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# **Stream Stability at Highway Structures**

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16. Abstract  This document provides guidelines for identifying stream instability problems at highway stream crossings and for the selection and design of appropriate countermeasures to mitigate potential damages to bridges and other highway components at stream crossings. It is a metricated update of the version published in 1991 under Contract No. DTFH61-89-C-00003. The HEC-20 manual covers geomorphic and hydraulic factors that affect stream stability and provides a step-by-step analysis procedure for evaluating stream stability problems. Guidelines and criteria for selecting countermeasures for stream instability problems are summarized, and the design of three countermeasures (spurs, guide banks, and check dams) is presented in detail. Conceptual design considerations for many other countermeasures are summarized.			
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## LIST OF SYMBOLS

A	=	Cross-sectional flow area, m <sup>2</sup>
A <sub>n2</sub>	=	Cross-sectional flow area at bridge opening at normal stage, m <sup>2</sup>
b	=	Length of the bridge opening, m
C <sub>d</sub>	=	Coefficient of drag
D <sub>c</sub>	=	Diameter of sediment particle at incipient motion conditions, mm or m
D <sub>i</sub>	=	The i <sup>th</sup> percentile size of bed material finer than a given size, mm or m
D <sub>50</sub>	=	Median sediment size, mm or m
d <sub>m</sub>	=	Tailwater depth, m
d <sub>s</sub>	=	Local scour depth for free overfall, m
F	=	Impact imparted by debris, N
F <sub>d</sub>	=	Drag force per unit of bridge length, N/m
Fr	=	Froude Number
g	=	Acceleration of gravity, m/s <sup>2</sup>
H	=	Depth of submergence, m
H <sub>t</sub>	=	Total drop in head, measured from the upstream to the downstream energy grade line, m
K	=	Constant
L	=	Effective length of spur, or the distance between arcs describing the toe of spurs and the desired bank line, m
L <sub>s</sub>	=	Projected length of guide bank, m
M	=	Mass of the debris, kg
m	=	Roughness correction factor for sinuosity of the channel
n	=	Manning's roughness coefficient
n <sub>b</sub>	=	Base value for straight, uniform channel
n <sub>1</sub>	=	Value for surface irregularities in the cross section
n <sub>2</sub>	=	Value for variations in shape and size of the channel
n <sub>3</sub>	=	Value for obstructions
n <sub>4</sub>	=	Value for vegetation and flow conditions
P	=	Wetted perimeter, boundary), m
P <sub>c</sub>	=	Decimal fraction of material coarser than the armoring size
Q	=	Discharge, total discharge, m <sup>3</sup> /s
Q <sub>f</sub>	=	Lateral or floodplain discharge intercepted by the embankment, m <sup>3</sup> /s
$\frac{Q_t}{Q_{30m}}$	=	Guide bank discharge ratio
Q <sub>s</sub>	=	Sediment discharge, m <sup>3</sup> /s
Q <sub>30m</sub>	=	Discharge in 30 m of stream adjacent to the abutment, m <sup>3</sup> /s
q	=	Discharge per unit width, m <sup>3</sup> /s/m or m <sup>2</sup> /s

### LIST OF SYMBOLS (continued)

R	=	Hydraulic radius, ratio of flow area to wetted perimeter), m
$r_c$	=	Radius of the center of the stream, m
$r_i$	=	Radius of the inside bank, m
$r_o$	=	Radius of the outside bank at the bend, m
S	=	Stopping distance, m
S	=	Energy slope or channel slope, m/m
S	=	Spacing between spurs at the toe, m
V	=	Velocity or average velocity of flow, m/s
$V_{n2}$	=	Average velocity through the bridge opening, m/s
W	=	Width, m
Y	=	Depth, m
$Y_a$	=	Thickness of the armoring layer, m
$Y_s$	=	Depth of scour, m
Z	=	Bed elevation referenced to a common datum, m
$\gamma$	=	Specific weight of water, $N/m^3$
$\gamma_s$	=	Specific weight of sediment, $N/m^3$
$\Delta Z$	=	Difference in water surface elevation between the concave and convex banks, m
$\theta$	=	Expansion angle downstream of spur tips ( $^\circ$ ) or the acute angle between the bankline and a spur or abutment skewed in a downstream direction ( $^\circ$ )
$\rho$	=	Density of water, $kg/m^3$
$\tau$	=	Boundary shear stress, (Pa or $[N/m^2]$ )

## GLOSSARY

abrasion:	Removal of streambank material due to entrained sediment, ice, or debris rubbing against the bank.
afflux:	Backwater, the increase in water surface elevation upstream of a bridge relative to the elevation occurring under natural conditions.
aggradation:	General and progressive buildup of the longitudinal profile of a channel bed due to sediment deposition.
alluvial channel:	Channel wholly in alluvium; no bedrock is exposed in channel at low flow or likely to be exposed by erosion.
alluvial fan:	A fan-shaped deposit of material at the place where a stream issues from a narrow valley of high slope onto a plain or broad valley of low slope. An alluvial cone is made up of the finer materials suspended in flow while a debris cone is a mixture of all sizes and kinds of materials.
alluvial stream:	A stream which has formed its channel in cohesive or noncohesive materials that have been and can be transported by the stream.
alluvium:	Unconsolidated material deposited by water.
alternating bars:	Elongated deposits found alternately near the right and left banks of a channel.
anabranch:	Individual channel of an anabranching stream.
anabranching stream:	A stream whose flow is divided at normal and lower stages by large islands or, more rarely, by large bars; individual islands or bars are wider than about three times water width; channels are more widely and distinctly separated than in a braided stream.
apron:	Protective material placed on a streambed to resist scour.
apron, launching:	An apron designed to settle and protect the side slopes of a scour hole after settlement.
armor:	Surfacing of channel bed, banks, or embankment slope to resist erosion and scour.
armoring:	(a) Natural process whereby an erosion-resistant layer of relatively large particles is formed on a streambed due to the removal of finer particles by streamflow; (b) placement of a covering to resist erosion.
articulated concrete mass:	Rigid concrete slabs which can move without separating as scour occurs; usually hinged together with corrosion-resistant wire fasteners; primarily placed for lower bank protection.
average velocity:	Velocity at a given cross section determined by dividing discharge by cross-sectional area.
avulsion:	A sudden change in the channel course that usually occurs when a stream breaks through its banks; usually associated with a flood or a catastrophic event.
backwater:	The increase in water surface elevation relative to the elevation occurring under natural channel and floodplain conditions. It is induced by a bridge or other structure that obstructs or constricts the free flow of water in a channel.

