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DESIGN OF SPUR-TYPE STREAMBANK STABILIZATION STRUCTURES

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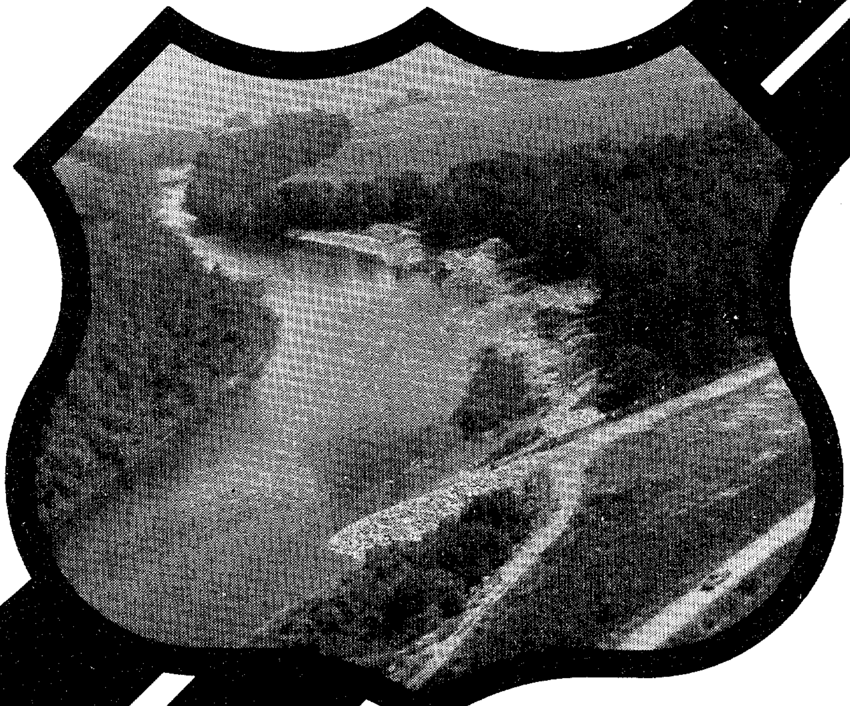

FOREWORD

Based on a thorough review of literature, analysis of several hundred field sites, and a recent laboratory study conducted by the Federal Highway Administration, recommendations for the general application and design of spur-type flow control and streambank stabilization structures are given. An example outlining the recommended procedure for establishing the geometric layout of spurs within a spur scheme is included.

Research and development in streambank stabilization is included in the Federally Coordinated Program of Highway Research, Development, and Technology Project 5H "Highway Drainage and Flood Protection." Dr. Roy E. Trent is the Project Manager and the Contracting Officer's Technical Representative for this study.

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

Richard E. Hay, Director
Office of Engineering
and Highway Operations
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NOTICE

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16. Abstract

A study of the applicability and design of spur-type flow-control and streambank stabilization structures has been conducted to establish design guidelines and other criteria for the use of spurs. The recommendations and findings are based on a thorough review of pertinent literature, analysis of several hundred field sites, and on a recent laboratory study conducted by the Federal Highway Administration. Recommendations for the general application of spur-type structures are given in relation to function of the spur, the erosion mechanisms that are countered by spurs, the environmental conditions best suited for the use of spurs, and potential negative impacts produced by spurs. An introduction to the most common types of spurs is given, along with discussions of the factors most important to the design of specific spur types. Design guidelines for establishing spur permeability, the required extent of protection, spur length, spur spacing, spur orientation, spur height, spur crest profile, and the shape of the spur tip or head are presented. An example outlining a recommended procedure for establishing the geometric layout of spurs within a spur scheme is recommended.

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acres	0.4	hectares
ounces	28	grams
pounds	0.45	kilograms
short tons (2000 lbs)	0.9	tonnes

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Chapter 1

INTRODUCTION

The purpose of this report is to provide guidelines for the application and design of spur or jetty type flow control structures. Spurs (or jetties, as they are often called) are defined as linear structures, permeable or impermeable, projecting into a channel from the bank for the purpose of altering flow direction, channelbank protection, inducing deposition, or reducing flow velocity along the bank. This report is intended to alert engineers to the utility of spurs, including economic and other advantages, as well as to provide a treatment of the effectiveness and limitations of spur-type structures as flow control and streambank-stabilization structures.

In the past, little guidance has been available for the design of spur-type structures. Few design guidelines have been available; those that are available are limited in scope and generally inaccessible to highway design engineers. The design of these structures has been primarily based on the designer's experience and numerous rules-of-thumb. While actual field design experience is indispensable when designing flow-control structures, many highway design engineers have only limited experience, indicating a need for some design guidance. There is also a need for more definite criteria relating to the behavior of spurs under various river-flow conditions. This would remove some of the uncertainty in their design and permit greater economy in the design of spur schemes by minimizing over-design as well as under-design. This design document addresses these needs by presenting guidelines for the design of spur-type flow control and bank-stabilization structures.

In this report the first consideration is the overall applicability of spur-type structures. This includes the function of the spur, the erosion mechanisms that are countered by spurs, the environmental conditions best suited for the use of spurs, an introduction to the most common types of spurs, and discussions of the factors most important to the design of specific spur types.

The actual design of spur systems is considered next. Guidelines for establishing spur permeability, the required extent or upstream and downstream limits of protection, spur length, spur spacing, spur orientation, spur height, spur crest profile, the shape of the spur tip or head, and maintaining channelbed and bank contact are included. An example outlining the procedure for establishing the geometric layout of spurs within a spur scheme is also included.

This report is based on a thorough literature review, extensive review and evaluation of spur field installations, numerous personal contacts with design engineers actively involved in designing flow-control structures, and a laboratory study designed to evaluate critical spur design parameters.

Chapter 2

CONSIDERATIONS IN THE SELECTION AND DESIGN OF SPUR-TYPE STRUCTURES

Criteria for the selection of a specific spur type are presented in this chapter. This includes a discussion of the general applicability of spurs, the applicability of each of the major spur types, and a closer look at the attributes of individual spur types.

GENERAL APPLICABILITY OF SPURS

Spurs are defined as permeable or impermeable linear structures that project into the channel for the purpose of altering flow direction, inducing deposition, and/or reducing flow velocities along a channelbank. Spurs can be classified as permeable or impermeable. They can be further classified by functional type as retardance-type structures, retardance/diverter structures, and diverter structures. Retardance and retardance/diverter structures are permeable structures; diverter structures are impermeable. Retardance spurs are designed to reduce the flow velocity in the vicinity of the bank as a means of protecting the channelbank. Retardance/diverter structures produce a flow retardance along the channelbank, but they also produce a deflection of flow currents away from the bank. Diverter spurs, on the other hand, function by diverting the primary flow currents away from the channelbank.

Function

The functions or purposes for which spur-type structures are best suited include protecting an existing bank-line, reestablishing some previous flow path or alignment, and controlling or constricting channel flows. These functions or purposes are discussed in detail in FHWA (1984). The primary advantage of spurs over other countermeasure types is their ability to provide flow control and constriction as well as the reestablishment of a previous or new flowpath. While spurs also are effective at streambank stabilization and protection in general, other countermeasure types can provide equivalent or perhaps better protection against general bank erosion (FHWA, 1984).

Erosion Mechanisms

Erosion mechanisms that can cause streambank failures are discussed in FHWA (1984). The erosion mechanism countered best by spurs is bank-particle displacement caused by abrasion and streamflow-induced shear stresses. Spurs counter these particle displacement erosion mechanisms by diverting the high-energy streamflow away from the bank. The immediate consequence is that the flow dynamics and forces responsible for bank erosion are moved away from the bank, greatly reducing or eliminating the potential for erosion. Spurs are particularly well-suited for protecting lower portions of the bank from erosion at the bank toe. Toe scour and the resulting undermining of channelbanks are discussed in FHWA (1984). Toe scour has been identified as a primary cause of bank failure. By moving the flow forces responsible for toe scour away from the bank, this erosion mechanism is effectively countered.

Bank-erosion processes also require a transporting mechanism to carry away the eroded material. By shifting the main flow stream away from the bank, the transporting mechanism is removed. Therefore, a channelbank that has been weakened by subsurface flow erosion, wave erosion, surface erosion, chemical action, or some other bank-deterioration mechanism (see FHWA, 1984) will be made less susceptible to total failure.

River Environment

Spur-type structures have been used successfully in a wide variety of channel environments. The channel environment plays more of a role in the design and selection of a specific type of spur or other countermeasure than it does in dictating the use of a general countermeasure type or group; this will be illustrated in later sections. Some general comments, however, can be made concerning channel size, bend radius, and bank characteristics as they relate to the use of spurs.

Channel Size

Spur-type structures are not well-suited for use on small-width (less than 150 feet) channels. On these narrow-width channels, spur design often will create excessive flow constriction at high streamflows and cause current deflections towards the opposite bank. Also, the excess channel constriction can cause greater channelbed scour than other countermeasure types that do not cause flow constriction. Deeper, more expensive foundations would be required to protect the flow structure from undermining caused by the excess bed scour. Spurs can be used effectively, however, on small channels where their function is to shift the location of the channel. In these cases, there usually is sufficient area available so that excessive flow constriction is not a problem.

Bend Radius

The use of spur-type structures for flow control and bank stabilization on short-radius bends (less than 350 feet) is usually not cost effective when compared to other countermeasure types. This is due to the short interspur spacing that would be required. Also, short-radius bends are typically found on channels having small widths; the consequences of using spurs on small channels has already been discussed.

Channelbank Characteristics

Channelbank characteristics related to the use of spurs include bank height, bank configuration, and bank vegetation. Spurs are best suited for the protection of low- (less than 10 ft) to medium-height (from 10 to 20 ft) banks from the erosion mechanisms discussed above. Protecting high banks with spurs often requires special design considerations and/or excess structural material. However, spurs that have successfully protected high channelbanks have been designed (see Figure 22a for example).

Bank configuration refers to the geometry of the bank. Because, in most cases, spurs do not require extensive bank reshaping or grading prior to construction, they are well-suited for use along steep-cut banks where significant site preparation would be required for other countermeasure types (see FHWA, 1984). Also, the use of spurs is not adversely affected by irregular bank lines. Again, spur use is recommended along irregularly shaped banks because excessive bank preparation and reshaping is not required to produce a smooth alignment around the bend.

One advantage in the use of spur-type structures is that they have been observed to provide an enhancing influence on bank vegetation. The erosive action of currents impinging directly on the bank will often prevent or hinder the natural volunteering of plant materials down the bank. Since spurs shift these main flow currents away from the bank, a greater opportunity exists for the natural volunteering of vegetation down the bank and into the "spur zone," helping to stabilize both the upper and lower sections of the channelbank. In environments characterized by high sediment loads, the vegetation will usually volunteer to the berm deposited between the spurs, enhancing the stabilizing characteristics of the spur scheme. In low sediment-yield environments, the reduced flow velocities within the spur zone create a more acceptable environment for vegetative growth, therefore allowing the advance of vegetative materials down the bank and into this zone during low-flow periods. Again, the additional vegetative growth thus created will enhance bank stabilization and help counter the lack of a deposited sediment berm in low sediment-yield environments. It also helps minimize the bank-scalloping characteristic of impermeable ' spur installations. The development of thick vegetation on the banks and between spurs also provides a mechanism for flow retardance and energy dissipation for spur-topping flow conditions, further enhancing bank stabilization. Bank vegetation also enhances the appearance of the bank by presenting a more natural-looking bankline.

System Impacts

The general impacts of stabilizing a channelbend are discussed in FHWA (1974) in terms of channel morphology. The impact produced by bank-stabilization schemes was also mentioned as a countermeasure selection criterion in FHWA (1984). The system impacts produced by spur-type flow control and bank-stabilization structures can be classified as environmental and esthetic.

Environmental Impacts

Environmental impacts include impacts on channel geometry, water quality, and biology.

Changes in channel geometry caused by channelbank stabilization are discussed in detail in FHWA (1984); discussions of the channel deepening that occurs in stabilized channelbends also are included. In channelbends stabilized with spur-type structures, this channel deepening can be magnified, particularly at the spur head. There are two reasons for this. First, spur schemes naturally constrict river flows in channelbends. In an attempt to maintain its previous level of discharge or flow conveyance, further scouring of the channelbed occurs. In addition, flow concentration at the spur head results in severe scour holes at and just downstream of the spurs. This channel reshaping has been documented both at field sites (Brice et al., 1978; Littlejohn, 1969; Fenwick, 1966) and in laboratory studies (FHWA, 1983; Ahmad, 1951a and b, and 1953; Franco, 1966).

The location of the scour trough discussed above provides another point of comparison between spurs and other countermeasure types. Because spurs shift the flow current away from the bank, they also shift the scour trough away from the bank, thus removing the immediate danger from undermining away from the bank. Streambank-stabilization schemes that have their primary component parallel to the channelbank (i.e., revetments, retardance structures, longitudinal dikes, and bulkheads) must be designed to protect against undermining along the entire length of the bank, adding significantly to the cost of the stabilization schemes. Because only the riverward ends of spur-type structures are impacted by the scour trough, only localized protection at the spur heads is required. Also, the risk of a catastrophic failure of the entire stabilization scheme as a result of toe erosion and undermining is lower with spurs than with other structure types because only the ends of the spur are impacted at any given time. Failure of the spur head still leaves additional spur length to provide partial protection for the bank until repairs can be made.

Several factors will affect the magnitude of the channel reshaping just discussed. First, the more severe the channel constriction, the more pronounced the resulting channel scour patterns will be. The channelbed composition also plays a role in the magnitude of these erosion patterns; channels cut in silt- and sand-size materials will exhibit greater depths and extents of erosion than channels in gravel- and cobble-size materials. Since impermeable spurs have a greater constricting effect on channel flows than permeable spurs, the erosion patterns produced by impermeable spurs can be expected to be more severe (assuming similar channel environments).

Impacts on channel geometry can also result from incorrect design and/or construction of the spur scheme. The geometric layout of the scheme is of primary importance. Misalignment of spurs can cause severe flow deflection and could initiate an erosion problem on the opposite bank. Figure 1 illustrates a case in point. The timber-pile spur shown was designed with a projected length (length perpendicular to the flow line) of 50 percent of the channel width. The resulting flow deflection has severely eroded the

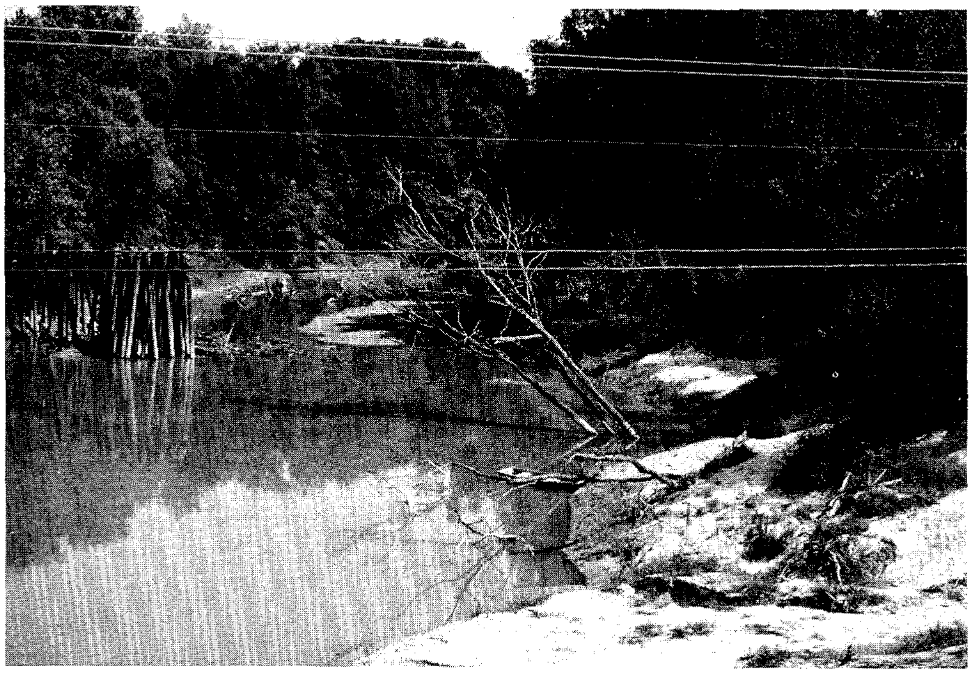


FIGURE 1. TIMBER-PILE SPUR SHOWING THE IMPACT OF EXCESSIVE FLOW DEFLECTION.

opposite channelbank as shown. Also, if the spurs produce too much flow constriction, excessive channel deepening may occur, which can undermine and cause the eventual failure of the spur structures. Time delays between initial design surveys and construction can also result in a final spur configuration whose geometric layout does not coincide with existing flow conditions. The U.S. Army Corps of Engineers (1981) has documented several cases where changes in stream pattern occurred between the time the initial design survey was conducted and construction was started. The shifting stream pattern resulted in a final spur configuration that was not compatible with flow conditions after the scheme was constructed. The potential impacts resulting from inappropriate spur-scheme layouts are the most significant drawbacks to the use of spur-type flow-control and bank-stabilization structures. The geometric layout of spur schemes is a more critical design consideration for spur-type structures than for other countermeasure types. This points out the need for careful and efficient planning, design, and construction of spur schemes.

Water-quality impacts result from changes in turbidity together with alteration of the local riverine habitat. The primary impacts are the increased turbidity and stripping of bank vegetation during construction. These activities can affect stream temperature and photosynthetic activities that in turn may affect algae or aquatic plant populations, dissolved oxygen, and other water-quality parameters. These are usually temporary impacts. Also, since the construction of spur schemes produces less bank disturbance than many other countermeasures, these impacts will be minimized if spurs are used.

Biological impacts can be broadly categorized as either terrestrial or aquatic. The major terrestrial impact is related to the alteration or elimination of riparian zone vegetation due to construction of project features. The riparian zone can provide support to a wide variety of plant and animal life and often provides a critical habitat for certain species. Riparian vegetation also supports aquatic species by providing a habitat and food-chain input for these species. Again, since these activities are primarily associated with construction activities, they are temporary in nature and are minimized through the use of spurs. In fact, spur schemes have been found to enhance the aquatic environment along the bank because of the flow retardance they produce near the bank.

Esthetic Impacts

Esthetic impacts relate to the appearance of the project area. These impacts are discussed in detail in FHWA (1984). Esthetic considerations relate more to the selection of a specific spur type than to the general applicability of spur-type structures. In this regard, comments relating to esthetics will be made when discussing individual spur types. Several general comments, however, can be made relating to the potential hazards associated with the use of spur schemes.

The hazards associated with spur schemes are related to recreational use of the river. The potential hazard spur-type structures can pose to boaters is of primary concern. Besides obstructing flow, spurs can also obstruct boats. Small boats can be pinned broadside along these structures, particularly the permeable spur types, if flows are below the spur crest. Also, when the spurs are just submerged, they can be hidden obstacles to power boats. To avoid these hazards, adequate warning signs should be posted to alert boaters and other recreational users to the potential hazard.

Spurs can also pose hazards in other recreational uses of a river, such as swimming and fishing. The hazards discussed above for boats also apply to people if they are swimming or fishing in the water around the structures. In urban areas, there is also a potential hazard to children who might find spurs attractive structures to play on or around. In general, permeable spurs and spur structures with sharp or pointed edges create a greater hazard than impermeable spurs. It is recommended that spurs not be used in areas that are heavily used for recreational activities.

Construction-Related Considerations

Construction-related factors influencing the choice of a countermeasure type include:

- required access and right of way,
- extent of bank disturbance,

- required construction methods, and
- local availability of construction materials.

Spurs provide an advantage in two of these areas. First, spurs generally require less construction right-of-way than revetments and other countermeasures because they do not necessitate bank grading or extensive bank reshaping/rebuilding. Also, construction of spurs produces less bank disturbance during construction than other flow-control and bank-stabilization countermeasures, thus producing less of an environmental impact on the channel during construction. The minimum bank disturbance created by the construction of spurs will also minimize the susceptibility of bank material to loss caused by exposure of the bank surface during high-flow periods.

Costs

A cost analysis and comparison of the most common types of flow control and streambank-stabilization structures is presented in FHWA (1984). This comparison indicates that spur-type structures will often provide a significant economic advantage over other countermeasure types for flow control and bank-stabilization purposes. This has been found to be particularly true where long reaches of gently curving meanders need to be stabilized. Spurs have also been found to provide a significant economic advantage where flow-control and/or flow realignment are the primary purpose(s) of the bank-stabilization scheme. The significant economic advantage that can be realized through the use of spurs is often the deciding factor in the selection of a spur scheme over some other countermeasure.

The data presented in FHWA (1984) indicate spur costs ranging from \$13/ft to \$445/ft, with an average of \$56.2/ft (1982 dollars). This cost variance reflects the diversity of the spur designs available, as well as site-specific costs such as channel environment, required site preparation, etc. Cost data for individual spur types will be presented in later sections. Note that all cost data reported herein have been adjusted to 1982 dollars.

SPUR TYPES

A wide variety of spur types are available. Spurs are classified by functional type as retardance spurs, retardance/diverter spurs, and diverter spurs. Retardance and retardance/diverter structures fall into the permeable-spur category; diverter structures are impermeable. Spurs within each of these categories can be further categorized by material and construction type as follows:

- RETARDANCE SPURS
  -fence type (wood or wire)

- RETARDANCE/DIVERTER SPURS
  -light fence (wood or wire)
  -heavy diverter

- DIVERTER SPURS
  - handpoints
  - transverse dike spurs

Common spur types from within these functional groups were illustrated in Figures 2 through 14. Additional descriptions of the more common spur types within each of these groups will be given below. The spur designs listed below are based on typical designs that have been used in the past. Many design variations of these spurs are possible using different materials and configurations.

Retardance Spurs

As mentioned previously, retardance spurs are designed to reduce the flow velocity in the vicinity of the channelbank or over the region of influence of the spur scheme. Retardance spurs are very similar in design and function to the general countermeasure classification of retardance structures as described in FHWA (1984). The primary difference is that retardance spurs are designed with their primary structural component perpendicular instead of parallel to the channelbank. Retardance spurs are further classified as fence-type and jack/tetrahedron spurs.

Fence Type

The most common fence-type retardance spur is the Henson spur jetty, which is illustrated in Figure 2. A typical design sketch of a Henson spur jetty is illustrated in Figure 15(a). Henson spurs are constructed of individual wood-fence panels mounted on steel-pipe piles or posts. The fence sections are typically constructed of 2-inch by 8-inch treated wood slats mounted vertically to a frame on 18-inch centers. Individual fence units can vary in size depending on the specific application, but they are typically 20 to 30 feet in length. The fence units, consisting of two pipe piles and one fence panel, are then used in multiples to make up the spur structure. One jetty can consist of any number of fence panels. The fence panels are mounted to be movable in the vertical direction and rigid in the lateral direction. The purpose of the free-floating design is to allow the structure to flex or shift with the channel bottom to maintain contact with the channelbed during flow events that would otherwise scour under the fence units. This is particularly important in channels having regime/low threshold sediment environments. The design and function (vertical flexibility) of these structures are patented by Hold That River Inc. under U.S. Patent No. 3,333,320. A similar wood-fence retardance spur design was reported by the COE (1978). The primary difference is that this design is fixed rigidly in the vertical direction. This design alternative is illustrated in Figure 15(b). Another spur type similar in function to the Henson spur (vertical flexibility) is marketed by the Ercon Corporation; patents are pending for this design. This structure is referred to as a

FIGURE 2. HENSON TYPE SPUR JETTY; BARZOS RIVER NEAR ROSHARON, TEXAS.

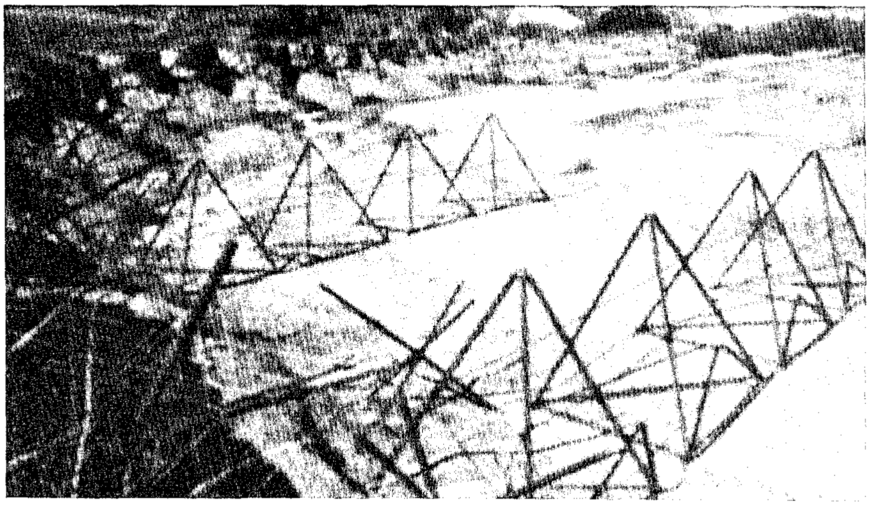


FIGURE 3. TETRAHEDRON SPURS; SAN BENITO RIVER, CALIFORNIA. (AFTER CALIFORNIA DEPT. OF PUBLIC WORKS, 1970)

FIGURE 4. WOOD-FENCE SPUR; BATUPAN BOGUE, GRENADA, MISSISSIPPI.

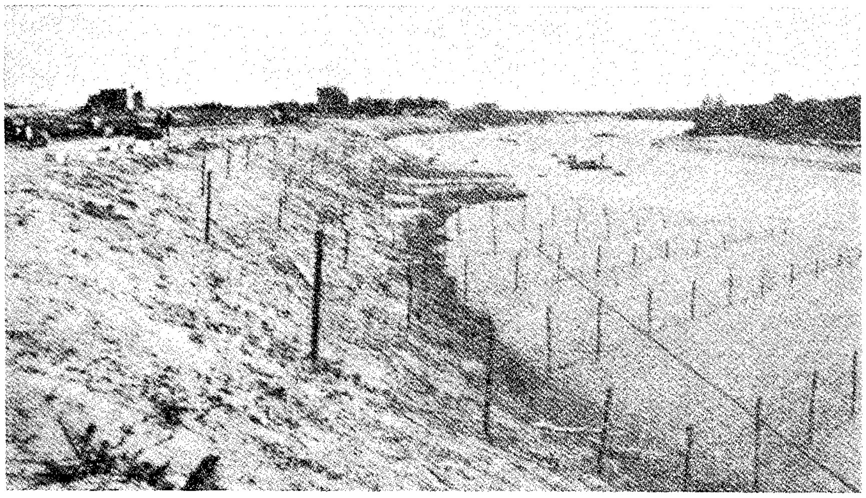


FIGURE 5. WIRE FENCE SPURS.
(AFTER CALIFORNIA DEPT. OF PUBLIC WORKS, 1970)

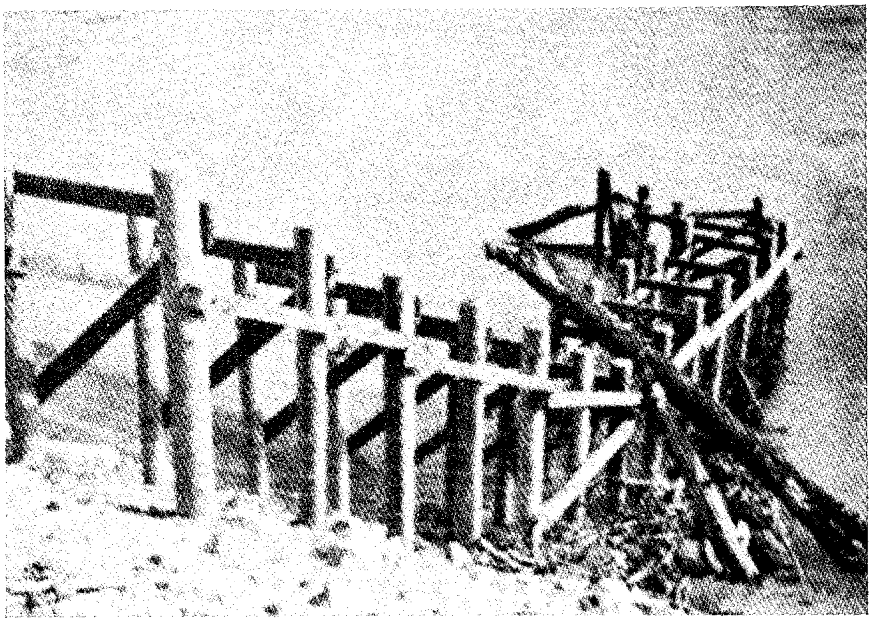


FIGURE 6. DOUBLE-ROW TIMBER PILE AND WIRE-FENCE SPUR.
(AFTER CALIFORNIA DEPT. OF PUBLIC WORKS, 1970)

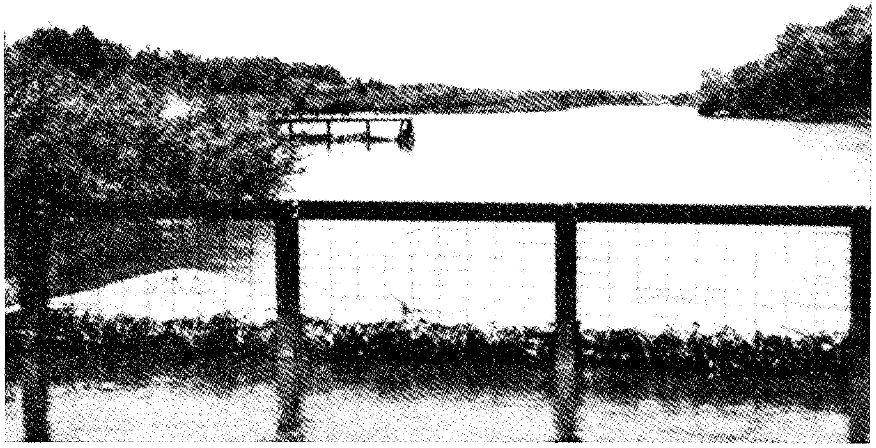


FIGURE 7. WELDED-WIRE AND STEEL H-PILE PERMEABLE SPUR;
ELKHORN RIVER AT SR-32 At WEST POINT, NEBRASKA.
(AFTER BRICE ET AL., 1978)

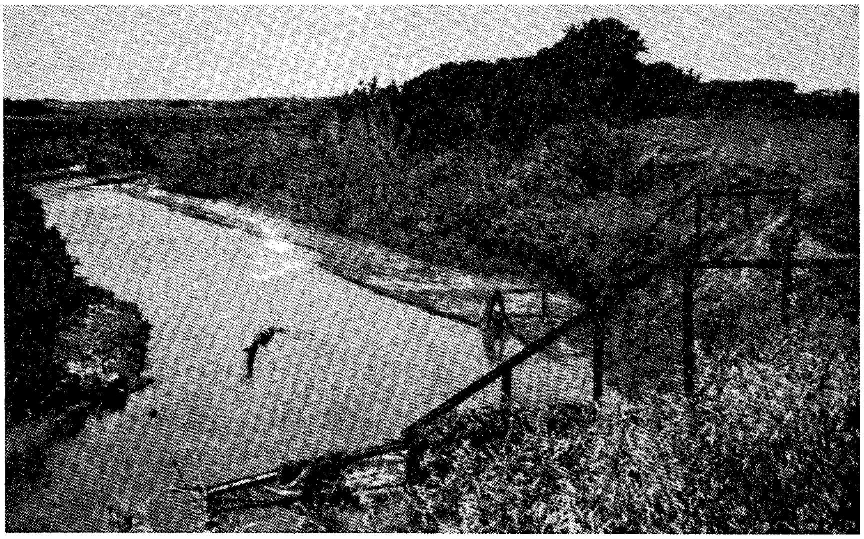


FIGURE 8. STEEL PILE/WELDED WIRE MESH SPUR; LOGAN CREEK NEAR PENDER, NEBRASKA. (AFTER BRICE ET AL., 1978)

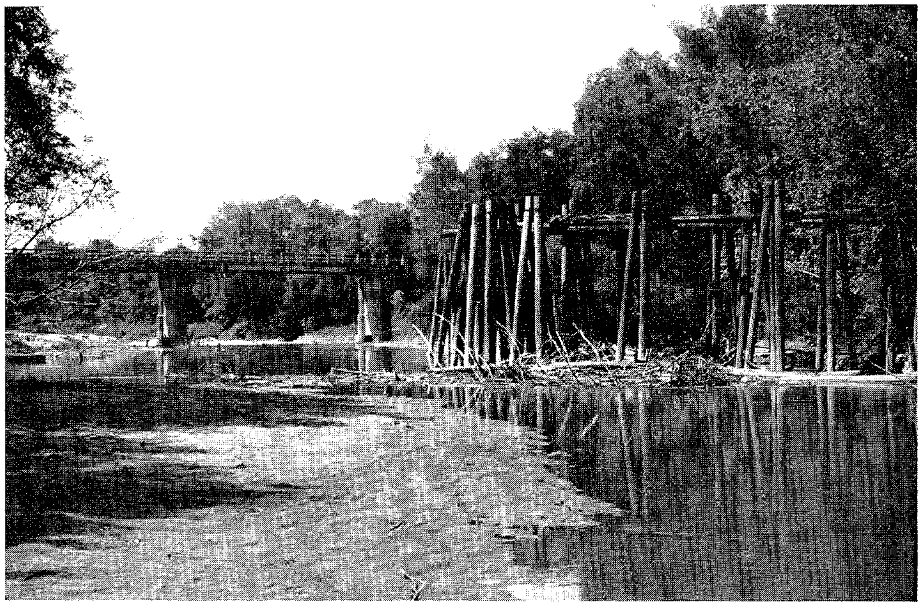


FIGURE 9. TIMBER PILE SPURS; BIG BLACK RIVER AT DURANT, MISSISSIPPI.

