87. Detailed cross-sectional data from flood studies was utilized. Nine reaches were defined for the purpose of studying aggradation and degradation (see Figure 32). Reaches No. 6 and No. 8 will have man-made sediment deposition areas.

Model results indicate that on the average, approximately 22 percent of sediment supplied from the upland watershed is washed through the study area. Figure 33 shows the comparison of the initial design profile and the final bed profile after a 100-year flood. Most of the study reaches will aggrade. However, Reach No. 7 will experience significant degradation due to channel contraction.

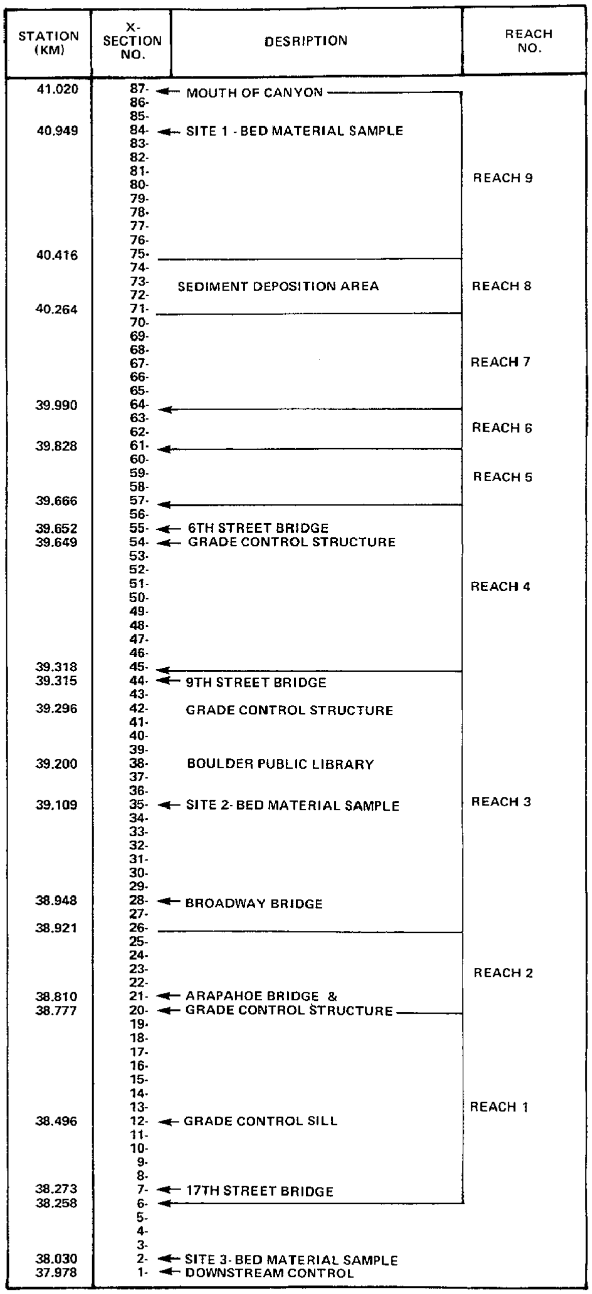


Figure 32. INDEX MAP OF CROSS-SECTIONS AND REACHES

The volumes of sediment moved by aggradation and degradation is listed in Table 16. The bed-material size ratio figures are arbitrary adjustments made in sediment sizes to determine the sensitivity of the model.

The model results were used to develop recommendations for minimizing the adverse impact of deposition and erosion.

The results indicated that the major sediment problems will be located upstream of 6th Street Bridge. From 6th Street downstream to 17th Street, the sedimentation problem will be minimal. There were no predicted problems associated with potential blockage due to sediment aggradation, local scour, and possible flow diversions. The effect of sediment movement on the flowline and channel geometry was predicted to be significant upsteam of 6th Street Bridge. Without proper maintenance work, sediments would migrate downstream of 6th Street Bridge. Regular maintenance programs after each major flood were recommended. Current channel design in the vicinity of Reach 7 is too restricted and causes serious scour problems, which in turn increase the sedimentation problems downstream. It was recommended that the restriction along Reach 7 be removed to the extent possible. The model could have been used to evaluate alternative channel profiles and shapes through Reach 7.

