

Countermeasures for Scour and Stream Instability at Bridges

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This paper presents short case histories where stream instability has led to the failure or partial failure of a bridge. In this context, stream instability can be characterized by either lateral instability or by vertical instability. In general lateral instability is caused by lateral migration of the stream or river, while vertical instability can be caused by a combination of contraction scour, long term aggradation or degradation, and local scour. In this paper, the design of three principal common countermeasures will be discussed. These include spurs, check dams and guide banks.

On April 5, 1987, span 3 and 4 of the New York State Thruway bridge over Schoharie Creek collapsed causing loss of life, destruction of property and severing of an important transportation artery. Subsequent investigations [1] of this failure indicated that pier scour during a near record flood was the cause of the failure of this bridge. The pier scour which caused this failure is one of several types of vertical instabilities in rivers and streams which endanger bridge structures.

Lateral instability can also endanger highway crossings over rivers and streams. For example, consider the failure of U.S. 51 highway bridge over the Hatchie River, in Tennessee. On April 1, 1989 portions of this bridge collapsed, also causing loss of life. Lateral shifting of the channel which undermined a bent, was identified as the cause for this disastrous failure.

These failures of bridges due stream instabilities are not isolated cases. There are many documented cases where either lateral and vertical stream instability have caused damage and/or failure of bridges throughout the United States. For example *Highways in the River Environment* [2] (HIRE) documents cases in Oklahoma, where the bridge crossing of State Highway 51 over the Cimarron river, and the crossing of U.S. Highway 62 over the Arkansas river, have sustained damage by lateral shifting. HIRE [2] and also FHWA reports [3] and [4] also document other cases, such as SR-16 crossing over Lawrence Creek, Louisiana and on the Russian River in California, where vertical and/or lateral instabilities have endangered bridge crossings.

Recently, FHWA has produced two reports concerning the impact of stream stability on bridges over streams and rivers. The first, HEC-18 [5], discusses methods to evaluate scour at bridges. The second HEC-20 [6] focuses on the evaluation of stream instability as well as the selection and design of countermeasures to control lateral and vertical instabilities.

Countermeasures for the control of scour and stream instabilities at bridges and abutments are revetments, spurs, guide banks and check dams. Additionally, riprap can be considered a countermeasure for local scour at piers and abutments. Monitoring and inspection is considered to be a non-structural countermeasure for scour and instability problems at highway crossings.

Revetments are rigid or flexible armor placed on or parallel to a bank or embankment as a protection against scour and lateral erosion. Revetments can be constructed from a wide variety of construction materials, including rock (riprap), soil cement, sheet piles, rock-filled wire baskets (gabions), crib dikes, concrete mattresses, jacks, tetrahedrons, and used tires.

Spurs are either pervious or impervious structures which extend from the banks of a stream at an angle to the flow. The slowing of the flow caused by the spur protects bank lines and encourages deposition of transported material. Spurs countermeasures can be constructed of embankments with riprap, sheet piles, rock, rock-filled wire baskets (gabions), crib dikes, concrete mattresses, jacks, tetrahedrons, or fences made of treated wood or steel.

Guide banks are structures constructed perpendicular to the approach of a highway crossing at the bridge opening to guide flood flows through the bridge opening. These structures are usually constructed of embankment material and protected with riprap to impede erosion of the structure.

Check dams are constructed in the channel to provide protection from a difference in the bed elevation of the stream. These structures can be constructed of rock, concrete, sheet piles, gabions, or treated timber piles.

Although riprap can be used as a construction material for the countermeasures discussed above, it also can be considered as a countermeasure in and of itself for the control of local scour at piers and abutments.

Selection of countermeasures for these stream instabilities are presented in HEC-11 [7], 18 [5] and 20 [6] as well as in HIRE [2]. This paper will focus on three countermeasures for stream instability. These are; 1) spurs, for the control of lateral instabilities; 2) check dams for the control of vertical instabilities; and 3) guide banks for the control of abutment scour. Other countermeasures will be briefly discussed.

COUNTERMEASURES FOR STREAM INSTABILITY

General

Streams and rivers continuously adjust their slope, alignment, and channel shape based upon the volume of water and sediment they must transport [2, 3, 4, 5, and 6]. The extent and rate of these adjustments depends on a complex interaction of the rivers flow, and the physical constraints such as bed, banks and structures in the rivers channel or on the floodplain. These movements of river channels either laterally or vertically constitutes instability from the highway departments standpoint.

The selection of countermeasures for stream instability depends on the type of instability (lateral or vertical), the characteristics of the stream, construction and maintenance requirements, and costs. Characteristics of the stream include the channel width, bank heights, bank vegetation, sediment transport, velocities and the extent of ice and in debris the river. The reader is referred to HEC-20 [6] for a detailed discussion of the selection of countermeasures for stream instabilities.

Three primary countermeasures recommended in HEC-20 [6] are spurs, guide banks, and check dams. Spurs are used primarily for controlling lateral instabilities, while check dams are used to control vertical instabilities (specifically channel degradation). Guide banks are recommended to control abutment scour and to provide a more uniform flow through the bridge opening. A fourth countermeasure for scour and stream instability is monitoring and inspection of bridges. These countermeasures are discussed in detail in subsequent sections of this text. Other countermeasures will be discussed in more general terms.