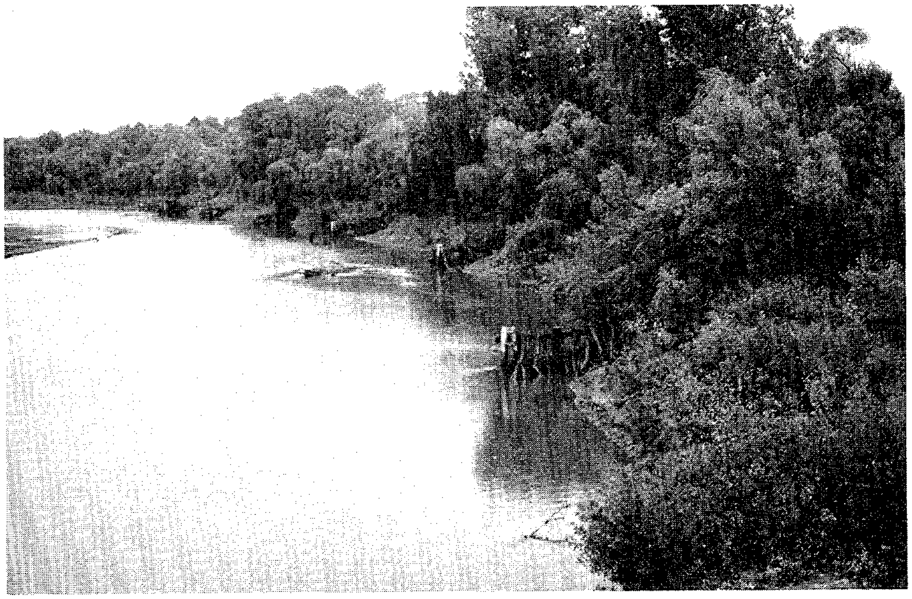


FIGURE 10. TIMBER PILE/SUSPENDED LOG SPURS; ELKHORN RIVER WEST OF ARLINGTON, NEBRASKA.

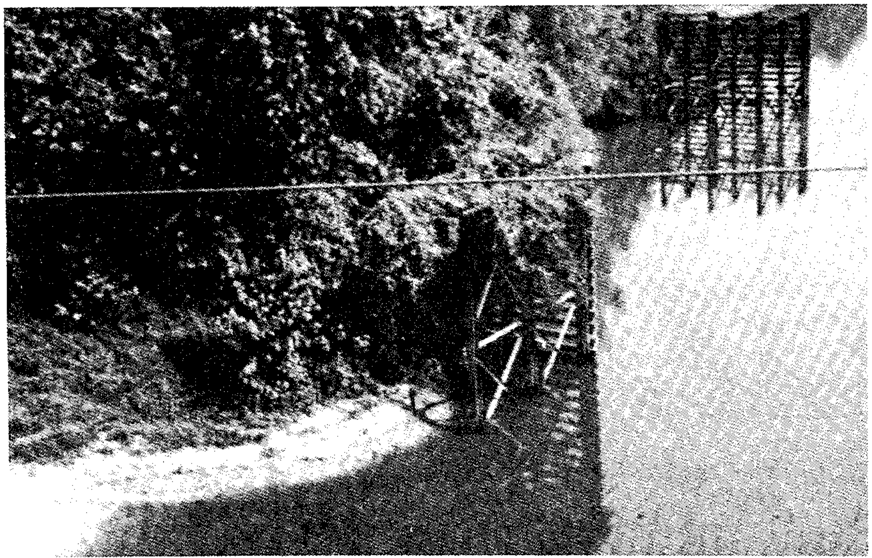


FIGURE 11. TIMBER PILE AND HORIZONTAL WOOD PLANK DIVERTER. STRUCTURE (AFTER BRICE ET AL., 1978)

FIGURE 12. ROCK RIPRAP SPUR; LOYALSOCK CREEK NEAR MONTOURSVILLE, PA. (COURTESY, PENNSYLVANIA DEPT. OF TRANSPORTATION, DISTRICT 3-0)

FIGURE 13. GABION SPUR; LOYALSOCK CREEK NEAR LOYALSOCKVILLE, PA.

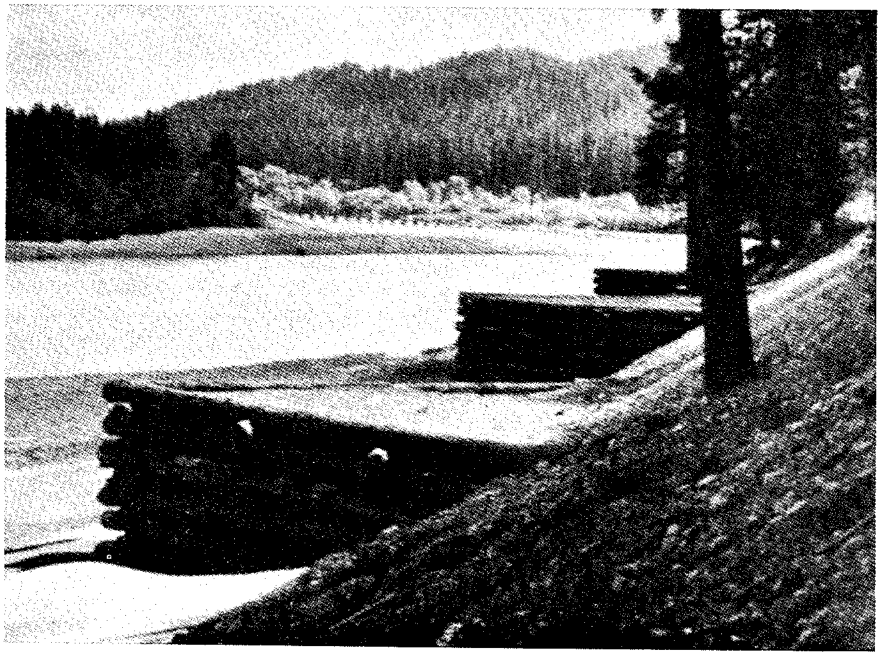


FIGURE 14. CRIB SPURS. (AFTER CALIFORNIA DEPARTMENT Of PUBLIC WORKS, 1970)

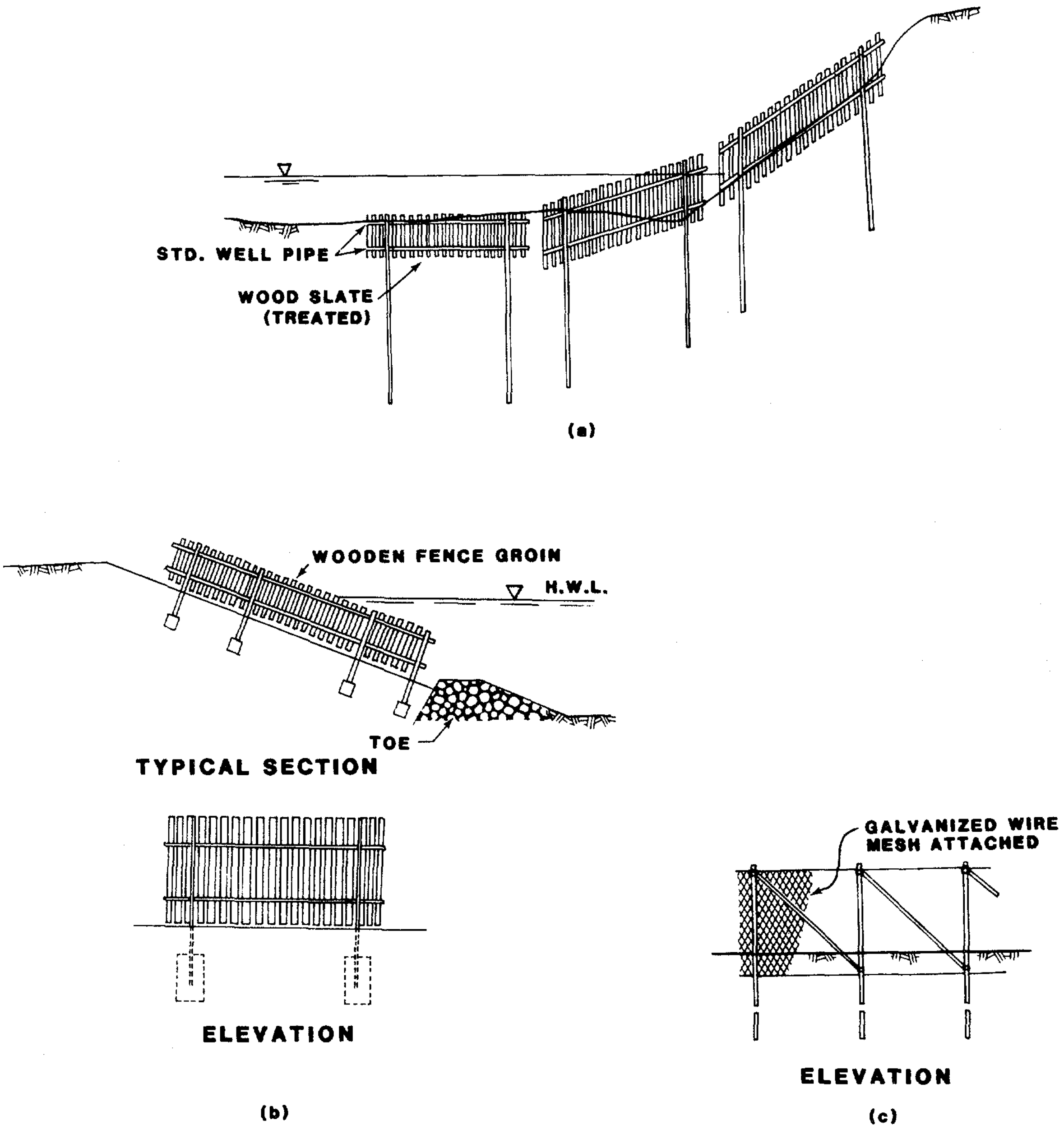


FIGURE 15. FENCE-TYPE RETARDANCE SPURS. (A) HENSON TYPE. (B) RIGID-WOOD FENCE TYPE (C) CHAINLINK FENCE TYPE.

palisade and has a net section made of strapping material that is supported by steel-pipe piles instead of the wood-fence unit. Additional variations on the fence-type retardance spurs are also possible; for example, using chainlink panels or other materials. A rigid chainlink design is shown in Figure 15c. Chainlink panels that are vertically flexible could also be used.

Fence-type retardance spurs are typically placed perpendicular to the channelbank to be protected, forming a flow retardance zone along the toe of the channelbank. A typical layout for a Henson-type retardance spur scheme is illustrated in Figure 16.

Jack/Tetrahedron Type

Jack and tetrahedron units have also been used to form retardance spurs. The basic structural units of these spurs, the jacks and tetrahedrons, are illustrated in Figure 17; part (a) illustrates a jack; part (b) illustrates a tetrahedron. These structural units are skeletal frames adaptable to permeable spurs by tying a number of similar units together in longitudinal alignments. Cables are used to tie the units together and anchor key units to deadmen. Struts and wires are added to the basic frames as needed to increase impedance to flow (either directly by their own resistance or indirectly by the debris they collect). Figure 3 illustrates a typical tetrahedron spur unit. The basic frame of the jack [see Figure 17 (a)] is a triaxial assembly of three mutually perpendicular bars acting as six cantilever legs from their central connection. Besides the steel-membered jack illustrated, concrete jacks have also been used. The tetrahedron frame [see Figure 17 (b)] is assembled from six equal members, three forming the triangular base and the others the three faces sloping upward from the base to an apex. Like other permeable spurs, jacks and tetrahedrons rely primarily on flow retardance and sediment deposition as their primary bank-protection mechanism. Various jack and tetrahedron designs have been patented in the past; the current status of these patents is unknown.

As mentioned above, jack and tetrahedron units are used to form retardance spurs by stringing them together with cables to form the spur system. Figure 18 illustrates a typical layout detail for tetrahedron spurs. A similar configuration would be used for jack spurs.

Retardance/Diverter Spurs

As mentioned previously, retardance/diverter spurs are permeable structures that are designed to function by retarding flow currents along the channelbank and providing flow deflection. This combination of functions makes them the most versatile of all spur types. Retardance/diverter spurs have been further classified as light fence structures and heavy diverter structures. These classifications generally separate the retardance/diverter structures by size and degree of permeability. In general, the light fence structures are smaller and more permeable than the heavy diverter structures. Retardance/diverter spurs are generally oriented with a downstream angle to enhance their flow-diversion qualities.

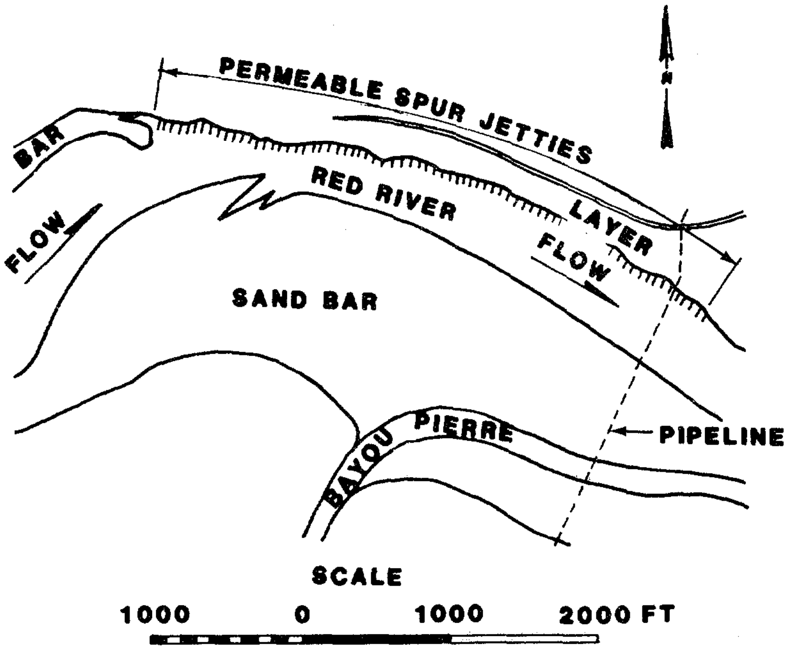


FIGURE 16. HENSON SPUR JETTY LAYOUT ON RED RIVER AT PEROT, LA.

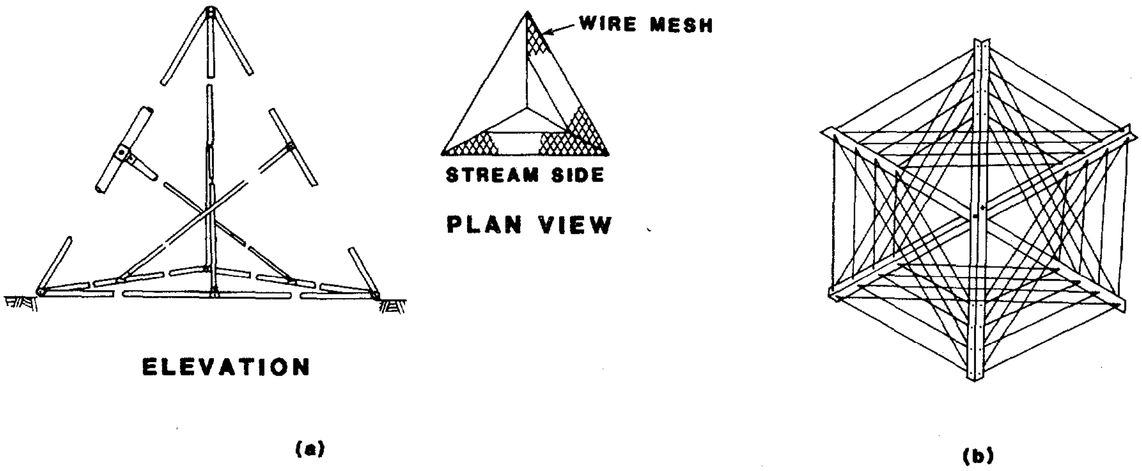
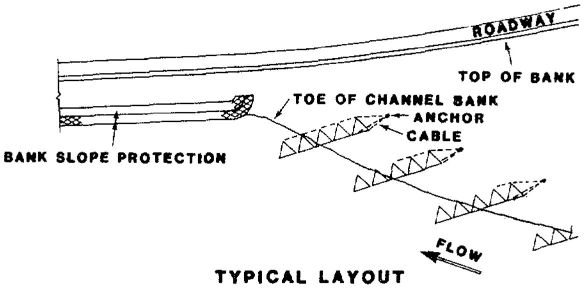
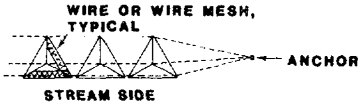


FIGURE 17. STEEL JACK AND TETRAHEDRON DETAILS.
(A) STEEL JACK DETAILS, (B) STEEL TETRAHEDRON DETAILS.



TYPICAL LAYOUT



PART PLAN

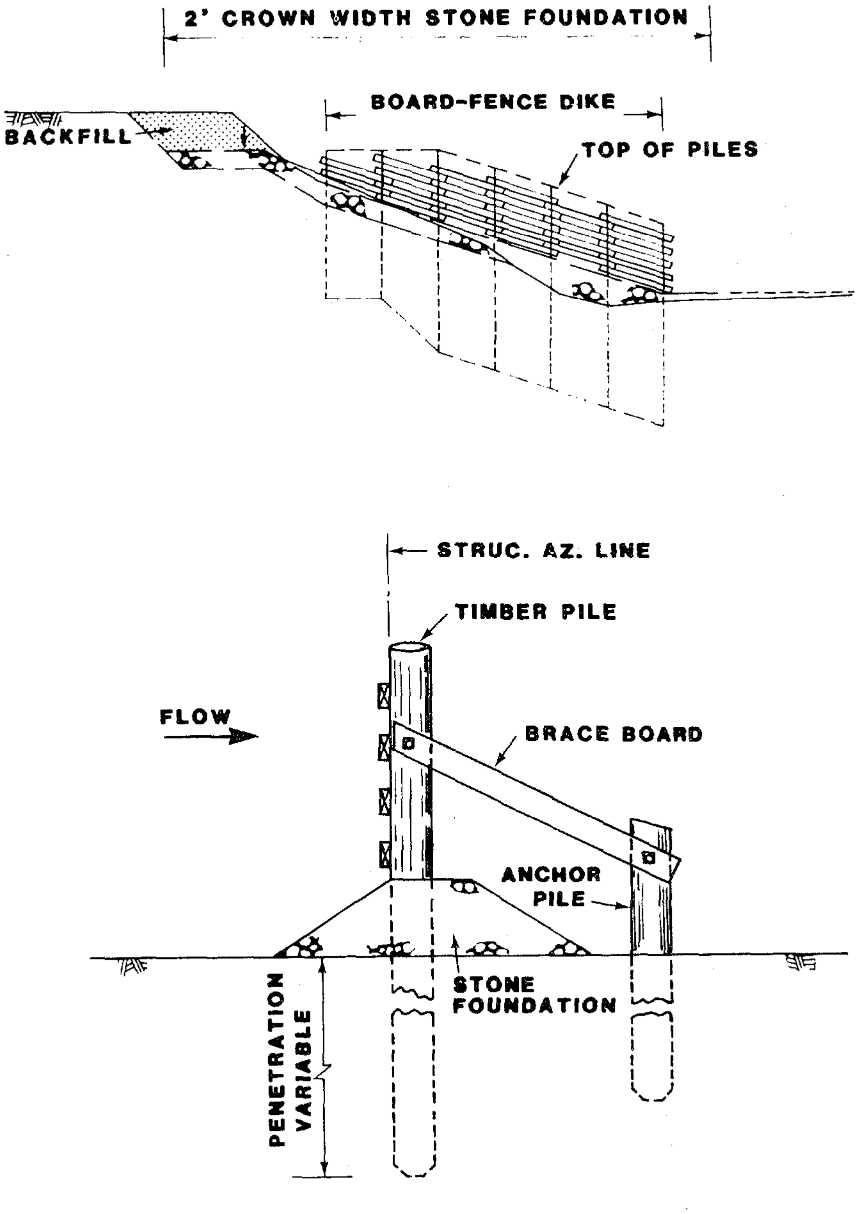
FIGURE 18. LAYOUT DETAILS OF TETRAHEDRON SPURS.

Light Fence Type

A variety of both wood and wire or chainlink structures have been used as light-fence type retardance/diverter structures. Figures 4 through 6 illustrate the three most typical designs: a wood-fence spur, a light-link or wire-fence structure, and a double-row timber pile and wire-fence structure.

Figure 19 illustrates a typical design sketch of a wood fence type structure. In this particular design the vertical supports are timber piles, and the horizontal members are 3-inch by 8-inch planks. Note how the structure is braced to provide additional strength against flow currents and that a stone foundation is used to resist undermining and to provide a key to tie the structure to the channelbank.

Figures 20 and 21 illustrate design sketches for two wire-fence retardance/diverter spurs. In Figure 20, a light-duty wire fence structure is shown. This design consists of a wire mesh supported by vertical pipe posts, with pipes used as horizontal and diagonal bracing. Figure 21 shows a timber-pile wire fence structure. Timber piles are used as the vertical support members in this design with 8-inch by 8-inch timbers used as horizontal bracing. Again, a wire-mesh screen is attached to this structural frame. Although both figures show double-row structures, both single and double-row configurations have been used. The double-row configuration has been much more successful than the single-row design because of the additional structural rigidity and flow retardance provided by the second row. To provide protection against undermining, the entire fence screening is usually extended below the channelbed. Also, the structure is usually designed to extend into the channelbank to prevent outflanking.



END VIEW

FIGURE 19. TYPICAL DESIGN SKETCH OF WOOD-FENCE SPUR.

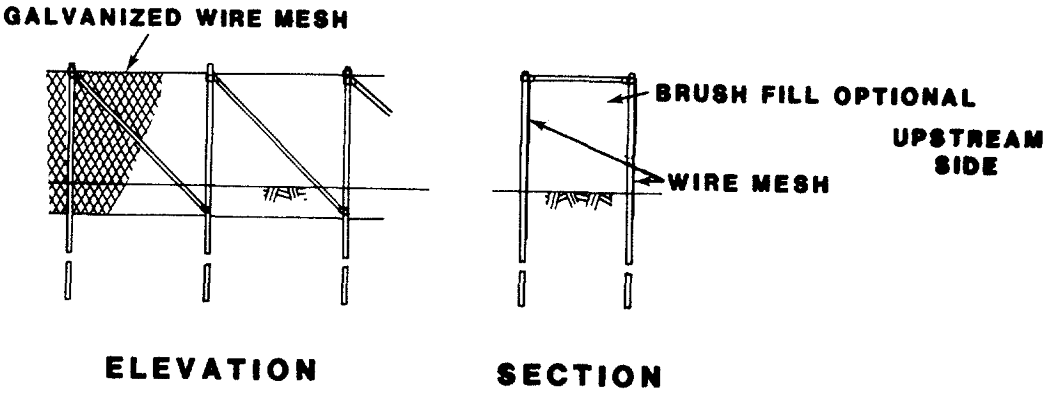


FIGURE 20. DETAILS OF LIGHT-FENCE-TYPE SPUR.

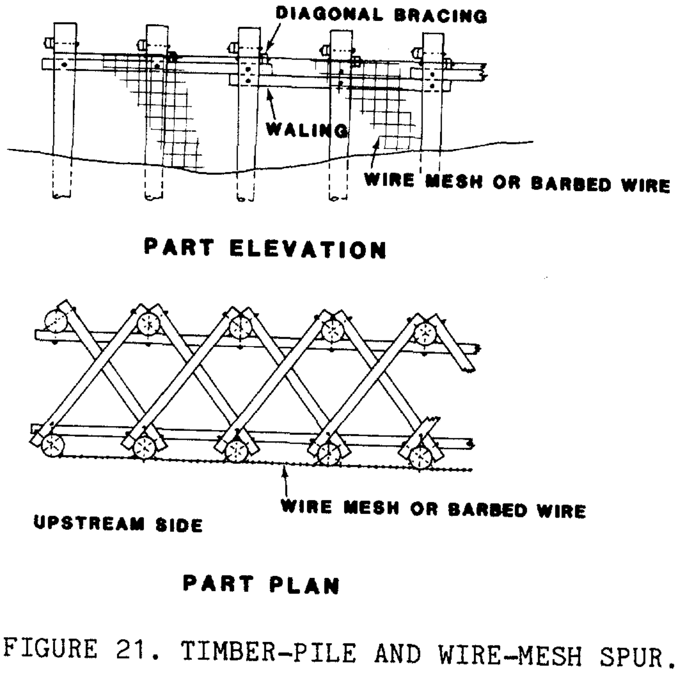


FIGURE 21. TIMBER-PILE AND WIRE-MESH SPUR.

Heavy Diverter Spurs

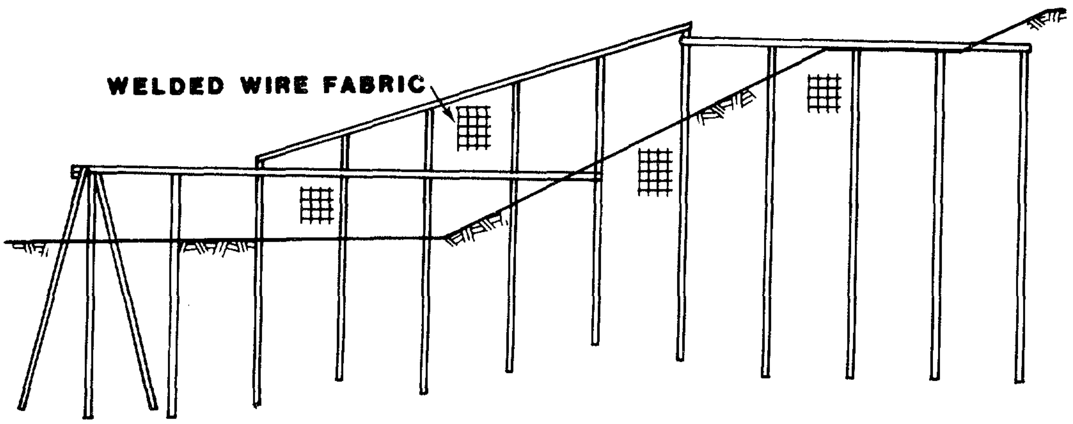
Heavy diverter spurs are illustrated in Figures 7 through 11; steel pile and welded wire-mesh spurs and numerous timber-pile designs are detailed.

Two steel-pile and welded-wire mesh spurs are illustrated in Figures 7 and 8. Typical design sketches for these structures are given in Figure 22. These structures are the most permeable of the permeable diverter structures. They are constructed by suspending a wire-mesh or welded-wire fabric on a support frame of steel "I" or "H" beams. Other materials such as timber piles could be used for the support frame. Part (a) of Figure 22 illustrates a structural design that has been used for the protection of high channelbanks; part (b) illustrates a design for lower channelbanks. In both design configurations a triple-pile header is used to provide sufficient structural rigidity to the spur head to resist damage from large floating debris. Here again, the welded-wire mesh is extended to below the channelbed to minimize underscouring, and the structure is extended into the channelbank to prevent outflanking.

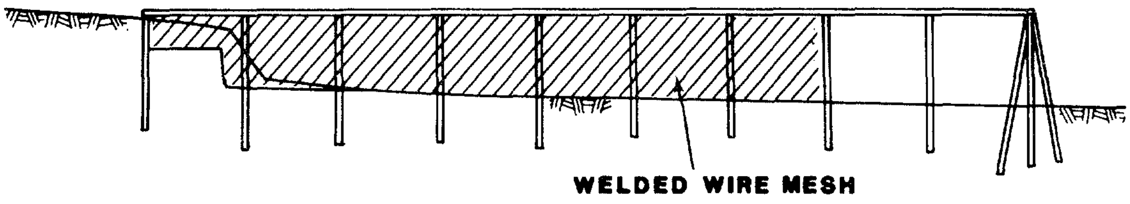
Figures 9 and 10 illustrate two timber-pile spurs. Timber piles are the basic component of most permeable diverter structures designed. Single piles or pile clumps (three or more piles to a clump) constitute the basic construction unit for these structures. Timber-pile spurs of various designs have been used including single piles in line, single piles staggered, single piles in multiple rows, single and multiple rows of pile clumps, and staggered rows of pile clumps. Both single piles and pile clumps have been spaced at various distances to provide various degrees of permeability. Rows of piles or pile clumps are then usually braced with planks or additional piles.

Figure 23 [(a) through (c)] illustrates design sketches for three timber-pile spur designs. The design illustrated in Figure 23 (a) consists of three pile clusters joined by horizontal timber-pile stringers lashed to the vertical pile clusters. As mentioned above, single or multiple rows of pile clusters and stringers can be used, depending on the needs of individual sites; up to three rows have been used in the past. An alternate design is illustrated in Figure 23 (b). This design consists of alternate single vertical piles straddling a single horizontal-pile stringer. This design is commonly used by the COE on large rivers to provide flow constriction for navigational purposes. The design is also applicable for bank-stabilization applications. Figure 23 (c) illustrates another timber-pile structure. This design uses widely-spaced vertical piles with trees slashed to the horizontal stringers to reduce the structure's permeability.

Another retardance/diverter spur using timber piles for the vertical support structure are horizontal wood-plank structures. Figure 11 illustrates one such structure. As is the case with other spur types, many design variations are possible for pile and horizontal-plank structures. Figure 24 shows a typical design sketch for the spur illustrated in Figure 11. This design uses a double row of timber piles as vertical supports.