The CSU water and sediment routing model has been applied to two other practical design problems. One application was the analysis of degradation below an emergency spillway in the T or C Williamsburg Watershed, New Mexico (Simons and Li, 1978). Both the local scour immediately below the structure and the general degradation pivoting from a downstream control point were considered in the analysis. Figure 34 shows the time lapse change of local scour and general degradation. In order to check the applicability of the mathematical model, a large-scale physical model (1:30) was utilized by another agency to estimate local and general scour for the design freeboard hydrograph. The results of these independent efforts were quite close, demonstrating a successful application of the technology of routing sediment by size fractions.

Similarly, the model was used in the analysis of erosion and deposition problems associated with the Conrock gravel mining operation in San Juan Creek and Bell Canyon of Orange County, California (Simons and Li, 1978). The model provided an estimate of the erosion and deposition response of the stream and gravel pit subject to different hydrologic inputs.

Three storms, in January, February, and March of 1978, induced significant degradation and the data available provided a test for the model. The simulation was made using time steps of four hours. The time lapse changes of elevation at the original gravel pit boundary (Station 16+00) is given in Figure 35. The simulated results are excellent when compared with

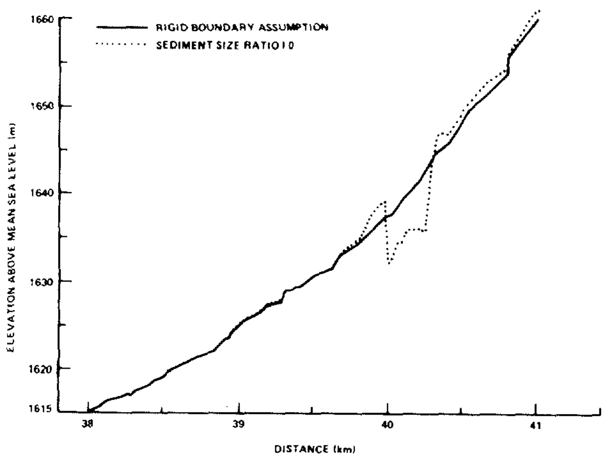


Figure 33. COMPARISON OF INITIAL DESIGN AND FINAL BED PROFILES (THALWEG LEVEL) AFTER 100-YEAR FLOOD

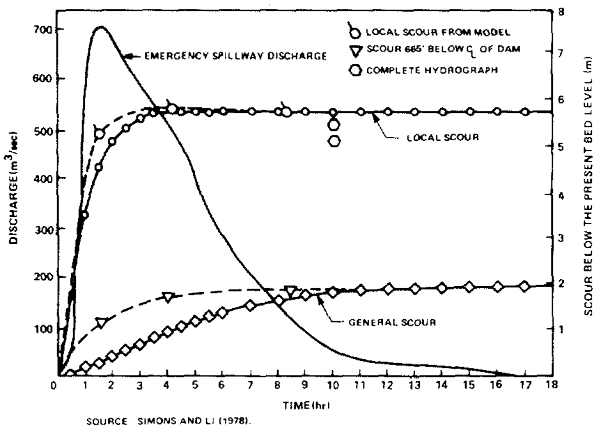


Figure 34. LOCAL AND GENERAL SCOUR BELOW THE EMERGENCY SPILLWAY IN THE T OR C WILLIAMSBURG WATERSHED, NEW MEXICO

field measurements. The mathematical model was utilized to evaluate four alternative gravel mining and rehabilitation plans.

Summary

The sizable number of references indicates that many useful techniques are available to highway engineers for analyzing gradation changes. Techniques range from simple slide-rule calculations to sophisticated computer models such as described above. It is recommended that the simpler techniques be emphasized in Phase II. Cost-benefit analyses of math models should be attempted so that highway engineers can determine when such models are warranted.

REMEDIAL MEASURES

General Considerations

Selecting an appropriate remedial measure is the final step in the solution of a gradation problem. This section of the report will present a brief picture of information on remedial measures available in the literature. Also, the case history data base described earlier is an excellent reference on remedial measures. The generally used types of remedial measures will be summarized.

Survey of Current Literature

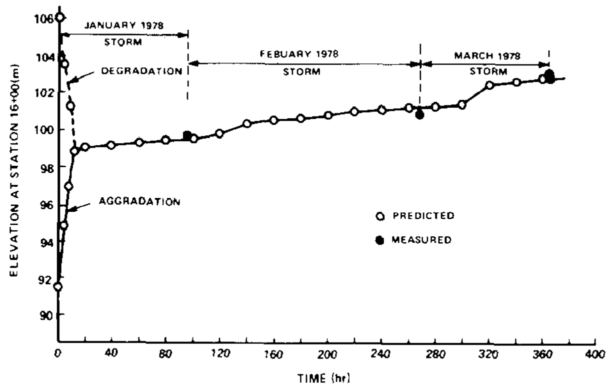
The subject of remedial measures for gradation problems has received little specific attention in the literature. Most references deal with problems of bank erosion. Some useful information is available, however.

