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Design Guidelines for Spur-Type Flow-Control Structures

SCOTT A. BROWN

ABSTRACT

A study investigating the applicability and design of spur-type flow-control and stream-bank stabilization structures has been conducted to establish design guidelines for the use of spurs. The study was conducted jointly by the Sutron Corporation and the Pennsylvania State University for FHWA. The findings and recommendations are presented, and recommendations for the general application of spur-type flow-control structures are given in relation to the 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, and design guidelines for establishing spur permeability, the required extent of protection, spur length, spur spacing, spur orientation, and spur height are presented. An example outlining a recommended procedure for establishing the geometric layout of spurs within a spur scheme is presented also.

Spurs are defined as permeable or impermeable linear structures that project into a channel to alter flow direction, induce deposition, or reduce flow velocities along a channel bank. Spurs can be classified as permeable or impermeable; they can be classified further by function as retardance structures, retardance-diverter structures, and diverter structures. Retardance and retardance-diverter structures are permeable; 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 channel bank. Retardance-diverter structures retard the flow along the channel bank, but they also deflect flow currents away from the bank. Diverter spurs, on the other hand, function by diverting the primary flow currents away from the channel bank. Design guidelines primarily for retardance-diverter and diverter spurs are dealt with in this paper.

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 based primarily on the designer's experience and numerous rules of thumb. Although actual field design experience is indispensable when flow-control structures are designed, many highway design engineers have only limited experience in this field, indicating a need for some design guidance. A study was sponsored by FHWA to address this need.

The FHWA study included considerations of the overall applicability of spur-type flow-control and stream-bank stabilization structures, the applicability and attributes of individual spur types, criteria for the selection of a specific spur type, and guidelines for the design of spurs. Guidelines for the actual design of spur systems are covered in

this paper. Guidelines for establishing spur per-
meability, the required extent or upstream and down-
stream limits of protection, spur length, spur spac-
ing, spur orientation, spur height, spur crest
profile, and spur tip or head shape, and for main-
taining channel-bed and bank contact are included.
An example outlining the procedure for establishing
the geometric layout of spurs within a spur scheme
is also included. Applicability and spur-type se-
lection guidelines are covered in a report by FHWA
(1).

The design guidelines presented here are based on
a thorough literature review, extensive review and
evaluation of spur field installations, numerous
personal contacts with design engineers actively in-
volved in designing flow-control structures, and a
laboratory study designed to evaluate critical spur
design parameters (2). The following summary of the
major design recommendations presented in the FHWA
report is organized by design component for easy
reference.

PERMEABILITY

For retardance-diverter structures, a variety of
spur permeabilities can be and have been designed.
The various levels of spur permeability are typi-
cally obtained by using different densities of wood
slats or wire mesh attached to the support struc-
tures. Sample design details of spurs of various
permeabilities are given in the FHWA report (1). As
referred to here, spur permeability is defined as
the percentage of the spur's surface that is open or
unobstructed. In environments where it can be rea-
sonably assumed that the permeable structure will
not clog with floating debris or other material, the
determination of a particular spur's permeability
requires only 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 computa-
tion of a given spur permeability.

The magnitude of spur permeability appropriate
for a given flow-control or channel-bank stabiliza-
tion application is inversely proportional to the
magnitude of flow retardance required, the level of
flow control desired, or the channel-bend radius.
In all cases, the greater the magnitude of the vari-
able, the lesser the degree of spur permeability.
Where it is necessary to provide a significant re-
duction in flow velocity or a high level of flow
control or where the structure is being used on a
sharp bend, the spur's permeability should not ex-
ceed 35 percent. Where it is necessary to provide a
moderate reduction in flow velocity or a moderate
level of flow control or where the structure is be-
ing used on a mild to moderate channel bend, spurs
with permeabilities up to 50 percent can be used.
In environments where only a mild reduction in ve-
locity is required, where bank stabilization without
a significant amount of flow control is necessary,
or where there are mildly curving to straight chan-
nel 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 par-
ticular environment.