(a)



(b)

FIGURE 22. TYPICAL DESIGN SKETCHES FOR STEEL-PILE AND WIRE-MESH SPURS (A) HIGH BANK DESIGN, (B) LOW BANK DESIGN.

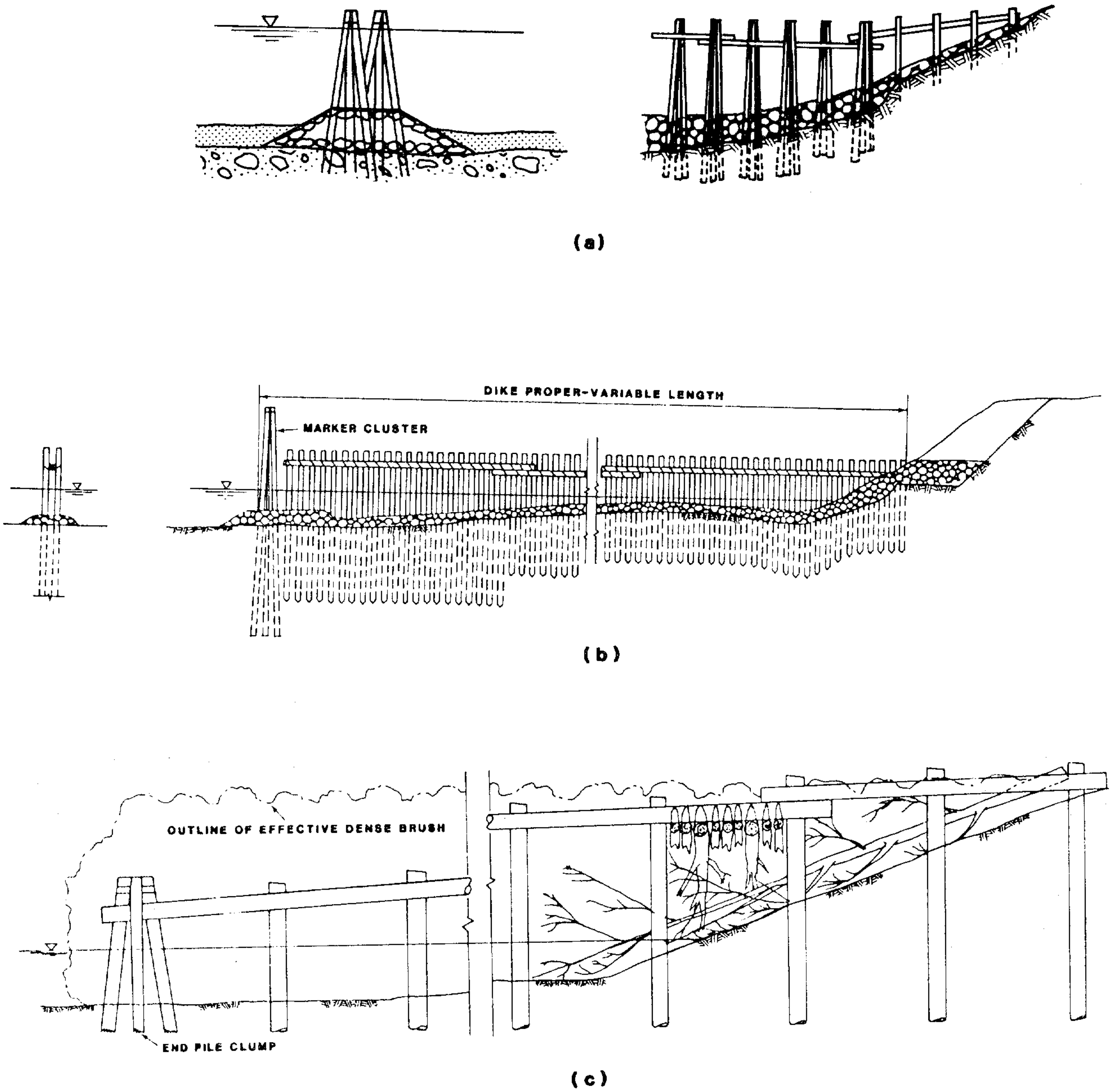


FIGURE 23. TYPICAL DESIGN OF TIMBER PILE DIVERTER SPURS
(A) DESIGN SKETCH FOR PILE CLUSTER SPUR
(B) DESIGN SKETCH FOR DOUBLE-ROW, SINGLE PILE SPUR
(C) DESIGN SKETCH FOR TIMBER PILE SPUR WITH SLASHED TREES.

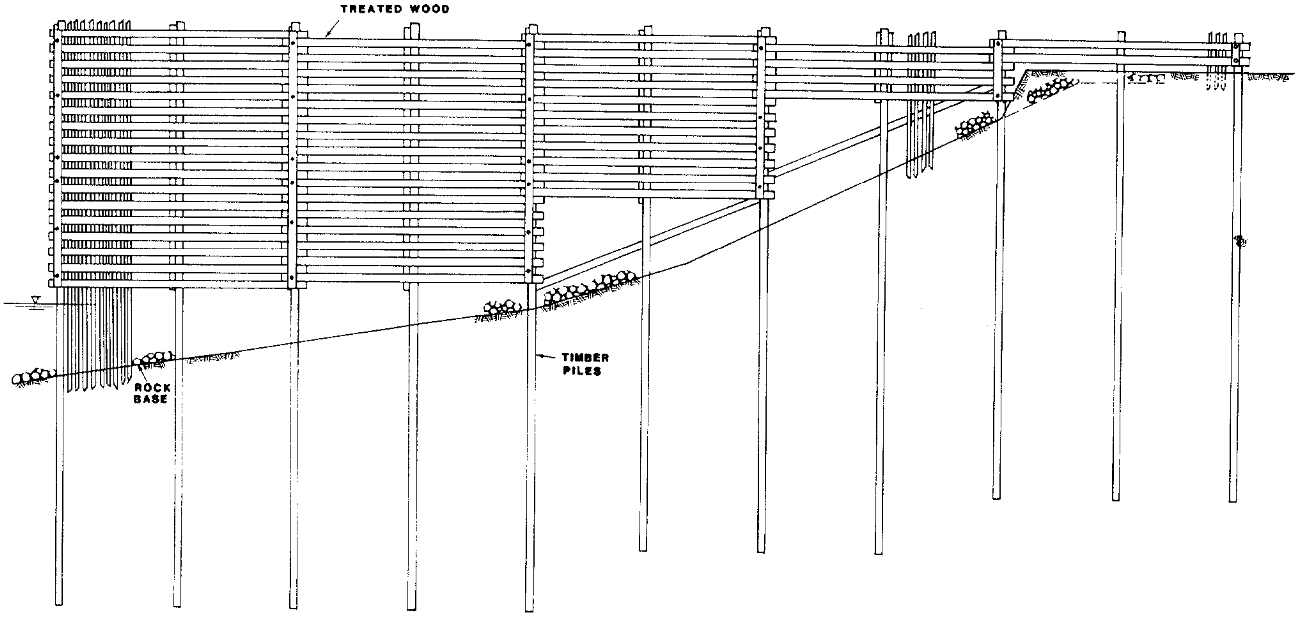


FIGURE 24. TYPICAL DESIGN SKETCH FOR TIMBER-PILE AND WOOD PLANK RETARDANCE/DIVERTER SPUR.

Four by eight diagonal and horizontal bracing is used between the two rows. Horizontal four by eight timbers are also used as horizontal sheathing on the upstream face of the upstream row of piles. In this particular design, pole screening is used on the upstream face of the downstream row of piles. Other designs use the downstream row of piles for bracing and do not include a facing material.

As is the case for other retardance/deflector spurs, the structural members of these structures should be well anchored to the channelbank to prevent outflanking and should be extended below the channelbed for a sufficient distance so that they will not be undermined by local scour.

Diverter Spurs

Diverter spurs are impermeable structures that are designed to function by diverting the primary flow currents away from the channelbank. Several diverter spurs were illustrated in Figures 12 through 14 . Diverter spurs are most commonly constructed of dumped riprap since it is almost universally available and economical. Furthermore, constructing spurs with this material is relatively easy. Diverter spurs have also been constructed using gabion and crib designs. To enhance their flow-diversion qualities, diverter spurs are usually constructed with a downstream orientation (as are the retardance/diverter structures discussed above). The two primary subclassifications of diverter structures are hardpoints and transverse-dike spurs. The primary difference between these two types of diverter spurs is the structure's length.

Hardpoints

Hardpoints are short structures that extend only a limited distance outward from the channelbank, and have a slight downstream orientation. Their primary function is to protect an existing bankline; by definition, they are not long enough to be used for flow control or realignment, or to provide flow constriction. Figure 25 illustrates a typical hardpoint design. The designs shown are constructed of dumped riprap; however, gabion designs could also be used. Hardpoints are made up of two parts; a spur section and a root section. The spur section functions as the hardpoint and deflects flow currents away from the channelbank. The root section extends into the channelbank to help anchor the structure to the bank and prevent outflanking during high flows. Rock hardpoints are particularly well-suited for use on narrow channels because they do not create any significant flow obstruction.

Transverse-Dike Spurs

Transverse-dike spurs are the most widely used impermeable spurs. These structures are most commonly constructed of dumped rock riprap. Where rock of sufficient size is not available, however, gabion and crib designs have also been used. Sheet-pile, asphalt, and concrete spurs have also been designed. The cost of these structures will be prohibitive in most cases.

Transverse-dike spurs are similar to the rock hardpoints described above except that the spur section is longer in length. In general, transverse dikes will extend into the stream past the point where the highest velocities occur. Their function is to move the thalweg from its position along an eroding bank to a more favorable alignment. Transverse-dike spurs are illustrated in Figures 26 through 29 .

Figure 26 shows a riprap-dike design. These structures can be constructed using a uniform stone gradation, or with a small rock or earth core surrounded with a larger rock facing. The stone used on the exterior of the structure must be of sufficient size to resist the erosive action of river flows. Where stone of a size large enough to resist the erosive forces in a river is not available, a gabion or crib design can be used.

A typical gabion spur structure is illustrated in Figure 27. Gabions are compartmented rectangular containers made of galvanized steel hexagonal wire mesh and filled with stone. A typical gabion detail is illustrated in Figure 27. Individual gabion baskets are then stacked, wired together, and filled to form the spur structure. Note the base mat used in the design to support the spur structure; this mat helps to protect the structure from failure caused by undermining from local scour.

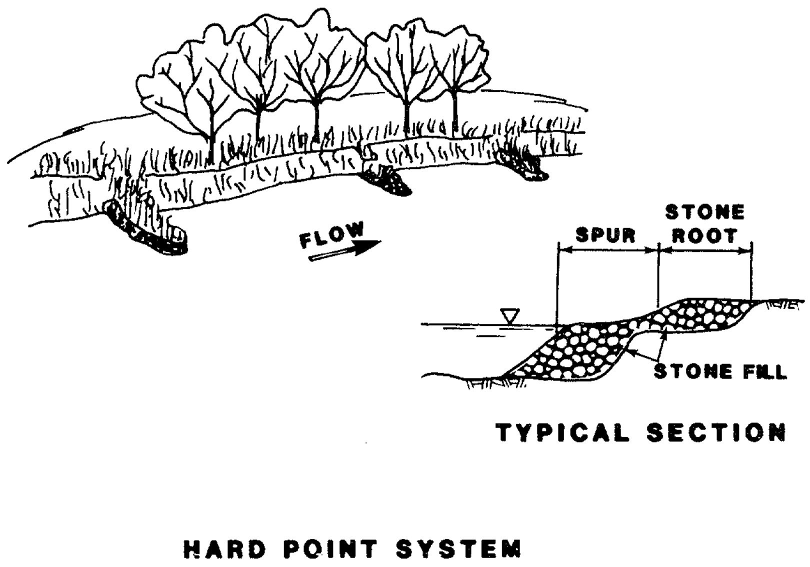


FIGURE 25. TYPICAL ROCK HARDPOINT DESIGNS.

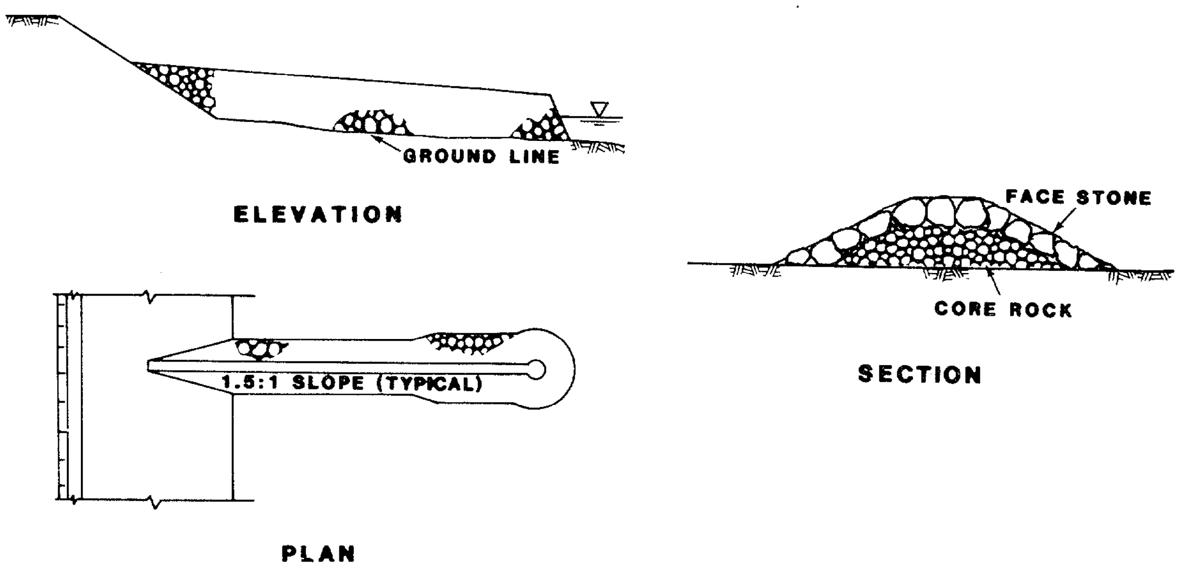


FIGURE 26. TYPICAL DESIGN SKETCH FOR DUMPED RIPRAP TRANSVERSE DIKE SPUR.

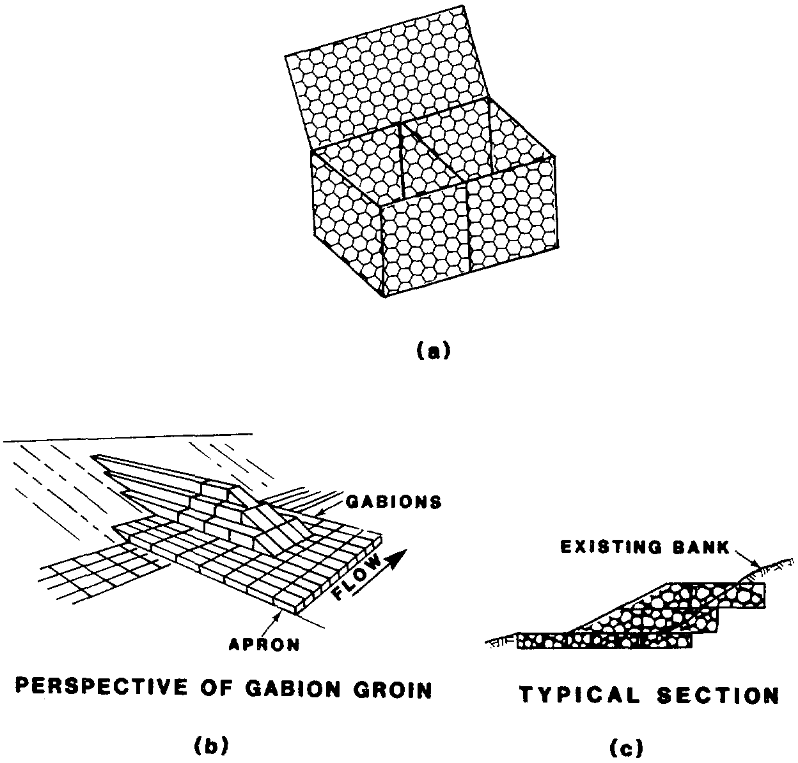
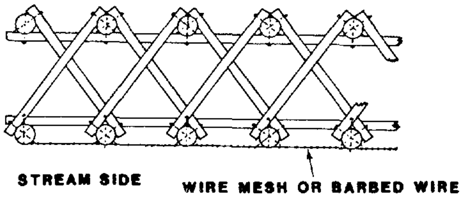
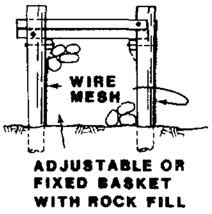


FIGURE 27. TYPICAL DESIGN DRAWING FOR GABION TRANSVERSE DIKE SPUR.



PART PLAN



SECTION

FIGURE 28. TYPICAL DESIGN SKETCH FOR WIRE CRIB DESIGN.

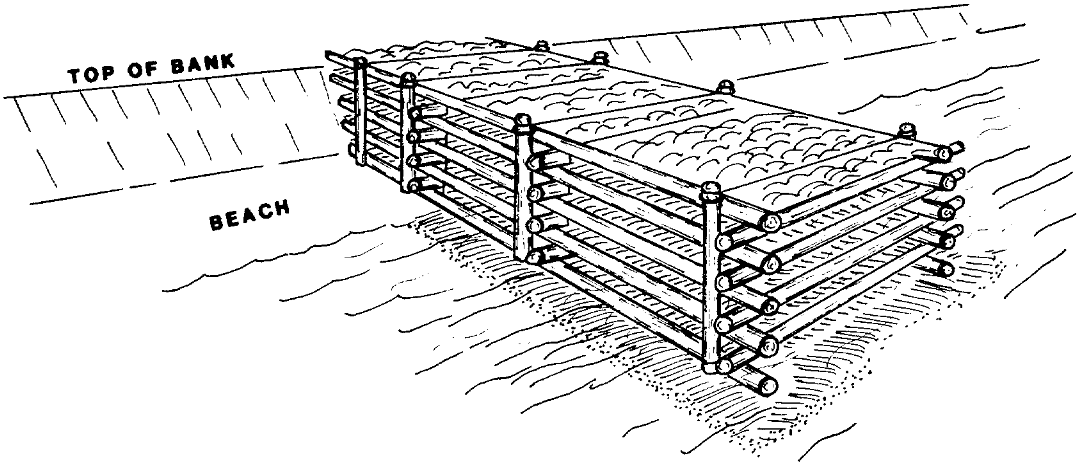


FIGURE 29. SKETCH OF RECTANGULAR TIMBER ROCK-FILL CRIB SPUR.

A typical crib design is illustrated in Figure 28. This design is identical to the double-row timber pile and wire-fence retardance/deflector spur illustrated in Figure 21 except that the space between the fences is filled with stone. Other double-row fence designs could be converted to impermeable diverter spurs by adding rock fill as well. Other crib designs could also be used, such as the timber crib illustrated in Figure 29. Of significant importance to crib-spur design is the security of the base of the crib from loss of the fill material upon scour along the base of the structure. The structure should be extended to a sufficient depth below the channelbed, and a sufficient volume of rock should be used in environments where local scour might threaten the stability of the structure.

As with the hardpoint designs discussed above, all the transverse-dike spurs mentioned should be designed with a root section to anchor the structure to the channelbank to prevent outflanking.

PRIMARY FACTORS INFLUENCING THE DESIGN AND SELECTION OF A SPUR TYPE

There are numerous factors that influence the selection of a specific spur type for a given streambank-stabilization situation. However, six primary factors have been identified. These include:

- spur function or purpose,
- erosion mechanism countered,
- sediment environment,
- flow environment,

- bend radius/flow alignment, and
- ice and debris conditions.

Consideration of these factors provides guidance for the selection of an appropriate functional spur type. It is important to remember that the factors listed are often interrelated, and it is their combined effect or the total environment that must be considered when designing a bank-protection scheme.

Table 1 has been constructed to aid in the selection of an appropriate spur type for a given situation. In Table 1, the primary factors influencing the selection of a specific spur type are listed across the top, and the primary spur types are evaluated in terms of those selection criteria. A scale from 1 to 5 is used in the table to indicate a specific spur type's applicability for the given condition. A value of 1 indicates a disadvantage in using that spur type for the given condition, and a value of 5 indicates a definite advantage in using that spur type. Table 1 is designed to be a design aid for selecting a spur type. The table can be used by summing the values for the specific site conditions along horizontal lines. The spur type having the highest sum would ideally be the best for the given situation. It is not advisable, however, to select only one spur type from this table. Several of the better spurs should be selected for more detailed consideration based on other factors such as cost, availability of materials, maintenance requirements, structure impacts, etc.

The following discussions provide general guidance regarding the manner in which the primary spur selection criteria affect the selection and design of various spur types.

Spur Function/Purpose

Flow-control and/or bank-stabilization schemes are generally constructed to function in one of the following capacities:

- to protect an existing bankline,
- to reestablish some previous flow alignment, and
- to provide flow constriction.

Combinations of the above functions are also possible.

Retardance-type spurs are usually light structures designed to reduce the flow velocity in the vicinity of the channelbank. As such, they are best suited for protecting an existing bank line. They are not as well-suited for either of the other functions mentioned, although wire-fence and jack/tetrahedron-type spurs have been used to reestablish some previous flow alignment where only a minor shift in flow orientation is necessary.

TABLE 1. SPUR TYPE SELECTION TABLE.

SPUR TYPE	FUNCTION			EROSION MECHANISM				SEDIMENT ENVIRONMENT			FLOW ENVIRONMENT						BEND RADIUS			ICE/DEBRIS ENVIRONMENT		
											VELOCITY			STAGE								
	Protect Ext. Bank	Re-est. Prev. Align.	Flow Construction	Transport	Shear Stress - Toe	Shear Stress - Upper Bank	Abrasion	Regime/Low Threshold	Medium Threshold	High Threshold/Rigid	Low	Medium	High	Low	Medium	High	Large	Medium	Small	Minimal	Light Debris	Large Debris/Ice
RETARDANCE																						
Fence Type	3	2	2	3	3*	1	1	4	3	2	3	3	2	3	2	1	3	2	1	3	3	2
Jack/Tetrahedron	3	3	1	3	3	1	1	4	3	1	3	2	1	3	2	1	3	2	1	2	4	1
RETARDANCE/DEFLECTOR																						
Light Fence	3	3	3	3	3	2	2	3	3	2	3	3	2	3	3	2	3	3	2	3	4	2
Heavy Diverter	3	4	4	3	3	4	3	2	3	3	3	3	2	3	4	4	3	3	2	3	4	3
DEFLECTOR																						
Hardpoint	3	4	4	3	3	3	4	2	3	4	3	3	4	3	3	2	3	4	4	3	3	5
Transverse Dike	3	4	4	3	3	3	4	2	3	4	3	3	4	3	3	2	3	4	3	3	3	5

*Henson spur jetties are rated a 4 for this condition

1. Definite disadvantage to the use of this type structure.
2. Some disadvantage to the use of this type structure.
3. Adequate for condition.
4. Some advantage to the use of this type structure.
5. Significant advantage to the use of this type structure.

Retardance/deflector structures have been used effectively for all three functions or purposes listed. As is the case with retardance structures, retardance/diverter structures function by producing a flow retardance along the channelbank. They are also designed to produce a diversion of flows. The heavier diverter-type retardance/deflector spurs have been found to provide an advantage over other types of permeable structures where flow constriction and/or the reestablishment of some previous flow alignment are primary concerns.

Impermeable deflector spurs function by deflecting the main flow current away from the bank. Like retardance/deflector spurs, they have been found to provide an advantage where flow constriction and/or the reestablishment of some new or previous flow alignment is desired. They are also as effective as other spur types when the primary function is to protect an existing bank-line.

Erosion Mechanism

Erosion mechanisms countered by spur-type flow-control and streambank-stabilization structures are:

- transport by streamflow,
- particle displacement at the toe of the bank
- particle displacement along middle and upper bank by streamflow-induced shear stresses, and
- particle displacement by abrasion.

Combinations of these mechanisms are also possible. Detailed descriptions of each of these mechanisms are presented in FHWA (1984).

A **sediment-transporting mechanism** must be present for erosion to occur. This mechanism is provided by the flowing water. All spur types will effectively counter this mechanism by retarding and/or deflecting the streamflow currents in the vicinity of the bank erosion. However, under some medium to high flow-velocity environments, some of the more permeable retardance and retardance/diverter spurs will not provide sufficient flow retardance to reduce flow velocities below the critical transport level. Welded wire mesh (Figure 23), other wire-fence spurs (Figures 15, 20, and 21), and jack and tetrahedron designs (Figure 17) are examples of structures that might not provide sufficient flow retardance in some flow environments.

Particle displacement at the toe of the streambank caused by streamflow-induced shear stresses can also be countered by most of the spur types identified, as long as other conditions (to be discussed below) are met. Again, the vehicles used are flow deflection and/or flow retardance. As is the case with the transport mechanism, however, the more permeable retardance and retardance/diverter structures might not provide sufficient flow retardance in some high-flow velocities to resist erosion caused by streamflow-induced shear stresses.

Particle displacement on the middle or upper portions of the streambank caused by streamflow-induced shear stresses can be best countered through the use of the larger retardance/deflector or deflector-type spurs. Retardance-type structures will usually only provide protection to the toe of the streambank, and therefore, are not effective for upper-bank protection. Some of the larger retardance/deflector structures provide some advantage in this area, especially if moderate to high banks need to be protected. One design particularly adaptable to protecting middle and upper portions of the channelbank is the steel-pile and wire-mesh spur illustrated in Figure 22(a).

Abrasion occurs when solid materials, such as debris and ice, carried by the flowing water collide with and dislodge surface soil particles. Countering streambank erosion caused by abrasion requires a spur that provides flow deflection and will not be significantly damaged by the agent causing the abrasion.. For these applications, the impermeable deflector structures have two significant advantages over other spur types. First, impermeable diverter spurs function by deflecting currents and any floating debris away from the channelbank. Impermeable structures also have more structural mass than most permeable structures and, therefore, are subject to less damage from floating debris. The light retardance structures have a history of being severely damaged by floating debris. This is because of their small size and the fact that permeable structures will become clogged with floating debris, increasing the hydraulic forces on the structure. Therefore, these structures should not be used. Retardance/deflector spurs are designed to deflect flow currents, as are the impermeable deflector spurs. Their permeability, however, makes them debris skimmers like the retardance structures. The light fence retardance/diverters are prone to damage from the floating debris and therefore, are not recommended. However, some of the heavier retardance/diverter structures have been found to be effective at resisting abrasion forces.

Sediment Environment

When discussing a spur's effectiveness in a given sediment environment, it is appropriate to refer to spurs as either permeable or impermeable. Referring to the classification scheme outlined above, retardance spurs and retardance/deflector spurs are permeable, and deflector spurs are impermeable.

Both permeable and impermeable spurs have been used in a wide range of sediment environments. Sediment environments (or channelbed conditions) can be defined as regime, threshold, or rigid. For purposes of identifying an appropriate spur type, the sediment environment can be classified as regime/low threshold, medium threshold, or high threshold/rigid. A regime channel is one whose bed is in motion under virtually all channel-flow conditions. Low threshold channels are those channels whose channelbeds are in motion under all but some very low flow conditions. Therefore, regime/low threshold environments are characterized by large suspended and bed-sediment loads under most flow conditions. These channels are typically cut through noncohesive sand- and silt-size materials. Medium threshold channels are typically cut through sand- and gravel-size materials whose channelbeds are mobile for moderate and high channel-flow conditions. Channels cut through cohesive materials can also be considered medium threshold. High threshold/rigid channels are typically cut through larger gravel-, cobble-, and boulder-size materials. These materials will remain stable or rigid under most flow conditions, but will become mobile during high flows.

Permeable spurs are best suited for regime/low threshold and medium threshold environments. Permeable retardance spurs have been found to be particularly effective in regime/low threshold environments. In fact, they generally provide an advantage over other spur types in these environments. The flow retardance created by retardance spur schemes creates a depositional environment within the retarded flow zone along the channelbank for the suspended and bed-sediment loads carried by these channels. This produces a sediment berm or bench that will stabilize the base of the channelbank. Also, by lowering flow velocities in this zone, permeable retardance spur schemes will reduce or eliminate the transporting ability of channel flows adjacent to the bank. This is important in cases where erosion resulting from bank-weakening mechanisms (wave erosion, subsurface flow and drainage, etc.) is occurring. As discussed previously, Henson-type spurs provide a particular advantage in these highly dynamic environments because of their vertical flexibility. Other fence-type structures will also function well. Jack and tetrahedron structures have also been quite effective in these environments except where there are high-flow velocities. In high-velocity environments the jacks and tetrahedrons do not provide sufficient flow retardance and are often lost to scour.

Permeable retardance/deflector spurs have also performed well in regime/low-threshold channels. Because of their flow deflection characteristics, however, they are better suited for medium-threshold environments. This is particularly true of the larger heavy diverter structures. Local scour problems associated with these larger structures have resulted in structural undermining in some cases when they are used in regime/low-threshold environments.

The above discussion is not meant to imply that permeable spurs should not be used on channels that do not carry large sediment loads. In some cases, the flow retardance produced by the spur scheme can be designed to provide the desired level of bank protection. This is particularly true of permeable retardance/deflector structures. These structures are designed to function as flow deflectors as well as retardance structures. Permeable retardance spurs and the light fence retardance/deflector structures are not suited as well for use on high threshold/rigid channels.

Impermeable deflector spurs are best suited for use on high threshold/rigid channels. They have been used effectively, however, in some regime and low-threshold environments. There are several drawbacks that make impermeable deflector spurs less acceptable than permeable spurs in truly alluvial channels (regime/low threshold and some medium-threshold environments). In truly alluvial environments, impermeable diverter spurs will cause sediment deposition along the channelbank in a similar fashion as permeable structures. However, this deposition will be to a much lesser degree than with permeable structures. The primary source of deposition between impermeable spurs is from spur-topping flows. These flow conditions have been observed to carry significant amounts of suspended material into zones between spurs, where it is then deposited as a result of the lower transport capacity between spurs. Another source of sediment for deposition comes from suspended materials carried into the interspaces by the expansion of flow as it passes the spur tips. Again, this material deposits due to the low transporting capacity of the currents between spurs. It is important to keep in mind that the amount of deposition that can be expected between impermeable spurs is less than that induced by permeable structures.

When using impermeable deflector structures in alluvial environments it is important to recognize the potentially detrimental impacts they can have. Flow concentration and local scour are primary among these impacts. Flow concentration is inherent in impermeable spur design. A consequence of the flow-constricting effect produced by spurs is a concentration of flow lines along the riverward tip of each spur. The flow concentration in this area results in a magnified potential for erosion of the channelbed in the vicinity and just downstream of the tip of the impermeable structures. This condition is much more pronounced in high-velocity environments and around sharp bends than it is in low-velocity environments and around mild bends. The occurrence of significant erosion at and downstream from the spur tip has been observed by the authors at numerous field sites and is well documented in reported laboratory studies (FHWA, 1983; Ahmad, 1951a and 1951b). Local scour is a primary concern in alluvial environments because of the highly erosive nature of the gravel-, sand-, and silt-size material comprising the channelbed. The potential for excessive erosion at the scour tip, combined with the high cost of providing protection against the erosion is a drawback in the use of impermeable diverter spurs in alluvial environments.

The flow concentration and local scour conditions just described are characteristic of impermeable installations in all river environments. In high threshold/rigid channels (those cut through large gravel- and cobble-size materials); however, these conditions pose less of a threat to the stability of impermeable spur schemes. Flow concentration at the spur tip will still cause erosion in these environments. Because of the low transportability of the coarse materials making up the channelbed, and the natural channelbed armoring that occurs in these environments, however, it will be of a much smaller magnitude. In most cases, only a limited amount of erosion (in comparison with truly alluvial environments) will occur. This can usually be anticipated and adequately designed at little additional cost.