Monitoring and Inspection

One of the most important countermeasure for scour and stream instability at bridges is monitoring and inspection. Monitoring and inspection should evaluate the long term aggradation, degradation, contraction scour, and local scour. Additionally, monitoring and inspection should assess the degree, location and rate of lateral shifting or widening of the river channel both upstream and downstream of the river crossing.

The frequency of monitoring and inspection depends on the vulnerability of the bridge to scour and stream instability. This frequency depends on whether or not the bridge is considered to be *scour critical* or not. A scour critical bridge is defined as a bridge whose foundation material and/or depth is unknown or insufficient to protect the bridge from failure caused by scour or stream instability.

At a minimum, for a non scour critical bridge, inspection frequency should be FHWA's mandatory two year cycle with a five year underwater inspection cycle for bridges with

foundations which cannot be inspected from the surface. For scour critical bridges, as an interim measure, monitoring during floods and inspection shortly thereafter can be used as a countermeasure. If monitoring a scour critical bridge during a flood is selected as an interim measure instead of closing the bridge, then piers and abutments must have interim protection such as riprap, or a method to determine that scour is not undermining the foundation must be provided. At this time the sizing of riprap to resist scour is not *fail-safe*. Therefore, even if riprap is placed around piers or abutments, the bridge must be monitored during floods and inspected afterwards.

Spurs

A spur is a previous or impervious structure projecting from the stream bank into the channel. Spurs are used to deflect flowing water away from, or to reduce flow velocities in critical zones near the stream bank, to prevent erosion of the bank, and to establish a more desirable channel alignment or width. The main function of spurs is to reduce flow velocities near the bank, and encourage sediment deposition. As sediment is deposited behind the spurs the stability of the banks is enhanced. Since the presence of spurs moves the location of scour away from the bank, partial failure of the spur can often be repaired before bridges and structures are damaged.

Spurs can be used to arrest meander migration and to channelize wide, poorly defined streams into better defined channels. The use of spurs to establish and maintain a well-defined channel location, cross-section, and alignment in braided streams can decrease required bridge lengths, decreasing the cost of bridge construction and maintenance.

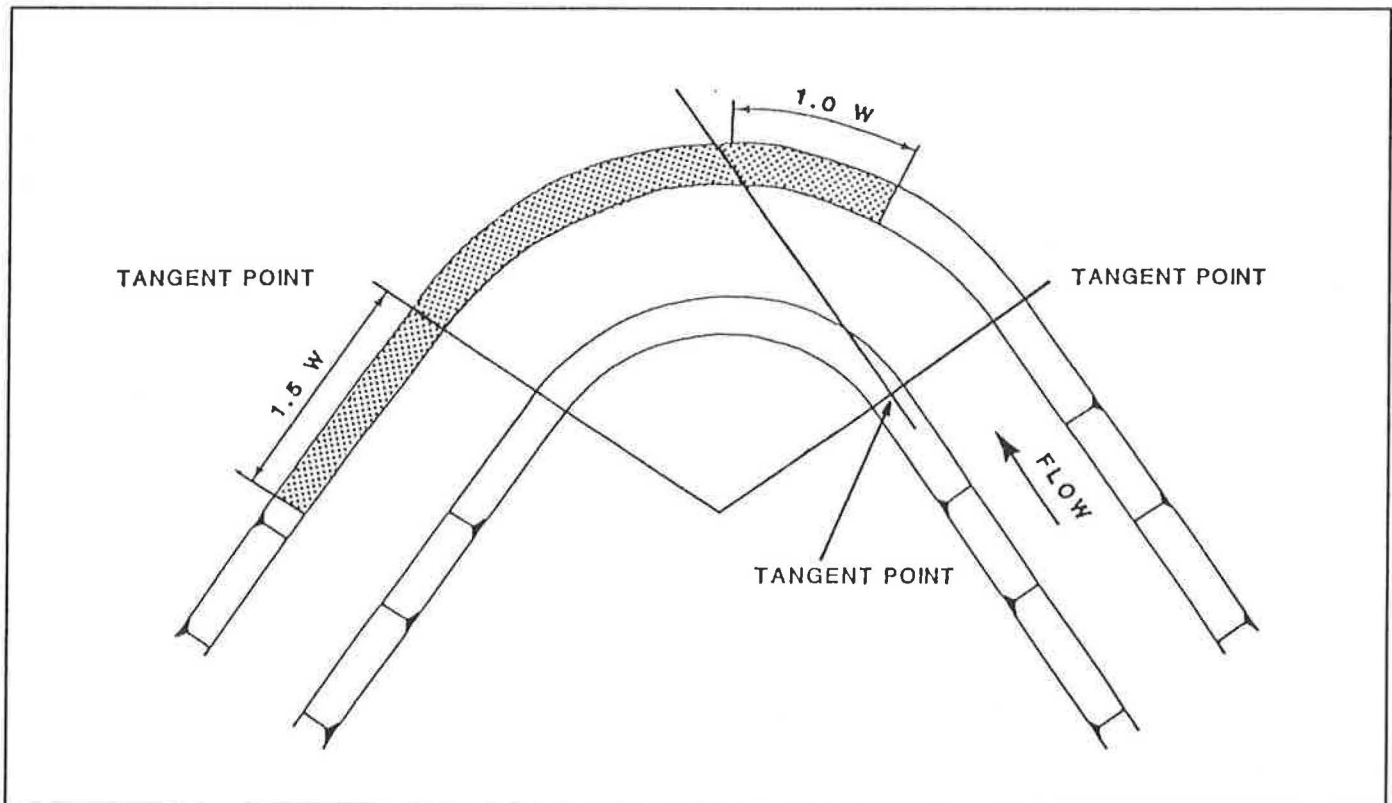


Figure 1 Extent of Protection Required at a Channel Bend (After [6]).