The best current reference on countermeasures is Brice and Blodgett (1978). Virtually all currently used countermeasures are described. Brice and Blodgett rate the performance of many of these measures at numerous bridge sites given in their case history data base.

Brice and Blodgett classified remedial measures according to six major categories. These categories with examples are as follows:

Table 16. COMPUTED DEGRADATION OR AGGRADATION VOLUMES FOR THE 100-YEAR FLOOD

Bed Material Size Ratio	Volume of Degradation and Aggradation by Reach (m^3)								
	1	2	3	4	5	6	7	8	9
1.0	-149	550	1,830	- 929	1,646	18,088	-22,117	6,047	10,659
0.75	-274	811	2,888	-1,299	2,187	24,433	-30,014	8,370	11,844
1.25	- 93	414	1,175	- 660	1,225	8,465	-11,175	4,540	9,816



SOURCE SIMONS AND LI (1978).

Figure 35. TIME LAPSE CHANGES OF ELEVATION AT THE ORIGINAL GRAVEL PIT BOUNDARY (STATION 16+00) OF THE CONROCK GRAVEL MINING PET IN SAN JUAN CREEK, CALIFORNIA

Flexible Revetment or Bed Armor

Dumped rock riprap, rock-and-wire mattress, gabion, car body, planted vegetation, precast-concrete block, willow mattress

Rigid Revetment or Bed Armor

Concrete pavement, sacked concrete, concrete-grouted riprap, concrete-filled fabric mat, bulkhead

Flow-Control Structures

Spur, retard, dike, spur dike, check dam, jack field

Special Devices for Protection of Piers

Drift deflector, abrasion armor at pier nose

Modifications of Bridge, Approach Roadway, or Channel

Underpinning or jacketing of pier, construction or overflow section on roadway, realignment of approach channel

Measures Incorporated into Design of a Replacement Bridge

Increased bridge length, fewer or no piers in channel

The performance of a countermeasure was rated according to the following scheme:

1. Function
   - A. prevented or controlled hydraulic problem
   - B. reduced or partially controlled hydraulic problem
   - C. no apparent effect on hydraulic problem
2. Damage to countermeasure
   - A. sustained no significant damage
   - B. sustained significant damage
3. Unwanted effects of countermeasure
   - A. caused no problem
   - B. caused some problem.

For example, the rating of AAA for a countermeasure indicated that it prevented or controlled a hydraulic problem, was not significantly damaged, and caused no problem.

The format of the Brice-Blodgett report is quite good and will serve as a good example for the part of the Phase II report describing countermeasures to gradation problems. No specific reference is made in the Brice-Blodgett report concerning countermeasures for gradation change. It is possible to derive the information by referring to the sites which they identify as having gradation problems and reading the countermeasure description. This will be done so that their case histories can be incorporated in Phase II.

A number of other references contain information which may be useful for selecting countermeasures for gradation problems. Two of the better references for countermeasures for degradation are Volkert et al. (1973) and Heede (1976). Volkert et al. provide a theoretical analysis of the spacing and design of sills to halt degradation. Heede describes a number of methods for halting gully formation. These methods may have transfer value to the degradation problem.

Few countermeasures to aggradation are available. One is simply digging the channel back to its original grade. Colson and Wilson (1973) describe the results of excavating under bridges to increase their flow capacity. Their work has transfer value to the gradation problem.

The ASCE [ASCE (1972),ASCE Task Committee (1975)] has published a considerable amount of general reference material on the control of alluvial rivers. Bank protection has received the most attention; only occasional reference is made to methods for control of gradation such as sills or drop structures.

Case History Data Base

The best available source of information on countermeasures for gradation problems is the case history data base contained in Appendix A of this Interim Report. Countermeasure selection and design will remain primarily an art. The bridge engineer may view case histories similar to his own and base his decision on past experience.

Table 17 is a preliminary analysis of the countermeasure information in the case history data base. The numbers in the table correspond to case histories in Appendix A.

Two general classes of countermeasures are identified. These classes are channel stability and bridge stability. Channel stability measures are designed to prevent or redirect the channel bed changes. Bridge stability measures are designed to allow the channel free movement or to make the bridge stable under any foreseeable channel change.