Flow Environment

The channel-flow environment includes consideration of both channel-flow velocities and flow stage. Consideration of channel-flow velocities includes both the magnitude of the velocity, as well as the frequency of occurrence of a specified flow velocity. For classification purposes, channel flow velocities will be classified as low, medium, and high. Low-velocity environments are defined as those where the dominant or controlling flow velocities are less than four feet per second. Medium velocity environments are defined as those where the dominant or controlling flow velocities are greater than four feet per second but less than eight feet per second. High-velocity environments are defined as those where the dominant or controlling flow velocities are greater than eight feet per second. The frequency of occurrence is reflected in the terms "dominant or controlling." The dominant or controlling velocities are those primarily responsible for the erosion process. In one situation these velocities might be associated with normal low-flow conditions. In another situation the dominant or controlling velocities might be associated only with extreme flow events.

Flow stage can be classified in terms similar to flow velocity. A low flow stage will be considered to be one where the dominant or controlling flow stage is less than 10 feet. A medium flow stage is one where the dominant or controlling flow stage is greater than 10 feet but less than 18 feet. A high flow stage is one where the dominant or controlling flow stage is greater than eighteen 18 feet.

Channel Velocity Environment

The applicability of various spur types with respect to the channel's velocity environment is in many ways related to the channel's sediment environment. It is the interaction of the flow environment and the channel's bed-material constituency that determines the sediment-transport environment of a particular stream. The channel-flow velocity is also related to the size and structural integrity of a spur. Generally, the larger and more rigid the spur scheme, the better its adaptability to the more severe flow environments.

As discussed above, retardance spurs are best suited for regime and low-threshold sediment environments. Within these environments, however, retardance spurs have not been successful in high-velocity environments, or some of the higher medium-velocity environments. In these environments, the retardance spurs generally do not provide sufficient flow retardance and are often undermined or outflanked due to the dynamic nature of the channelbed combined with the high flow velocities. This has been found to be particularly true for jack and tetrahedron structures. Jack and tetrahedron designs should not be used in the higher medium- or high-velocity environments. Retardance spurs are also smaller and less structurally rigid than other spur types and, therefore, are more susceptible to structural damage in high-velocity environments than other types of spurs.

Because of their permeability to flow, retardance/deflector spurs are also subject to undermining and outflanking in high- velocity environments. However, because they divert channel flows and provide flow retardance, they have been effective in higher velocity environments than retardance spurs. Retardance/deflector spurs are also more structurally rigid than retardance spurs, and therefore, can withstand higher flow forces. However, the extremely permeable retardance/ diverter spurs (such as the welded wire mesh structures illustrated in Figure 22) should not be used in the higher medium- and high-velocity environments because they will not provide sufficient flow retardance.

Deflector spurs have been found to be effective over the widest range of flow conditions. Because of their structural rigidity, impermeable deflector spurs are the least susceptible to damage in high-velocity environments of any of the spur types. For this reason they are generally considered to be applicable for low-, medium-, and high-velocity environments. It must be remembered, however, that they are subject to limitations in regime and low-threshold sediment environments.

Flow Stage

Flow stage must be considered in light of the height of bank to be protected. For example, if the primary cause of erosion to be protected against occurs at low stages (as defined above), or affects only the lower portions of the channelbank, then spurs suitable for low-stage conditions should be used. Conversely, if the primary cause of erosion occurs at high stages, or impacts upper portions of high banks, spurs suited for countering high flow stages should be used.

As indicated in Table 1, all of the major spur types are suited for use under low stage conditions. Under medium stage conditions, retardance spurs are at a slight disadvantage because at this point some of the outflanking characteristics discussed above have been observed. However, this disadvantage can be overcome in some cases by increasing the structure height and ensuring that the retardance-spur structures are adequately tied to the channelbank to prevent or minimize the potential for outflanking. Although spur-type structures are generally not well-suited to protecting against high stage conditions, some large retardance/deflector spurs have been found to be adaptable to these conditions. This is due to their structural design carrying up and into the channelbank. For example, see Figure 22(a).

Another stage consideration is the impact produced by spur-topping flow stages. As the flow stage reaches and exceeds the spur crest, a zone of magnified flow turbulence is created just downstream of the spur structure along the channelbank (FHWA, 1983). This zone of flow turbulence can cause accelerated streambank erosion between individual spurs, particularly if the channelbank between spurs is not well vegetated or protected with a light layer of riprap or some other revetment. The laboratory studies conducted for FHWA (1983) indicate that this is primarily a problem with impermeable spurs. Because permeable spurs allow flow to pass through the structure, there is very little additional disturbance as the spur crest is exceeded. However, this is not the case with impermeable structures. As the stage exceeds the crest elevation of impermeable structures, a high level of turbulence is generated on the downstream side of the structure as the flow passes over the structure and into the zone between spurs. It has been observed that the greater the spur angle in the downstream direction, the greater the generated turbulence. The implication is that spurs should be designed with crest elevations that should not be exceeded frequently. If this is not practical, an impermeable structure should be used.

Bend Radius

The radius of the channelbend to be protected is another factor that must be considered when selecting a spur type. Channelbend radii can be classified as small, medium, and large. These definitions correspond to channelbend radii greater than 350 feet but less than 800 feet, greater than 800 feet but less than 2000 feet, and greater than 2000 feet, respectively. Spur-type structures are not well-suited for use on small channels having channelbend radii less than 350 feet. Therefore, the small channelbend category is limited to channels having radii greater than 350 feet but less than 800 feet.

The degree of bend curvature required or desired is directly proportional to the level or intensity of flow control needed to eliminate or minimize the streambank erosion. As is indicated in Table 1, the more passive, permeable retardance structures perform as well as other spur types on large-radius channelbends. This statement can be extended to include some of the larger medium-radius bends as well. However, smaller radius bends require a more positive flow control, and retardance-type spurs become less acceptable. Because of their flow-deflection qualities, permeable retardance/deflector spurs have been used effectively on both large- and medium-radius channelbends. Because of their permeability, however, they have not been as effective as impermeable deflector spurs on small-radius channelbends. As indicated in Table 1, impermeable deflector spurs provide an advantage over other spur types on both medium and small channelbends. This is primarily due to their capacity as positive flow-control structures. On extremely small radius bends (bend radii less than 350 feet), the larger transverse-dike impermeable structures will cause excessive flow constriction and scour problems that will make them unacceptable. Impermeable hardpoint spurs have however, been used effectively on some channelbends less than 350 feet in radius because they do not cause a significant flow obstruction.

Debris and Ice-Load Environment

Debris and ice-load environments are defined in Table 1 as minimal debris, light debris, and large debris and ice. Minimal debris refers to flow environments that rarely carry ice or debris of any size. Light debris refers to the flow environments that typically carry debris loads of small or lightweight material. Large debris and ice refer to large branch- and tree-size material, as well as significant ice loadings.

Debris and ice-load environments affect the function as well as the stability of spurs. Retardance spurs function best when there is light debris present to reduce the permeability of the structures and enhance their flow-retardance qualities. However, large debris and ice will damage these light structures and render them ineffective. This is particularly true of the wire-fence and jack/tetrahedron designs. The wire-fence and jack/tetrahedron designs have also been found to be less effective than other spur types in minimal debris environments. Without light debris to clog partially or block the structural frames of some of these structures, they do not provide sufficient flow retardance to protect the channelbank adequately.

Retardance/deflector spurs have been used successfully in most debris and ice environments. Like retardance spurs, the presence of light debris enhances the effectiveness of retardance/deflector spurs and makes them particularly adaptable to environments where light debris is present. Because of their flow-deflection qualities, these structures have also been moderately effective in minimal debris environments. The large structural size of heavy diverter spurs makes this type of retardance/diverter acceptable in large debris and ice environments as well. However, some of the lighter fence-type retardance/diverters are susceptible to extensive damage in environments characterized by large debris and ice.

Impermeable deflector spurs have been used effectively in all categories of debris and ice environments. They provide a significant advantage, however, over other spur types in large debris and ice environments. Impermeable deflector spurs divert much of the floating debris instead of skimming it from the surface as do permeable structures. Also, their structural mass makes them less susceptible to damage than the lighter permeable structures. This does not, however, imply that they will not be damaged by floating debris, only that the damage will be less severe.

OTHER CONSIDERATIONS

The selection criteria discussed above are by no means the only factors that should be considered when selecting a type of spur for a specific site. Other considerations include:

- costs,
- channel size,
- channelbed fluctuations,
- vegetation,
- vandalism and maintenance,
- construction-related impacts,
- channel geometry impacts, and
- aesthetics.

Channel geometry impacts, aesthetics, and construction-related impacts were discussed under "Environmental Impacts" earlier in this Chapter. Each of the remaining items will be discussed briefly below. Of these, structure costs have the most significant impact on the ultimate selection of an appropriate spur type.

Costs

The final cost of a spur scheme will be dependent on many factors including, but not limited to:

- the spur type and specific design,
- channel size and bank height,
- hydraulic conditions,
- right-of-way costs,
- site-preparation requirements,
- local labor and material costs,
- maintenance costs, etc.

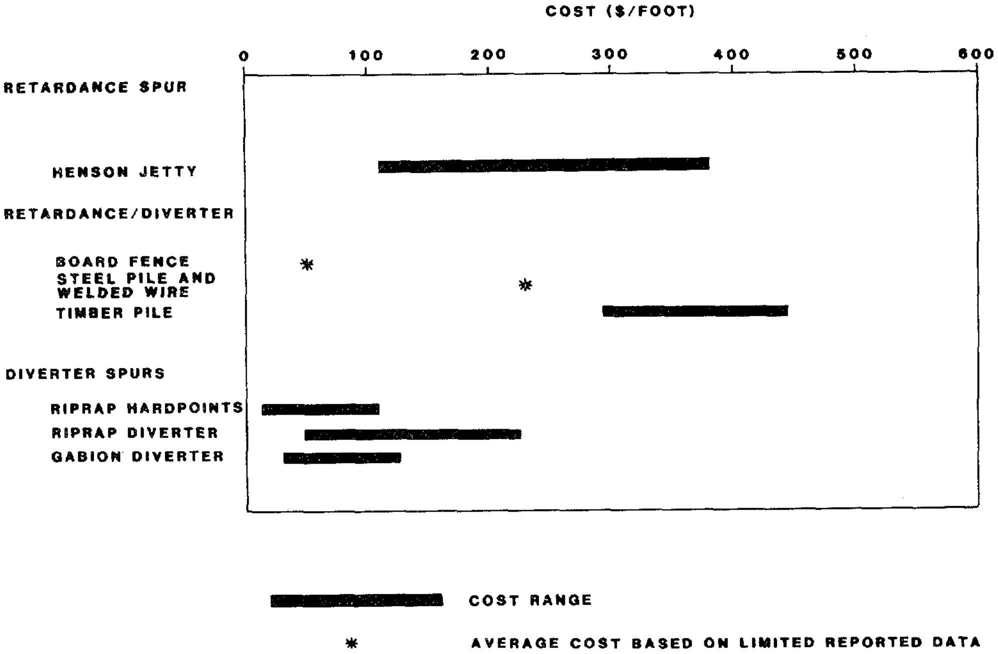


FIGURE 30. SPUR COST COMPARISON.
(ALL COSTS REPORTED IN 1982 DOLLARS)

Cost data for individual spur types are presented in Figure 30. Cost data for spur installations are not readily available; in many cases, no cost records are kept for spur installations. In other cases where cost data are available, they are reported as a lump sum along with other items such as bridge-repair costs. For these reasons, cost data are not available for many spur types. Also, the data that are available usually are biased by the specific design requirements of the sites for which they were designed. The following information on spur costs should only be used as a rough guide in any cost analysis. The actual cost of a spur scheme should be based on the specific design being considered and the local cost of required construction activities and materials. All cost data have been adjusted to a 1982 base using Engineering News Record's average annual construction cost index. Also, all costs are reported as dollars per foot of bank protected.

The only retardance spur for which reported cost data were available was the Henson spur jetty, illustrated in Figures 2 and 15. The costs reported ranged from $110/foot to $380/foot. All sites where costs were reported were on medium-width channels with medium to high banks. Also, they all had moderate channelbend radii. However, all Henson spur installations consist of the same components and protect only lower portions of the bank. Therefore, bank height is not a significant consideration. The component primarily responsible for the cost variance reported was spur spacing. Spacings reported ranged from 40 to 100 feet. Costs reported for sites having spur spacings from 40 to 50 feet ranged from $300/foot to $380/foot;

at the other end of the scale, schemes having 100-foot spacings had reported costs in the neighborhood of $110/foot to $150/foot. Although less expensive, the schemes designed with 100-foot spacings have not been as effective at stabilizing channelbanks as the 40- to 50-foot spacings.

Cost data were found for four of the retardance/diverter spurs. Data for the board-fence structures (similar to those illustrated in Figures 4 and 19) were reported by the U.S. Corps of Engineers (1981). Five installations were reported having an average cost of $51/foot. These structures were on small- to medium-width channels with medium-height banks and mild channelbends. They were constructed at 100-foot spacings and had lengths of approximately 25 feet.

The other retardance/diverter structures for which cost data were available were all heavy diverter structures. Two steel-pile and welded-wire fence structures were documented on the Soldier River by Brice et al. (1978) (see Figures 22(a) and 8). The average reported cost for these structures was $230/foot. The Soldier River is a medium-width channel with medium to high channelbanks. The structures were placed on meandering channelbends. Structure length was about 110 feet with a interspur spacing of 110 feet. These structures are designed to protect the entire bank height.

Cost data were also available for several timber-pile retardance/deflector spurs. The costs ranged from $295/foot to $445/foot. These structures were all on medium-width channels with medium to high channelbanks and were on moderate channelbends. Spur spacing ranged from 130 feet to 450 feet; spur lengths ranged from 55 feet to 150 feet. The two designs for which cost data were available were pile structures with timber piles as horizontal members (see Figures 23 and 9), and timber-pile structures with wood-plank sheathing as horizontal members (see Figures 24 and 11). The cost of the timber-pile structure with horizontal-pile stringers was $445/ft.; the average cost of the timber-pile structure with wood-plank sheathing as horizontal members was $332.50/foot.

Cost data were also available for diverter spurs. Costs for riprap hardpoints (see Figure 25) ranged from $13/foot to $110/foot. The primary factor affecting the reported costs is hardpoint spacing, which is dependent on channelbend radius. Other factors influencing the cost of these structures are site preparation and bank height. The low end of the reported range was for hardpoints spaced at 100 feet and having lengths of 68 feet. The $110/foot hardpoints were designed with 100-foot lengths, spaced at 40 feet on mild channelbends in channels having large widths and medium bank. A comparison of these costs indicates that hardpoint spacing is one of the important design parameters that must be defined.

Costs for both gabion and riprap diverter structures were reported. The costs reported for gabion spur installations (see Figures 22 and 13) ranged from $32/foot to $126/foot. The low end of the scale was for 10-foot long spurs in a small channel with low channelbanks. The higher cost was reported for 25-foot long spurs on a medium-width channel with low channelbanks. Both ends of the cost range reported were documented on channels having sharp bend radii. No cost data were reported on channels having mild bends or medium to high channelbank heights. Also, cost data were not reported for larger structures. Cost data for large riprap diverter structures ranged from \$50/foot to \$226/foot. Here again, a major factor reflected in the cost range is the spur length and spacing.

Channel Size

Channel size considerations were discussed earlier in this chapter in relation to the applicability of spurs in general. It was stated that spurs are generally unacceptable for use on small or narrow-width channels (widths less than 150 feet). In general, this is true. Several spur types, however, have been used effectively on some of the larger narrow-width channels. The spur types that have been used effectively on narrow-width channels include the smaller permeable fence structures and rock hardpoints. Actually, any spur that can be designed only to produce a minimal flow constriction (less than 10 to 15 percent of the channel width) could be used. However, spurs should not be used at sharp bends on narrow channels.

Channelbed Fluctuations

The streambed elevation of alluvial channels is known to fluctuate as a result of local scour, general scour, dynamic scour, and aggradation and degradation processes. In truly alluvial regime/low-threshold channels, these processes occur continually and can cause extreme fluctuations in channelbed surface levels. Channelbed surface level fluctuations caused by one or more of the above-mentioned actions have been a primary cause of structural undermining and failure of spur-type structures as well as other structures constructed in river environments. Spur structures designed for use in alluvial environments must be designed to contend with these bed-level fluctuations. Henson spur jetties (see Figures 2 and 15) are particularly adaptable to these environments. This is due to the vertical flexibility of the fence panels. As discussed previously, these panels shift downward with the bed profile. This allows them to maintain contact with the channelbed at all times so that the retardance structure is not undermined. Thus, the toe of the channelbank remains stable even under severe bed-scour conditions. Other permeable spurs are designed to counter undermining by extending the spur's retardance structure (wire or wood facing) for a distance below the channelbed. This is sufficient in many cases, except where the anticipated scour depth is underestimated. Extending the retardance structure to below the channelbed is also costly in many cases because of the extra excavation that is required. This is particularly true if the site is underwater. To avoid the need to extend the permeable facing below the channelbed, many permeable structures, particularly the retardance diverter structures, are designed with a rock toe or blanket to protect them against undermining from local scour. Impermeable diverter spurs can be designed with extra structural mass (rock volume) to armor the channelbed in the vicinity of the spur to protect it against undermining.

Vegetation

The existence or lack of channelbank vegetation is another environmental characteristic that should be considered during the design of spur schemes. The advantages of bank vegetation were discussed in general earlier in this chapter. As mentioned, in areas where significant bank vegetation exists, this vegetation will usually volunteer to the bank and into the "spur zone" helping to stabilize both the upper and lower sections of the channelbank.

In regard to the selection of a specific spur type, it should be noted that when impermeable diverter structures are used in environments lacking channelbank vegetation, severe bank scalloping has been observed between the spur structures. This scalloping has been known to outflank spurs, leaving them unattached to the channelbank. Environments lacking bank vegetation are usually located in arid regions of the country where most riverbeds are cut through alluvial materials. In these environments, permeable retardance or retardance/diverter structures should be used.

Vandalism and Maintenance

Vandalism, particularly in urban areas, is a problem that must be dealt with when designing spurs as well as other bank-protection schemes. Both the U.S. Army Corps of Engineers (1981) and Keeley (1971) document cases of vandalism. Vandalism can render ineffective a technically effective bank-protection scheme. Vandals' efforts include dismantling; burning; cutting with knives, hatchets, and axes; etc. If vandalism is determined to be an important consideration, steps can be taken to reduce the vandals' chances of succeeding. For example, steel structural members could be used instead of wood, or the wood could be treated to eliminate or minimize the possibility of burning. Also, other structural types that are less susceptible to vandalism could be used, such as rock riprap structures.

Maintenance requirements also must be considered. Virtually all streambank protection schemes require some degree of maintenance. The need to repair a bank stabilization structure can result from vandalism or damage from excessive hydraulic conditions and/or ice and debris conditions. In general, the greater the structural integrity of the spur, the less susceptible it is to adverse flow and debris conditions. However, the dynamic nature of rivers makes it virtually impossible to predict all possible combinations of forces to which a bank-stabilization scheme will be subject. Also, it is not usually economically justifiable to build countermeasures that will resist all possible combinations of flow and debris impingement forces. Therefore, a regular program of inspection and maintenance is important to ensure economical, efficient, and reliable streambank protection. Of course, there will be an associated cost, which must be considered when evaluating alternative bank-stabilization schemes.

Chapter 3

DESIGN OF SPUR SYSTEMS

The previous chapter discussed at length considerations important to the selection and design of spurs. In this chapter criteria for the design of spur systems will be presented; criteria for spur permeability, geometry, and structure height will be presented first, followed by general comments on spur-crest profile, bed and bank contact, and spur-head form.

The criteria presented here are based in part on a recent laboratory investigation of spur-type structures conducted by FHWA (1983). The laboratory report produced as a result of this study is available for interested researchers. However, it contains little information beyond what is presented here that would be useful to the design engineer.

PERMEABILITY

Considerations of spur permeability were discussed in relation to the selection of an appropriate spur type (retardance structure, retardance/diverter structure, diverter structure) in the last chapter. However, for both the retardance and retardance/diverter structures, a variety of spur permeabilities can be and have been designed. Spur permeability as referred to in this report is defined as the percentage of the spur's surface area that is open or unobstructed. In environments where the permeable structure can be reasonably assumed not to clog with floating debris or other material, the determination of a particular spur's permeability only requires computation of the unobstructed flow area within the structure. In most environments, however, the spur's effective permeability will be reduced as floating debris clogs the face of the spur. An estimate of the amount of spur clogging that will occur must be considered in the computation of a given spur's permeability. The amount of spur clogging that can be expected to occur is difficult to estimate and must in most cases be based on experience.

The magnitude of spur permeability appropriate for a given flow control or channelbank stabilization application is inversely proportional to the magnitude of flow retardance required, the level of flow control desired, and/or the channel bend radius. In all cases, the greater the magnitude of the variable, the lesser the degree of spur permeability. It is recommended that where it is necessary to provide a significant reduction in flow velocity, a high level of flow control, or where the structure is being used on a sharp bend, the spur's permeability should not exceed 35 percent. Where each of the above variables is moderate, spur permeabilities up to 50 percent are acceptable. In environments where only a mild reduction in velocity is required, where bank stabilization without a significant amount of flow control is necessary, or on mildly curving channelbends, spurs having effective permeabilities up to 80 percent have been used effectively. However, these high degrees of permeability are not recommended unless experience has shown them to be effective.

Additional comments can be made regarding specific spur types identified in Chapter 2 based on their field performance. The permeability of jack and tetrahedron retardance spurs (see Figure 17) is set by their design. The permeability of these structures is generally greater than 80 percent. However, because of their high level of permeability, they do not provide sufficient flow retardance on their own to be effective as bank-stabilization or flow-control structures. Where they have been effective, it has been because they have trapped a sufficient volume of light floating debris to reduce their effective permeability to an estimated value of approximately 50 to 60 percent. Thus, it is recommended that jack and tetrahedron retardance spurs be used only where it can be reasonably assumed that the structures will trap a sufficient volume of floating debris to produce an effective permeability of 60 percent or less.

Henson-type retardance spurs (see Figure 15) are characteristically built with a structural permeability of approximately 50 percent. This degree of spur permeability has been found to be adequate for most cases reported. However, in environments characterized by significant volumes of large floating debris and high flow velocities, the reduced permeability caused by spur clogging often produces hydraulic forces that damage the structure. In these environments, a greater permeability of the spur structure should be considered. It is recommended that Henson-type spurs be designed to have an effective permeability of approximately 50 percent.

A variety of retardance/diverter spurs were documented in Chapter 2 (Figures 19 to 24). There was no standard spur permeability found for any of these structures, although most of these structures fell in the 25 percent to 50 percent effective permeability range. Exceptions were found in the lightweight wire and welded wire mesh spurs illustrated in Figures 7 through 9, which typically had structural permeabilities of 80 percent or more and effective permeabilities of approximately 70 percent. These high-permeability structures were used in environments where only a mild reduction in velocity is required, where bank stabilization without a significant amount of flow control is necessary, or on mildly curving channelbends. In general, the criteria for retardance spurs is as discussed above for permeable spurs in general.

Recent laboratory investigations (FHWA,1983) provide additional insight into how various spur permeabilities impact the behavior of spurs. The following is a brief summary of the conclusions and findings from the FHWA laboratory investigation relating to spur permeability. This information can be used in conjunction with the information provided above, and the spur-type selection criteria presented in the previous chapter to select an appropriate spur permeability for a given bank-stabilization situation.

One area of comparison between spurs of different permeabilities is the scour pattern produced downstream of the spur tip. As might be expected, the laboratory data indicated that the greater the spur permeability, the less severe the scour pattern downstream of the spur tip. As spur permeability increases, the magnitude of scour downstream of the spur decreases slightly in size, but more significantly in depth. Figure 31 illustrates the relationship between spur permeability and scour depth for spurs having lengths equal to 20 percent of the channel's width. As can be seen, the scour depth decreases with increasing spur permeability regardless of the spur angle to flow. Figure 31 also illustrates that impermeable spurs produce the greatest change in scour elevation over a given range of spur angles, indicating a greater variability of local scour at the spur tip for the range of spur angles tested. Similar trends were also observed for other spur lengths. Therefore, if an important design consideration is to minimize the size and depth of local scour just downstream of the spur, spur permeability should be maximized.

The type of vertical structural member used in the permeable spur also has a bearing on the amount of scour produced downstream of the spur tip. Round-membered verticals produced significantly less scour than square vertical members. This implies that all vertical structural members should be round or streamlined to minimize local scour where possible. Here again, if minimizing local scour depth is an important consideration for a particular design, spurs having round or streamlined vertical support members should be used.

Flow concentration at the spur tip is another area of comparison between spurs of various permeabilities. A dimensionless velocity, V', defined as the ratio of the velocity recorded in the vicinity of the spur tip to the average cross section velocity upstream of the spur was used to define flow concentration at the tip of spurs in the FHWA laboratory investigation. The findings indicated that the greater the spur permeability, the lower the value of V'. Again, this finding held regardless of spur projected length or angle. However, the more significant finding was the magnitude of the difference in flow concentration (as measured by V') between impermeable and permeable spurs. Figure 32 illustrates this difference. Note how the V' curve plotted for the impermeable spurs falls significantly higher than those plotted for the permeable spurs. Also, note that the curves plotted for the permeable spurs fall over a fairly narrow band width, indicating that V' is less sensitive to changes in spur permeability when the degree of permeability is greater than 35 percent than it is when the degree of permeability is less than 35 percent. Although different in magnitude, similar relationships were found for other spur angles.

Additional comments can be made regarding the magnitude of V' found during the laboratory studies for spurs having permeabilities greater than 35 percent. Note in Figure 32 that for spur angles greater than 120 degrees and permeabilities greater than 35 percent the corresponding values of V' are less than 1. This indicates that the maximum velocity off the spur tip for these spurs is less than the average channel velocity upstream of the spur, or that there is very little acceleration of flow around the spur tip for these spur configurations. Based on this information, if minimizing flow

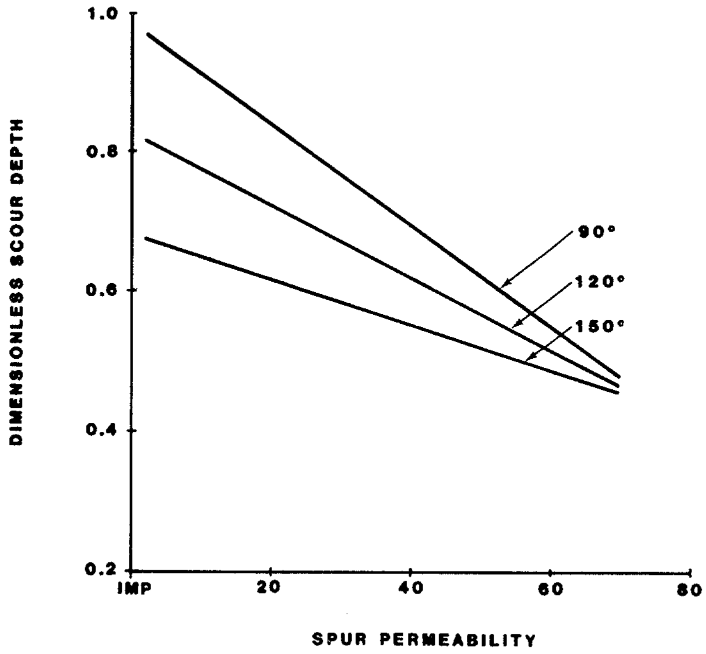


FIGURE 31. PLOT OF SPUR PERMEABILITY VS. SCOUR DEPTH.

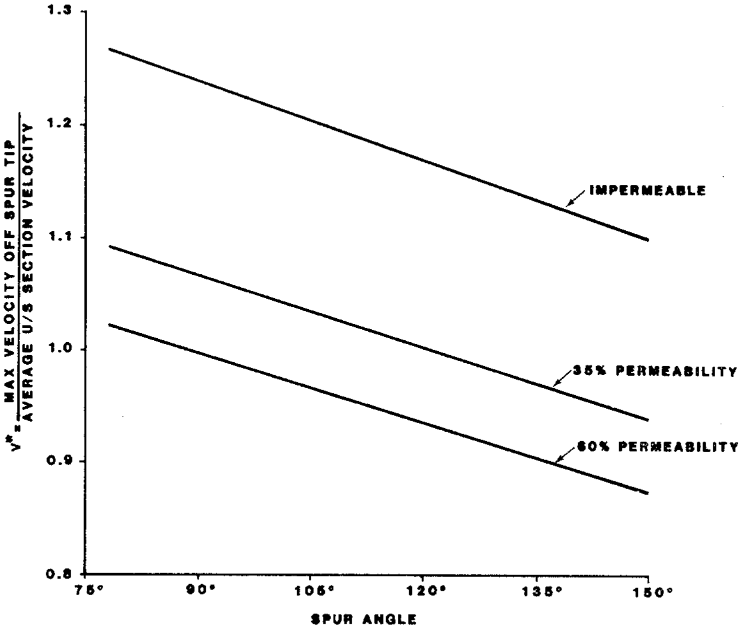


FIGURE 32. SPUR ANGLE VS. V'.

concentration off the spur tip is important to a particular spur design, a spur with a permeability greater than 35 percent should be used.

It is important to note that the curves plotted in Figure 32 are based on experimental data collected in a straight flume, for spurs with projected lengths equal to 20 percent of the channel width. Similar trends were observed for other spur lengths. The values of V' reported in the laboratory study are qualitative in nature, and are not recommended for field application. Values of V' would be expected to be higher in real channelbends due to centrifugal acceleration and the natural flow concentration at the outside of the channelbend in curved channels.

Spur permeability was also found to impact the length of bank protected downstream of the spur. An expansion angle downstream of the spur tip was used as a measure of the length of bank protected during the FHWA laboratory study. The expansion angle was defined as the angle between a flow tangent at the spur tip, and a line between the spur tip and a point on the near bank where the flow has reexpanded to impact the channelbank. This measure of length of bank protected was used to avoid including the projected spur length parallel to the channelbank in the measure of length of bank projected. Figure 33 illustrates the relationship between spur permeability and the length of bank protected as measured by the expansion angle for spurs having projected lengths equal to 20 percent of the channel's width. Figure 33 indicates that the expansion angle increases with increasing spur permeability in all instances. This indicates that the more permeable the spur, the shorter the length of channelbank protected downstream of the spurs riverward tip. Figure 33 also illustrates that the expansion angle remains almost constant until a permeability of almost 35 percent is reached. Beyond this point the expansion angle increases much more rapidly. Similar trends were found for other spur configurations during the FHWA laboratory study. The implication here is that spurs with permeabilities up to approximately 35 percent protect almost the same length of channelbank downstream of the spur tip as do impermeable spurs; spurs having permeabilities greater than approximately 35 percent protect shorter lengths of channelbank, and this length decreases with increasing spur permeability. Relationships for the length of bank protected for the various spur types will be discussed in the next section with considerations of spur geometry.