Spur design includes setting the limits of bank protection required; selection of the spur type to be used; and design of the spur installation including spur orientation, spacing, length, and height. Care must be exercised to carefully evaluate local scour at spurs and to protect them with riprap as necessary.

Limits of Spur Field

Spurs are constructed to protect a length of channel bank. As such a length of bank will require several spurs. The longitudinal extent of channel bank requiring protection is discussed in HEC-20 [6]. The minimum extent of bank protection determined from Figure 1 should be adjusted according to field inspections to determine the limits of active scour. In general, surveys of field installations of bank protection have found that protection commonly extends farther upstream than necessary and not far enough downstream.

Spur Type

Spur types are classified based upon their permeability as deflector spurs, retarder/deflector spurs, and retarder spurs. The permeability of spurs is defined simply as the percentage of the spur surface area facing the stream flow that is open. Deflector spurs are impermeable spurs which function by diverting the primary flow currents away from the bank. Retarder/deflector spurs are semi-permeable and function by retarding flow velocities at the bank and diverting flow away from the bank. Retarder spurs are more permeable and function by retarding flow velocities near the bank.

The primary factors influencing the selection of a specific spur type are the function, erosion mechanism of the stream, the sediment transport of the stream, flow velocities and depths, and whether ice or debris is present in the river. The selection of spur type for design purposes is discussed in detail in HEC-20 [6] and HIRE [2].

Spur Orientation

It is recommended that the spurs be oriented at an angle of approximately 90 degrees to the desired bank line. The only exception is for the spur furthest upstream which should be angled downstream to provide a smoother transition of the flow lines near the bank and to minimize scour at the nose of the leading pier. Subsequent spurs downstream should all be set normal to the desired bank line to minimize construction costs.

Spur Spacing

Spur spacing is a function of spur length, spur angle, permeability, and the degree of curvature of the bend. The flow expansion angle, the angle at which flow expands toward the bank downstream of a spur, is a function of spur permeability and the ratio of spur length to channel width. Figure 2 indicates that the expansion angle for impermeable spurs is almost constant at 17 degrees. Spurs with 35 percent permeability have almost the same expansion angle except where the spur length is greater than about 18 percent of the channel width.