Recent laboratory studies (2) have provided addi-
tional insight into how various spur permeabilities
affect spur behavior. The following is a summary of
the findings from the FHWA laboratory investigation
relating to spur permeability:

1. 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.
2. The vertical structural members of permeable
spurs should be round or streamlined to minimize
local scour effects.
3. The greater the spur permeability, the lower
the magnitude of flow concentration at the spur tip.
4. If minimizing the magnitude of flow deflec-
tion and flow concentration at the spur tip is im-
portant to a particular spur design, a spur with a
permeability greater than 35 percent should be used.
5. The more permeable the spur, the shorter the
length of channel bank protected downstream of the
spur's riverward tip.
6. Spurs with permeabilities up to approximately
35 percent protect almost the same length of channel
bank as do impermeable spurs; spurs having permea-
bilities greater than approximately 35 percent pro-
tect shorter lengths of channel bank, and this
length decreases with increasing spur permeability.
7. Because of the increased potential for ero-
sion of the channel bank in the vicinity of the spur
root and immediately downstream when the flow stage
exceeds the crest of impermeable spurs, it is recom-
mended that impermeable spurs not be used along
channel banks composed of highly erodible material
unless measures are taken to protect the channel
bank in this region.

GEOMETRY

The geometry of a spur system is made up of several
components that, when combined, produce the spur
system's geometric form. These components include
the longitudinal extent of the spur system and the
length, spacing, and orientation of individual
spurs. The longitudinal extent of the spur system
describes the length of channel bank that is to be
protected; the length, spacing, and orientation of
individual spurs are self-explanatory. In this sec-
tion, there will be a brief discussion of each com-
ponent separately and then they will be considered
together to provide criteria for delineating an ap-
propriate spur geometry.

Extent of Bank Protection

The extent of channel-bank protection required on a
typical eroding channel bend has been investigated
by several researchers, including Parsons (3),
Apmann (4), and the U.S. Army Corps of Engineers
(5). These investigators as well as others have
found that a common mistake in streambank protection
is to provide protection too far upstream and not
far enough downstream.

Criteria for establishing the extent of channel-
bank protection have been developed by the U.S. Army
Corps of Engineers (5) in a series of model stud-
ies. From these studies, it was concluded that the
minimum distances for extension of protection are an
upstream distance of 1.0 channel width and a down-
stream distance of 1.5 channel widths from corre-
sponding reference lines as shown in Figure 1. A
similar criterion for establishing the upstream
limit of protection was found by FHWA (2); however,
a downstream limit of 1.1 times the channel width
was found. The FHWA study was not, however, as ex-
tensive in this respect as that of the Corps of En-
gineers.

These criteria are based on analysis of flow con-
ditions in symmetric channel bends under ideal lab-
oratory conditions. Real-world conditions are
rarely as simple. In actuality, many site-specific
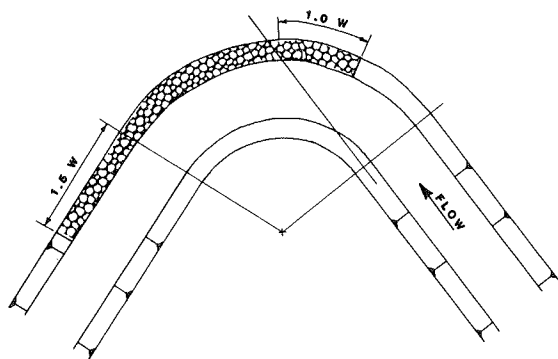factors have a bearing on the actual length of bank

FIGURE 1   Extent of protection required around a channel bend (5).

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 a bridge abutment) might already be producing a stabilizing effect on the bend so that only a part of the channel bend would need to be stabilized. In addition, the magnitude or nature of the flow event might cause erosion problems only in a localized portion of the bend, again requiring that only a short channel length be stabilized. Therefore, the foregoing criteria should be used only as a starting point. From here, additional analyses of site-specific factors should be conducted, including field reconnaissance, evaluation of flow traces for various flow conditions, and review of flow and erosion forces for various flow-stage conditions. Information from these analyses should then be combined with personal judgment and a knowledge of the flow processes occurring at the local 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 channel-bank 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 channel banks 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 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 provide a smooth flow alignment.