backwater area:	The low-lying lands adjacent to a stream that may become flooded due to backwater.
bank:	The side slopes of a channel between which the flow is normally confined.
bank, left (right):	The side of a channel as viewed in a downstream direction.
bank full discharge:	Discharge that, on the average, fills a channel to the point of overflowing.
bank protecting:	Engineering works for the purpose of protecting streambanks from erosion.
bank revetment:	Erosion-resistant materials placed directly on a streambank to protect the bank from erosion.
bar:	An elongated deposit of alluvium within a channel, not permanently vegetated.
base floodplain:	The floodplain associated with the flood with a 100-year recurrence interval.
bed:	The bottom of a channel bounded by banks.
bed form:	A recognizable relief feature on the bed of a channel, such as a ripple, dune, plane bed, antidune, or bar. They are a consequence of the interaction between hydraulic forces (boundary shear stress) and the sedimentary bed.
bed layer:	A flow layer, several grain diameters thick (usually two) immediately above the bed.
bed load:	Sediment that is transported in a stream by rolling, sliding, or skipping along the bed or very close to it; considered to be within the bed layer.
bed load discharge (or bed load)	The quantity of bed load passing a cross section of a stream in a unit of time.
bed material:	Material found on the bed of a stream (May be transported as bed load or in suspension).
bedrock:	The solid rock exposed at the surface of the earth or overlain by soils and unconsolidated material.
bed shear (tractive force):	The force per unit area exerted by a fluid flowing past a boundary.
boulder:	A rock fragment whose diameter is greater than 250 mm.
braid:	A subordinate channel of a braided stream.
braided stream:	A stream whose flow is divided at normal stage by small mid-channel bars or small islands; the individual width of bars and islands is less than about three times water width; braided stream has the aspect of a single large channel within which are subordinate channels.
bridge opening:	The cross-sectional area beneath a bridge that is available for conveyance of water.
bridge waterway:	The area of a bridge opening available for flow, as measured below a specified stage and normal to the principal direction of flow.
bulkhead:	A vertical, or near vertical, wall that supports a bank or an embankment; also may serve to protect against erosion.

caving:	The collapse of a bank caused by undermining due to the action of flowing water. Also, the falling in of the concave side of a bend of which the curvature is changing.
channel:	The bed and banks that confine the surface flow of a stream.
channelization:	Straightening or deepening of a natural channel by artificial cutoffs, grading, flow-control measures, or diversion of flow into a man-made channel.
cellular-block mattress:	Interconnected concrete blocks with regular cavities placed directly on a streambank or filter to resist erosion. The cavities can permit bank drainage and the growth of vegetation where synthetic filter fabric is not used between the mattress and bank.
channel diversion:	The removal of flows by natural or artificial means from a natural length of channel.
channel pattern:	The aspect of a stream channel in plan view, with particular reference to the degree of sinuosity, braiding, anabranching.
channel process:	Behavior of a channel with respect to shifting, erosion and sedimentation.
check dam:	A low dam or weir across a channel used to control stage or degradation.
choking (of flow):	Excessive constriction of flow which may cause severe backwater effect.
clay:	A particle whose diameter is in the range of 0.00024 to 0.004 mm.
clay plug:	A cutoff meander bend filled with fine grained cohesive sediments.
cobble:	A fragment of rock whose diameter is in the range of 64 to 250 mm.
concrete revetment:	Plain or reinforced concrete slabs placed on the channel bed to protect it from erosion.
confluence:	The junction of two or more streams.
constriction:	A natural or artificial control section, such as a bridge crossing, channel reach or dam, with limited flow capacity in which the upstream water surface elevation is related to discharge.
contact load:	Sediment particles that roll or slide along in almost continuous contact with the streambed.
contraction:	The effect of channel constriction on flow streamlines.
countermeasure:	A measure intended to prevent, delay or reduce the severity of hydraulic problems.
contraction scour:	Scour in a channel or on a floodplain that is not localized at a pier, abutment, or other obstruction to flow. In a channel, contraction scour results from the contraction of streamlines and usually affects all or most of the channel width.
Coriolis force:	The inertial force caused by the Earth's rotation that deflects a moving body to the right in the Northern Hemisphere.
crib:	A frame structure filled with earth or stone ballast, designed to reduce energy and to deflect streamflow away from a bank or embankment.

critical shear stress:	The minimum amount of shear stress required to initiate soil particle motion.
crossing:	The relatively short and shallow reach of a stream between bends; also crossover.
cross section:	A section normal to the trend of a channel.
current:	Water flowing through a channel.
cut bank:	The concave wall of a meandering stream.
cutoff:	(a) A direct channel, either natural or artificial, connecting two points on a stream, thereby shortening the original length of the channel and increasing its slope; (b) A natural or artificial channel which develops across the neck of a meander loop.
cutoff wall:	A wall, usually of sheet piling or concrete, that extends down to scour-resistant material or below the expected scour depth.
daily discharge:	Discharge averaged over one day.
debris:	Floating or submerged material, such as logs or trash, transported by a stream.
deflector:	Alternative term of "spur."
degradation (bed):	A general and progressive lowering of the channel bed due to erosion.
density of water-sediment mixture:	Bulk density (mass per unit volume), including both water and sediment.
depth of scour:	The vertical distance a streambed is lowered by scour below a reference elevation.
design flow (design flood):	The discharge that is selected as the basis for the design or evaluation of a hydraulic structure.
dike:	An impermeable linear structure for the control or containment of overbank flow. A dike-trending parallel with a streambank differs from a levee in that it extends for a much shorter distance along the bank, and it may be surrounded by water during floods.
dike (groin, spur, jetty):	A structure extending from a bank into a channel that is designed to: (a) reduce the stream velocity as the current passes through the dike, thus encouraging sediment deposition along the bank (permeable dike); or (b) deflect erosive current away from the streambank (impermeable dike).
dominant discharge:	(a) The discharge which is of sufficient magnitude and frequency to have a dominating effect in determining the characteristics and size of the stream course, channel, and bed; (b) That discharge which determines the principal dimensions and characteristics of a natural channel. The dominant formative discharge depends on the maximum and mean discharge, duration of flow, and flood frequency. For hydraulic geometry relationships, it is taken to be the bankfull discharge which has a return period of approximately 1.5 years in many natural channels.
drift:	Alternative term for "debris."

eddy current:	A vortex-type motion of a fluid flowing contrary to the main current, such as the circular water movement that occurs when the main flow becomes separated from the bank.
entrenched stream:	Stream cut into bedrock or consolidated deposits.
ephemeral stream:	A stream or reach of stream that does not flow for parts of the year. As used here, the term includes intermittent streams with flow less than perennial.
erosion:	Displacement of soil particles on the land surface due to water or wind action.
erosion control matting:	Fibrous matting (e.g., jute, paper, etc.) placed or sprayed on a streambank for the purpose of resisting erosion or providing temporary stabilization until vegetation is established.
estuary:	Tidal reach at the mouth of a stream.
fabric mattress:	Grout-filled mattress used for streambank protection.
fetch:	The area in which waves are generated by wind having a rather constant direction and speed; sometimes used synonymously with fetch length.
fetch length:	The horizontal distance (in the direction of the wind) over which wind generates waves and wind setup.
fill slope:	Side or end slope of an earth fill embankment.
filter:	Layer of fabric, sand, gravel, or graded rock placed between bank revetment and soil for the following purposes: (1) to prevent the soil from moving through the revetment by piping, extrusion, or erosion; (2) to prevent the revetment from sinking into the soil; and (3) to permit natural seepage from the streambank, thus preventing the buildup of excessive hydrostatic pressure.
filter blanket:	A layer of graded sand and gravel laid between fine-grained material and riprap to serve as a filter.
filter cloth:	Geosynthetic fabric that serves the same purpose as a granular filter blanket.
fine sediment load (wash load):	That part of the total sediment load that is composed of particle sizes finer than those represented in the bed. Normally, the fine-sediment load is finer than 0.062 mm for sand-bed channel. Silts, clays and sand could be considered wash load in coarse gravel and cobble-bed channels.
flanking:	Erosion resulting from streamflow between the bank and the landward end of a countermeasure for stream stabilization.
flashy stream:	Stream characterized by rapidly rising and falling stages, as indicated by a sharply peaked hydrograph. Most flashy streams are ephemeral, but some are perennial.
floodplain:	A nearly flat, alluvial lowland bordering a stream, that is subject to inundation by floods.
flow-control structure:	A structure either within or outside a channel that acts as a countermeasure by controlling the direction, depth, or velocity of flowing water.
flow slide:	Saturated soil materials which behave more like a liquid than a solid. A flow slide on a channel bank can result in a bank failure.