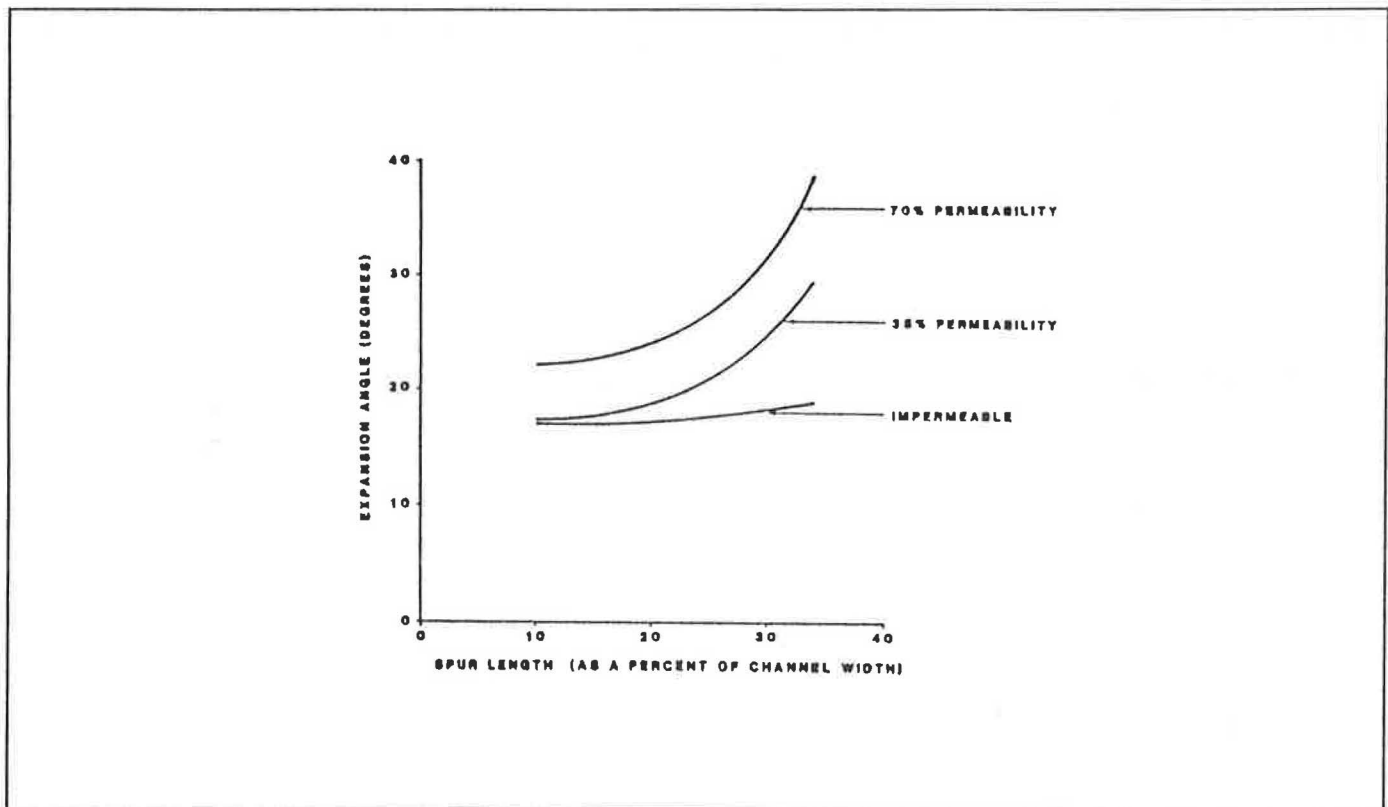


Figure 2 Relationship between spur length and expansion angle for several spur permeabilities. (From [6]).

The expansion angle for spurs increases as the permeability of the spur and as the ratio of spur length to channel width increases. The angle the spur makes with the flow (spur orientation) also influences the expansion angle but to a lesser degree.

Spurs should be spaced using Equation 1. This insures that the flow as it expands from the nose of the upstream spur will not intersect the bank to be protected before intersecting the next spur downstream.

$$S = L \cot \theta \quad (1)$$

where

S = is the spacing between spur toes. In the case of the furthest downstream spur this is the distance between the spur and the bank downstream. (ft),

L = is the effective length of spur, or the distance between the toe of spurs and the desired bank line, (ft) and

θ = is the expansion angle downstream of spur tips (degrees)

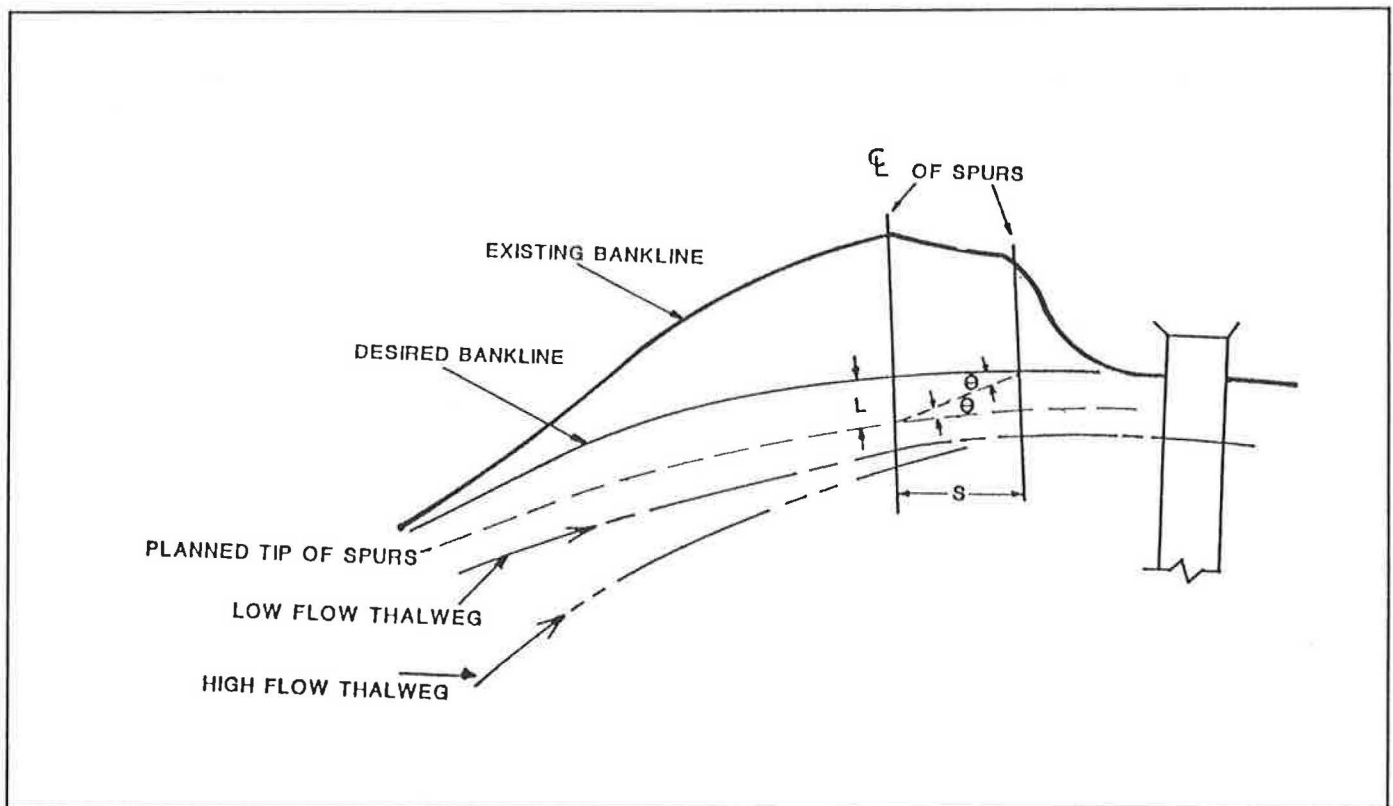


Figure 3 Illustration of spur spacing in a meander bend.