One additional observation from the laboratory studies sponsored by FHWA relating to spur permeability is the difference in the impact caused by spur-topping flows. During the laboratory studies, it was found that as the flow stage exceeds the crest of the spur there is an excessive amount of turbulence caused in the vicinity of the spur root and immediately downstream that results in erosion of portions of the upper channelbank in this area. This bank disturbance was much more evident for the impermeable spurs investigated than it was for the permeable spurs studied. However, there was no significant difference observed in this regard among the various degrees of permeability of the permeable spurs tested. The excess flow turbulence and bank erosion evidenced in the case of the impermeable spurs is caused by acceleration and deceleration of the channel flows as they pass over and down the downstream face of the impermeable structures (see Figure 34). Because

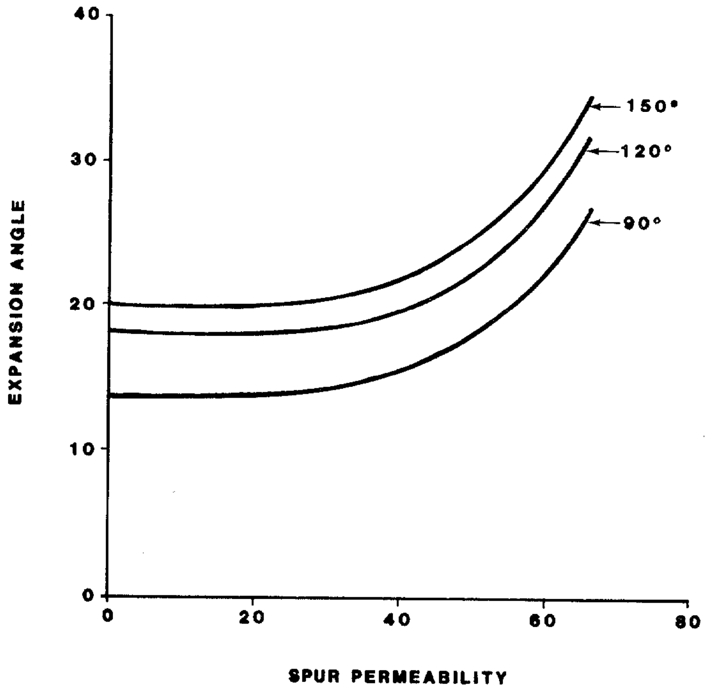


FIGURE 33. SPUR PERMEABILITY VS. EXPANSION ANGLE.

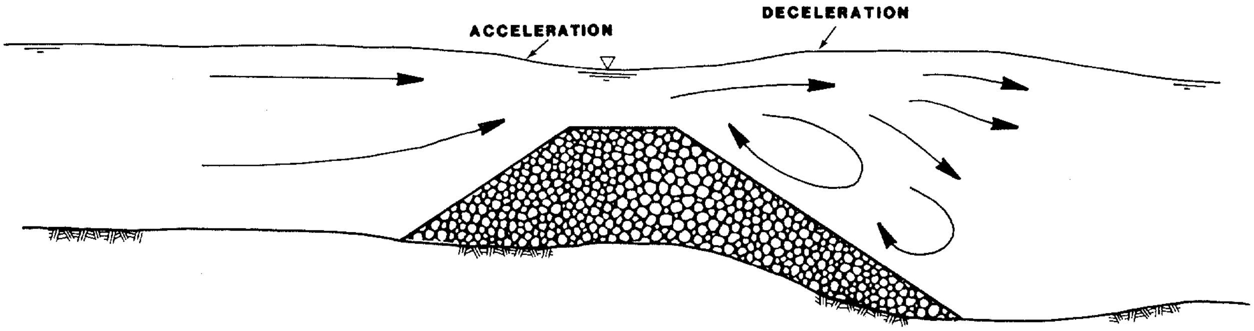


FIGURE 34. FLOW OVER IMPERMEABLE SPURS.

permeable spurs allow a flow equalization on both sides of the structure this acceleration/deceleration turbulence is only minimal for permeable spurs. Because of the increased potential for erosion of the channelbank in the vicinity of the spur root and immediately downstream when the flow stage exceeds the crest of impermeable spurs, it is recommended that impermeable spurs not be used along channelbanks composed of highly erodible material, unless measures are taken to protect the channelbank in this area.

GEOMETRY

The geometry of a spur system is made up of several components that produce the spur system's geometric form when combined. These components include the longitudinal extent of the spur system, the length of individual spurs, the spacing of individual spurs, and the orientation of individual spurs. The longitudinal extent of the spur system describes the length of channelbank that is to be protected; the length, spacing, and orientation of individual spurs are self-explanatory. In this section, each of these components will be looked at individually and then as a whole to provide criteria for delineating an appropriate spur geometry.

Extent of Bank Protection

The extent of channelbank protection required on a typical eroding channelbend has been investigated by several researchers, including Parsons (1960), Apmann (1972), and the U. S. Army Corps of Engineers (1981). These investigators, as well as others, have found that a common misconception in streambank protection is to provide protection too far upstream and not far enough downstream. The following discussions will consider criteria for establishing the longitudinal extent for bank-stabilization measures.

Criteria for establishing the extent of channelbank protection have been developed by the U.S. Army Corps of Engineers (1981). These criteria are based on a series of model studies to define more completely the limits of bank protection as suggested by Parsons (1960). From these studies, it was concluded that the minimum distances for extension of protection are an upstream distance of 1.0 channel widths and a downstream distance of 1.5 channel widths from corresponding reference lines as shown in Figure 35. A similar criterion for establishing the upstream limit of protection was found by FHWA (1983); however, a downstream limit of 1.1 times the channel width was found. The FHWA study was not, however, as extensive in this respect as the COE study.

The above criteria are based on analysis of flow conditions in symmetric channelbends under ideal laboratory conditions. Real-world conditions are rarely as simplistic. In actuality, many site-specific factors have a bearing on the actual length of bank that should be protected. A designer will find the above criteria difficult to apply on mildly curving bends or on channels having irregular, nonsymmetric bends. Also, other channel controls (such as bridge abutments) might already be producing a stabilizing effect on the bend so that only a part of the channelbend needs to be stabilized. In addition, the magnitude or nature of the flow event might only cause

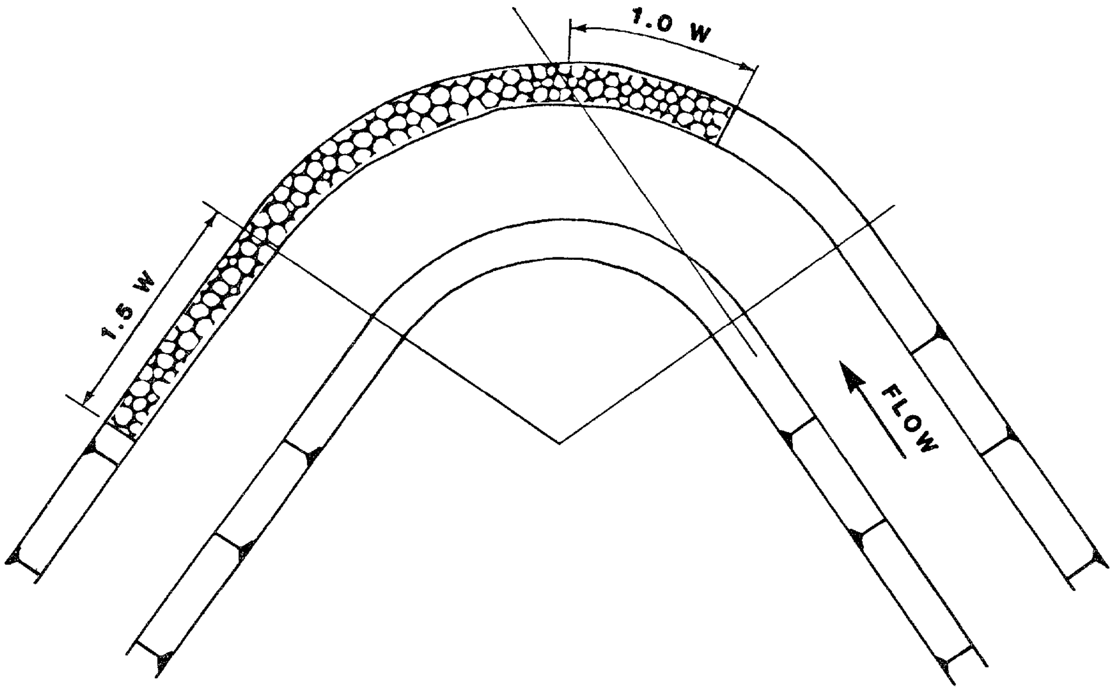


FIGURE 35. EXTENT OF PROTECTION REQUIRED AROUND A CHANNEL BEND. (AFTER U.S. ARMY CORPS OF ENGINEERS, 1981)

erosion problems in a very localized portion of the bend, again requiring only that a short channel length be stabilized. Therefore, the above criteria should only be used as a starting point. Additional analysis of site-specific factors will define the actual extent of protection required.

In many cases, the longitudinal extent of the channelbank that should be protected can be identified through field reconnaissance. If the channel is actively eroding, the upstream limit of erosion scars on the channelbank will identify the upstream limit of the channelbank that should be protected. It is recommended that any bank-stabilization scheme extend approximately one channel width upstream of the point where the bank scars first appear. The downstream limit of protection is not as easy to define. Since the natural progression of bank erosion is in the downstream direction, the present visual limit of erosion might not define the downstream limit of potential erosion. Additional analysis based on consideration of flow patterns in the channelbend may be required. Additional analysis is also required if no definite erosion scars are present to define the upstream limit of protection.

An important factor in the consideration of the length of bank to be protected is the channelbank length that will be impacted by channel-flow forces severe enough to cause dislodging and/or transport of bank material. The dynamics of flow in channelbends are covered in detail in FHWA (1984). This coverage includes discussions of flow patterns in channelbends and

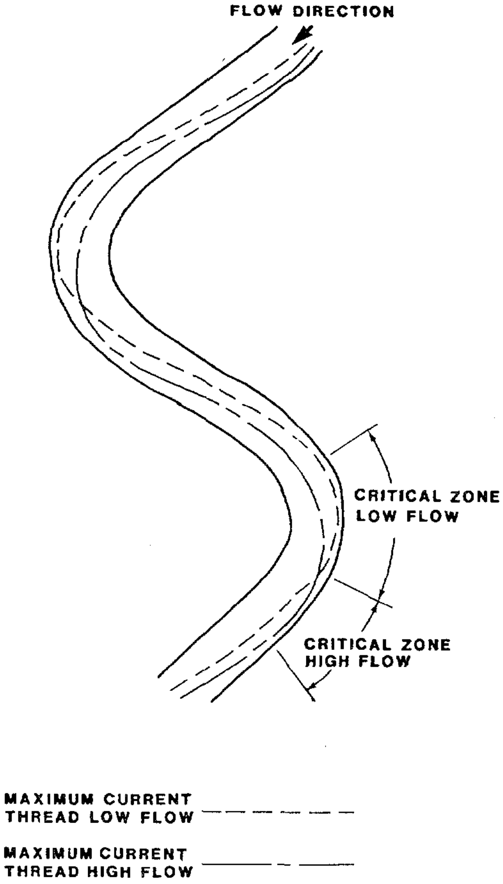


FIGURE 36. SHIFT IN MAXIMUM CURRENT THREAD WITH CHANGING STAGE.

indicates how these flow patterns change with flow magnitude, flow stage, and whether or not the flow event is occurring on the rising or falling limb of the runoff hydrograph. Figure 36 illustrates a typical shift in the location of the main flow thread or thalweg between the low and high flow conditions. The critical erosion zones for these flow conditions are also indicated. Consideration of these critical erosion zones dictates the length of channelbank that must be protected by a bank-stabilization scheme.

When establishing the length of channelbank that will be impacted by channel flow forces severe enough to cause dislodging and/or transport of bank material, the first step is to establish the river's flow paths for various flow conditions. As illustrated in Figure B-31, this is done by delineating the main flow paths for several flow conditions. The general discussion in FHWA (1984) of flow in channelbends can be used to help determine the locations of the channel's thalweg for various flow stages. However, this will probably not provide sufficient information. More explicit information can be obtained for the low flow condition by conducting channel surveys during low flow periods. Channel surveys are usually impractical during medium to high flow periods so that other means must be used to establish flow conditions for these higher discharges. Some of the best information available can come from aerial photographs taken of the sites under different flow conditions. Additional information can be obtained by flying over the site during periods of high flow, or observing the channelbend in question from a vantage point such as a bridge or nearby hill. Accurate prediction of the location of shifting flow patterns in a channelbend requires a thorough knowledge of flow processes in channelbends and an understanding of the flow conditions characteristic of the bend in question.

The above analysis will indicate the bank regions impacted by channel flows under various flow conditions. Not all of these flow conditions, however, will necessarily cause bank erosion problems. As discussed previously, evidence of the upstream limit of erosion can usually be identified by field observations. If no evidence of an initial point of erosion can be discerned (either from field investigation or observations from aerial photographs), other methods must be used. One such method is to estimate the shear stress in the channelbend for various flow conditions. Methods for estimating shear stress in channelbends are presented in FHWA (1984). Comparing the actual shear stresses computed with critical shear stresses for the channelbank will define the flow condition for which erosion begins. The point where the flow pattern for this critical flow condition impacts the channelbank would define the upstream limit of bank protection. The downstream limit of channelbank protection would be defined as the furthest downstream contact point for the design discharge being considered. Normally, this downstream limit is extended to provide a factor or margin of safety in the design.

As indicated previously, the extent of bank protection can also be influenced by existing channel controls. The most common situation encountered is the existence of a bridge somewhere along the channelbend. If the bridge has an abutment immediately adjacent to the channelbank, it will act as a control point with respect to channel stability. The location of the bridge abutment (or other channel control such as a rock outcrop) will usually define the downstream limit of the protection required. It is rare that significant erosion will occur downstream of the channel control; however, if the analysis of flow patterns indicates that excessive erosion might occur downstream of the channel control, the protection should extend beyond the control.

The above discussions provide techniques by which the extent of bank protection required can be estimated. Due to the uncertainties in the analytical methods presented, no one of them should be used independently. The recommendation is that the extent of bank protection be evaluated using a variety of techniques including the following:

- empirical methods,
- field reconnaissance,
- evaluation of flow traces for various flow-stage conditions, and

- review of flow and erosion forces for various flow-stage conditions.

Information from these approaches should then be combined with personal judgement and a knowledge and awareness of the flow conditions impacting at the site to establish the appropriate limits of protection.

Spur Length

Spur length as referred to here is the projected length of the spur perpendicular to the main flow direction; it is reported as a percentage of the channel width at bank-full stage. Both the projected spur length and the channel width used in these computations reflect lengths measured from the desired channelbank line. On channels having smooth, regular bank lines these lengths are measured from the actual bank. When the spurs are being used to shift the channel to a new location or provide a new smooth alignment along channelbanks that have been severely eroded, the actual spur projected length and the channel width should be measured from the desired bank line and not the actual bank line. In these later cases, the actual spur projected length will be longer than the projected lengths to be recommended here. Actual spur lengths may vary within a spur scheme to ensure that the flow alignment provided lines up to an even curvature.

A review of pertinent literature reveals that available criteria for establishing spur length are very site-specific. For example, Richardson and Simons (1974) recommend that the minimum length be 50 feet and the maximum length be less than 10 to 15 percent of the bank-full channel width on straight reaches, long radius bends, and braided channels. The 50-foot minimum length is based on economic considerations, since the use of shorter spurs might make it cheaper to riprap the bank. Also, Acheson (1968) reports that gabion spurs should extend 20 to 30 feet out from the bank. However, these are rather broad-based statements that do not consider many of the site-specific factors influencing spur length considerations.

The appropriate length of spurs within a bank-stabilization scheme is dependent on the spur's behavior in the particular environment, as well as the desired flow alignment (as discussed above). The behavior of specific spur types was investigated during laboratory studies sponsored by FHWA (1983). During these studies it was shown that the length of both permeable and impermeable spurs impacts the local scour depth at the spur tip, the magnitude of flow concentration at the spur tip, the length of channelbank protected by individual spurs, and the apparent current deflection angle caused by the spurs. The relationships between each of these parameters and spur length are illustrated in Figure 37. For each of the variables plotted in Figure 37 (with the exception of the length of channelbank protected), as the spur length increases the dependent variable moves in a direction indicating a worsening condition with respect to the spur's performance. Figure 37 illustrates that the length of bank protected increases with spur length. The relationships plotted are for spurs of various permeabilities

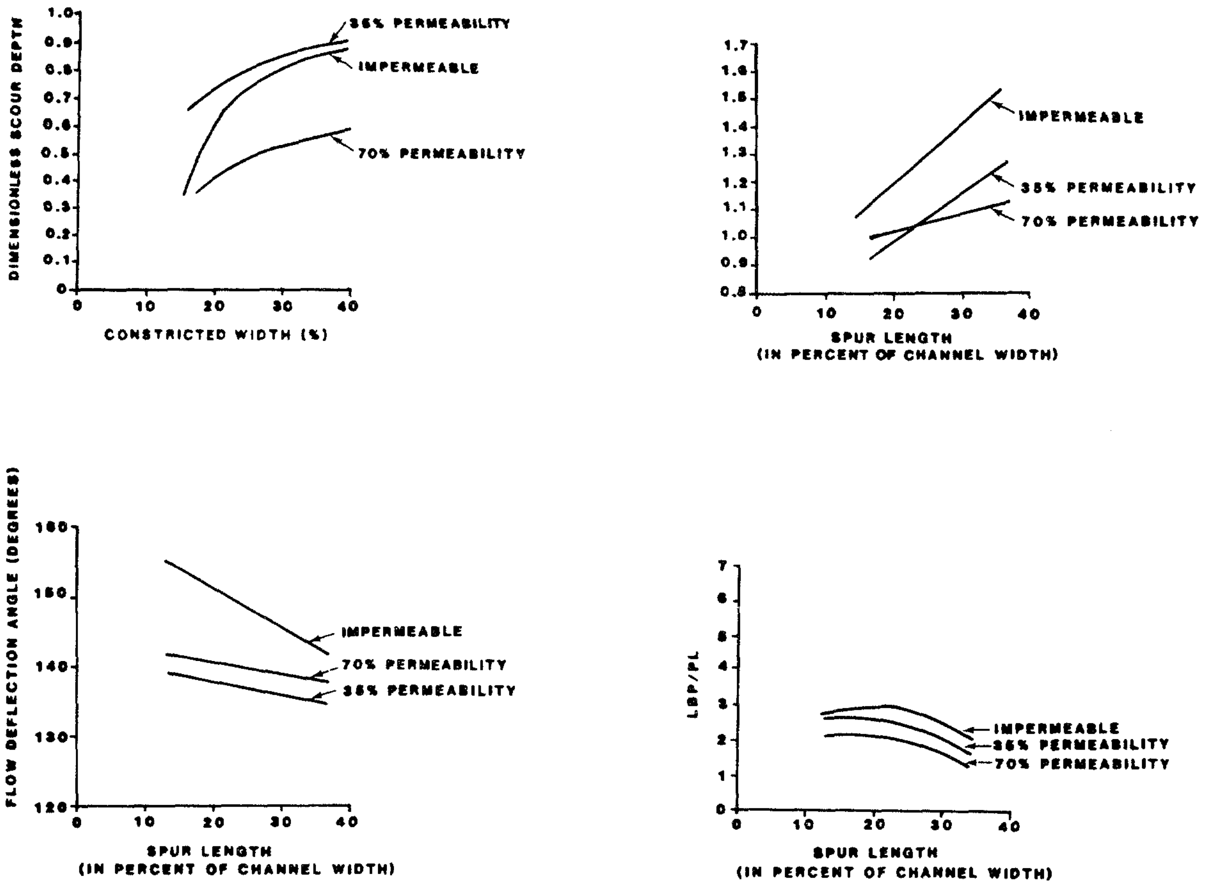


FIGURE 37. RELATIONSHIPS BETWEEN SPUR LENGTH AND (A) SCOUR DEPTH, (B) A DIMENSIONLESS SPUR TIP VELOCITY, (C)FLOW DEFLECTION ANGLE, AND (D) THE LENGTH OF CHANNELBANK PROTECTED BY INDIVIDUAL SPURS. (RELATIONSHIPS FOR SPURS OF VARIOUS PERMEABILITIES ALL CONSTRUCTED PERPENDICULAR TO THE MAIN FLOW CURRENT.)

constructed perpendicular to the main flow current. Similar relationships were found for spurs having orientations ranging to 150 degrees. The following is a brief description of the trends illustrated in Figure 37.

In Figure 37(A), a dimensionless scour depth is used to illustrate the trends between spur length and scour depth. The dimensionless scour elevation is defined as the depth of scour divided by an arbitrary depth to unitize the values. As indicated in the figure, as the spur length increases the scour depth increases. Also, the figure indicates that as the spur length increases, the rate of increase of the scour depth decreases. Thus, to minimize scour depth, spur length should be minimized.

The dimensionless velocity plotted in Figure 37(B) demonstrates how flow concentration at the spur tip varies with spur length. The dimensionless velocity (V') is defined as the maximum measured velocity in the vicinity of the spur tip divided by the average approach velocity upstream of the spur. Figure 37(B) indicates that the greater the spur length, the greater the value of V' (or the greater the magnitude of flow concentration at the spur tip). Figure 37(B) also indicates that the greater the spur's permeability, the less sensitive the value of V' is to spur length. Therefore, a unit increase in length for a permeable spur will have less increase in spur-tip velocity than will a comparable increase in the length of a impermeable spur.

Another important design parameter is the amount of flow deflection caused by the spur. Figure 37(C) illustrates the impact of spur length on the flow deflection angles produced by various spur types. The flow deflection angle is defined as the angle between the direction of flow deflection off the spur tip and the flow tangent at the spur tip measured in the upstream direction from the former to the latter. As illustrated in the figure, as the spur length increases, the flow deflection angle decreases, indicating a steeper cross channel deflection of flow currents. Also, impermeable spurs are much more sensitive to this parameter than are permeable spurs, meaning that a unit increase in the spur's length has a greater impact on flow deflection angles for impermeable spurs than it does for permeable spurs.

Another important design parameter is the length of channelbank protected by individual spurs. To define this relationship, a term length of channelbank protected divided by the spur's projected length (LBP/PL) was evaluated. The relationship between spur length and LLB/PL is illustrated in Figure 37(D). The trend illustrated for impermeable spurs indicates that LBP/PL increases slightly with spur projected length to a maximum of approximately a 20 percent constricted width, and then decreases. This implies that an optimum spur length exists at the 20 percent constricted width length. The increase in the value of LBP/PL up to the maximum at 20 percent is only minor, however, and does not indicate a significant advantage to the 20 percent length over shorter lengths. Data collected from permeable spur experiments did not indicate a similar maximum. The permeable spur trend indicated is that the greater the spur length, the smaller the relative length of channelbank protected. Figure 37(D) also indicates that the value of LBP/PL remains fairly constant for both permeable and impermeable spurs to a spur length of about 20 percent of the channel's width. Therefore, to this point there is a near linear relationship between the spur length and the length of bank protected by the spur. For spur lengths greater than 20 percent of the channel's width, LBP/PL drops off more rapidly indicating that increasing the spur length beyond this point produces less of an increase in length of bank protected. The significance of this is that a spur having a length not greater than 20 percent of the channel width should be used to maximize the length of channelbank protected per unit projected length of the spur. Although not indicated in the figure, the laboratory data also indicate that the greater the spur angle, the more rapid the drop in LBP/PL with increasing spur length beyond 20 percent of the channel's width.

Evaluation of field sites also provides insight into the determination of an appropriate spur length. A review of field- site data indicates that spur projected lengths used at successful spur field installations ranges from 3 percent of the channel width to approximately 30 percent of the channel width. The most common range, however, is 10 to 20 percent. Impermeable spurs generally fell in the lower end of this range, with lengths usually less than 15 percent of the channel width. Permeable spurs were commonly found with lengths up to 20 or 25 percent of the channel width. However, the effective length of permeable spurs is a function of spur permeability, and only the more permeable structures were effective at the longer lengths.

The above discussions indicate that the appropriate length of spurs within a given bank-stabilization scheme are dependent on the spur's behavior in the given environment. This makes the selection of an appropriate spur length site-specific. The proper approach is to identify the factors important to the site (e.g., Is minimizing the magnitude of flow concentration at the spur tip of greater importance than providing a greater length of protected bank per individual spur?) and select a spur length that appears to provide the best balance between the conflicting criteria. This will require determining the magnitudes of flow concentration, local scour depth, and the length of bank protected for various configurations to see how each varies with spur length at the given site.

The following general recommendations are given with regard to spur length:

- The projected length of impermeable spurs should be held to less than 15 percent of the channel width at bank-full stage.

- The projected length of impermeable spurs should be held to less than 25 percent of the channel width. However, this criterion depends on the magnitude of the spur's permeability. Spurs having permeabilities of less than 35 percent should be limited to projected lengths not to exceed 15 percent of the channel's bank-full flow width. Spurs having permeabilities of 80 percent should be limited to projected lengths of up to 25 percent of the channel's bank-full flow width. Between these two limits, a linear relationship between the spur permeability and spur length should be used.

Spur Spacing

The spacing of spurs in a bank-protection scheme is a function of spur length, angle, and permeability, as well as the channelbend's degree of curvature (FHWA, 1983).

Typically, spur spacing has been related to spur length by a spacing factor, which is the ratio of a spur's spacing to its projected length. Values of the spacing factor reported in the literature range from less than 1 for retardance spurs to 6 for impermeable diverter spurs. Fenwick (1969) reports spacing ratio values of 2 to 2.5 for flow constriction applications (comparable to retardance spur design) on large rivers and a value of 3 for angled dikes used for bank protection (comparable to retardance diverter and diverter structures). Richardson and Simons (1974) recommend values of 1.5 to 2.0 for retardance-type applications, and 3 to 6 for retardance-diverter and diverter applications. On straight- or large-radius bends, Richardson and Simons recommend values of 4 to 6; values of 3 to 4 are recommended on small- to moderate-radius bends. Additionally, Acheson (1968) recommends a spacing factor of 2 to 4, depending on the degree of bend curvature. While these recommendations hint at the relationship between spur spacing, the spur's permeability, and the degree of channelbend curvature, they do not provide definite criteria in these respects.

The recent laboratory investigation sponsored by FHWA (1983) provides additional information that is useful in establishing a criterion for spur spacing. In the FHWA study, two parameters were used to define the length of channelbank protected by individual spurs in a straight flume: the length of channelbank protected divided by the spur's projected length (LBP/PL), and the flow expansion angle downstream of the spur tip. The results of the FHWA study indicate that the length of channelbank protected by individual spurs is best represented by the flow expansion angle.

The flow expansion angle is defined as the angle between a flow tangent at the spur tip and a line between the spur tip and the point on the channelbank where the flow reexpands to impact the channelbank. The definition of expansion angle is illustrated in Figure 38. The results of the FHWA laboratory study indicated that for a spur of given permeability, the expansion angle downstream of the spur tip varied only with the spur's length. Figure 39 illustrates the relationships found between spur length and the expansion angle for various spur permeabilities. As indicated in Figure 38, the expansion angle for impermeable spurs is almost constant at a value of 17 degrees. In contrast, the expansion angles for the permeable spurs were found to increase exponentially with spur projected length. Additionally, for spur lengths less than approximately 18 percent of the channel width, spurs having a permeability of 35 percent produce approximately the same expansion angles as impermeable spurs. This indicates that they protect approximately the same length of channelbank. Also, as spur permeability increases, the length of channelbank protected by the spur decreases and is indicated by an increasing flow expansion angle.

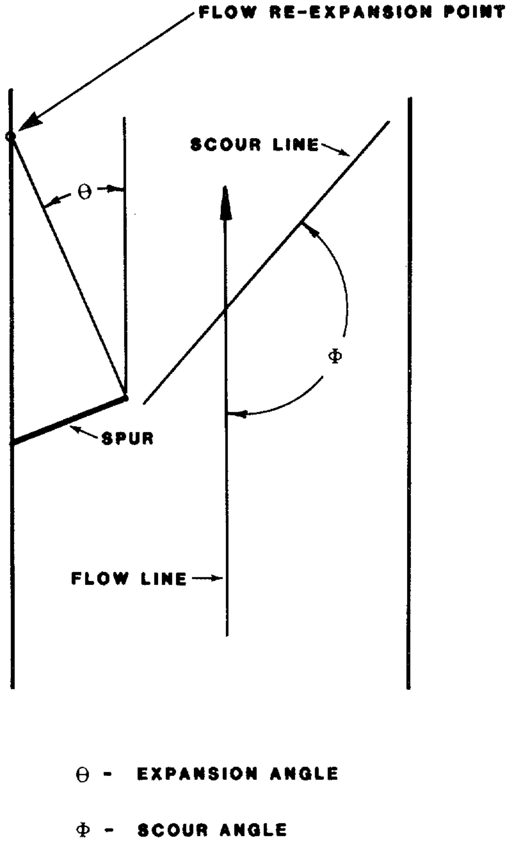


FIGURE 38. DEFINITION SKETCH OF FLOW EXPANSION ANGLE.

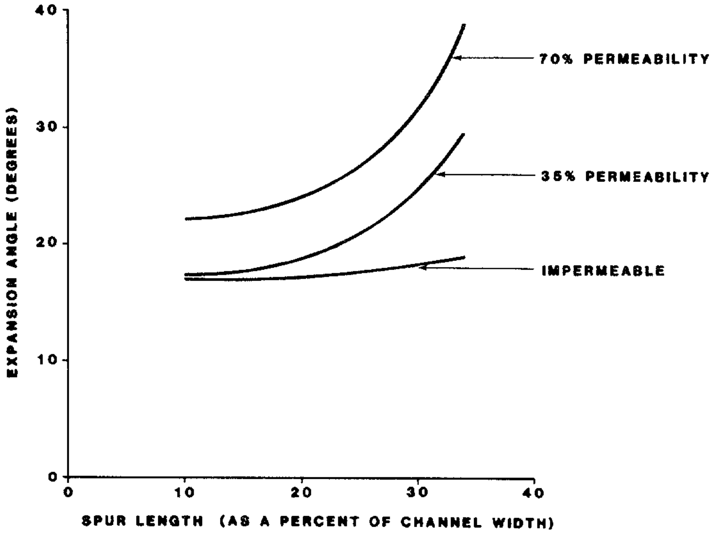


FIGURE 39. RELATIONSHIP BETWEEN SPUR LENGTH AND EXPANSION ANGLE FOR SEVERAL SPUR PERMEABILITIES.

The use of an expansion angle as a criterion for establishing spur spacing (or the length of channelbank protected by an individual spur) has several advantages over other criteria, such as the ratio LBP/PL. As illustrated above, the expansion angle is largely dependent only on permeability and the spur's length perpendicular to the direction of the flow field. In comparison, the LBP/PL parameter is also dependent on the spur's projected length parallel to the channelbank. Also, the value of LBP/PL will vary with bend radius, whereas a single expansion angle can be applied regardless of the bend curvature (as will be demonstrated below). Also, it was determined from the data collected during the FHWA study that the expansion angle is not significantly affected by spur angle as long as the angle was held to a value of 120 degrees or less. For these reasons, it is recommended that an expansion angle be used to define the appropriate spur spacing.

Additional information relative to spur spacing was documented during experiments conducted during the FHWA studies on multiple spur schemes in meandering channelbends. It was found that the direction and orientation of the channel thalweg plays a major role in determining an acceptable spacing between individual spurs in a bank-stabilization scheme. It was found that the maximum acceptable spacing between spurs can be determined by projecting a tangent to the flow thalweg at and through the spur tip and defining the location of the next downstream spur by the point where the projected flow tangent intersects the channelbank on the bend. A simple example of the application of this principle is illustrated in Figure 40. The first step is to locate the channel thalweg. As discussed previously, the location of the main flow current or thalweg in a channelbend shifts with flow stage. This concept was illustrated in Figure 36. For simplicity, the flow thalweg illustrated in Figure 40 corresponds to a low-flow condition.