fluvial geomorphology:	The science dealing with the profiles and planforms of streams and rivers.
Froude Number:	A dimensionless number that represents the ratio of inertial to gravitational forces. High Froude Numbers can be indicative of high flow velocity and the potential for scour.
gabion:	A basket or compartmentalized rectangular container made of wire mesh, filled with cobbles or other rock of suitable size. Gabions are flexible and permeable blocks with which flow- and erosion-control structures can be built.
geomorphology/ morphology:	That science that deals with the form of the Earth, the general configuration of its surface, and the changes that take place due to erosion of the primary elements and in the buildup of erosional debris.
grade-control structure (sill, check dam):	Structure placed bank to bank across a stream channel (usually with its central axis perpendicular to flow) for the purpose of controlling bed slope and preventing scour or headcutting.
graded stream:	A geomorphic term used for streams that have apparently achieved a state of equilibrium between the rate of sediment transport and the rate of sediment supply throughout long reaches. Any change which alters the state of equilibrium can lead to action by the stream to reestablish equilibrium.
gravel:	A rock fragment whose diameter ranges from 2 to 64 mm.
groin:	A structure built from the bank of a stream in a direction transverse to the current. Many names are given to this structure, the most common being "spur," "spur dike," "transverse dike," "jetty," etc. Groins may be permeable, semi-permeable, or impermeable.
guide bank:	Preferred term for spur dike.
hardpoint:	A streambank protection structure whereby "soft" or erodible materials are removed from a bank and replaced by stone or compacted clay. Some hard points protrude a short distance into the channel to direct erosive currents away from the bank. Hard points also occur naturally along streambanks as passing currents remove erodible materials leaving nonerodible materials exposed.
headcutting:	Channel degradation associated with abrupt changes in the bed elevation (headcut) that generally migrates in an upstream direction.
helical flow:	Three-dimensional movement of water particles along a spiral path in the general direction of flow. These secondary-type currents are of most significance as flow passes through a bend; their net effect is to remove soil particles from the cut bank and deposit this material on the point bar.
hydraulic radius:	The cross-sectional area of a stream divided by its wetted perimeter.
hydraulic problem:	An effect of streamflow, tidal flow, or wave action such that the integrity of the highway facility is destroyed, damaged, or endangered.
incised reach:	A stretch of stream with an incised channel that only rarely overflows its banks.
incised stream:	A stream which has cut its channel through the bed of the valley floor, as opposed to one flowing on a floodplain.
island:	A permanently vegetated area, emergent at normal stage, that divides the flow of a stream. Islands originate by establishment of vegetation on a bar, by channel avulsion, or at the junction of minor tributary with a larger stream.

jack:	A device for flow control and protection of banks against lateral erosion consisting of three mutually perpendicular arms rigidly fixed at the center. Kellner jacks are made of steel struts strung with wire, and concrete jacks are made of reinforced concrete beams.
jack field:	Rows of jacks tied together with cables, some rows generally parallel with the banks and some perpendicular thereto or at an angle. Jack fields may be placed outside or within a channel.
jetty:	(a) An obstruction built of piles, rock, or other material extending from a bank into a stream, so placed as to induce scouring or bank building, or to protect against erosion; (b) A similar obstruction to influence stream, lake, or tidal currents, or to protect a harbor.
lateral erosion:	Erosion in which the removal of material is extended in a lateral direction, as contrasted with degradation and scour in a vertical direction.
launching:	Release of undercut material (stone riprap, rubble, slag, etc.) downslope or into a scoured area.
levee:	An embankment, generally landward of top bank, that confines flow during high-water periods, thus preventing overflow into lowlands.
littoral drift:	The transport of material along a shoreline.
local scour:	Scour in a channel or on a floodplain that is localized at a pier, abutment, or other obstruction to flow.
lower bank:	That portion of a streambank having an elevation less than the mean water level of the stream.
mattress:	A blanket or revetment materials interwoven or otherwise lashed together and placed to cover an area subject to scour.
meander or full meander:	A meander in a river consists of two consecutive loops, one flowing clockwise and the other counter-clockwise.
meander belt:	The distance between lines drawn tangent to the extreme limits of successive fully developed meanders.
meander length:	The distance along a stream between corresponding points at the extreme limits of successive fully developed meanders.
meander loop:	An individual loop of a meandering or sinuous stream lying between inflection points with adjoining loops.
meander ratio:	The ratio of meander width to meander length.
meander width:	The amplitude of swing of a fully developed meander measured from midstream to midstream.
meandering channel:	A channel exhibiting a characteristic process of bank erosion and point bar deposition associated with systematically shifting meanders.
meander scrolls:	Low, concentric ridges and swales on a floodplain, marking the successive positions of former meander loops.

meandering stream:	A stream having a sinuosity greater than some arbitrary value. The term also implies a moderate degree of pattern symmetry, imparted by regularity of size and repetition of meander loops.
median diameter:	The particle diameter of the 50th percentile point on a size distribution curve such that half of the particles (by weight, number, or volume) are larger and half are smaller.
mid-channel bar:	A bar lacking permanent vegetal cover that divides the flow in a channel at normal stage.
middle bank:	The portion of a streambank having an elevation approximately the same as that of the mean water level of the stream.
migration:	Change in position of a channel by lateral erosion of one bank and simultaneous accretion of the opposite bank.
natural levee:	A low ridge formed along streambanks during floods by deposition that slopes gently away from the channel banks.
nominal sediment	Equivalent spherical diameter of a hypothetical sphere of the same volume as a given stone.
nonalluvial channel:	A channel whose boundary is completely in bedrock.
normal stage:	The water stage prevailing during the greater part of the year.
overbank flow:	Water movement overtop bank either due to stream stage or to inland surface water runoff.
oxbow:	The abandoned bow-shaped or horseshoe-shaped reach of a former meander loop that remains after a stream cuts a new, shorter channel across the narrow neck between closely approaching bends of a meander.
perennial stream:	A stream or reach of a stream that flows continuously for all or most of the year.
phreatic line:	The upper boundary of the seepage water surface landward of a streambank.
pile dike:	A type of permeable structure for the protection of banks against caving; consists of a cluster of piles driven into the stream, braced and lashed together.
pipng:	Removal of soil material through subsurface flow of seepage water that develops channels or "pipes" within the soil bank.
point bar:	An alluvial deposit of sand or gravel lacking permanent vegetal cover occurring in a channel at the inside of a meander loop, usually somewhat downstream from the apex of the loop.
poised stream (stable stream):	A stream which, as a whole, maintains its slopes, depths, and channel dimensions without any noticeable raising or lowering of its bed. Such condition may be temporary from a geological point of view, but for practical engineering purposes, the stream may be considered stable.
quarry-run stone:	Stone as received from a quarry without regard to gradation requirements.
railbank protection:	A type of countermeasure composed of rock-filled wire fabric supported by steel rails or posts driven into streambed.