Spur spacing in a bend can be established on a scale plan view of the stream by drawing a line or arc describing the desired flow alignment as shown in Figure 3. This location should represent the desired location of the thalweg along the outside bank. The desired flow alignment may differ from existing conditions or represent no change in conditions, depending on whether there is a need to arrest erosion or reverse erosion that has already occurred. Base upon the desired flow alignment, a second line, describing the desired bank location can be established.

As a third step, a line which will connect the toe of the spurs in the installation. The distance from this line to the line describing the desired bank line, along with the expansion angle, will set the spacing between spurs. The line or arc describing the ends of spurs projecting into the channel will be essentially parallel or concentric with the arc describing the desired flow alignment.

Length, Height

Impermeable spurs are generally designed not to exceed the bank height because erosion at the end of the spur in the over bank area could increase the probability of outflanking at high stream stages. Where stream stages are greater than or equal to the bank height, impermeable spurs should be equal to the

bank height. If flood stages are lower than the bank height, impermeable spurs should be designed so that overtopping will not occur at the bank.

The crest of impermeable spurs should slope downward away from the bank line. Use of a sloping crest will avoid the possibility of overtopping at the bank, which could cause damage to the spur or to the stream bank.

Permeable spurs, and in particular those constructed of light wire fence, should be designed to a height that will allow heavy debris to pass over the top. However, highly permeable spurs consisting of jacks or tetrahedrons are dependent on light debris collecting on the spur to make them less permeable. The crest profile of permeable spurs is generally level except where bank height requires the use of a sloping profile.

In general the length of the spur is dictated by the location and spacing discussed earlier. The length must be sufficient to extent from the nose of the spurs to, or beyond the bank line. The bank side of the spurs should be anchored and tied into the existing bank to prevent outflanking by the stream.

Scour and Protection

Scour around spurs must be checked. Scour will be less for permeable spurs than for impermeable spurs. The determination of the extent of local scour at spurs is discussed

in HEC-20 [6] and also in HIRE [2]. For impermeable spurs, rock riprap should be placed on the upstream and downstream faces as well as on the nose of the spur to inhibit erosion of the spur. Depending on the embankment material being used, a gravel sand or fabric filter may be required.

It is recommended that riprap be extended below the bed elevation to a depth of five feet. Riprap should also extend to the crest of the spur, in cases where the spur would be submerged at design flow, or to two feet above the design flow, if the spur crest is higher than the design flow depth. Riprap should be placed on the upstream side of the spur and along the downstream side if the spur will be overtopped.

Guide Banks

When embankments encroach on wide flood plains, the flows from these areas must flow parallel to the approach embankment, to the bridge opening. These flows, can erode the approach embankment. At the abutment the severity of the contraction is increased by the returning flow, and can

reduce the effective bridge opening, thus increasing the severity of scour at the abutments of the bridge. Guide banks can be used effectively in these cases to prevent erosion of the approach embankments by cutting off the flow adjacent to the embankment, guide stream flow through a bridge opening, and to transfer scour away from abutments to prevent damage caused by abutment scour. Guide banks are often in other literature referred to as *Spurs* or *Spur Dikes*. However, this terminology is confused. Therefore the term *Guide Banks* is used, because it is more descriptive and will not be confused with *Spurs*.

Figure 4 presents a typical guide bank plan view. Without this guide bank, over bank flows would return to the channel at the bridge opening, which can increase the severity of contraction at the abutment. Note, that the scour hole which normally would occur at the abutment of the bridge is moved upstream away from the abutment.