With the channel thalweg located, a tangent to the thalweg at the point where the bend radius passes through the spur tip (line OR) is drawn (line AB). This flow tangent is then projected to the spur tip as illustrated by line A'B'. The point where this line intersects the channelbank (point 1) defines the location of the root of the next downstream spur.

As illustrated above, the spacing criteria are extremely dependent on the location of the flow thalweg through the bend. Therefore, a thorough knowledge of flow conditions in the channelbend will be required of the designer. Also, since the flow thalweg shifts with flow stage, consideration of multiple flow thalwegs is required to establish the appropriate spacing within a channelbend. The channel thalweg that produces the steepest flow tangent at the tip of each spur will dictate the spacing between that spur and the next downstream spur. This implies that different flow thalwegs (corresponding to different flow-stage conditions) will be critical for spurs located at different points in the bend. Also, because of the sharp curvature of the flow thalweg near the downstream end of the channelbend during high flow conditions, these spacing criteria indicate that it will be necessary to space spurs in the downstream end of the bend closer together. This, in fact, was found to be the case in the FHWA studies. Also, review of

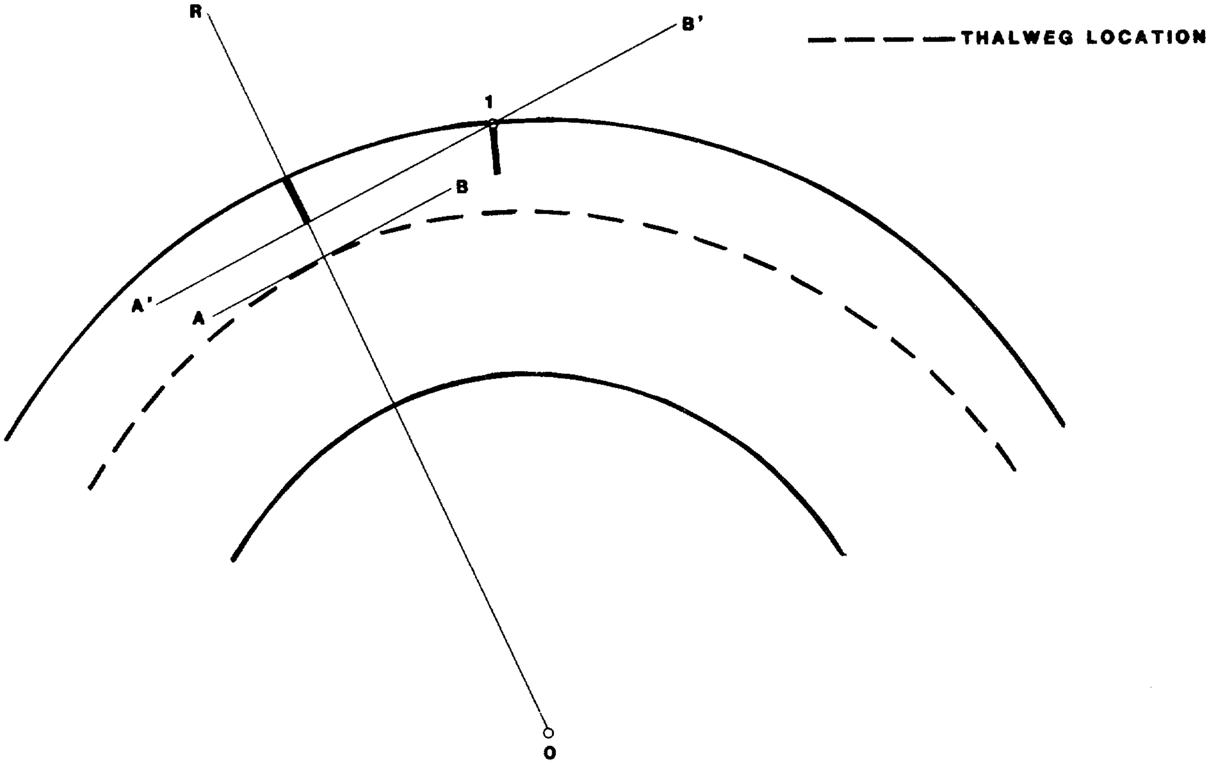


FIGURE 40. DEFINITION SKETCH FOR SPUR SPACING CRITERIA.

field sites where spur schemes have failed indicate that this failure usually occurs near the downstream end of the scheme, which indicates a need for more concentrated protection in this area.

Several additional comments can be made based on the results of the FHWA studies. It was found that reducing the spacing between individual spurs to spacings closer than the maximum indicated by the spacing criteria presented above resulted in a reduction of local scour at the spur tips. Reducing the spacing between spurs in this way reduces the magnitude of the expansion/contraction between spurs and as such, minimizes the magnitude of flow acceleration at the tip of the downstream spur in each of the two-spur sets. Also, it was found that reducing the spacing between spurs caused the stabilized thalweg to shift further away from the concave bank towards the centerline of the channel. This finding is illustrated in Figure 41, which provides a comparison of the flow thalweg resulting from wide and close spacings of spurs oriented at 120 degrees. These findings indicate that some spacing closer than the maximum recommended by the spacing criteria indicated above should be used.

In summary, a spacing criteria based on the projection of a tangent to the flow thalweg and projected off the spur tip is recommended. It is

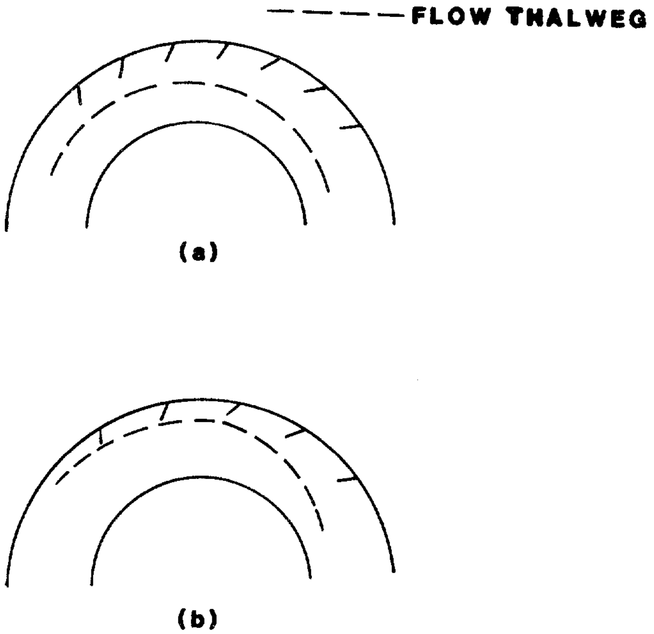


FIGURE 41. COMPARISON OF FLOW THALWEGS FOR TWO-SPUR SPACINGS.

further recommended that the spacing determined in this fashion (as illustrated in Figure 40) be reduced by an amount equal to the expansion angle for that particular spur type, as indicated in Figure 39. Application of this spacing concept will be illustrated in a later example.

Spur Orientation

Spur orientation refers to the spur's angle with respect to the orientation of the main flow current within the channelbank. Figure 42 illustrates the definition of spur angle as used within the context of this report. Historically, guidelines for spur orientation have been based primarily on the personal experience and judgement of design engineers. Spur angles used at documented spur sites range from 30 to 150 degrees. They are, however, typically greater than 90 degrees.

Although both permeable and impermeable spurs have been constructed at various angles to flow, permeable spurs should be placed normal to the flow line unless their purpose is flow diversion. This is an economic consideration. Permeable retardance spurs are usually designed to provide flow retardance within a given flow zone; therefore, they function equally as well in this respect whether they are constructed parallel or at an angle to the flow line. Since spurs normal to the bank provide the shortest

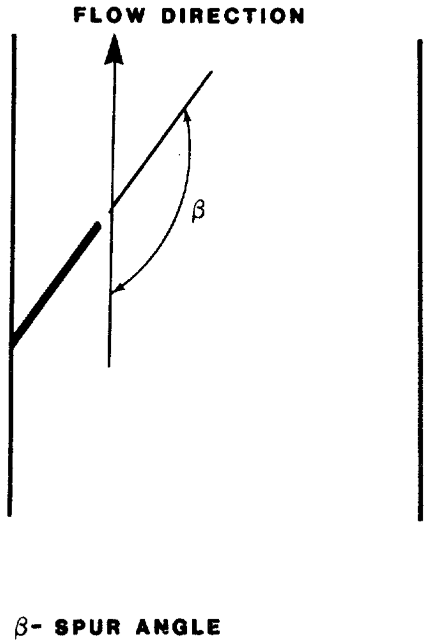


FIGURE 42. DEFINITION SKETCH FOR SPUR ANGLE.

connection between the bank and the spur head, they are cheaper and should be used where appropriate. Besides being cheaper to construct, spurs perpendicular to the bank are less susceptible to damage from wave action.

In general, permeable retardance/diverter and impermeable diverter spurs should be oriented so that they guide flows efficiently through the channelbend while protecting the channelbank for all the flow conditions to which they will be subject. There is, however, a difference of opinion as to how this should be accomplished. As mentioned above, spurs typically have been set at angles of 30 to 150 degrees. However, at a symposium on the design of spurs and dikes held at the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi, it was reported that spurs angled downstream perform better than spurs angled upstream (Pokrefke, 1978). It was also stated that spurs angled upstream are generally not used by the Corps of Engineers because of their greater resistance to flow and end scour, and their tendency to accumulate debris and ice. Impermeable spurs in New Zealand have been designed normal to flow (90 degrees) and at various angles up to 120 degrees (Acheson, 1968). Acheson also recommends that where spurs are to have a diversionary effect, the spur furthest upstream should have a flat angle to the flow line; subsequent spurs should be placed at increasing angles; the last spur may be nearly at right angles to the bank. A similar design was developed by Brown (1979) for stabilization of the Loyalsock Creek in Pennsylvania using impermeable spurs, and a similar design orientation has been used with permeable spurs by the Iowa Department of Transportation.

The primary criterion for establishing an appropriate orientation for the spurs within a given spur scheme is to provide a scheme that efficiently and economically guides the flow through the channelbend, while at the same time protects the channelbank and minimizes the adverse impacts on the channel system. Meeting these criteria requires consideration of how various spur angles impact flow patterns around individual spurs, flow concentration at the spur tip, scour depths at and just downstream of the spur tip, the length of channelbank protected by individual spurs, and flow deflection.

Figure 43 illustrates flow patterns around single impermeable spurs having angles ranging from 30 to 150 degrees in a straight flume. Note that the most abrupt constriction occurs for the spur angled at 90 degrees; the least abrupt constriction occurs for the spur angled at 150 degrees, signifying a milder impact on channel flows. From the figure, it can also be seen That spurs angled downstream produce a less severe constriction of flows than those angled upstream or oriented normal to flow. Similar findings were found for permeable spurs during a recent study by FHWA (1983). During the FHWA study, flow concentration at the spur tip was measured using the parameter V' as described previously. The trend found was for V' to decrease with increasing spur angle beyond 90 degrees, implying a reduction in flow concentration and relative flow velocity at the spur tip with increasing spur angle.

Figure 43 also documents the length of channelbank protected by spurs of various angles. As indicated, the greater the spur angle, the greater the length of bank protected. However, as indicated in the last section, the increase in the length of channelbank protected with increasing spur angle is equal to the increased projected length of the spur parallel to the channelbank. Ahmad's findings (illustrated in Figure 43) confirm that the length of channelbank protected downstream of the spur tip does not vary with spur angle, and the flow expansion angle for impermeable spurs is approximately 17 degrees as found during the FHWA study. The implication is that spur orientation does not in itself result in a greater length of channelbank protected; it is the greater spur length associated with spur oriented at steeper angles that results in the greater length of channelbank protected. Thus, the tradeoff between spur orientation and length of bank protected is one of economics; whether it is cheaper to construct a smaller number of spurs at longer lengths, or a greater number of spurs at a shorter length for the spur type being considered must be determined.

The angle of inclination of a spur also affects the magnitude of local scour at the spur head. Since channelbed scour is determined in large part by the magnitude of flow velocities, it would be expected that the higher the flow concentration the greater the local scour in the vicinity of the spur tip. This is in fact the case. Figure 44 provides a comparison of scour hole patterns at the head of impermeable spurs angled from 30 to 150 degrees. This figure, which comes from experimental work done by Ahmad (1953) indicates that the area impacted by scour increases slightly as the orientation moves away from 90 degrees. However, the more important indicator here is scour depth. The contours in the figure represent scour depth divided by initial depth. The figure shows that the maximum scour

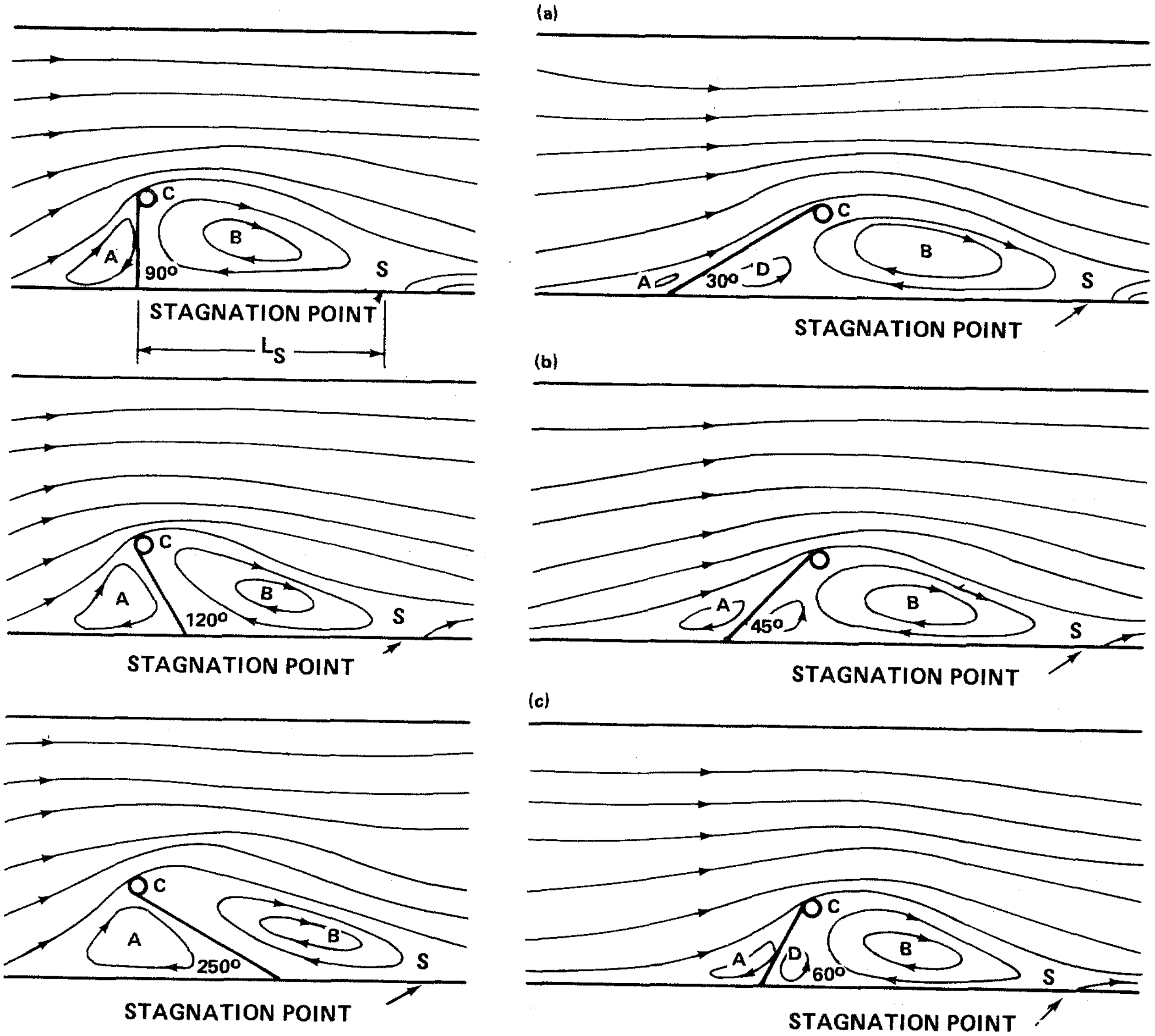


FIGURE 43. FLOW PATTERNS OBSERVED AROUND SPURS OF DIFFERENT ORIENTATIONS. (AFTER AHMAD, 1953)

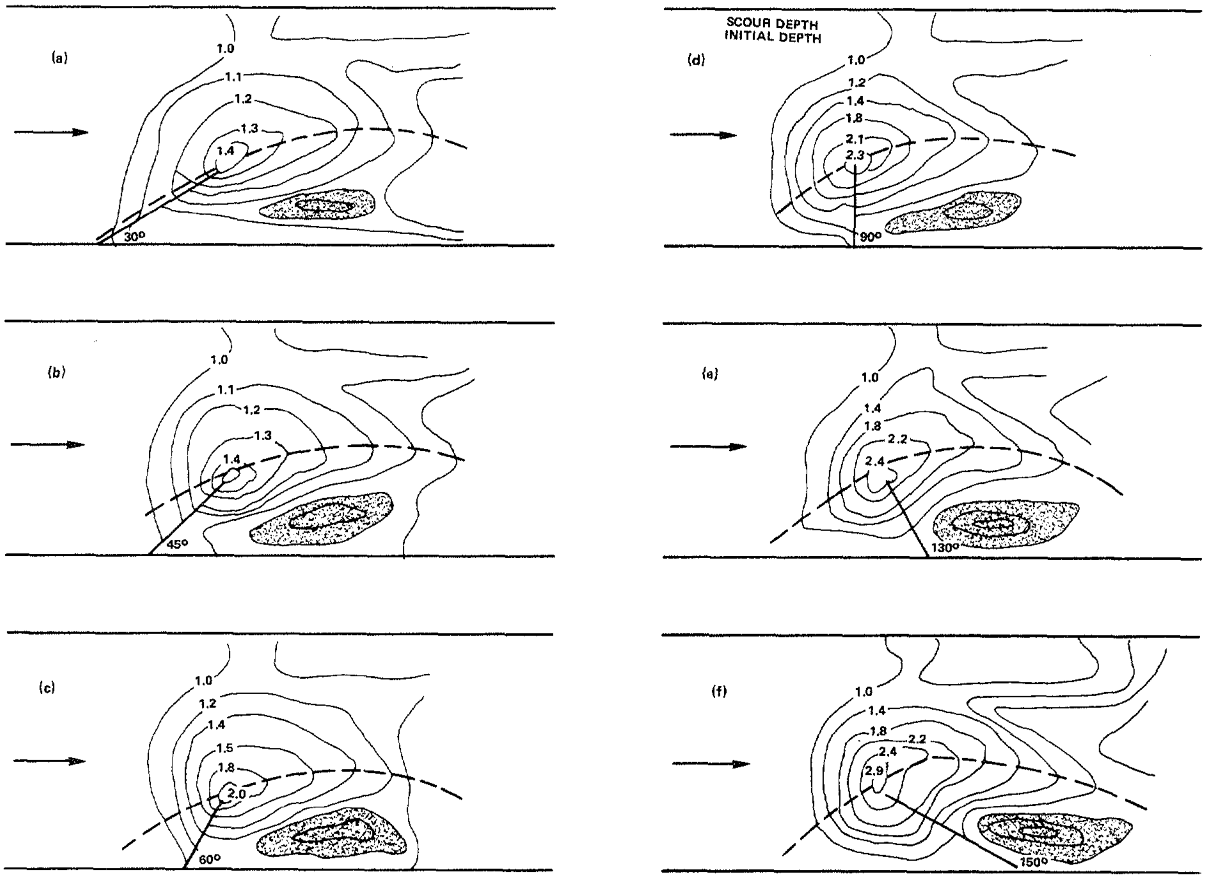


FIGURE 44. LOCAL SCOUR PATTERNS AT THE TIP OF
IMPERMEABLE SPURS. (AFTER AHMAD, 1953)

depth is inversely proportional to the spur angle. That is, the smaller the spur angle, the greater the scour depth. The greatest scour depths occur for spurs angled upstream; the least local scour is associated with spurs angled downstream.

Ahmad's findings with respect to scour depth were confirmed during the recent FHWA study, during which it was found that scour depth always decreases with increasing spur angle. It was also found that impermeable spurs produce the greatest change in scour elevation over a given range of spur angles, indicating the greatest variability of local scour at the spur tip. Also, this variability in scour depth with spur angle decreases with decreasing spur permeability. As spur permeability increases beyond 35 percent, it was observed that the rate of change of scour elevation with spur angle and spur length becomes very small, indicating that permeable spurs are not as sensitive to these parameters with regard to the magnitude of local scour as are impermeable spurs.

The amount of flow deflection produced by spurs is another factor that is controlled by the spur's orientation. Figure 38 provides a definition sketch of the flow deflection angle being discussed here. It was found during the FHWA studies that for impermeable spurs and spurs with permeabilities up to about 35 percent the deflection angle increased with increasing spur angle. For spurs tested during the FHWA study with permeabilities greater than 70 percent, no change in deflection angle with changing spur orientation was found. Flow deflection angles ranged from approximately 140 degrees to 160 degrees for impermeable spurs with spur angles ranging from 90 degrees to 150 degrees. Impermeable spurs with a permeability of approximately 35 percent had flow deflection angles ranging from approximately 130 to 145 degrees for spurs having angles of 90 degrees to 150 degrees. These findings were for single spurs in a straight channel. However, because the magnitude of the flow deflection angle will be impacted by the complex forces affecting flow in channelbends, the actual flow deflection angles recorded during the FHWA laboratory study will not reflect actual flow deflection angles in the field. However, the trends indicated can be expected to hold.

It is interesting that the flow deflection angles found during the FHWA study indicate a steeper flow deflection for permeable spurs than for the impermeable spurs tested. An explanation for this lies in consideration of the shape of the riverward tip of the spur. The impermeable spurs used in the experiments had smoothly rounded tips, which allowed for a smoother flow transition around the spur tip. However, the permeable spurs had sharp edged or square tips. This difference in head form was seen to have a distinct impact on the amount of flow deflection created by the spur.

Another factor that has been observed to be a function of spur orientation is the effect of spur-topping flows on the channelbank behind and just downstream of the spur. During the FHWA studies, it was observed that there is a disturbance on the channelbank at the spur root and immediately downstream that is caused by the near-bank flows passing over the spur crest. This disturbance impacts only the upper portions of the channelbank; the lower portions of the channelbank remain protected by the spur.

Flow patterns observed when the spur crest is submerged are illustrated in Figure 45 for two spur orientations. The flow component across the spur crest is of primary concern with respect to spur orientation. As illustrated in Figure 45, flow passes over the spur crest in a direction generally perpendicular to the spur crest. Therefore, as the spur angle is increased, the flow over the spur crest becomes aimed more directly towards the bank, resulting in a more severe impact on the channelbank (compare Figures 45(a) and (b). The magnitude of this upper-bank disturbance has been observed to be much more severe for impermeable spurs and permeable spurs with permeabilities less than 35 percent. For permeable spurs of greater permeability, the impact of spur-topping flows becomes less severe with increasing permeability. For permeable spurs with permeabilities greater than 70 percent, very little impact on the upper channelbank was observed.

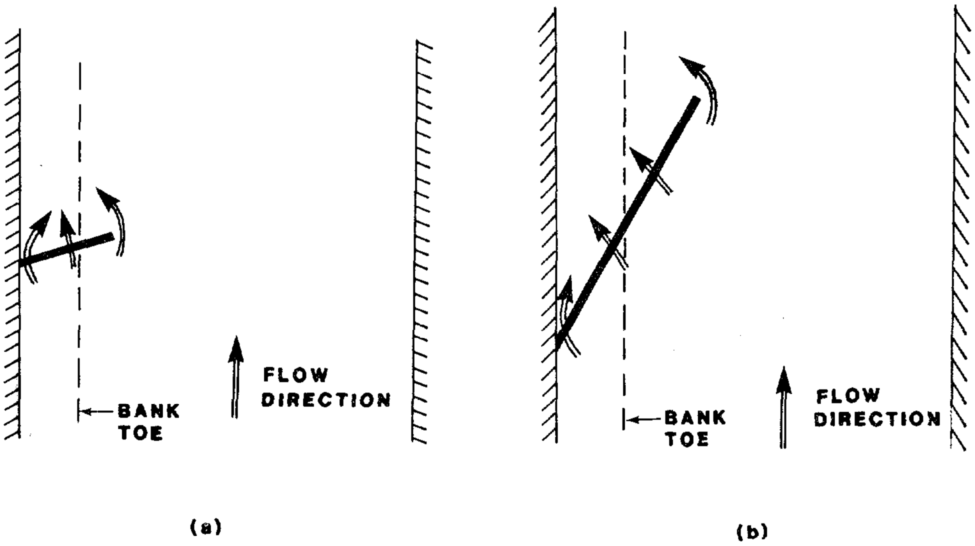


FIGURE 45. FLOW COMPONENTS IN THE VICINITY OF SPURS WHEN THE CREST IS SUBMERGED.

Please note also that these comments are based on laboratory findings in a test channel with highly erodible banks. Field observations indicate that this upper-bank erosion is not a problem if upper portions of the bank are well vegetated or otherwise stabilized. In arid regions, however, with little upper-bank vegetation, these flow conditions could result in upper-bank erosion if not otherwise stabilized.

During the FHWA study, consideration of multiple spurs within a bank-stabilization scheme on a meandering channel revealed additional insight into the impact spur orientation has on flow in channelbends. During these studies, spur orientation was found to have a direct effect on the position of the channel thalweg (main flow current) in the channelbend. Spurs having steeper orientations (around 90 degrees) were found to force the thalweg more towards the center and inside portions of the channel through the channelbend. This correlates with the findings of the single spur experiments, and indicates that steeply angled spurs provide a more positive, or active, flow control. Spurs oriented at greater angles to the channel flow provide a less abrupt flow control, allowing the channel thalweg to shift closer to the concave channelbank. Figure 46 compares the location of the channel thalweg produced by spurs angled at 120 degrees and 150 degrees to the thalweg.

Additional conclusions from the FHWA study indicate that spurs designed to provide flow diversion should be designed to provide a gradual flow training through the channelbend. This is accomplished by designing the spur system so that the spur furthest upstream is at a flat angle (that is, a large angle as defined here) and then reducing the spur angle for each subsequent spur. For example, the optimum scheme found in the FHWA laboratory study had the upstream-most spur oriented at approximately 150

FIGURE 46. COMPARISON OF THALWEG POSITIONS PRODUCED BY SPURS ANGLED AT (A) 120 DEGREE, AND (B) 150 DEGREES.

degrees. Subsequent spurs within the spur scheme had angles of 140, 130, 125, 120, 115, and 110 degrees, respectively. Reducing the spur angle as one moves downstream provides stronger flow control at the downstream limit of the scheme based on the findings presented above. It is recommended that spurs within a spur scheme be set with the upstream-most spur set at approximately 150 degrees to the main flow current at the spur tip, and with subsequent spurs having incrementally smaller angles approaching a minimum angle of 90 degrees at the downstream end of the scheme. The actual angles used within the scheme are left to the judgement of the designer. Actual spur angles should be set based on the designer's experience and local site conditions. Local site conditions that should be considered include flow constriction, local scour, flow concentration at the spur tip, flow deflection, and the need to produce a relative shift in the channel thalweg location. The impact each of these factors has on spur angles was discussed above.

The following is a summary of conclusions regarding spur orientation:

- Retardance spurs should be designed perpendicular to the flow direction.

- Retardance/diverter and diverter spurs should be designed to provide a gradual flow training around the bend. This is accomplished by maximizing the flow efficiency within the bend while minimizing any negative impacts to the channelbend.

- The greater the spur angle the smaller the magnitude of local scour at the spur tip.

- The greater the spur angle the smaller the magnitude of flow concentration at the spur tip.

- The greater the spur angle the smaller the angle of flow deflection.

- The smaller the spur angle the greater the magnitude of flow control as represented by a greater shift of the flow thalweg away from the concave (outside) channelbank.

- It is recommended that spurs within a spur scheme be set with the upstream-most spur set at approximately 150 degrees to the main flow current at the spur tip, and with subsequent spurs having incrementally smaller angles approaching a minimum angle of 90 degrees at the downstream end of the scheme.

The criteria for setting an appropriate spur orientation for spurs within a stabilization scheme will be demonstrated in the following example.

Geometric Design Example

The following example is intended to provide a step-by-step approach for establishing the geometric layout of a spur scheme. Figure 47 shows a meandering channel that has encroached on a bridge abutment. In this situation, it is desired to establish the bankline that existed prior to the erosion shown. Also, because of severity or sharpness of the channelbend and the need for a positive flow deflection, an impermeable spur scheme will be designed.

Step 1. ESTABLISH THE LIMITS OF THE FLOW CONTROL/BANK STABILIZATION SCHEME

Figure 48 illustrates the procedure used to set the limits of the flow-control scheme. First, the eroded bank area is defined. Delineation of this area can be determined from field surveys. It is important that the design engineer visit the site not only to establish the limits of the eroded area, but also to become familiar with flow conditions at the site.

Next, the minimum limits of protection are established. As illustrated, a distance of 1.5 times the channel width is measured downstream of the downstream limit of curvature of the bend to locate the minimum downstream limit of protection. However, since the bridge abutment itself has acted as a channel control, the downstream limit of protection can be set at the upstream side of the abutment.

The upstream limit of flow control or bank protection is set by measuring a distance equal to 1 channel width upstream of the upstream reference line. The upstream reference line is set by projecting a tangent to the convex channelbank just upstream of the beginning of curvature for the bend. In this case, however, bank erosion was observed upstream of this limit. Therefore, the upstream limit of protection is set at the point of observed erosion.

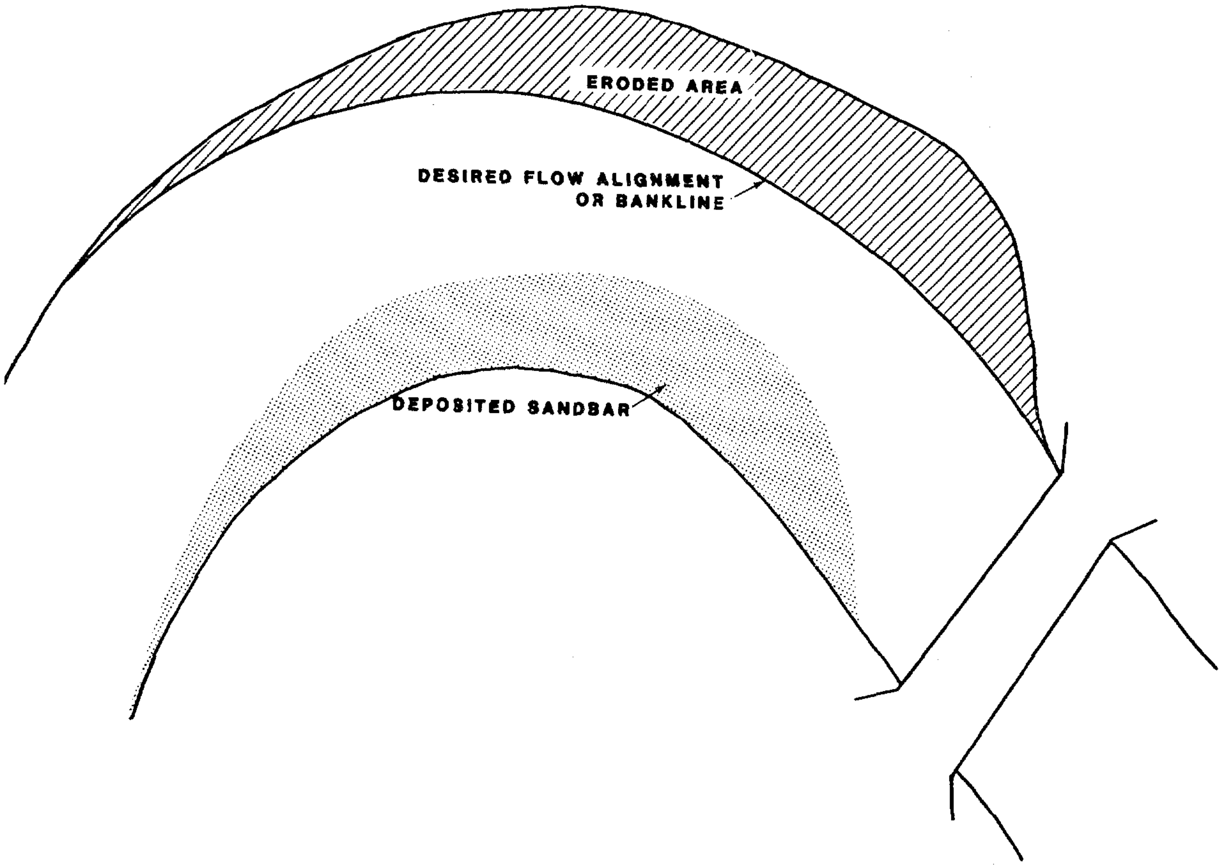


FIGURE 47. CHANNELBEND SHOWING ERODED AREA, DESIRED FLOW ALIGNMENT, AND DEPOSITED SANDBAR.