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 earlier). The behavior of specific spur types was investigated during the recent laboratory studies conducted by FHWA (2). The following summary of the findings from the FHWA laboratory studies indicates that as spur length is increased,

1. The scour depth at the spur tip increases,
2. The magnitude of flow concentration at the spur tip increases,

3. The severity of flow deflection increases, and
4. The length of channel bank protected increases.

The following general recommendations are given regarding spur length:

1. The projected length of impermeable spurs should be held to less than 15 percent of the channel width at bank-full stage.
2. 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

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. Based on this criterion, spur spacing is a function of the spur's length only. Based on the FHWA laboratory study (2), however, it was found that spur spacing is also dependent on the spur's orientation, its permeability, the channel bend's degree of curvature, and the direction and orientation of the channel's flow thalweg. Each of these factors is an integral part of a method for establishing spur system geometry, which will be presented later. The spacing criterion presented is based on the projection of a tangent to the flow thalweg off the spur tip.

In addition, the following comments can be made regarding the impact that various spur spacings have on flow patterns in channel bends:

1. 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 and
2. Reducing the spacing between spurs in a bank stabilization scheme causes the flow thalweg to stabilize farther from the concave bank toward the center of the channel.

Spur Angle and Orientation

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 channel bend and at the same time protects the channel bank and minimizes the adverse impacts on the channel system. Meeting these criteria requires consideration of how various spur angles influence flow patterns around individual spurs, flow concentration at the spur tip, scour depths at and just downstream of the spur tip, the length of channel bank protected by individual spurs, and flow deflection.

The following list describes how the foregoing criteria are affected by a spur's orientation:

1. Spurs angled downstream produce a less severe constriction of flows than those angled upstream or normal to the flow.
2. The greater an individual spur's angle in the downstream direction, the less the flow concentra-

tion and local scour at the spur tip. Also, the greater the angle, the less severe the flow deflection toward the opposite channel bank.

3. 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 permeable spurs.

4. Spur orientation does not in itself result in a change in the length of channel bank protected for a spur of given projected length. It is the greater spur length parallel to the channel bank associated with spurs oriented at steeper angles that results in the greater length of protection.

5. 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) channel bank.

It is recommended that spurs within a retardance-diverter or diverter spur scheme be set so that the spur that is farthest upstream is approximately 150 degrees to the main flow current at the spur tip and subsequent spurs are at incrementally smaller angles approaching a minimum angle of 90 degrees at the downstream end of the scheme. The method of establishing the spur angle and orientation presented in the geometric design example in the next section should be used to set the orientation of individual spurs within a spur scheme.

Geometric Design Example

A step-by-step approach for establishing the geometric layout of a retardance-diverter or diverter spur scheme follows. This method is designed to provide an optimal geometric layout. Figure 2 shows a meandering channel that has encroached on a bridge abutment. The objective in this situation is to establish the bank line that existed before the erosion shown. Also, because of severity or sharpness of the channel bend and the need for a positive flow deflection, an impermeable spur scheme will be designed. The steps in the procedure are as follows:

Step 1: establish the limits of the flow-control and bank stabilization scheme,

Step 2: set the desired flow alignment and maximum flow constriction,

Step 3: estimate the flow thalwegs through the bend,

Step 4: locate and orient spur 1,

Step 5: locate spur 2,

Step 6: orient spur 2, and

Step 7: locate and orient subsequent spurs.

Setting Limits of Protection

In Figure 3 the procedure used to set the limits of the flow-control scheme is shown. 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, because 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 one channel width upstream of the upstream reference line, which is set by projecting a tangent to the convex channel bank 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 was set upstream of the point of observed erosion.