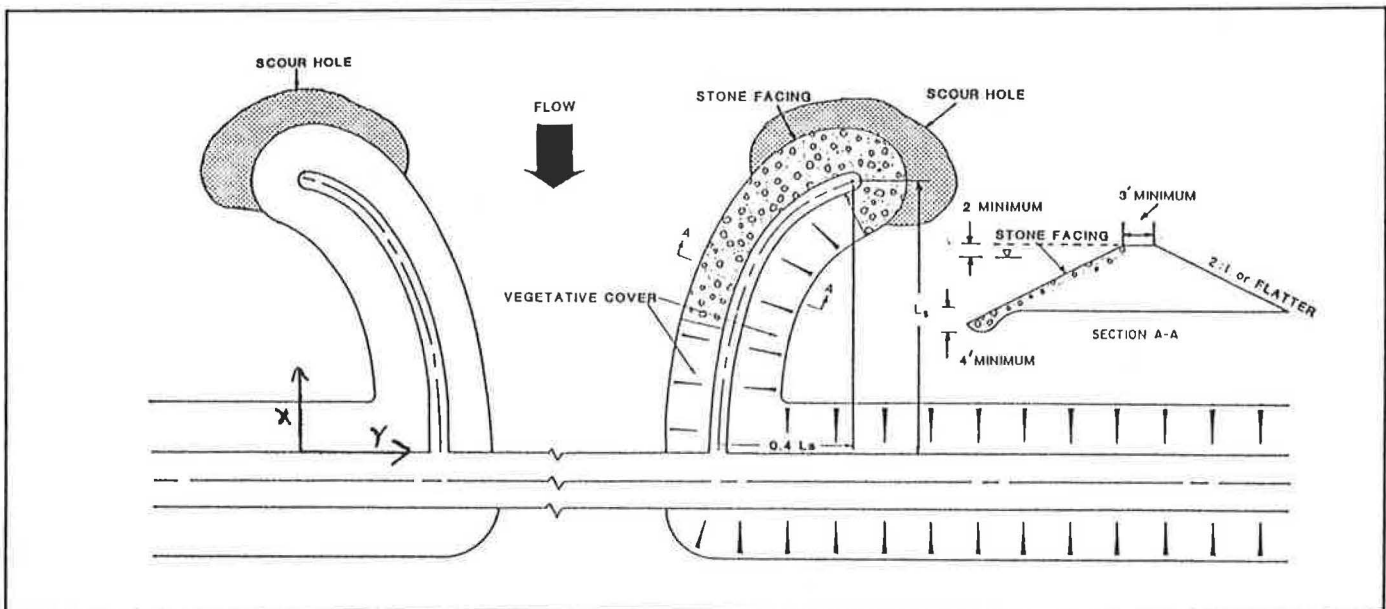


Figure 4 Typical Guide Bank

Guide banks can be used on both sand and gravel bed streams. Principal factors to be considered when designing guide banks, are their orientation to the bridge opening, upstream and downstream length, plan shape, cross-sectional shape, and crest elevation.

Orientation and Plan Shape

Guide banks begin and extend upstream from the abutments of the bridge opening. If guide banks are used on both sides of the stream, the distance between the guide banks at the bridge opening should be set equal to the distance between bridge abutments. Best results are obtained by using guide banks with a plan form shape in the form of a quarter of an ellipse, with the ratio of the major axis (length L_s) to the minor axis (offset) equal to 2.5 : 1. This allows for a gradual constriction of the flow. For design purposes, the length of the guide bank, measured perpendicularly from the approach embankment to the upstream nose of the guide bank, is denoted as L_s . The amount of expansion of each guide bank (offset), measured

from the abutment, parallel to the approach, should be $0.4 L_s$.

The plan view orientation can be determined using Equation 2 which is the equation of an ellipse with origin at the nose of the guide bank. For this equation, the orientation of the orthogonal axes for X and Y are shown on Figure 4.

$$\frac{X^2}{L_s^2} + \frac{Y^2}{(0.4L_s)^2} = 1 \quad (2)$$

Length

For design of guide banks, the length of the guide bank, L_s , can be determined using a nomograph which was developed from laboratory tests performed at Colorado State University and from field data compiled by the U.S. Geological Survey [6]. For design purposes the utilization of the nomograph which is presented in Figure 5 involves the following parameters:

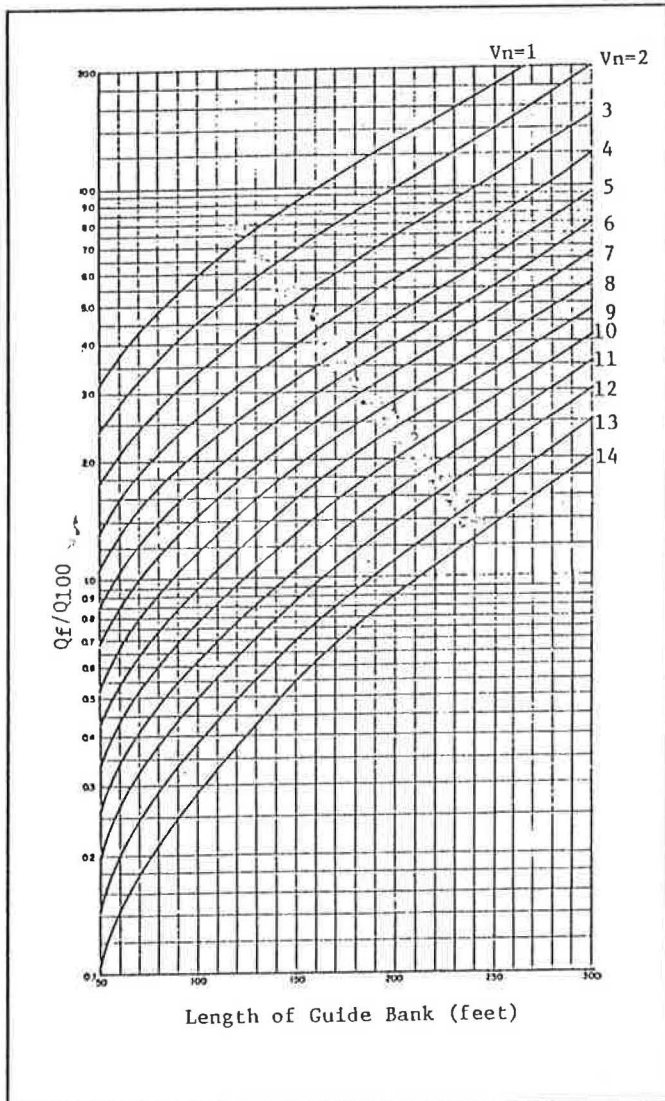


Figure 5 Nomograph to Determine Guide Bank Length
(After [6])