Riprap is by far the most popular channel stabilization measure. Abutment and pier protection (including riprap, as a special case) are the most popular bridge stability measures. For Phase II it will be necessary to analyze the countermeasures for effectiveness, much as was done by Brice and Blodgett (1978). Another important analysis of the countermeasures will be to determine which are effective against both gradation changes and lateral movement, as the two problems often occur together.

Table 17. COUNTERMEASURES

Purpose	Countermeasure	Case History Number
Channel Stability	Check Dams	16, 18, 34, 46, 95, 110
	Cutoff-Walls/Drop Structures	1, 5, 6, 11, 26, 31, 50, 58, 59, 62, 77, 87, 96, 98, 103, 104
	Culvert + Drop Flume/ Drop Flume	32, 33, 34, 87
	Riprap	14, 17, 18, 19, 24, 39, 42, 43, 53, 54, 55, 58, 59, 61, 62, 75, 83, 89, 90, 92, 93, 94, 96, 100
	Revetments	14, 56, 62, 77, 80, 84, 99
	Retards	14, 65, 86, 90
	Spurs	54, 62, 77, 99, 108
	Rail Bank	8, 77, 99, 102, 110
	Channel Excavation/ Realignment	3, 77, 78, 83, 87, 106
	Channel Clearing/Widening	10, 48, 60, 103
	Streambed Mining/Excavation Halted	9, 20, 21, 23
	Continued Maintenance	25, 36, 88, 92, 108, 109
Bridge Stability	Culverts/Inlet Structures	52, 60, 79, 99, 108, 109
	Abutment Protection	2, 6, 13, 30, 50, 51, 53, 57, 61, 88, 99, 100, 103, 104
	Pier Protection	15, 20, 23, 43, 54, 55, 56, 61, 64, 71, 76, 88, 100, 103, 110
	Structural Support	2, 49, 62
	Load Restrictions	2
	Bridge Lengthening	52, 89, 90, 91, 92, 93, 94
	Design Foresight	40, 64, 71
	Construction of New Bridge	2, 3, 28, 38, 61, 78, 83, 86, 105, 107

CHAPTER VI

SUMMARY AND CONCLUSIONS

GENERAL DESCRIPTION OF STUDY

This interim report describes the first phase of an investigation of the impact of long-term changes in stream gradients on highway crossings. The primary purpose of this first phase investigation was to develop a case history data base. The data base contains examples of the impact of gradation changes on bridge crossings throughout the U.S. The data base is analyzed to determine the types and causes of gradation problems. A survey of the current technology for analyzing gradation changes is included.

STUDY SUMMARY

Case History Data Base

Bridge sites suitable for inclusion in the case history data base were obtained from state highway departments. Most of the sites were visited and photographed. Some sites were obtained from reports of other investigators such as Brice and Blodgett (1978).

Two hundred and seventy-five sites were identified as suitable for this study. One hundred and ten were documented for reasons of economy. Each site entered in the data base contains a detailed site description, a history of the gradation problem, a description of the countermeasures attempted, and a general discussion of the causes and effects of the gradation change.

Analysis of Case History Data Base

Several preliminary analysis were performed on the case history data base. Sites were grouped according to whether aggradation or degradation was occurring. Causes of gradation problems were identified and sites grouped by type of problem.

Degradation is a much more common problem than aggradation. Out of the 110 sites, 81 were degrading. In general degradation has more severe impact on bridges. Footings, piles and abutments are undermined. Channel widening frequently accompanies degradation. This widening causes other problems.

Man's activities are almost totally responsible for gradation problems. Less than one case history in five had natural causes contributing to the gradation change. Channel alteration, primarily straightening, is the major cause of degradation. Streambed mining and construction of dams and control structures also contribute to gradation problems. Alluvial fans appear to be the only significant natural cause of gradation changes. Bridges built on alluvial fans usually suffer from aggradation.

Regionalization

Virtually every river in the U.S. which flows in an alluvial bed has a potential for gradation change. The prevalance of man's activities as chief cause of gradation problems means that most rivers suffer to some degree.

The best regional indicator of gradation change potential is a sediment yield map for the U.S. or the area in question. High sediment yield correlates with erodibility and the potential for gradation shifts.

Certain river systems are now chronically affected by gradation problems because of channelization, damming and other activities. The Missouri River and its tributaries near Omaha, Nebraska, is a good example. A number of rivers in Mississippi and Tennessee are also chronically affected by gradation problems.