Setting Maximum Flow Constriction

The object here is to shift the channel-flow alignment to that which existed before the bank erosion. This desired flow alignment was shown in Figure 2. The dashed line in Figure 4 represents a 10 percent constriction of the channel width, which 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
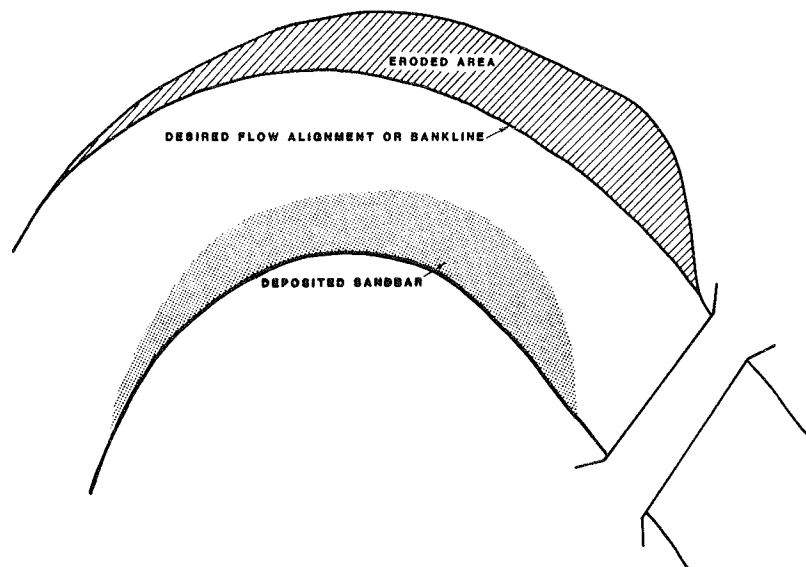

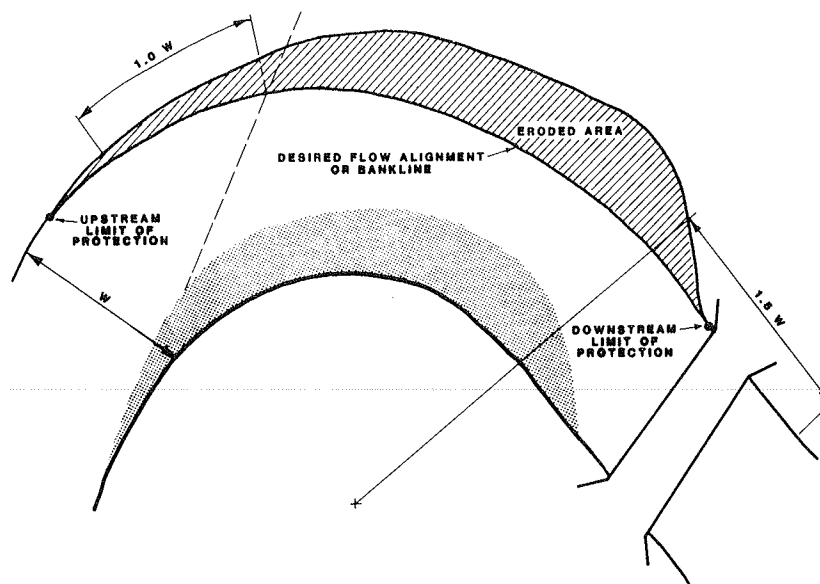FIGURE 2 Channel bend showing eroded area, desired flow alignment, and deposited sandbar.

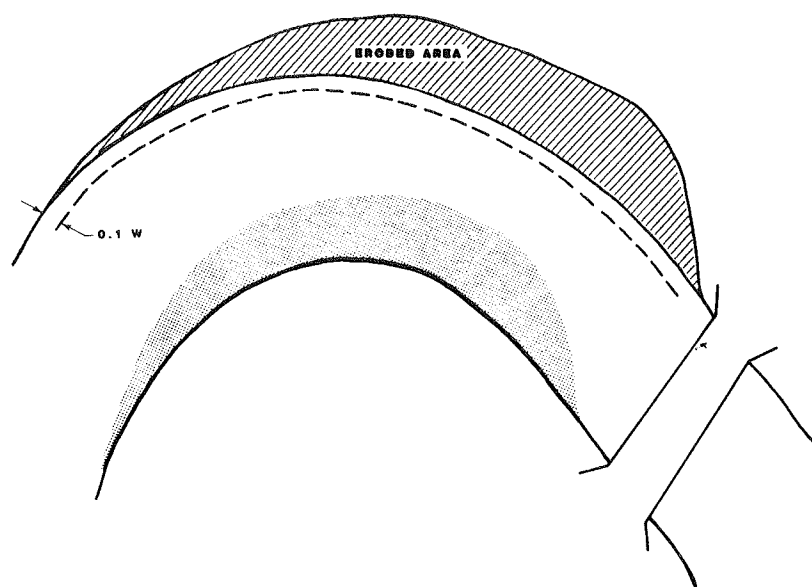FIGURE 3   Setting the limits of protection.