Q = Total discharge of the stream (cfs),

Q_f = Lateral or flood plain discharge of either flood plain (cfs),

Q_{100} = Discharge in 100 feet of flood plain adjacent to the main channel which is cut off by the approach embankment (cfs),

b = Length of the bridge opening (ft),

A_{n2} = Cross-sectional flow area at the bridge opening at normal stage (ft^2)

$V_{n2} = \frac{Q}{A_{n2}}$ = Average velocity through the bridge opening (cfs),

$\frac{Q_f}{Q_{100}}$ = Guide bank discharge ratio

L_s = Projected length of guide bank.

The nomograph should be used to determine the guide bank length for designs greater than 50 feet and less than 250 feet. If the nomograph indicates the length required to be greater than 250 feet the design should be set at 250 feet. For guide banks less than 50 feet, no guide bank is required.

Cross-Section And Crest Elevation

In contrast to spurs, guide banks should be designed so that they will not be overtopped at the design discharge. If this were allowed to occur, unpredictable cross flows and eddies could scour and undermine abutments. In general a minimum of 2 feet of freeboard, above the design water surface elevation should be maintained.

The cross-sectional shape and size of guide banks should be similar to spurs discussed previously. That is to say that the minimum crest width should be 3 feet, however widths of 10 to 12 feet are more common due to construction methods used. The upstream end of the guide bank should be round nosed. Side slopes should be 2:1 or flatter.

Some states construct short guide banks downstream of the abutments to minimize scour due to rapid expansion of the flow at the downstream end of the abutments. These shorter guide banks are usually less than 50 feet long and are sometimes referred to as *heels*.

Check Dams

Check dams or channel drops are used downstream of highway crossings to control vertical instabilities by arresting head cutting, general channel degradation or the progression of nickpoints upstream. Typically check dams are usually built of rock riprap, concrete, sheet piles, gabions, or treated timber piles.

Check dams can initiate erosion of banks and the channel bed downstream of the structure as a result of energy dissipation and turbulence at the drop. This local scour can undermine the check dam and cause failure. The use of energy dissipaters downstream of check dams can reduce the energy available to erode the channel bed and banks. In some cases it may be less costly to construct several consecutive drops of shorter height to minimize extensive erosion control.

Lateral erosion of channel banks just downstream of drop structures is another adverse result of check dams and is caused by turbulence produced by energy dissipation at the drop, bank slumping from local channel bed erosion, and eddy action at the banks. The solution to this problem is to place revetment or riprap on the stream bank.

Design Considerations

A typical vertical drop is diagramed in Figure 6. For lack of any better equation, the Veronese equation (Equation 3) is recommended for all conditions to estimate the depth of scour downstream of a vertical drop for submerged and unsubmerged conditions [6].

$$d_s = K H_i^{0.225} q^{0.54} - d_m \quad (3)$$

where

d_s = Local scour depth for a free overfall, measured from the stream bed downstream of the drop, (ft),

q = Discharge per unit width, (cfs per foot of width),

H_i = Total drop in head, measured from the upstream to the downstream energy grade line, (ft),

d_m = Tail water depth, (ft).