rapid drawdown:	Lowering the water against a bank more quickly than the bank can drain without becoming unstable.
reach:	A segment of stream length that is arbitrarily bounded for purposes of study.
regime:	The condition of a stream or its channel as regards stability. A stream is in regime if its channel has reached a stable form as a result of its flow characteristics.
regime channel:	Alluvial channel that has attained, more or less, a state of equilibrium with respect to erosion and deposition.
regime change:	A change in channel characteristics resulting from such things as changes in imposed flows, sediment loads or slope.
regime formula:	A formula relating stable alluvial channel dimensions or slope to discharge and sediment characteristics.
reinforced-earth bulkhead:	A retaining structure consisting of vertical panels and attached to reinforcing elements embedded in compacted backfill for supporting a streambank.
reinforced revetment:	A streambank protection method consisting of a continuous stone toe-fill along the base of a bank slope with intermittent fillets of stone placed perpendicular to the toe and extending back into the natural bank.
retard (retarder structure):	A permeable or impermeable linear structure in a channel parallel with the bank and usually at the toe of the bank, intended to reduce flow velocity, induce deposition, or deflect flow from the bank.
revetment:	Rigid or flexible armor placed to inhibit scour and lateral erosion. (See bank revetment).
riffle:	A natural, shallow flow area extending across a streambed in which the surface of flowing water is broken by waves or ripples. Typically, riffles alternate with pools along the length of a stream channel.
riparian:	Pertaining to anything connected with or adjacent to the banks of a stream.
riprap:	In the restricted sense, layer or facing of broken rock or concrete dumped or placed to protect a structure or embankment from erosion; also the broken rock or concrete suitable for such use. Riprap has also been applied to almost all kinds of armor, including wire-enclosed riprap, grouted riprap, sacked concrete, and concrete slabs.
river training:	Engineering works with or without the construction of embankment, built along a stream or reach of stream to direct or to lead the flow into a prescribed channel. Also, any structure configuration constructed in a stream or placed on, adjacent to, or in the vicinity of a streambank that is intended to deflect currents, induce sediment deposition, induce scour, or in some other way alter the flow and sediment regimes of the stream.
rock-and-wire mattress:	A flat or cylindrical wire cage or basket filled with stone or other suitable material and placed as protection against erosion.
roughness coefficient:	Numerical measure of the frictional resistance to flow in a channel, as in the Manning's or Chezy's formulas.

rubble:	Rough, irregular fragments of materials of random size used to retard erosion. The fragments may consist of broken concrete slabs, masonry, or other suitable refuse.
sack revetment:	Sacks (e.g., burlap, paper, or nylon) filled with mortar, concrete, sand, stone or other available material used as protection against erosion.
saltation load:	Sediment bounced along the streambed by energy, turbulence of flow, and by other moving particles.
sand:	A rock fragment whose diameter is in the range of 0.062 to 2.0 mm.
scour:	Erosion due to flowing water; usually considered as being localized as opposed to general bed degradation.
scoured depth:	Total depth of the water from water surface to a scoured bed level (compare with "depth of scour").
sediment or fluvial sediment:	Fragmental material transported, suspended, or deposited by water.
sediment concentration:	Weight or volume of sediment relative to quantity of transporting or suspending fluid or fluid-sediment mixture.
sediment discharge:	The quantity of sediment that is carried past any cross section of a stream in a unit of time. Discharge may be limited to certain sizes of sediment or to a specific part of the cross section.
sediment load:	Amount of sediment being moved by a stream.
sediment yield:	The total sediment outflow from a watershed or a drainage area at a point of reference and in a specified time period. This outflow is equal to the sediment discharge from the drainage area.
seepage:	The slow movement of water through small cracks and pores of the bank material.
seiche:	Long-period oscillation of a lake or similar body of water.
set-up:	Raising of water level due to wind action.
shallow water (for waves):	Water of such a depth that waves are noticeably affected by bottom conditions; customarily, water shallower than half the wavelength.
shoal:	A submerged sand bank. A shoal results from natural deposition on a streambed which has resisted all erosion; thus, the water is of necessity compelled to pass over it.
sill:	(a) A structure built under water, across the deep pools of a stream with the aim of changing the depth of the stream; (b) A low structure built across an effluent stream, diversion channel or outlet to reduce flow or prevent flow until the main stream stage reaches the crest of the structure.
silt:	A particle whose diameter is in the range of 0.004 to 0.062 mm.
sinuosity:	The ratio between the thalweg length and the valley length of a sinuous stream.
slope (of channel or stream):	Fall per unit length along the channel centerline.

slope protection:	Any measure such as riprap, paving, vegetation, revetment, brush or other material intended to protect a slope from erosion, slipping or caving, or to withstand external hydraulic pressure.
sloughing:	Sliding of overlying material; same ultimate effect as caving, but usually occurs when a bank or an underlying stratum is saturated.
slope-area method:	A method of estimating unmeasured flood discharges in a uniform channel reach using observed high-water levels.
slump:	A sudden slip or collapse of a bank, generally in the vertical direction and confined to a short distance, probably due to the substratum being washed out or having become unable to bear the weight above it.
soil-cement:	A designed mixture of soil and Portland cement compacted at a proper water content to form a blanket or structure that can resist erosion.
sorting:	Progressive reduction of size (or weight) of particles of the load carried down a stream.
spill-through abutment:	A bridge abutment having a fill slope on the streamward side.
spur:	A permeable or impermeable linear structure that projects into a channel from the bank to alter flow direction, induce deposition, or reduce flow velocity along the bank.
spur dike/guide bank:	A dike extending upstream from the approach embankment at either or both sides of the bridge opening. Guide banks may also extend downstream from the bridge.
stable channel:	A condition that exists when a stream has a bed slope and cross section which allows its channel to transport the water and sediment delivered from the upstream watershed without aggradation, degradation, or bank erosion (a graded stream).
stage:	Water-surface elevation of a stream with respect to a reference elevation.
stone riprap:	Natural cobbles, boulders, or rock dumped or placed as protection against erosion.
stream:	A body of water that may range in size from a large river to a small rill flowing in a channel. By extension, the term is sometimes applied to a natural channel or drainage course formed by flowing water whether it is occupied by water or not.
streambank erosion:	Removal of soil particles or a mass of particles from a bank surface due primarily to water action. Other factors such as weathering, ice and debris abrasion, chemical reactions, and land use changes may also directly or indirectly lead to bank erosion.
streambank failure:	Sudden collapse of a bank due to an unstable condition such as due to removal of material at the toe of the bank by scour.
streambank protection:	Any technique used to prevent erosion or failure of a streambank.
suspended sediment discharge (suspended load):	The quantity of sediment passing through a stream cross section in a unit of time suspended by the turbulence of flow.