FIGURE 4   Setting maximum flow constriction.

also minimizes the chance that spurs will deflect currents into the opposite channel bank.

Estimating 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. A general knowledge of flow patterns in channel bends and how these flow patterns change with varying stages of discharge is required to establish appropriate flow thalweg locations. Discussions of this nature are beyond the scope of this paper. Sketching three thalweg locations corresponding to low, medium, and high channel flow conditions will usually provide sufficient definition. Figure 5 shows these three thalweg locations for the sample conditions. A thorough knowledge of flow in natural channel bends is required for accurate estimation of these thalweg locations.

Location and Orientation of Spur 1

Figure 6 shows the procedure used to locate and orient the first spur, the one that is farthest upstream. First the bend radius line R1 is drawn from the center of curvature of the bend through the point limiting the upstream 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, because it will generally follow the desired flow alignment. Such a flow tangent is shown in Figure 6 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'
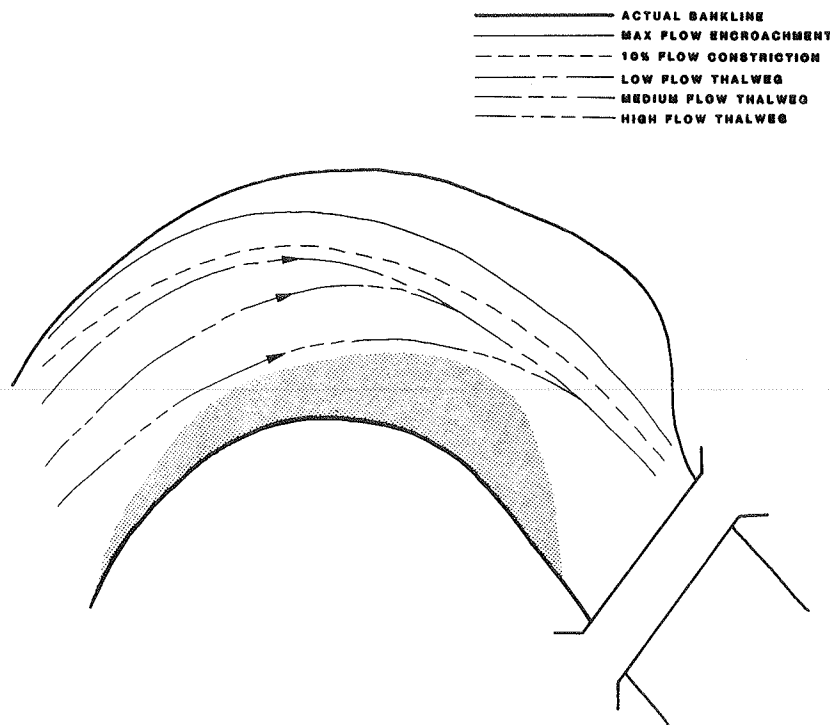
ACTUAL BANKLINE
MAX FLOW ENCROACHMENT
10% FLOW CONSTRICTION
LOW FLOW THALWEG
MEDIUM FLOW THALWEG
HIGH FLOW THALWEG

FIGURE 5 Estimates of thalweg locations for various flow conditions.