$K = 1.32$

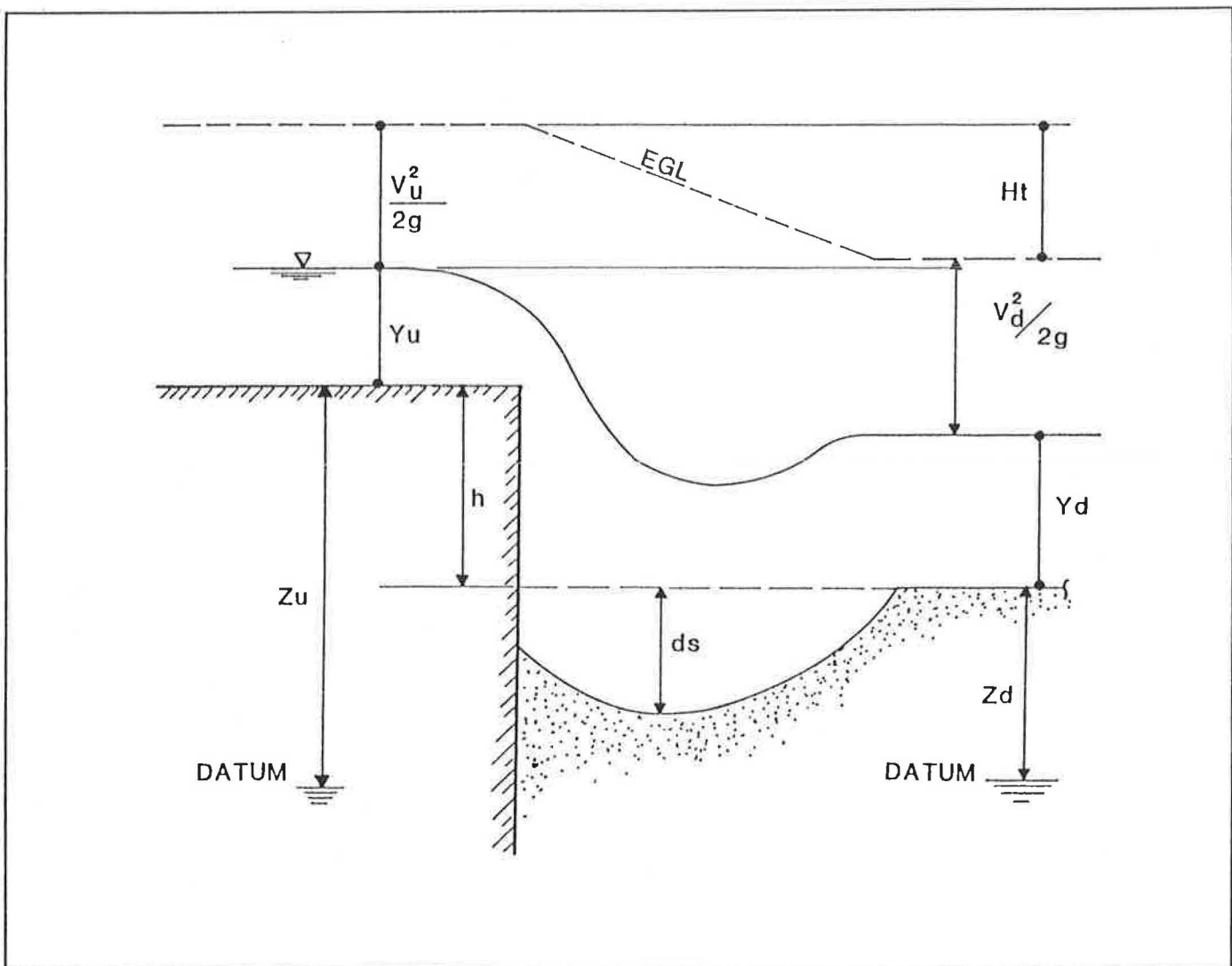


Figure 6 Schematic of a Vertical Drop Caused by a Check Dam (After [6])

It should be noted that H_t is the difference in the total head from upstream to downstream. This can be computed using Bernoulli's equation for steady uniform flow Equation 4.

$$H_t = \left\{ Y_u + \frac{V_u^2}{2g} + Z_u \right\} - \left\{ Y_d + \frac{V_d^2}{2g} + Z_d \right\} \quad (4)$$

where

Y = Depth (ft)

V = Velocity (ft/s)

Z = Bed elevation referenced to a common datum (ft)

g = Acceleration due to gravity 32.2 ft/s^2

The subscripts u and d refer to upstream and downstream of the channel drop respectively.

It should be noted that the depth of scour as estimated by the above equation is independent of the grain size of the bed material. This concept acknowledges that the bed will scour regardless of the type of material composing the bed but the rate of scour depends on the composition of the bed. In some cases, with large or resistive material, it may take years or decades to develop the maximum scour hole. In these cases the design life of the bridge may need to be considered when designing of the check dam.

The check dam must be designed structurally to withstand the forces of water and soil assuming that the scour hole is as deep as estimated using the equation above. Therefore, the designer should consult soils and structural engineers so that the check dam will be stable under these scoured conditions. In some case a series of check dams may be employed to minimize construction costs of foundations.

Other Countermeasures

Other countermeasures for the control of lateral and vertical instabilities include revetments, riprap, hardpoints, jacks, tetrahedrons, longitudinal, rock dikes, vane dikes, crib dikes, bulkheads, and soil cement. The selection and design of these countermeasures are discussed in FHWA publications HEC-11[7], HEC-18 [5], HEC-20 [6] and HIRE [2].

Many of these countermeasures can be used to enhance the function of one of the countermeasures discussed in this paper. In some cases, the use of these other countermeasures can be used as temporary methods for immediate protection of a bridge or highway encroachment.

One of the most promising methods of stabilizing banks when large rock is not available is the use of soil cement. This method mixes cement with native soils which is placed along

river banks. This strengthens the banks and helps to resist the erosive action of the flow. The use of soil cement has been shown to be an effective means to protect banks.

SUMMARY AND DISCUSSION

Recognizing that the failure or damage to bridges and highway crossings due to lateral and vertical instabilities of the stream and rivers, the Federal Highways Administration has produced a series of Hydraulic Engineering Circulars (HEC) to aid highway engineers. These publications provide for the selection, evaluation and design of countermeasures to protect highway bridges and highway crossings from scour and instabilities of the river.

Three principal countermeasures for the protection of bridges are spurs, for lateral instabilities, check dams, for vertical instabilities, and guide banks for the improvement of the flow hydraulics through bridge openings and as a countermeasure to control abutment scour. These designs of these three countermeasures are described in this paper.

An important distinction in terminology between guide banks and spur dikes was made in this paper. That is, that the term guide bank is a more descriptive term for structures which align and guide the flow through the bridge opening. The use of the term *spur dike* which guide banks are often referred to as, is too often confused with *spurs*. The function of guide banks are to align the flow while the function of spurs are to divert or impede the flow.

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