sub-bed material:	Material underlying that portion of the streambed which is subject to direct action of the flow.
submeander:	A small meander contained within the banks of a perennial stream channel. These are caused by relatively low discharges after the flood has subsided.
subcritical, supercritical flow:	Open channel flow conditions with Froude Number less than and greater than unity, respectively.
tetrahedron:	Component of river-training works made of six steel or concrete struts fabricated in the shape of a pyramid.
tetrapod:	Bank protection component of precast concrete consisting of four legs joined at a central joint, with each leg making an angle of 109.5° with the other three.
thalweg:	The line extending down a channel that follows the lowest elevation of the bed.
tieback:	Structure placed between revetment and bank to prevent flanking.
timber or brush mattress:	A revetment made of brush, poles, logs, or lumber interwoven or otherwise lashed together. The completed mattress is then placed on the bank of a stream and weighted with ballast.
toe of bank:	That portion of a stream cross section where the lower bank terminates and the channel bottom or the opposite lower bank begins.
toe protection:	Loose stones laid or dumped at the toe of an embankment, groin, etc., or masonry or concrete wall built at the junction of the bank and the bed in channels or at extremities of hydraulic structures to counteract erosion.
total sediment load (or total load):	The sum of suspended load and bed load or the sum of bed material load and wash load of a stream.
trench-fill revetment:	Stone, concrete, or masonry material placed in a trench dyg behind and parallel to an eroding streambank. When the erosive action of the stream reaches the trench, the material placed in the trench armors the bank and thus retards further erosion.
turbulence:	Motion of fluids in which local velocities and pressures fluctuate irregularly in a random manner as opposed to laminar flow where all particles of the fluid move in distinct and separate lines.
uniform flow:	Flow of constant cross section and velocity through a reach of channel at a given instant. Both the energy slope and the water slope are equal to the bed slope under conditions of uniform flow.
unit discharge:	Discharge per unit width (may be average over a cross section, or local at a point).
unit shear force (shear stress):	The force or drag developed at the channel bed by flowing water. For uniform flow, this force is equal to a component of the gravity force acting in a direction parallel to the channel bed on a unit wetted area. Usually in units of stress, Pa (N/m <sup>2</sup> ).
unsteady flow:	Flow of variable cross section and velocity with respect to time.
upper bank:	The portion of a streambank having an elevation greater than the average water level of the stream.

velocity:	The rate of motion in a fluid on a stream or of the objects or particles transported therein, usually expressed in m/s.
velocity-weighted sediment concentration:	The dry weight of sediment discharged through a cross section during unit time.
wandering channel:	A channel exhibiting a more or less non-systematic process of channel shifting, erosion and deposition, with no definite meanders or braided pattern.
wandering thalweg:	A thalweg whose position in the channel shifts during floods and typically serves as an inset channel that conveys all or most of the stream flow at normal or lower stages.
wash load:	Suspended material of very small size (generally clays and colloids) originating primarily from erosion on the land slopes of the drainage area and present to a negligible degree in the bed itself.
waterway opening width (area):	Width (area) of bridge opening at (below) a specified stage, measured normal to the principal direction of flow.
weep hole:	A hole in an impermeable wall or revetment to relieve the neutral stress or pore pressure in the soil.
windrow revetment:	A row of stone placed landward of the top of an eroding streambank. As the windrow is undercut, the stone is launched downslope, thus armoring the bank.
wire mesh:	Wire woven to form a mesh; where used as an integral part of a countermeasure, openings are of suitable size and shape to enclose rock or broken concrete or to function on fence-like spurs and retards.



# CHAPTER 1

## INTRODUCTION

### 1.1 PURPOSE

The purpose of this document is to provide guidelines for identifying stream instability problems at highway-stream crossings and for the selection and design of appropriate countermeasures to mitigate potential flood damages to bridges and other highway components at stream crossings.

### 1.2 BACKGROUND

Approximately 84 percent of the 575 000 bridges in the National Bridge Inventory (NBI) are built over streams. A large proportion of these bridges span alluvial streams that are continually adjusting their beds and banks. Many, especially those on more active streams, will experience problems with scour and bank erosion during their useful life. The magnitude of these problems is demonstrated by the average annual flood damage repair costs of approximately \$50 million for highways on the Federal aid system.

### 1.3 FACTORS THAT AFFECT STREAM STABILITY

Factors which affect stream stability and, potentially, bridge stability at highway stream crossings can be classified as geomorphic factors and hydraulic factors. Rapid and unexpected changes can occur in streams in response to man's activities in the watershed and/or natural disturbances of the fluvial system, making it important to anticipate changes in channel geomorphology, location and behavior. Geomorphic characteristics of particular interest to the highway engineer are the alignment, geometry, and form of the stream channel. The behavior of a stream at a highway crossing depends not only on the apparent stability of the stream at the bridge, but also on the behavior of the stream system of which it is a part. Upstream and downstream changes may affect future stability at the site. Natural disturbances such as floods, drought, earthquakes, landslides, forest fires, etc., may result in large changes in sediment load in a stream and major changes in the stream channel. These changes can be reflected in aggradation, degradation, or lateral migration of the stream channel.

The bed material of a stream can be a cohesive material, sand, gravel, cobbles, boulders, or bedrock. Bank material is also composed of these materials and may be dissimilar from the bed material. Obviously, the stability and the rate of change in a stream is dependent on the material in the bed and banks.

Man-made changes in the drainage basin and the stream channel, such as alteration of vegetative cover and changes in pervious (or impervious) area can alter the hydrology of a stream, sediment yield and channel geometry. Channelization, stream channel straightening, streamside levees and dikes, bridges and culverts, reservoirs, gravel mining, and changes in land use can have major effects on streamflow, sediment transport, and channel geometry and location. Geomorphic factors are discussed in chapter 2.

Hydraulic factors which affect stream channel and bridge stability are numerous and include bed forms and their effects on sediment transport, resistance to flow, flow velocities and flow depths. They also include the magnitude and frequency of floods; characteristics of floods, (i.e., duration, time to peak, and time of recession); and flow classification (e.g., unsteady, nonuniform, turbulent, supercritical or subcritical); ice and other floating debris in the flow; flow constrictions. Other factors are bridge length, location, orientation, span lengths, pier location and design; superstructure elevation and design; the location and design of countermeasures; and the effects of natural and man-made changes which affect the hydrology and hydraulic flow conditions of the stream. In the bridge reach, bridge design and orientation can induce contraction scour and local scour at piers and abutments. Hydraulic factors are discussed in chapter 3.

## 1.4 COUNTERMEASURES

Numerous measures are available to counteract the actions of man and nature which contribute to the instability of alluvial streams. These include measures installed in or near the stream to protect highways and bridges by stabilizing a local reach of the stream, and measures which can be incorporated into the highway design to ensure the structural integrity of the highway in an unstable stream environment. The selection, location, and design of countermeasures are dependent on hydraulic and geomorphic factors that contribute to instability, as well as costs and construction and maintenance considerations.

## 1.5 MANUAL ORGANIZATION

This manual is organized to: (1) familiarize the user with the important geomorphic and hydraulic factors which are indicators of and contributors to potential and existing stream and bridge stability problems (chapters 2 and 3), (2) provide a procedure for the analysis of potential and existing stability problems (chapter 4), and (3) provide guidance for selecting and designing appropriate countermeasures to mitigate instability problems (chapters 5 and 6, respectively). Chapter 7 contains selected references.

## 1.6 METRIC SYSTEM

This edition of HEC-20 uses SI metric units. **In appendix A, the metric (SI) unit of measurement is explained. The conversion factors, physical properties of water in the SI system of units, sediment particle size grade scale, and some common equivalent hydraulic units are also given.** This edition uses for the unit of length the meter (m), of mass the kilogram (kg), of weight/force the newton (N), of pressure the Pascal (Pa,  $\text{N}/\text{m}^2$ ), and of temperature degrees centigrade ( $^{\circ}\text{C}$ ). The unit of time is the same in SI as in the English system (seconds, s). Sediment particle size is given in millimeters but in calculations the decimal equivalent of millimeters in meters is used ( $1 \text{ mm} = 0.001 \text{ meter}$ ).