ACTUAL BANKLINE
MAX FLOW ENCROACHMENT
10% FLOW CONSTRICTION
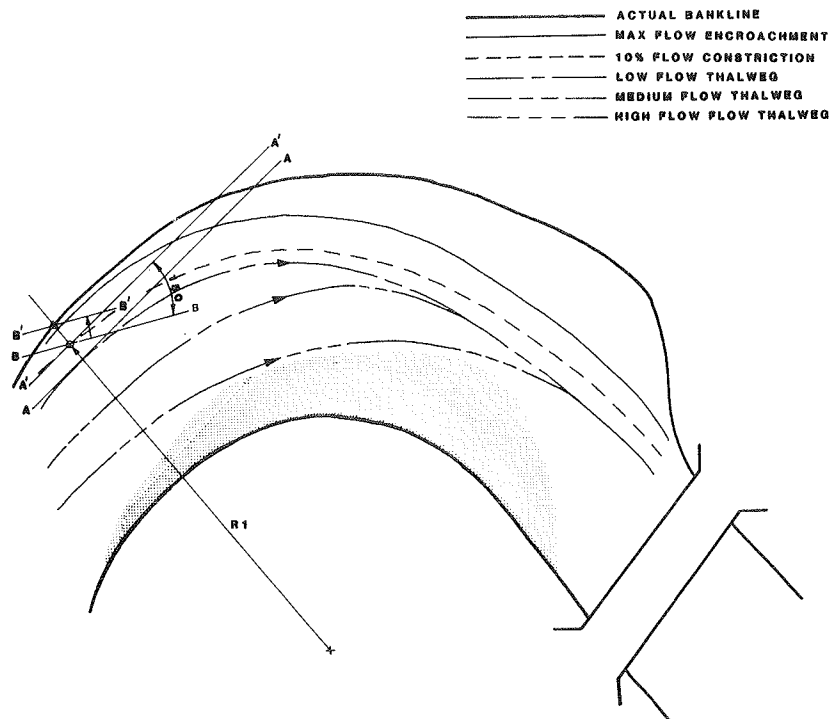LOW FLOW THALWEG
MEDIUM FLOW THALWEG
HIGH FLOW FLOW THALWEG

FIGURE 6 Location and orientation of first spur.

is then drawn through the point defining the up-
stream limit of protection (spur location point)
parallel to line BB. This line defines the location
of the centerline of the spur. The spur length is
then set between the eroded bank line and the 10
percent flow-constriction line.

Location of Spur 2

The approach to locating the second spur is shown in
Figure 7. This approach will be used to locate each
subsequent spur. First another radius line, R2 in
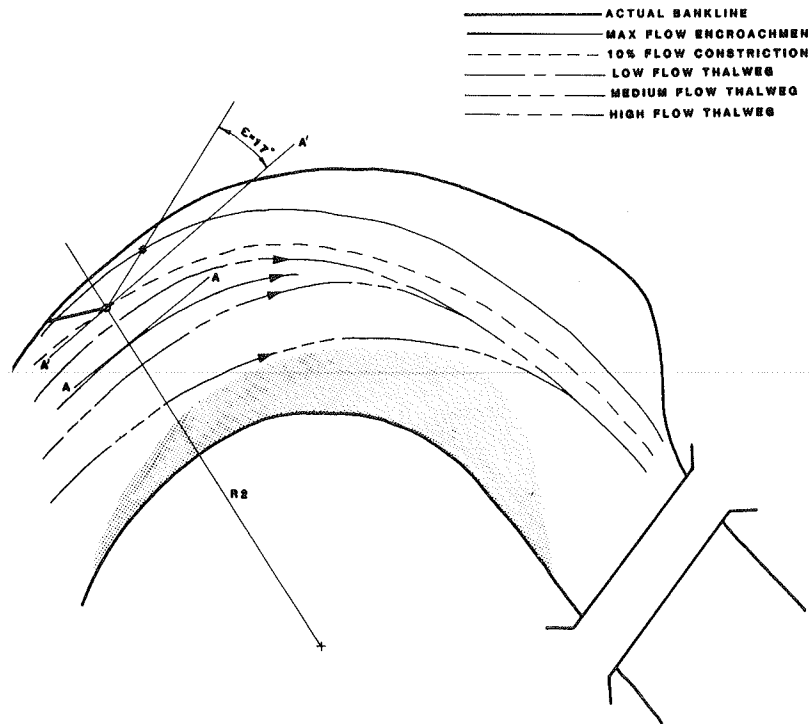Figure 7, is drawn through the tip of the previous

FIGURE 7   Location of second spur.