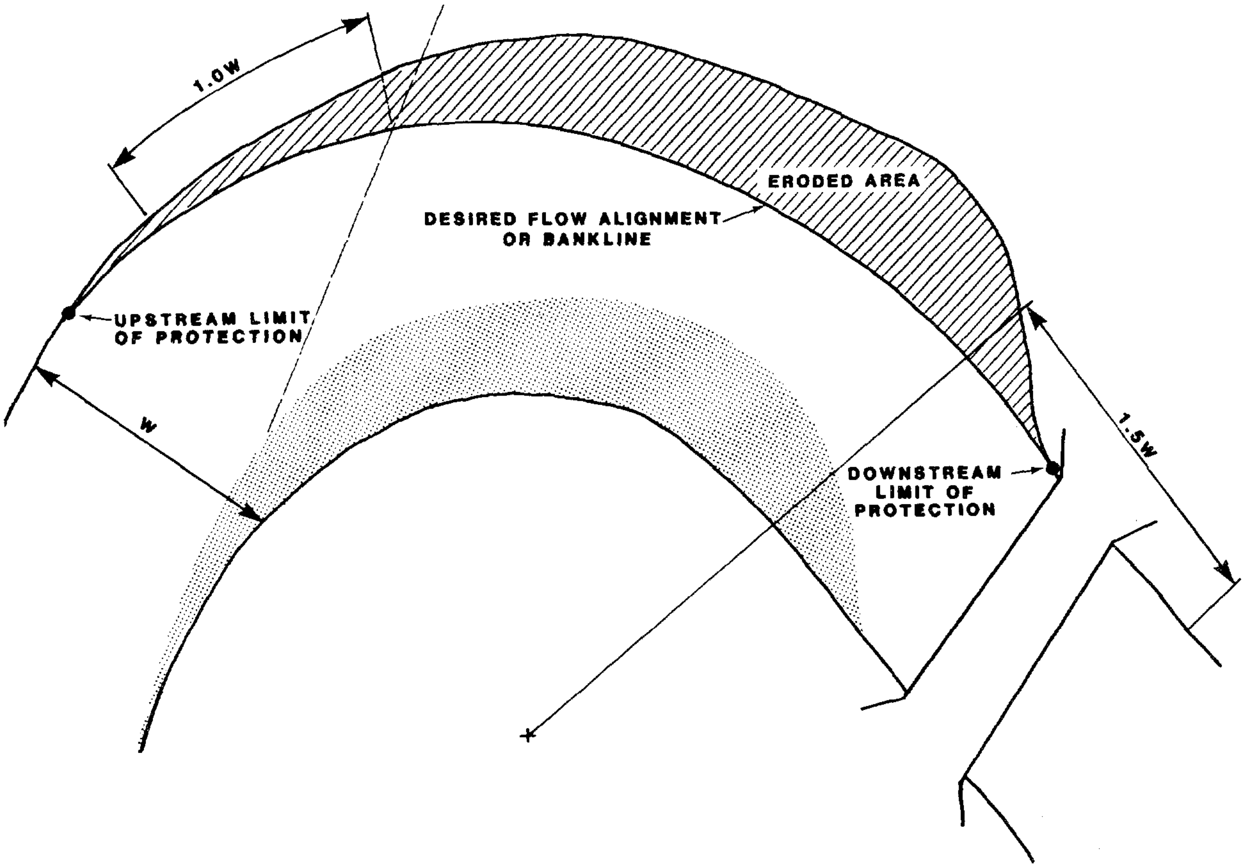


FIGURE 48. SETTING THE LIMITS OF PROTECTION.

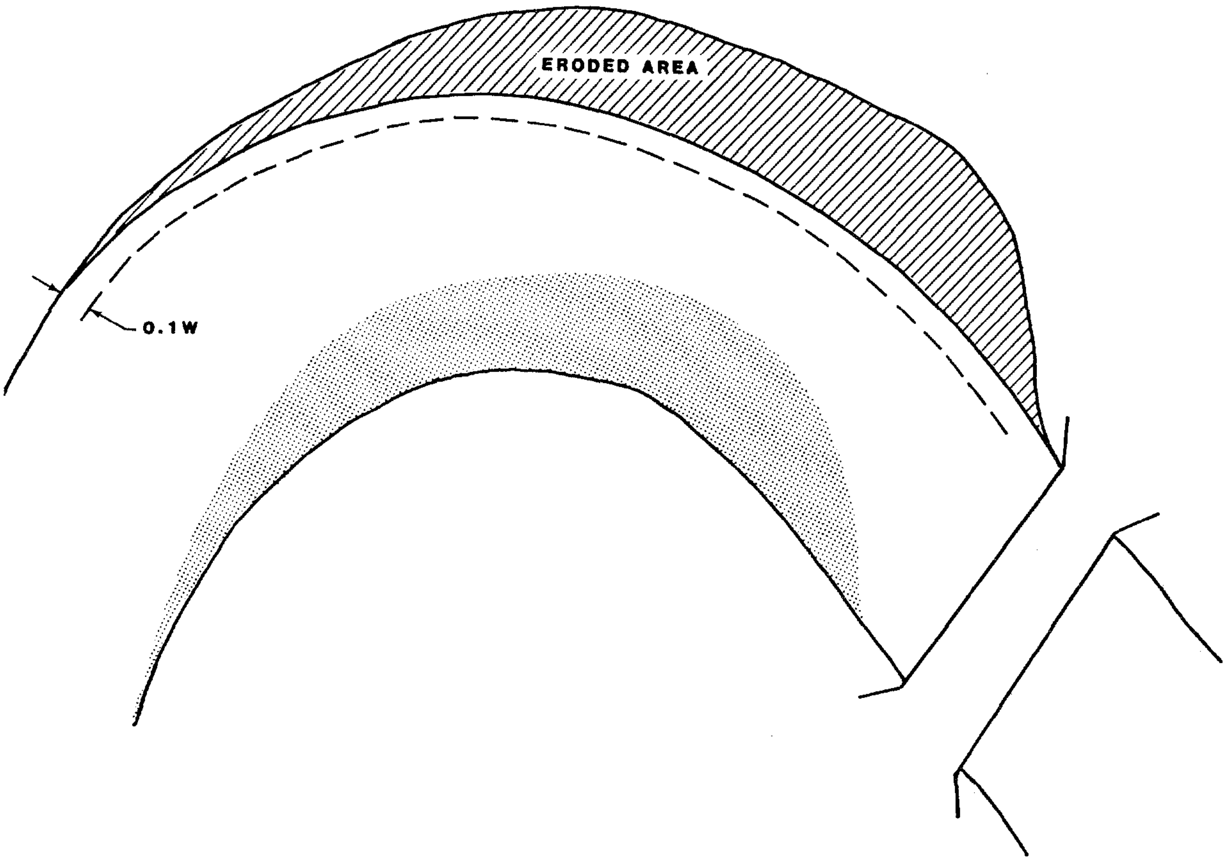


FIGURE 49. SETTING MAXIMUM FLOW CONSTRICTION.

Step 2. SET DESIRED FLOW ALIGNMENT AND MAXIMUM FLOW CONSTRICTION

The object here is to shift the channel-flow alignment to that which existed prior to the bank erosion. This desired flow alignment is illustrated in Figure 49. The dashed line in the figure represents a 10 percent constriction of the channel width. This 10 percent constriction is being used to establish the length of individual spurs. A 10 percent constriction was selected here to minimize local scour and flow concentration at the spur tip. Limiting the flow constriction to 10 percent also minimizes the chance of spurs deflecting currents into the opposite channelbank.

Step 3. ESTIMATE FLOW THALWEGS THROUGH BEND

The design criteria for spur spacing and orientation rely on a prediction of the location of the channel flow thalweg for various flow conditions. Sketching three thalweg locations, one corresponding to low, medium, and high channel flow conditions, will usually provide sufficient definition. Figure 50 illustrates these three thalweg locations for the example conditions. A thorough knowledge of flow in natural channelbends is required for accurate estimation of these thalweg locations.

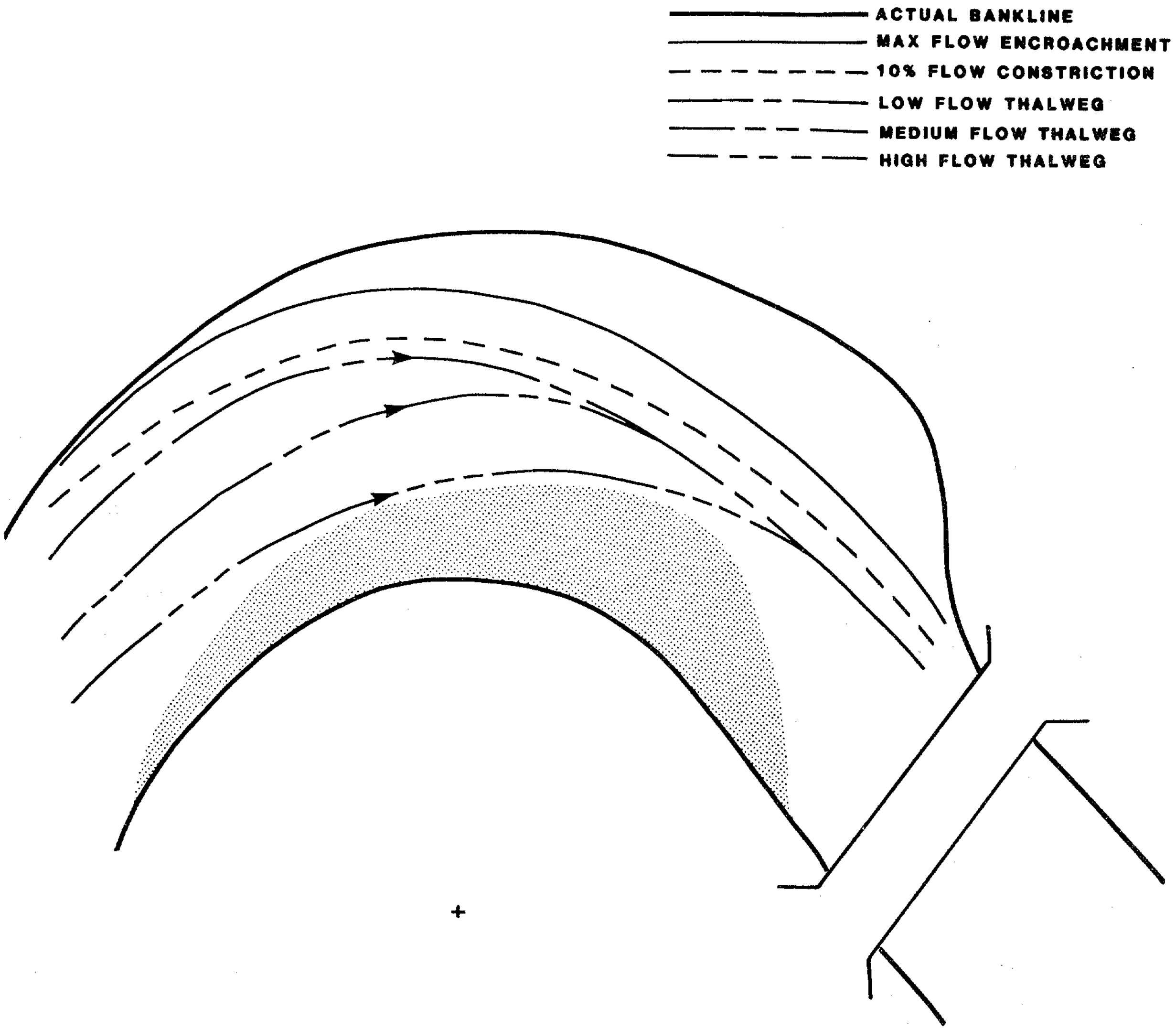


FIGURE 50. ESTIMATES OF THALWEG LOCATIONS FOR VARIOUS FLOW CONDITIONS.

Step 4. LOCATION AND ORIENTATION OF SPUR #1

Figure 51 illustrates the procedure used to locate and orient the first upstream-most spur. First the bend radius line R1 is drawn from the center of curvature of the bend through the point defining the upstream limit of the protection as defined in step 1. Next, a flow tangent to the estimated flow stream-line at the spur tip is drawn. Typically, the low-flow thalweg location should be used, since it will generally follow the desired flow alignment. Such a flow tangent is illustrated in Figure 51 as line AA. The flow tangent is then shifted along the radius line R1 until the 10 percent flow constriction line is reached (see line A'A'). The spur angle of 150 degrees is then turned in an upstream direction (clockwise) from line A'A', to establish the line BB, which is parallel to the desired spur orientation through the constricted width line where it intersects the radius line (R1). The line B'B' is then drawn through the the point defining the upstream limit of protection (spur location point) parallel to line BB. This line defines the location of the center line of the spur. The spur length is then set between the eroded bankline, and the 10 percent flow constriction line.

Step 5. LOCATION OF SPUR #2

The approach to locating the second spur is illustrated in Figure 52. This same approach will be used to locate each subsequent spur. First, another radius line, R2 in Figure 51, is drawn through the tip of the previous spur. The location of the next downstream spur depends on the orientation of a tangent to the channel thalweg where it intersects line R2. However, we have sketched three flow thalweg lines representing different flow conditions. The appropriate flow thalweg is for the flow condition that intersects line R2 at one quarter of the distance from the flow constriction line. Line AA in Figure 52 illustrates the tangent drawn to the quarter-point thalweg curvature off the tip of Spur #1. Line AA is then slid along line R2 to the tip of Spur #1 as indicated by line A'A' in the figure. From line A'A', an expansion angle of 17 degrees (as determined for impermeable spurs at 10 percent constriction in Figure 39) is turned towards the concave bank line (counterclockwise). The location of the next downstream spur is defined by the point at which the rotated line intersects the maximum flow encroachment line. This point is indicated by an asterisk (*) in the figure.

Step 6. ORIENTATION OF SPUR #2

Setting the orientation of spur #2 and each subsequent spur is the same as the procedure for orienting spur #1. As illustrated in Figure 53, the first step is to draw a radius line, R3, through the spur location point (*). Next, a flow tangent to the estimated flow stream-line at the spur tip is drawn (line AA as discussed in step 4). Line AA is shifted along line R3 to the tip of the spur (see line A'A') The spur angle of 140 degrees is then turned in an upstream direction from line A'A' to establish the line BB. The line B'B' is then drawn through the spur location point (*). Line B'B' defines the centerline of spur #2. The spur length is then set between the eroded bankline, and the 10 percent flow constriction line.

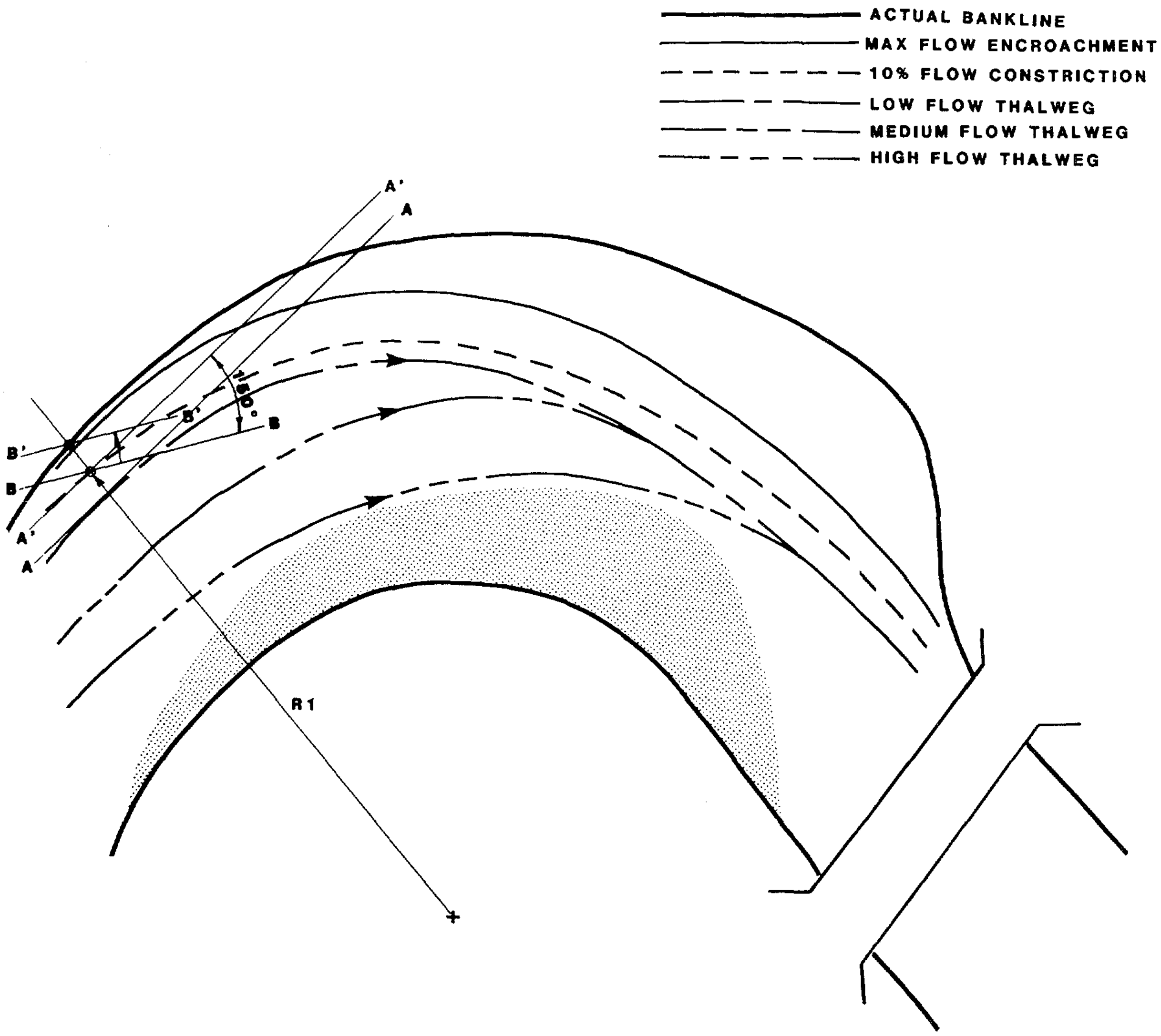


FIGURE 51. LOCATION AND ORIENTATION OF FIRST SPUR.

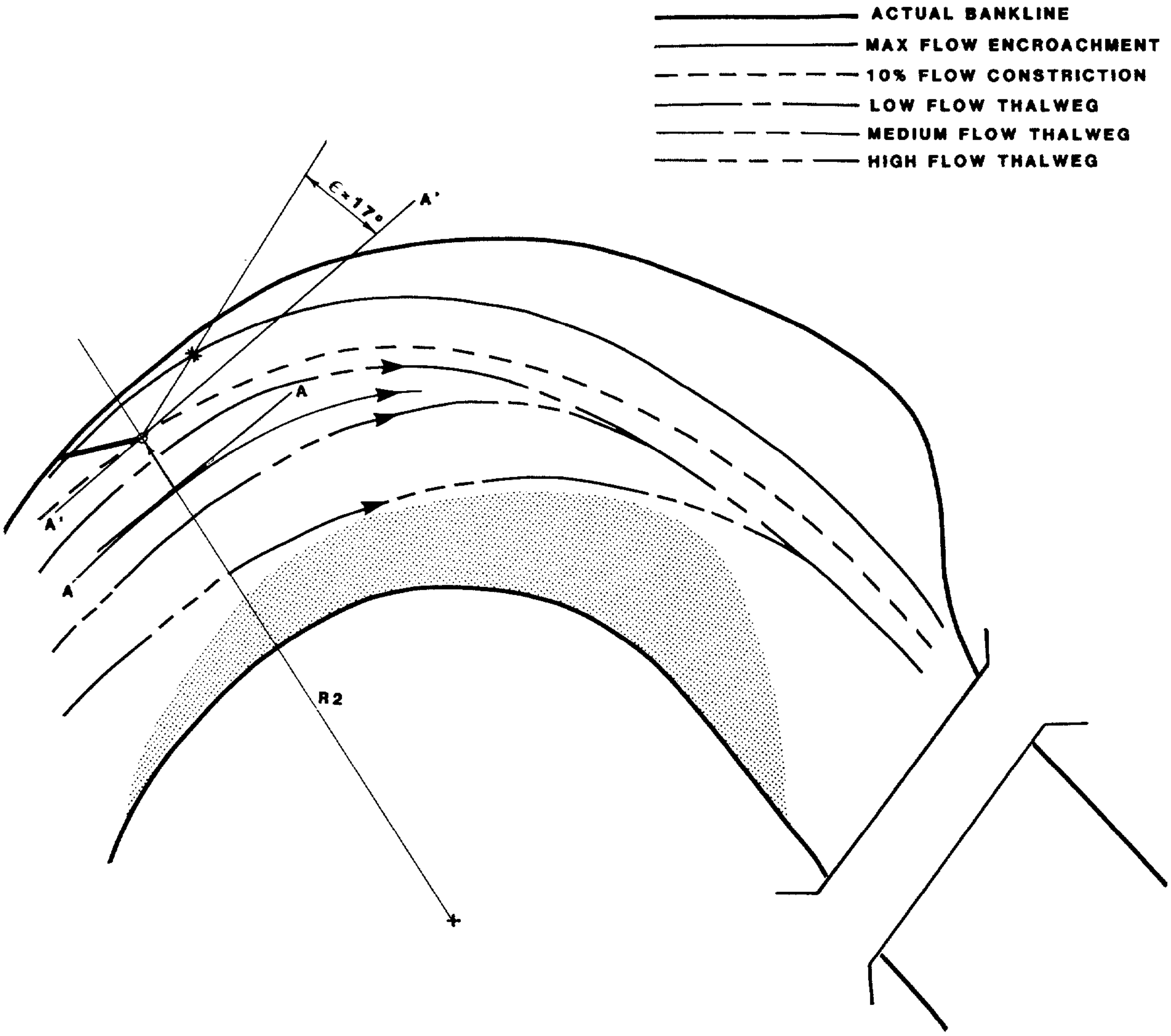


FIGURE 52. LOCATION OF SECOND SPUR.

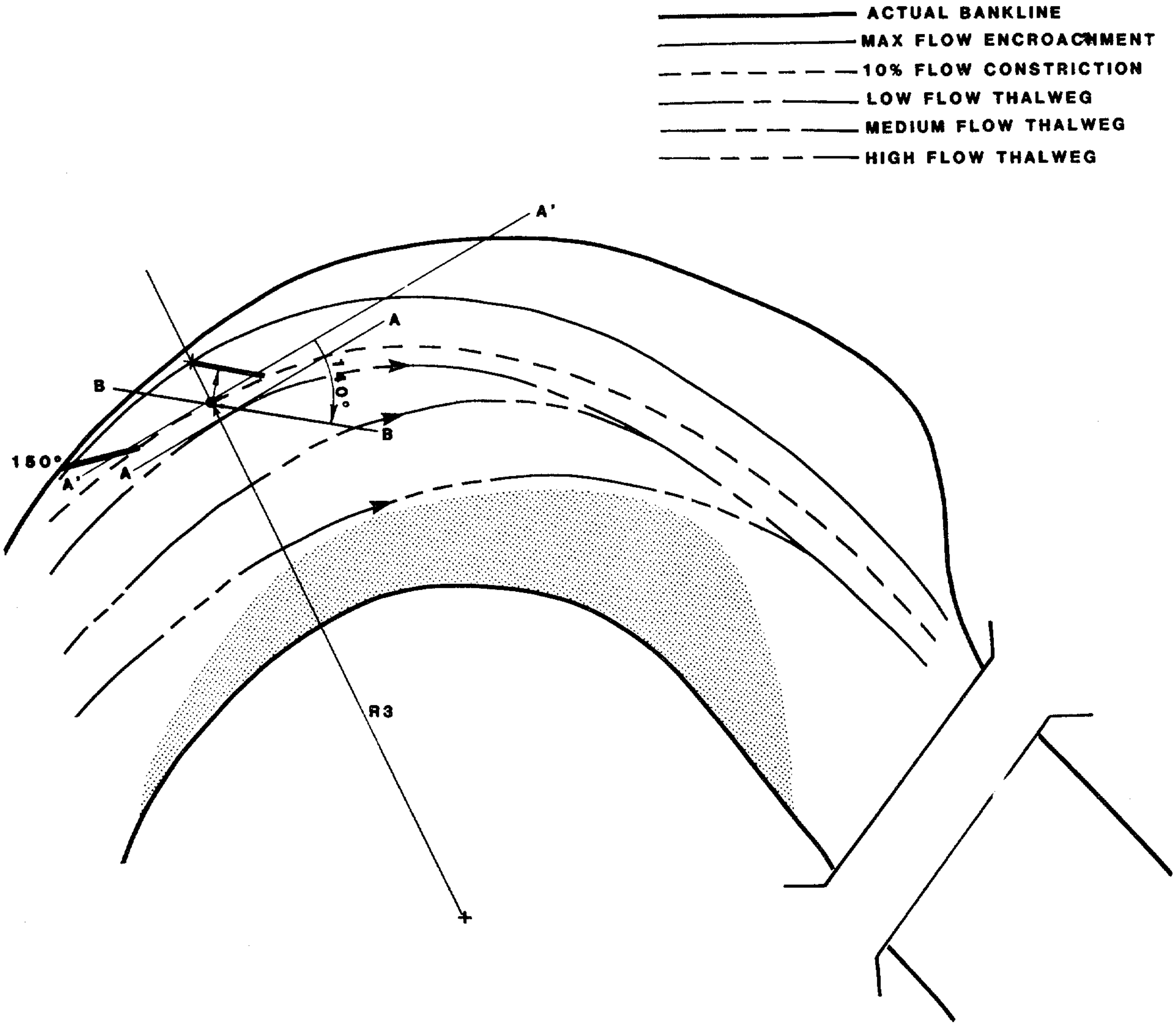


FIGURE 53. ORIENTATION OF SPUR NUMBER 2.

Step 7. LOCATION AND ORIENTATION OF SUBSEQUENT SPURS

Steps 5 and 6 are repeated until the downstream limit of protection is reached. Figure 54 illustrates the final geometry developed in this way.

Several additional comments can be made about the example presented above. The spur angles used when setting out the example spur scheme are illustrated in Figure 54. Note that the spur angles decrease from 150 degrees to 120 degrees and then remain constant. This was done to provide maximum flow efficiency through the channelbend. This example documents a relatively sharp bend curvature requiring a maximum in flow efficiency. For this reason the spurs were not angled more steeply. The magnitude of this limiting spur angle should be set based on conditions particular to each site.

Also, note the dogleg in the next to the last spur. This dogleg was designed into this spur to minimize the spur's total length and thus, its cost. This leg of the spur is not impacted by channel flows since it is inside the maximum flow encroachment line. Doglegs such as this can be designed where they will provide an economic advantage without impacting the effectiveness of the stabilization scheme.

It is also interesting to note the relative spacing of the spurs. Notice that the spurs on the downstream half of the bend are closer together. As such, the scheme provides a more positive control of flow in this area. The reduced spacing of the spurs in this area provided by the spacing criteria presented correlates well with the need for greater flow control in the downstream half of the channelbend (FHWA,1983).

STRUCTURE HEIGHT

The height to which spurs should be constructed is primarily a function of the height of channelbank to be protected. Factors that influence the appropriate height of bank protection are as follows:

- the mechanism causing the erosion,
- the existing channelbank height,
- the design flow stage, and
- the flow stage at which significant debris loads become a problem.

The erosion mechanism is important in establishing the spur height because it defines the vertical regions of the bank that are impacted by the erosion process and require protection. For example, if the channelbank is to be protected against toe erosion, the spurs need only be high enough to protect the toe of the channelbank. On the other hand, if a mechanism causing erosion of upper-bank materials is the culprit, the spur should be designed to the height of the bank. Alternatively, if only the lower and middle portions of the bank are being impacted, a spur height that covers this region should be used.

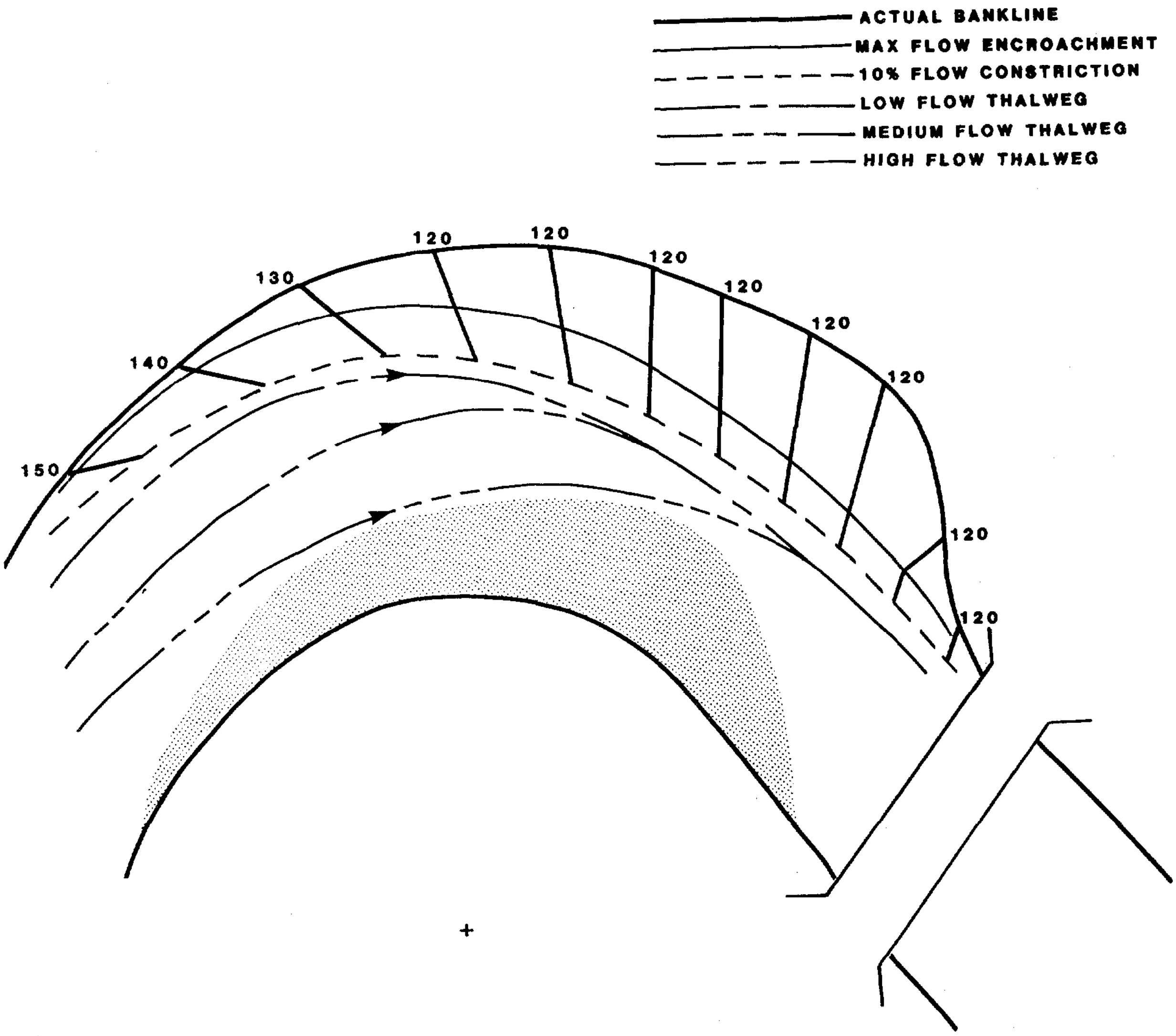


FIGURE 54. FINAL SPUR SCHEME GEOMETRY.