## CHAPTER 2

### GEOMORPHIC FACTORS AND PRINCIPLES

#### 2.1 INTRODUCTION

Most streams that highways cross or encroach upon are alluvial; that is, the streams are formed in materials that have been and can be transported by the stream. In alluvial stream systems, it is the rule rather than the exception that banks will erode; sediments will be deposited; and floodplains, islands and side channels will undergo modification with time. Alluvial channels continually change position and shape as a consequence of hydraulic forces exerted on the bed and banks. These changes may be gradual or rapid and may be the result of natural causes or man's activities.

Many streams are not alluvial. The bed and bank material is very coarse, and except at extreme flood events, does not erode. These streams are classified as sediment supply deficient, i.e., the transport capacity of the streamflow is greater than the availability of bed material for transport. The bed and bank material of these streams may consist of cobbles, boulders or even bed rock. In general, these streams are stable but should be carefully analyzed for stability at large flows.

A study of the plan and profile of a stream is very useful in understanding stream morphology. Plan view appearances of streams are varied and result from many interacting variables. Small changes in a variable can change the plan view and profile of a stream, adversely affecting a highway crossing or encroachment. This is particularly true for alluvial streams. Conversely, a highway crossing or encroachment can inadvertently change a variable, adversely affecting the stream.

Each of the geomorphic properties listed in the left column of figure 1 could be used as the basis of a valid stream classification. The stream classification presented here is based on stream properties observed on aerial photographs and in the field. Its major purpose is to facilitate the assessment of streams for engineering purposes, particularly regarding lateral stability of a stream. Each property has limited usefulness when considered alone, however, classification based on combinations of more than a few properties and categories of each become unwieldy. Since the most common stream types represent a characteristic association of properties, these common types will be described and their engineering significance discussed. Data and observations are derived from a study of case histories of 224 bridge sites in the United States and Canada.<sup>(1,2)</sup> The following section is organized according to figure 1. No particular significance is assigned to the order of the figure, and association of characteristics should not be inferred with descriptions above or below in the figure.

#### 2.2 GEOMORPHIC FACTORS AFFECTING STREAM STABILITY

##### 2.2.1 Stream Size

Stream depth tends to increase with size, and potential for scour increases with depth. Thus, potential depth of scour increases with increasing stream size.

The potential for lateral erosion also increases with stream size. This fact may be less fully appreciated than the increased potential for deep scour. Brice et al., cite as examples the lower Mississippi River, with a width of about 1500 m, which may shift laterally 30 m or more in a single major flood; the Sacramento River, where the width is about 300 m, is unlikely to shift more than 8 m in a single flood; and streams whose width is about 30 m are unlikely to shift more than 3 m in a single flood.<sup>(1)</sup> Except for the fact that the potential for lateral migration increases with stream size, no generalization is possible regarding migration rates.

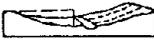
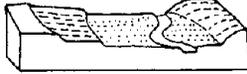
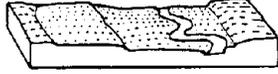
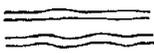
STREAM SIZE (SECT. 2.2.1)	Small ( $< 30$ m wide)	Medium (30-150 m)		Wide ( $> 150$ m)	
FLOW HABIT (SECT. 2.2.2)	Ephemeral	(Intermittant)	Perennial but flashy	Perennial	
BED MATERIAL (SECT. 2.2.3)	Silt-Clay	Silt	Sand	Gravel	Cobble or Boulder
VALLEY SETTING (SECT. 2.2.4)	 No valley, alluvial fan	 Low relief valley ( $< 30$ m deep)	 Moderate relief (30-300 m deep)	 High relief ( $> 300$ m deep)	
FLOODPLAINS (SECT. 2.2.5)	 Little or none ( $< 2$ x channel width)	 Narrow (2-10 x channel width)		 Wide ( $> 10$ x channel width)	
NATURAL LEVEES (SECT. 2.2.6)	 Little or none	 Mainly on concave		 Well developed on both banks	
APPARENT INCISION (SECT. 2.2.7)	 Not Incised		 Probably Incised		
CHANNEL BOUNDARIES (SECT. 2.2.8)	 Alluvial	 Semi-alluvial		 Non-alluvial	
TREE COVER ON BANKS (SECT. 2.2.8)	$< 50$ percent of bankline	50-90 percent of bankline		$> 90$ percent of bankline	
SINUOSITY (SECT. 2.2.10)	 Straight Sinuosity (1-1.05)	 Sinuous (1.06-1.25)	 Meandering (1.25-2.0)	 Highly Meandering ( $> 35$ percent)	
BRAIDED STREAMS (SECT. 2.2.10)	 Not braided ( $< 5$ percent)	 Locally braided (5-35 percent)		 Generally braided ( $> 35$ percent)	
ANABRANCHED STREAMS (SECT. 2.2.11)	 Not anabranching ( $< 5$ percent)	 Locally anabranching (5-35 percent)		 Generally anabranching ( $> 35$ percent)	
VARIABILITY OF WIDTH AND DEVELOPMENT OF BARS (SECT. 2.2.12)	 Narrow point bars	 Equiwidth	 Wider at bends	 Random variation	
		 Wide point bars		 Irregular point and lateral bars	

Figure 1. Geomorphic factors that affect stream stability (adapted from Brice and Blodgett).<sup>(1)</sup>

The size of a stream can be indicated by discharge, drainage area, or some measure of channel dimensions, such as width or cross-sectional area. No single measure of size is satisfactory because of the diversity of stream types. For purposes of stream classification (figure 1), bank-to-bank channel width is chosen as the most generally useful measure of size, and streams are arbitrarily divided into three size categories on the basis of width. The width of the stream does not include the width of the floodplain, but floodplain width is an important factor in bridge design if significant overbank flow occurs.

Bank-to-bank width is sometimes difficult to define for purposes of measurement when one of the banks is indefinite. This is particularly true at bends, where the outside bank is likely to be vertical and sharply defined but the inside bank slopes gradually up to floodplain level. The position of the line of permanent vegetation on the inside bank is the best available indicator of the bank line, and it tends to be rather sharply defined along many rivers in humid regions. The width of a stream is measured along a perpendicular drawn between its opposing banks, which are defined either by their form or as the riverward edge of a line of permanent vegetation. For sinuous or meandering streams, width is measured at straight reaches or at the inflections between bends, where it tends to be most consistent. For multiple channel streams, width is the sum of the widths of individual, unvegetated channels.

The Topographic Division of the U.S. Geological Survey (USGS) uses, insofar as possible, the so-called "normal" stage or the stage prevailing during the greater part of the year for representing streams on topographic maps. It finds that the "normal" stage for a perennial river usually corresponds to the water level filling the channel to the line of permanent vegetation along its banks. Normal stage is also adopted here to define channel width.

### **2.2.2 Flow Habit**

The flow habit of a stream may be ephemeral, perennial but flashy, or perennial. An ephemeral stream flows briefly in direct response to precipitation, and as used here, includes intermittent streams. A perennial stream flows all or most of the year, and a perennial but flashy stream responds to precipitation by rapid changes in stage and discharge. Perennial streams may be relatively stable or unstable, depending on other factors such as channel boundaries and bed material.

In arid regions, ephemeral streams may be relatively large and unstable. They may pose problems in determining the stage-discharge relationship and in estimating the depth of scour. A thalweg that shifts with stage and channel degradation by headcutting may also cause problems. In humid regions, ephemeral streams are likely to be small and pose few problems of instability.