spur. The location of the next downstream spur de-
pends on the orientation of a tangent to the channel
thalweg where it intersects line R2. However, three
flow thalweg lines have been sketched representing
different flow conditions. The appropriate flow
thalweg is that which intersects line R2 at one
quarter of the channel width from the flow-constric-
tion line. Line AA in Figure 7 illustrates the tan-
gent 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'. From line A'A', an expansion angle of 17 de-
grees (as determined for impermeable spurs at 10
percent constriction) is turned toward the concave
bank line (counterclockwise). The location of the
next downstream spur is defined by the point at
which the rotated line intersects the line of maxi-
mum flow encroachment. This point is indicated by
an asterisk in Figure 7.

Orientation of Spur 2

Setting the orientation of spur 2 and each subse-
quent spur is the same as the procedure for orient-
ing spur 1. As shown in Figure 8, the first step is
to draw a radius line (R3) through the spur location
point (asterisk). Next a flow tangent to the esti-
mated 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 bank line and the 10 percent
flow-constriction line.

Location and Orientation of Subsequent Spurs

Steps 5 and 6 are repeated until the downstream

limit of protection is reached. Figure 9 shows the
final geometry developed in this manner.

Several additional comments can be made about the
example just presented. The spur angles used when
setting out the sample spur scheme are shown in Fig-
ure 9. Note that the spur angles decrease from 150
degrees to 120 degrees and then remain constant.
This was done to provide a more efficient flow path
through the channel bend. This example documents a
relatively sharp bend requiring maximum flow effi-
ciency. 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. The dogleg was designed into this spur to
minimize its total length and thus its cost. This
leg of the spur is not affected by channel flows be-
cause it is inside the maximum flow encroachment
line. Doglegs such as this can be designed where
they will provide an economic advantage without af-
fecting the stabilization scheme. It is also inter-
esting to note the relative spacing of the spurs:
those on the downstream half of the bend are closer
together, which provides a more positive control of
flow in this region (1,2).

SPUR HEIGHT

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

  1. The mechanism causing the erosion,
  2. The existing channel-bank height,
  3. The design flow stage, and
  4. The flow stage at which significant debris
loads become a problem.

With these factors in mind, the following recommen-
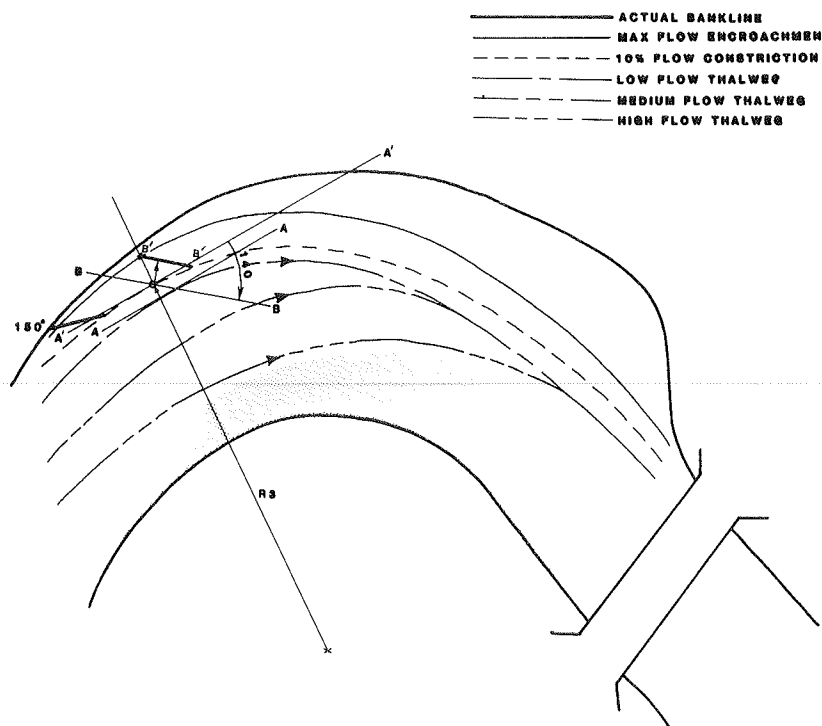dations are made for establishing the height of spur
systems:

ACTUAL BANKLINE
MAX FLOW ENCROACHMENT
10% FLOW CONSTRICTION
LOW FLOW THALWEG
MEDIUM FLOW THALWEG
HIGH FLOW THALWEG

FIGURE 8 Orientation of spur 2.