The existing bank height and design flow stage can be considered together when establishing an appropriate spur height. If the flow stage to be protected against (usually a design flow of given frequency), is lower than the channelbank height, the design stage should be used to set the spur height. If the design flow stage is higher than the bank height, spurs are generally only designed to a height equal to the bank height. It has been found (Pokrefke, 1978) that constructing a spur to bank height does not reduce its effectiveness when overtopped; overtopping of spurs by as much as 3 feet does not affect the spurs' efficiency. Impermeable spurs are generally not constructed above bank height to eliminate the possibility of out-flanking of the spur by flow concentration and erosion behind the spur at high river stages. The most commonly advised height for spurs is that which corresponds to bank height.

Designing spurs lower than flow stages that carry significant debris loads is more important for permeable spurs than for impermeable spurs because of the flow-skimming qualities of the permeable structures. The elevation of the top of these structures should be well below the high-water level to allow the heavy debris to pass over the top and prevent damage to the structure.

The effect of flow submergence on the behavior of a spur is related to defining an appropriate spur height. Recently, it has been found (FHWA, 1983) that the behavior of impermeable spurs with respect to flow deflection and local scour and flow concentration at the spur tip is worse for flow stage conditions lower than the crest of the spur than when the spur crest is submerged. For example, Figure 55 compares the scour patterns generated by submerged and nonsubmerged spurs. As illustrated, the scour pattern generated for the nonsubmerged case is larger and deeper.

Based on the above statements, the following recommendations are made for establishing the height of spur systems:

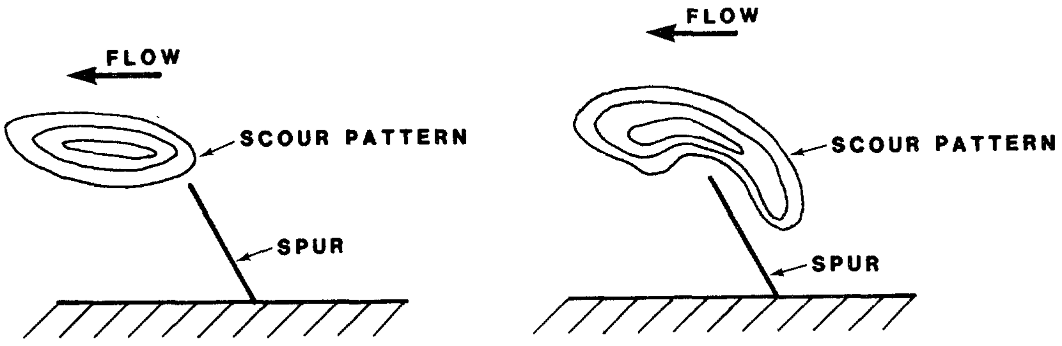
- The spur height should be sufficient to protect the regions of the channelbank impacted by the erosion process.

- If the design flow stage is lower than the channelbank height, spurs should be designed to a height no more than three feet lower than the design flow stage.

- If the design flow stage is higher than the channelbank height, spurs should be designed to bank height.

- Permeable spurs should be designed to a height that will permit the passage of heavy debris over the spur crest and not cause structural damage.

- When possible, impermeable spurs should be designed to be submerged by approximately three feet under their worst design flow condition, thus minimizing the impacts of local scour and flow concentration at the spur tip, and the magnitude of flow deflection.



(a) (b)

FIGURE 55. COMPARISON OF SCOUR PATTERNS GENERATED BY (A) SUBMERGED, AND (B) NONSUBMERGED IMPERMEABLE SPURS.

CREST PROFILE

Spur crest profile is related to spur height. Permeable spurs are usually designed with level crests, although in special cases where high banks are to be protected, sloping crest designs have been used (see Figure 22).

Impermeable spurs have been constructed with both level crests and crests sloping towards the head. Both Acheson (1968) and Jansen et al. (1979) suggest that impermeable spurs be designed with a slight fall towards the head. Richardson and Simons (1974) recommend that level crest spurs be placed normal to flow and sloping crest spurs be placed normal or angled downstream to flow. Simons, et al. (1979) also recommend sloping crest dikes for bank protection. The main advantage of sloping crest spurs is that they allow different amounts of flow constriction with stage. The sloping crest also allows the accommodation of changes in meander trace with stage. Franco (1966) indicates that sloping crest spurs are as effective as level-crested designs.

The following is a list of recommendations regarding crest profile:

- Permeable spurs should be designed with level crests unless bank height or other special conditions dictate the use of a sloping crest design.
- Impermeable spurs should be designed with a slight fall towards the head, thus, allowing different amounts of flow constriction with stage (particularly important in narrow width channels), and the accommodation of changes in meander trace with stage.

BED AND BANK CONTACT

A spur's ability to maintain contact with the channelbed and bank is fundamental to the spur's structural stability. Undermining and/or outflanking are the most commonly reported failure mechanisms for spurs used as flow control and streambank-stabilization countermeasures. Maintaining bed and bank contact is primarily a problem in highly alluvial channel environments where the channelbed surface fluctuates widely in response to changing flow conditions.

Channelbed Contact

The mechanisms by which spurs maintain contact with the channelbed vary with spur type.

Impermeable rock riprap spurs can be designed with excess stone in the spur head to counter undermining at the spur tip in the event of streambed elevation changes. As illustrated in Figure 56, as the streambed lowers, the stone material will launch channelward, armoring the area around the spur tip against future drops in the channelbed. In a design of this type, care must be taken to size the riprap properly to provide a sufficient volume of material for the launching process.

Gabion spurs can also be designed to counter changes in streambed elevation at the spur head. This is done by extending the wire and stone base course or mat channelward beyond the tip of the spur head to armor the channelbed in the vicinity of the spur tip. Figure 57 illustrates that as the streambed lowers, the base mat will drop with the bed to armor the area around the spur tip against future drops in the channelbed. Gabion spurs are not as flexible as riprap spurs in this respect; therefore, they should be used with caution in highly alluvial environments.

Several design techniques to protect against undermining of permeable spurs are also available. The first technique, illustrated in Figure 58, is to provide a rock-toe foundation for the spur. In a fashion similar to that of the rock riprap spurs discussed above, fluctuations in channelbed level will cause the rock-toe material to launch and armor the area around the spur preventing undermining. Note that sufficient material must be included in the riprap blanket to armor against scour effects. This is particularly important at the head of the structure, where an additional mass of material might be needed (see Figure 58).

To avoid undermining of pile structures, the vertical support members should be driven to a depth significantly below the anticipated scour level. It has also been found that round vertical piles induce a much smaller depth of local scour than do square vertical piles (FHWA, 1983). It has also been observed (FHWA, 1983) that extending the facing material of permeable spurs to a depth below the channelbed surface and below anticipated scour depths has a significant stabilizing effect on the channelbed in the vicinity of the spur. This technique is illustrated in Figure 59. In this case, the wire

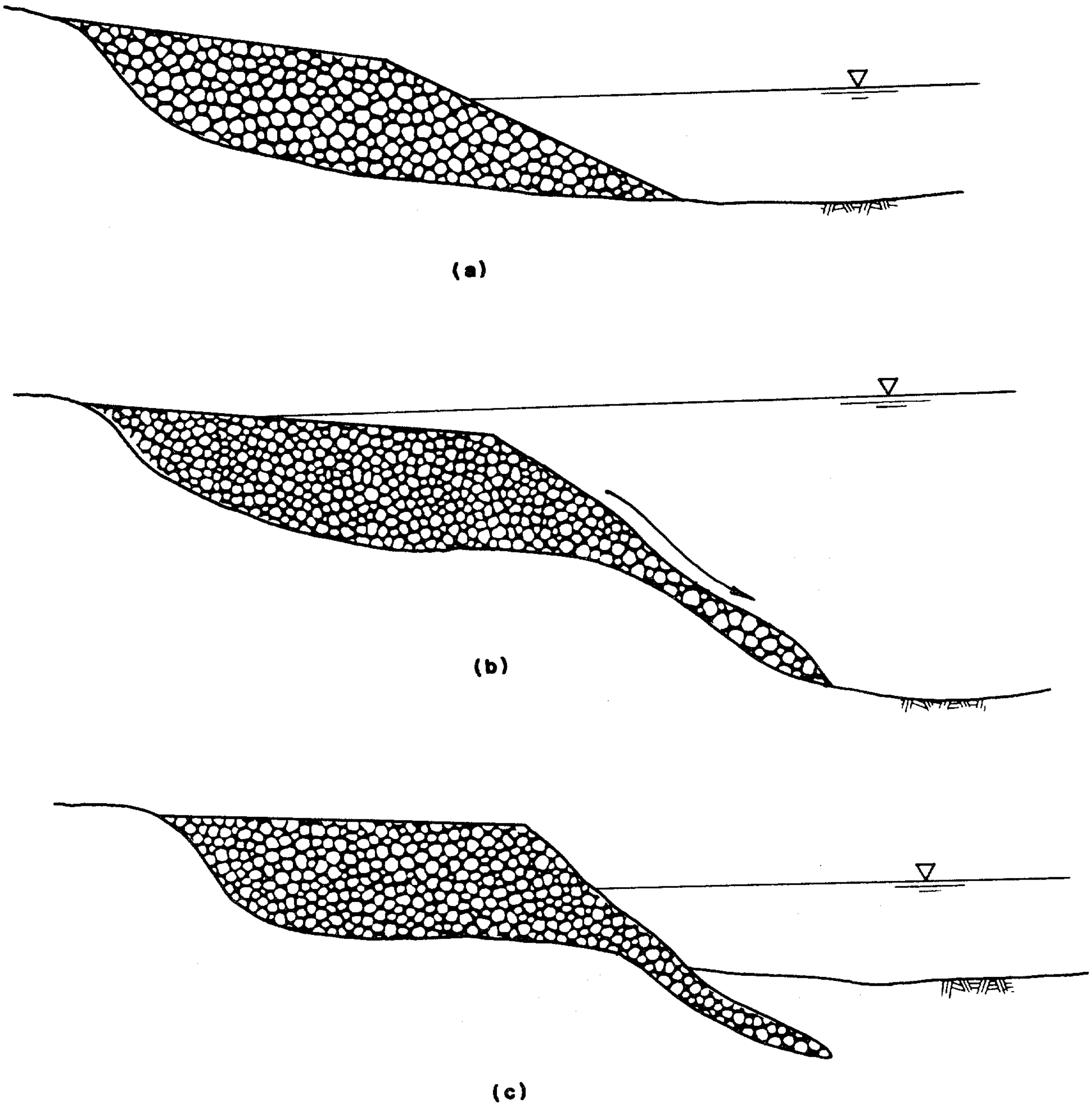


Figure 56. ROCK RIPRAP SPUR ILLUSTRATING LAUNCHING OF STONE TOE PROTECTION. (A) BEFORE LAUNCHING AT LOW FLOW (B) DURING LAUNCHING, AT HIGH FLOW (C) AFTER LAUNCHING AT LOW FLOW

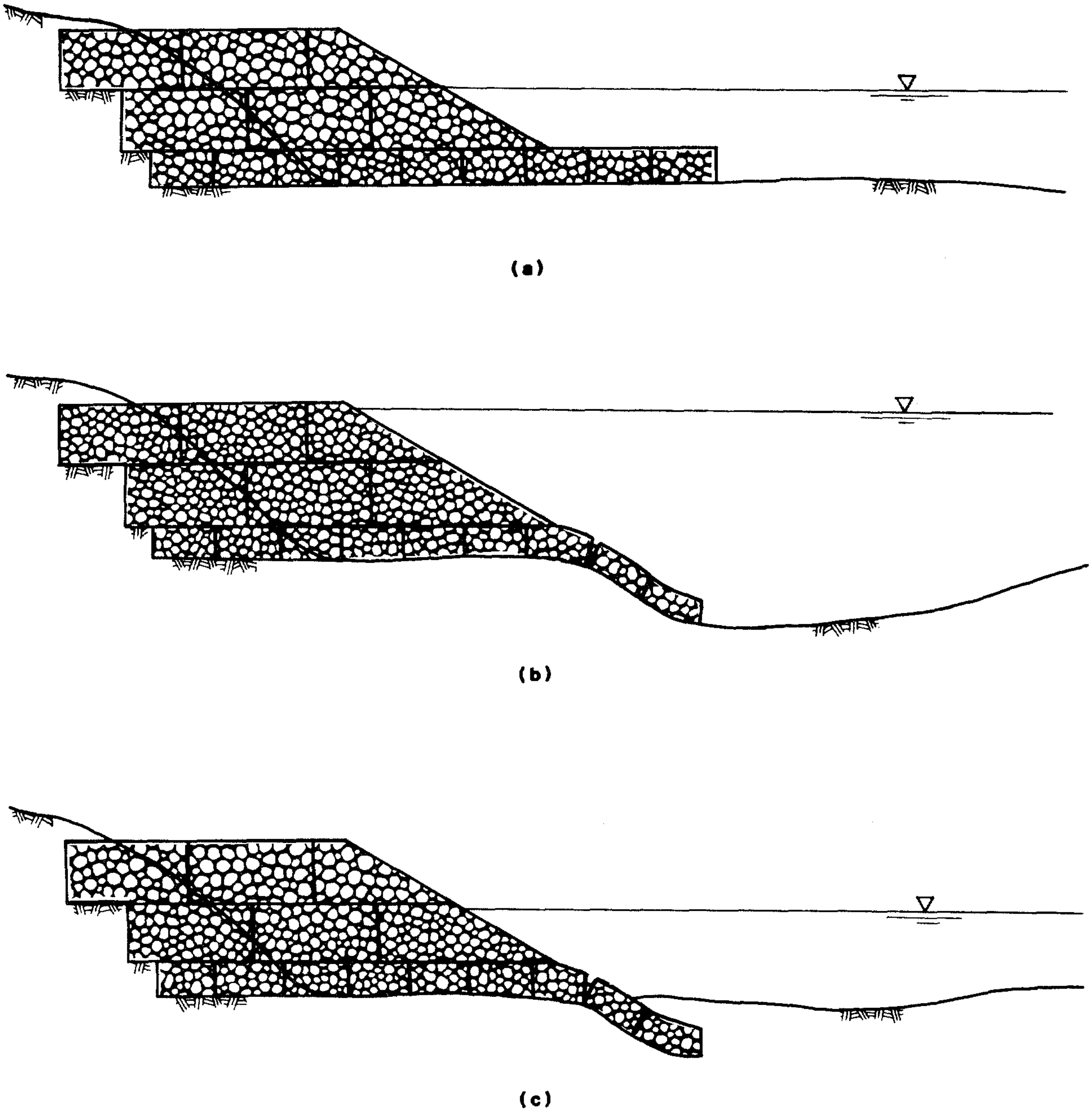


FIGURE 57. GABION SPUR ILLUSTRATING FLEXIBLE MAT TIP PROTECTION. (A) BEFORE LAUNCHING AT LOW FLOW (B) DURING LAUNCHING, AT HIGH FLOW (C) AFTER LAUNCHING AT LOW FLOW

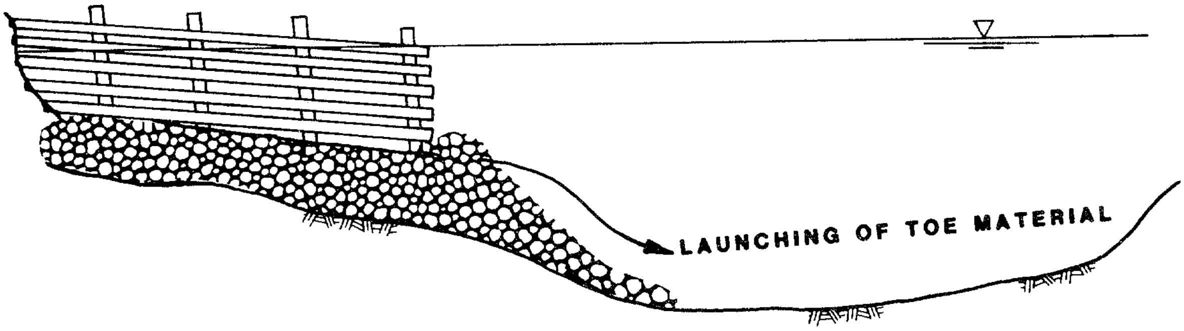


FIGURE 58. PERMEABLE WOOD-SLAT, FENCE SPUR SHOWING LAUNCHING OF STONE TOE MATERIAL.

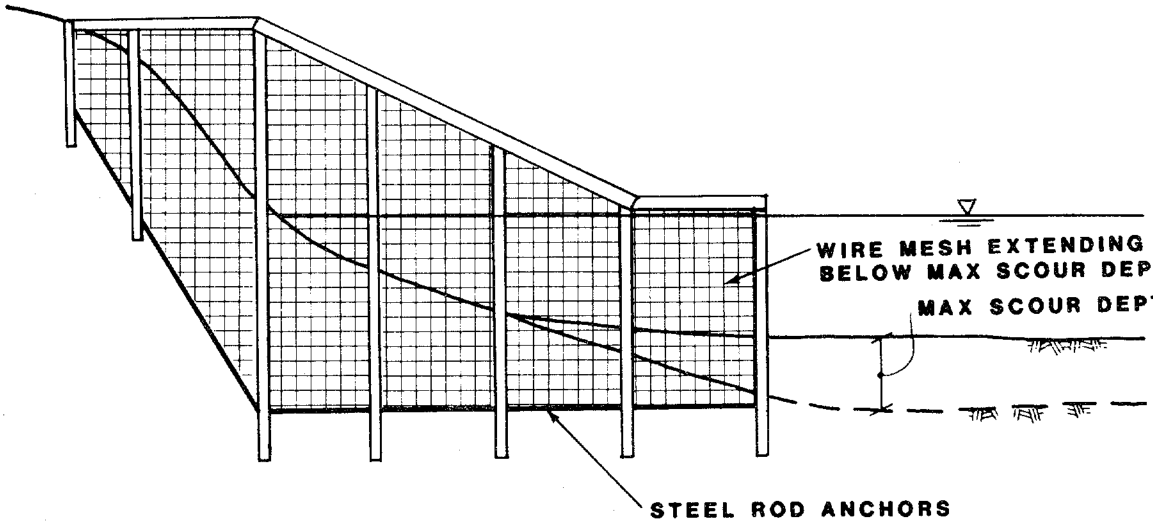


FIGURE 59. WIRE MESH SPUR WITH THE MESH SCREEN EXTENDED BELOW THE MAXIMUM ANTICIPATED SCOUR DEPTH.

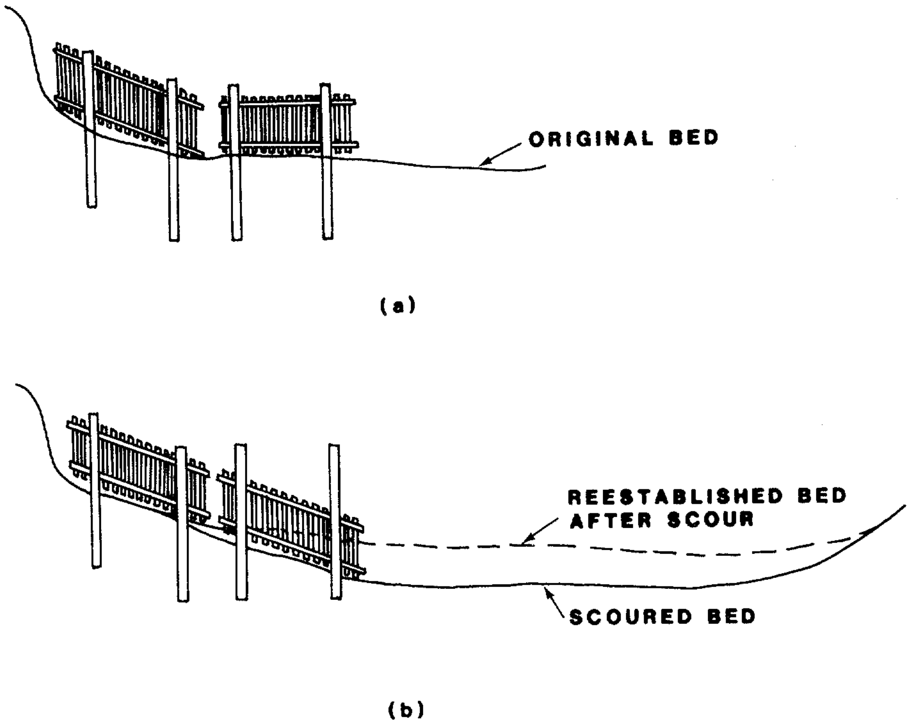


FIGURE 60. HENSON SPURS (A) RESTING ON ORIGINAL CHANNELBED, AND (B) AFTER DROP IN CHANNELBED LEVEL.

mesh is rolled down the upstream face of the support members into an excavated trench. Some form of weighting mechanism can be attached to the bottom to secure the wire mesh to the bottom. An alternative to placing the wire in a pre-excavated trench is to lay a role of wire and an anchor weight on the channelbed or in a small trench and allow natural scour processes to sink the wire. This might require several additional vertical supports to be driven on the upstream side of the wire roll to guide it as it drops.

One additional technique for maintaining channelbed contact has been developed as a part of the patented Henson spur scheme marketed by Hold That River, Inc. of Houston, Texas. This technique is depicted in Figure 60. The Henson spur jetties shown maintain contact with the channelbed by being free to move vertically with the bed. They are vertical wood-slat fence units mounted on pipes that are driven to a depth that prohibits failure from undermining. As the channelbed drops during a storm event, the wood slat units slide on the pipes to maintain contact with the bed and provide protection against undermining of the structure. If the vertical channelbed drop during one flow event leaves the units buried or too low, additional

FIGURE 61. HENSON SPUR SHOWING OUTFLANKING.

units can be placed on top of the old units to restore the structure's height. A similar mechanism could be designed for other fence-type structures. However, care must be taken not to infringe on existing patents.

The recommendation is that careful consideration be given to designing a spur that will maintain contact with the channelbed and not be undermined.

Channelbank Contact

Another concern is the spur's ability to maintain contact with the channelbank. Spurs not adequately tied into the bank are susceptible to outflanking. A case in point is illustrated in Figure 61, where spur-topping flows continued to erode the upper portions of the channelbank, creating a flow channel behind the spurs. In this case failure to tie the spurs adequately to the bank resulted in continued bank movement. In contrast, Figure 62 illustrates a welded wire-mesh spur that was tied adequately to the bank by running the wire mesh for a distance into the bank.

The recommendation is that adequate consideration be given to tieing the spur structure adequately to the channelbank to avoid outflanking.

FIGURE 62. WIRE-MESH PERMEABLE SPUR ILLUSTRATING SPUR ROOT EXTENDING INTO CHANNELBANK.

SPUR HEAD FORM OR DESIGN

Numerous design shapes have been suggested for the head or riverward tip of spurs. These have included straight, T-head, L-head, wing, hocky, inverted hocky, etc. However, a simple straight spur head form is recommended. The only additional recommendation is that the spur tip be as smooth and rounded as possible. Smooth, well-rounded spur tips help minimize local scour, flow.

SUMMARY OF SPUR DESIGN RECOMMENDATIONS

The following is a summary of the major recommendations presented in this chapter; they are organized by design component for easy reference.

Permeability

o Where it is necessary to provide a significant reduction in flow velocity, a high level of flow control, or where the structure is being used on a sharp bend, the spur's permeability should not exceed 35 percent.

- Where it is necessary to provide a moderate reduction in flow velocity, a moderate level of flow control, or where the structure is being used on a mild to moderate channelbend, the spurs with permeabilities up to 50 percent can be used.

- In environments where only a mild reduction in velocity is required, where bank stabilization without a significant amount of flow control is necessary, or on mildly curving to straight channel reaches, spurs having effective permeabilities up to 80 percent can be used. However, these high degrees of permeability are not recommended unless experience has shown them to be effective in a particular environment.

- It is recommended that jack and tetrahedron retardance spurs be used only where it can be reasonably assumed that the structures will trap a sufficient volume of floating debris to produce an effective permeability of 60 percent or less.

- It is recommended that Henson-type spurs be designed to have an effective permeability of approximately 50 percent.

- The greater the spur permeability, the less severe the scour pattern downstream of the spur tip. As spur permeability increases, the magnitude of scour downstream of the spur decreases slightly in size, but more significantly in depth.

- The vertical structural members of permeable spurs should be round or streamlined to minimize local scour effects.

- The greater the spur permeability, the lower the magnitude of flow concentration at the spur tip.

- If minimizing the magnitude of flow deflection and flow concentration at the spur tip is important to a particular spur design, a spur with a permeability greater than 35 percent should be used.

- The more permeable the spur, the shorter the length of channelbank protected downstream of the spur's riverward tip.

- Spurs with permeabilities up to approximately 35 percent protect almost the same length of channelbank as do impermeable spurs; spurs having permeabilities greater than approximately 35 percent protect shorter lengths of channelbank, and this length decreases with increasing spur permeability.

- Because of the increased potential for erosion of the channelbank in the vicinity of the spur root and immediately downstream when the flow stage exceeds the crest of impermeable spurs, it is recommended that impermeable spurs not be used along channelbanks composed of highly erodible material unless measures are taken to protect the channelbank in this area.

Extent of Channelbank Protection

- A common mistake in streambank protection is to provide protection too far upstream and not far enough downstream.

- The extent of bank protection should be evaluated using a variety of techniques, including:

    - empirical methods,
    - field reconnaissance,
    - evaluation of flow traces for various flow stage conditions, and
    - review of flow and erosion forces for various flow stage conditions.

  Information from these approaches should then be combined with personal judgement and a knowledge of the flow processes occurring at the local site to establish the appropriate limits of protection.

Spur Length

- As the spur length is increased,

    - the scour depth at the spur tip increases,
    - the magnitude of flow concentration at the spur tip increases,
    - the severity of flow deflection increases, and
    - the length of channelbank protected increases.

- The projected length of impermeable spurs should be held to less than 15 percent of the channel width at bank-full stage.

- The projected length of permeable spurs should be held to less than 25 percent of the channel width. However, this criterion depends on the magnitude of the spur's permeability. Spurs having permeabilities less than 35 percent should be limited to projected lengths not to exceed 15 percent of the channel's flow width. Spurs having permeabilities of 80 percent can have projected lengths up to 25 percent of the channel's bank-full flow width. Between these two limits, a linear relationship between the spur permeability and spur length should be used.

Spur Spacing

- The spacing of spurs in a bank-protection scheme is a function of the spur's length, angle, and permeability, as well as the channelbend's degree of curvature.

- The direction and orientation of the channel's flow thalweg plays a major role in determining an acceptable spacing between individual spurs in a bank-stabilization scheme.

- Reducing the spacing between individual spurs below the minimum required to prevent bank erosion between the spurs results in a reduction of the magnitude of flow concentration and local scour at the spur tip.
- Reducing the spacing between spurs in a bank-stabilization scheme causes the flow thalweg to stabilize further away from the concave bank towards the center of the channel.
- A spacing criteria based on the projection of a tangent to the flow thalweg, projected off the spur tip, as presented in the above discussions, should be used.

Spur Angle/Orientation

- The primary criterion for establishing an appropriate spur orientation for the spurs within a given spur scheme is to provide a scheme that efficiently and economically guides the flow through the channelbend, while protecting the channelbank and minimizing the adverse impacts to the channel system.
- Spurs angled downstream produce a less severe constriction of flows than those angled upstream or normal to flow.
- The greater an individual spur's angle in the downstream direction, the smaller the magnitude of flow concentration and local scour at the spur tip. Also, the greater the angle, the less severe the magnitude of flow deflection towards the opposite channelbank.
- Impermeable spurs create a greater change in local scour depth and flow concentration over a given range of spur angles than do permeable spurs. This indicates that impermeable spurs are much more sensitive to these parameters than are permeable spurs.
- Spur orientation does not in itself result in a change in the length of channelbank protected for a spur of given projected length. It is the greater spur length parallel to the channelbank associated with spurs oriented at steeper angles that results in the greater length of channelbank protected.
- Retardance spurs should be designed perpendicular to the primary flow direction.
- Retardance/diverter and diverter spurs should be designed to provide a gradual flow training around the bend. This is accomplished by maximizing the flow efficiency within the bend while minimizing any negative impacts on the channel geometry.

- The smaller the spur angle, the greater the magnitude of flow control as represented by a greater shift of the flow thalweg away from the concave (outside) channelbank.

- It is recommended that spurs within a retardance/diverter or diverter spur scheme be set with the upstream-most spur at approximately 150 degrees to the main flow current at the spur tip, and with subsequent spurs having incrementally smaller angles approaching a minimum angle of 90 degrees at the downstream end of the scheme.

Spur System Geometry

- A step-by-step approach to setting out the geometry of a retardance/diverter or diverter spur scheme was presented above. The use of this approach will yield an optimal geometric spur system design.

Spur Height

- The spur height should be sufficient to protect the regions of the channelbank impacted by the erosion processes active at the particular site.

- If the design flow stage is lower than the channelbank height, spurs should be designed to a height no more than three feet lower than the design flow stage.

- If the design flow stage is higher than the channelbank height, spurs should be designed to bank height.

- Permeable spurs should be designed to a height that will permit the passage of heavy debris over the spur crest and not cause structural damage.

- When possible, impermeable spurs should be designed to be submerged by approximately three feet under their worst design flow condition, thus minimizing the impacts of local scour and flow concentration at the spur tip and the magnitude of flow deflection.

Spur Crest Profile

- Permeable spurs should be designed with level crests unless bank height or other special conditions dictate the use of a sloping crest design.

- Impermeable spurs should be designed with a slight fall towards the spur head, thus allowing different amounts of flow constriction with stage (particularly important in narrow-width channels), and the accommodation of changes in meander trace with stage.

Channelbed and Channelbank Contact

- Careful consideration must be given to designing a spur that will maintain contact with the channelbed and channelbank so that it will not be undermined or outflanked. Methods and examples presented herein can be used to ensure adequate bend and bank contact.

Spur Head Form

- A simple straight spur head form is recommended.
- The spur head or tip should be as smooth and rounded as possible. Smooth, well-rounded spur tips help minimize local scour, flow concentration, and flow deflection.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. Highway Design and Operation for Safety

Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. Traffic Control and Management

Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. Highway Operations

This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. Pavement Design, Construction, and Management

Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. Structural Design and Hydraulics

Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. RD&T Management and Coordination

Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.