### **2.2.3 Bed Material**

Streams are classified, according to the dominant size of the sediment on their beds, as silt-clay bed, sand bed, gravel bed, and cobble or boulder bed. Accurate determination of the particle size distribution of bed material requires careful sampling and analysis, particularly for coarse bed material, but for most of the bed material designations, rough approximations can be derived from visual observation.

The greatest depths of scour are usually found on streams having sand or sand-silt beds. The general conclusion is that scour problems are as common on streams having coarse bed material as on streams having fine bed material. However, very deep scour is more probable in fine bed material.<sup>(1)</sup> In general, sand-bed alluvial streams are less stable than streams with coarse or cohesive bed and bank material.

### **2.2.4 Valley Setting**

Valley relief is used as a means of indicating whether the surrounding terrain is generally flat, hilly, or mountainous. For a particular site, relief is measured (usually on a topographic map) from the valley bottom to

the top of the highest adjacent divide. Relief greater than 300 m is regarded as mountainous, and relief in the range of 30 to 300 m as hilly. Streams in mountainous regions are likely to have steep slopes, coarse bed materials, narrow floodplains and be nonalluvial, i.e., supply-limited sediment transport rates. In many regions, channel slope increases as the steepness of valley side slopes increases. Brice et al., reported no specific hydraulic problems at bridges at 23 study sites in mountainous terrain, at which all have beds of gravel or cobble-boulder.<sup>(2)</sup> Streams in regions of lower relief are usually alluvial and exhibit more problems because of lateral erosion in the channels.

Streams on alluvial fans or on piedmont slopes in arid regions pose special problems. A piedmont slope is a broad slope along a mountain front, and streams issuing from the mountain front may have shifting courses and poorly defined channels, as on an alluvial fan. Alluvial fans are among the few naturally occurring cases of aggradation problems at transverse highway crossing. They occur wherever there is a change from a steep to a flat gradient. As the bed material and water reaches the flatter section of the stream, the coarser bed materials are deposited because of the sudden reduction in both slope and velocity. Consequently, a cone or fan builds out as the material is dropped with the steep side of the fan facing the floodplain. Although typically viewed as a depositional zone, alluvial fans are also characterized by unstable channel geometries and rapid lateral movement. Deposition tends to be episodic, being interrupted by periods of fan trenching and sediment reworking.

The occurrence of deposition verses fan trenching on an alluvial fan surface are important factors in the assessment of stream stability at bridge crossings (figure 2). On an untrenched fan, the sediment depositional zone will be nearer the mountain front, possibly creating more channel instability on the upper fan surface than on the lower fan surface. In contrast, a fan that is trenched will promote sediment movement across the fan and move the depositional zone closer to the toe of the fan, suggesting that the upper fan surface will be more stable than the lower fan surface. However, the general instability of fan channels and their tendency for rapid changes during large floods, and the possible channel avulsion created by deposition near the fan head, suggest that any location of an alluvial fan surface is, or could easily become, an area where channel stability is a serious concern to bridge safety.

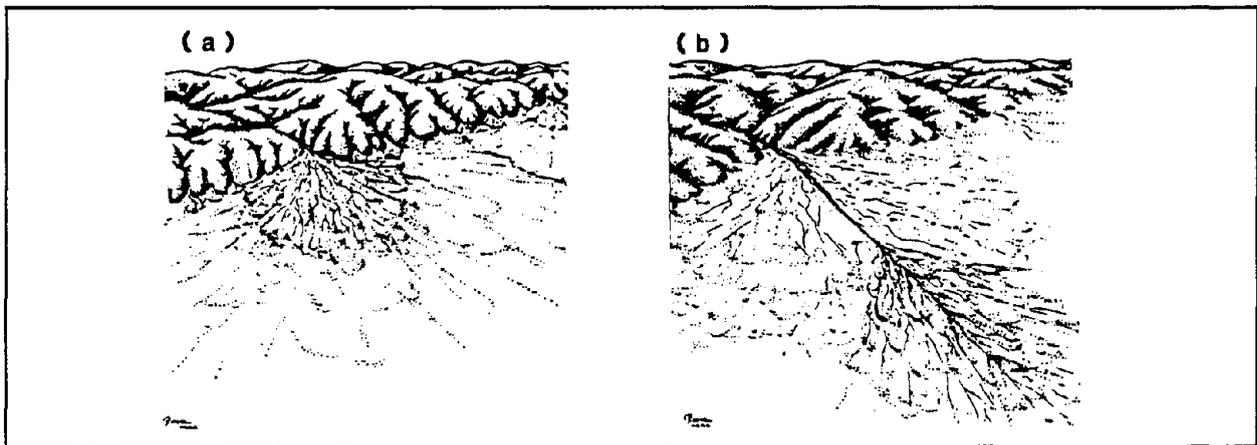


Figure 2. Diverse morphology of alluvial fans: (a) area of deposition at fan head, (b) fan-head trench with deposition at fan toe (after Schumm).<sup>(3)</sup>

There is considerable similarity between deltas and alluvial fans. Both result from reductions in slope and velocity, have steep slopes at their outer edges and tend to reduce upstream slopes. Deposits very similar to a delta develop where a steep tributary enters a larger stream. The steep channel tends to drop part of its sediment load in the main channel building out into the main stream. In some instances, drastic changes can occur in the main stream channel as a result of deposition from the tributary stream. Channels on both alluvial fans and deltaic deposits commonly change through avulsion, a sudden change in channel course that occurs when a stream breaks through its banks.

### **2.2.5 Floodplains**

Floodplains are described as the nearly flat alluvial lowlands bordering a stream that are subject to inundation by floods. Many geomorphologists prefer to define a floodplain as the surface presently under construction by the stream, which is flooded with a frequency of about 1.5 yr. According to this definition, surfaces flooded less frequently are terraces, abandoned floodplains, or flood-prone areas. However, flood prone areas are considered herein as part of the floodplain. Vegetative cover, land use, and flow depth on the floodplain are also significant factors in stream channel stability. In figure 1, floodplains are categorized according to width relative to channel width.

Over time, the highlands of an area are worn down, streams erode their banks, and the material that is eroded is utilized farther downstream to build banks and bars. Streams move laterally, pushing the highlands back. Low, flat valley land and floodplains are formed. As streams transport sediment to areas of flatter slopes and, in particular, to bodies of water where the velocity and turbulence are too small to sustain transport of the material, the material is deposited forming deltas. As deltas build outward, the upstream portion of the channel is elevated through deposition and becomes part of the floodplain. Also, the stream channel is lengthened and the slope is further reduced. The upstream streambed is filled in and average flood elevations are increased. As the stream works across the stream valley, deposition causes the total floodplain to raise in elevation. Hence, even old streams are far from static. Old rivers meander, and they are affected by changes in sea level, influenced by movements of the earth's crust, changed by delta formations or glaciation, and subject to modifications due to climatological changes and as a consequence of man's development.

### **2.2.6 Natural Levees**

Natural levees form during floods as the stream stage exceeds bankfull conditions. Sediment is then deposited on the floodplain due to the reduced velocity and transporting capacity of the flood in these overbank areas. The natural levees formed near the stream are rather steep because coarse material drops out quickly as the overbank velocity is smaller than the stream velocity. Farther from the stream, the gradients are flatter and finer materials drop out. Swamp areas are found beyond the levees.