ACTUAL BANKLINE
MAX FLOW ENCROACHMENT
10% FLOW CONSTRICTION
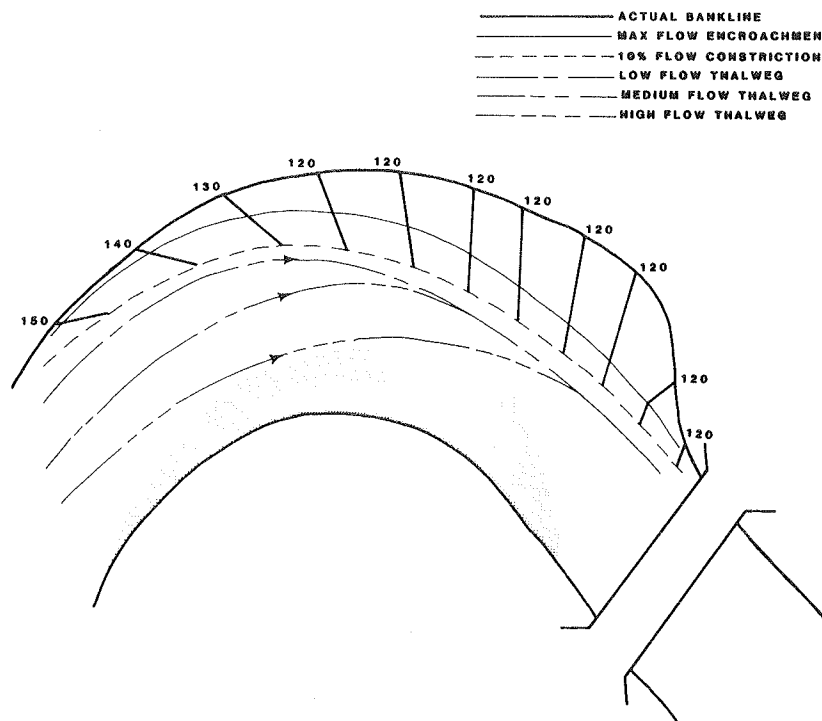LOW FLOW THALWEG
MEDIUM FLOW THALWEG
HIGH FLOW THALWEG

FIGURE 9 Final spur scheme geometry.

1. The spur height should be sufficient to pro-
tect the regions of the channel bank affected by the
erosion processes active at the particular site.

2. If the design flow stage is lower than the
channel-bank height, spurs should be designed to a
height no more than 3 ft lower than the design flow
stage.

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

4. Permeable spurs should be designed to a
height that will permit the passage of heavy debris
over the spur crest without causing structural
damage.

5. When possible, impermeable spurs should be
designed to be submerged approximately 3 ft 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

The following recommendations are made for spur-crest profile:

1. Permeable spurs should be designed with level crests unless bank height or other special conditions dictate the use of a sloping crest design.
2. Impermeable spurs should be designed with a slight drop toward 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.

CHANNEL-BED AND CHANNEL-BANK CONTACT

Careful consideration must be given to designing a spur that will maintain contact with the channel bed and channel bank so that it will not be undermined or outflanked. Methods for protecting against structure undermining include

1. Providing a rock toe at the base of the structure,
2. Driving vertical support members to a depth greater than anticipated scour depths,
3. Extending the structure's face material to a depth greater than anticipated scour depths, and
4. Designing the structure so that it can be flexible in the vertical direction and thus maintain bed contact.

To protect against outflanking, the structure should be designed with a root structure that extends for a distance into the channel bank.

SPUR-HEAD FORM

Numerous design shapes have been suggested for the head or riverward tip of the spur: straight, T-head, L-head, wing, hocky, inverted hocky, and so on. 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 and flow velocities at the spur tip.

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