Appraisal of Technology

An appraisal of current technology for analyzing gradation problems was conducted as part of this study. Books and papers describing gradation problems and calculation procedures were sought. Most references came from a computerized library search, the U.S.G.S. national library, files of state highway engineers, and the personal libraries of the principal investigators and the Contract Manager. An annotated bibliography of relevant references was prepared and is included as Appendix B of this report.

The technology assessment was divided into four parts. First, methods for recognizing the potential for gradation changes were obtained. Next, methods for measuring gradation problems directly were identified. Third, computational methods for analyzing problems were examined. Finally, methods for selecting and designing remedial measures were considered.

Gradation problems may be successfully recognized or anticipated by a number of means. Simple knowledge of regional tendencies may be adequate in some cases. Since man's activities are the primary cause of problems, a knowledge of impacts helps identify potential problems. Many gradation problems can be identified with a limited knowledge of geomorphology.

One of the most effective direct methods of measuring gradation problems is to record the distance from the bridge deck to the channel low point once a year. Plots of changes in stream stage versus discharge, sediment load versus time, and stream profile versus time all work well for identifying gradation problems.

Available methods for calculating changes in stream gradient fall into two categories. These categories are geomorphic methods and hydraulic networks. Lane's (1955) concept of an equilibrium between the product of water discharge times energy gradient and sediment discharge and diameter is quite useful. This principle can often be used to anticipate the type and direction of a gradient change. A number of empirical relationships between stream discharge and other channel hydraulic properties such as area and sinuosity may be used in conjunction with Lane's principle. By this means a semiquantitative estimate of a gradation change may be made.

Numerous hydraulic analysis procedures are available. The largest percentage deals with degradation downstream of a dam. Some deal with aggradation in the backwater area behind the dam. A number of the methods could be used to estimate the extent of gradation changes in highway problems.

The range of complexity in hydraulic analysis methods is quite large. The simplest analysis procedure predicts the limiting slope of a gradient change based on critical shear stress of the bed material. The most complex techniques use computer solutions of differential equations governing streamflow and sediment motion. These complex mathematical models may be useful for new bridge design in areas with severe gradation problems. Examples of both extremes in calculation procedures are provided in the main body of the report.

CONCLUSIONS

The following conclusions were reached during this study:

- The large number of case histories found indicates that gradation changes are a significant cause of maintenance problems at highway crossings.
- Man's activities, primarily channel straightening, streambed mining, and creation of dams, are the primary causes of gradation problems.
- The highway engineer should be aware of the principles of geomorphology in order to anticipate gradation changes from various impacting activities.
- Sufficient material exists in the literature to develop a report describing methods to analyze gradation changes.
- Mathematical models of sediment transport should be evaluated as to their costs and benefits in comparison with those of simpler analysis procedures.
- The prevalence of gradation problems indicates that inspection for changes in streambed elevation should be conducted annually at bridges in problem areas.
- Little practical knowledge exists concerning appropriate remedial measures for gradation problems.

CHAPTER VII

RECOMMENDATIONS

The large number (110) of case histories of gradation problems discussed here indicates that highway engineers would benefit from greater understanding of such problems. Specifically, the highway engineer should be aware of impacting activities which cause gradation change, methods to identify gradation problems, methods to calculate the extent of a problem, and appropriate remedial measures. Sufficient information is available from the case history data base developed here plus available literature to bring about such awareness. Specifically, it is recommended that:

- Information from the case history data base be used to study appropriate changes in design procedure to account for gradation changes. Impact should be determined for water surface profiles, flood limits, hydraulic properties such as width and depth, scour, debris, and lateral movement of the river.
- Several of the promising methods for calculating gradation changes should be evaluated together on one or more sets of data from the case history data base. Their capabilities in predicting the adjusted streambed profile, gradation rate, and the extent of a gradation problem upstream or downstream of a control point should be examined. Simple procedures as well as math models should be included.
- Methods identified as promising in the above evaluation should be documented for use by highway engineers. Adoption of a method should be based on cost/benefit considerations, ease of use, accuracy, data requirements, and ability to be used by average hydraulic engineers.
- An extensive study of the effectiveness of various remedial measures to arrest gradation changes should be undertaken. This will have to be based on the case history data base since literature on the subject is sparse. The effectiveness of check dams, riprap, energy dissipators, channel changes and sediment traps.

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The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

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Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

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This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.