Classification based on natural levees is illustrated in figure 1. Streams with well-developed natural levees tend to be of constant width and have low rates of lateral migration. Well-developed levees usually occur along the lower courses of streams or where the floodplain is submerged for several weeks or months a year. If the levee is breached, the stream course may change through the breach. Areas between natural levees and the valley sides may drain, but slowly. Streams tributary to streams with well-developed natural levees may flow approximately parallel with the larger stream for long distances before entering the larger stream.

### **2.2.7 Apparent Incision**

The apparent incision of a stream channel is judged from the height of its banks at normal stage relative to its width. For a stream whose width is about 30 m, bank heights in the range of 1.8 to 3.0 m are about average, and higher banks indicate probable incision. For a stream whose width is about 300 m, bank heights in the range of 3.0 to 4.6 m are about average, and higher banks indicate probable incision. Incised streams tend to be fixed in position and are not likely to bypass a bridge or to shift in alignment at a bridge. Lateral erosion rates are likely to be slow, except for western arroyos with high, vertical, and clearly unstable banks.

### **2.2.8 Channel Boundaries and Vegetation**

Although no precise definitions can be given for alluvial, semi-alluvial, or non-alluvial streams, some distinction with regard to the erosional resistance of the earth material in channel boundaries is needed. In geology, bedrock is distinguished from alluvium and other surficial materials mainly on the basis of age, rather

than on resistance to erosion. A compact alluvial clay is likely to be more resistant than a weakly cemented sandstone that is much older. Nevertheless, the term "bedrock:" does carry a connotation of greater resistance to erosion, and it is used here in that sense. An alluvial channel is in alluvium, a non-alluvial channel is in bedrock or in very large material (cobbles and boulders) that do not move except at very large flows, and a semi-alluvial channel has both bedrock and alluvium in its boundaries. The bedrock of non-alluvial channels may be wholly or partly covered with sediment at low stages, but is likely to be exposed by scour during floods.

Most highway stream crossings are over alluvial streams which are susceptible to more hydraulic problems than non-alluvial streams. However, the security of foundations in bedrock depends on the quality of the bedrock and the care with which foundations are set. Serious problems and failures have developed at bridges with foundations on shale, sandstone, limestone, glacial till, and other erodible rock. The New York State Thruway Schoharie Creek bridge failure is a recent catastrophic example of such a failure. Bed material at the bridge site was highly cemented glacial till which scoured, undermining spread footings.

Changes in channel geometry with time are particularly significant during periods when alluvial channels are subjected to high flows, and few changes occur during relatively dry periods. Erosive forces during high-flow periods may have a capacity as much as 100 times greater than those forces acting during periods of intermediate and low-flow rates. When considering the stability of alluvial streams, in most instances it can be shown that approximately 90 percent of all changes occur during that small percentage of the time when the discharge exceeds dominant discharge. A discussion of dominant discharge may be found in Highways in the River Environment (HIRE), but the bankfull flow condition is recommended for use where a detailed analysis of dominant discharge is not feasible.<sup>(4)</sup>

The most significant property of materials of which channel boundaries are comprised is particle size. It is the most readily measured property, and, in general, represents a sufficiently complete description of the sediment particle for many practical purposes. Other properties such as shape and fall velocity tend to vary with size in a roughly predictable manner.

In general, sediments have been classified into boulders, cobbles, gravel, sands, silts, and clays on the basis of their nominal or sieve diameters. The size range in each general class is given in table 1. Noncohesive material generally consists of silt (0.004 - 0.062 mm), sand (0.062 - 2.0 mm), gravel (2.0 - 64 mm), or cobbles (64 - 250 mm).

The appearance of the streambank is a good indication of relative stability. A field inspection of a channel will help to identify characteristics which are associated with erosion rates:

- Unstable banks with moderate to high erosion rates usually have slopes which exceed 30 percent, and a cover of woody vegetation is rarely present. At a bend, the point bar opposite an unstable cut bank is likely to be bare at normal stage, but it may be covered with annual vegetation and low woody vegetation, especially willows. Where very rapid erosion is occurring, the bank may have irregular indentations. Fissures, which represent the boundaries of actual or potential slump blocks along the bank line indicate the potential for very rapid bank erosion.
- Unstable banks with slow to moderate erosion rates may be partly reshaped to a stable slope. The degree of instability is difficult to assess, and reliance is placed mainly on vegetation. The reshaping of a bank typically begins with the accumulation of slumped material at the base such that a slope is formed, and progresses by smoothing of the slope and the establishment of vegetation.

Table 1. Sediment Grade Scale.

Size		Approximate Sieve Mesh Openings (per inch)		Class	
Millimeters	Microns	Inches	Tyler		U.S. Standard
4000-2000	---	180-160	---	---	Very large boulders
2000-1000	---	80-40	---	---	Large boulders
1000-500	---	40-20	---	---	Medium boulders
500-250	---	20-10	---	---	Small boulders
250-130	---	10-5	---	---	Large cobbles
130-64	---	5-2.5	---	---	Small cobbles
64-32	---	2.5-1.3	---	---	Very coarse gravel
32-16	---	1.3-0.6	---	---	Coarse gravel
16-8	---	0.6-0.3	2.5	---	Medium gravel
8-4	---	0.3-0.16	5	5	Fine gravel
4-2	---	0.16-0.08	9	10	Very fine gravel
2.00-1.00	2000-1000	---	16	18	Very coarse sand
1.00-0.50	1000-500	---	32	35	Coarse sand
0.50-0.25	500-250	---	60	60	Medium sand
0.25-0.125	250-125	---	115	120	Fine sand
0.125-0.062	125-62	---	250	230	Very fine sand
0.062-0.031	62-31	---			Coarse silt
0.031-0.016	31-16	---			Medium silt
0.016-0.008	16-8	---			Fine silt
0.008-0.004	8-4	---			Very fine silt
0.004-0.0020	4-2	---			Coarse clay
0.0020-0.0010	2-1	---			Medium clay
0.0010-0.0005	1-0.5	---			Fine clay
0.0005-0.0002	0.5-0.24	---			Very fine clay

- Eroding banks are a source of debris when trees fall as they are undermined. Therefore, debris can be a sign of unstable banks and of great concern due to potential blockage of bridge openings.
- Stable banks with very slow erosion rates tend to be graded to a smooth slope of less than about 30 percent. Mature trees on a graded bank slope are convincing evidence of bank stability. In most regions of the United States, the upper parts of stable banks are vegetated, but the lower part may be bare at normal stage, depending on bank height and flow regime of the stream. Where banks are low, dense vegetation may extend to the water's edge at normal stage. Where banks are high, occasional slumps may occur on even the most stable graded banks. Shallow mountain streams that transport coarse bed sediment tend to have stable banks.

Active bank erosion can be recognized by falling or fallen vegetation along the bank line, cracks along the bank surface, slump blocks, deflected flow patterns adjacent to the bank line, live vegetation in the flow, increased turbidity, fresh vertical faces, newly formed bars immediately downstream of the eroding area, and, in some locations, a deep scour pool adjacent to the toe of the bank. These indications of active bank erosion can be noted in the field and on stereoscopic pairs of aerial photographs. Color infrared photography is particularly useful in detecting most of the indicators listed above, especially differences in turbidity. Figure 3 illustrates some of the features which indicate that a bank line is actively eroding.<sup>(5)</sup>

Bank Materials. Resistance of a streambank to erosion is closely related to several characteristics of the bank material. Bank material deposited in the stream can be broadly classified as cohesive, noncohesive, and composite. Typical bank failure surfaces of various materials are shown in figure 4 and described as follows:<sup>(6)</sup>

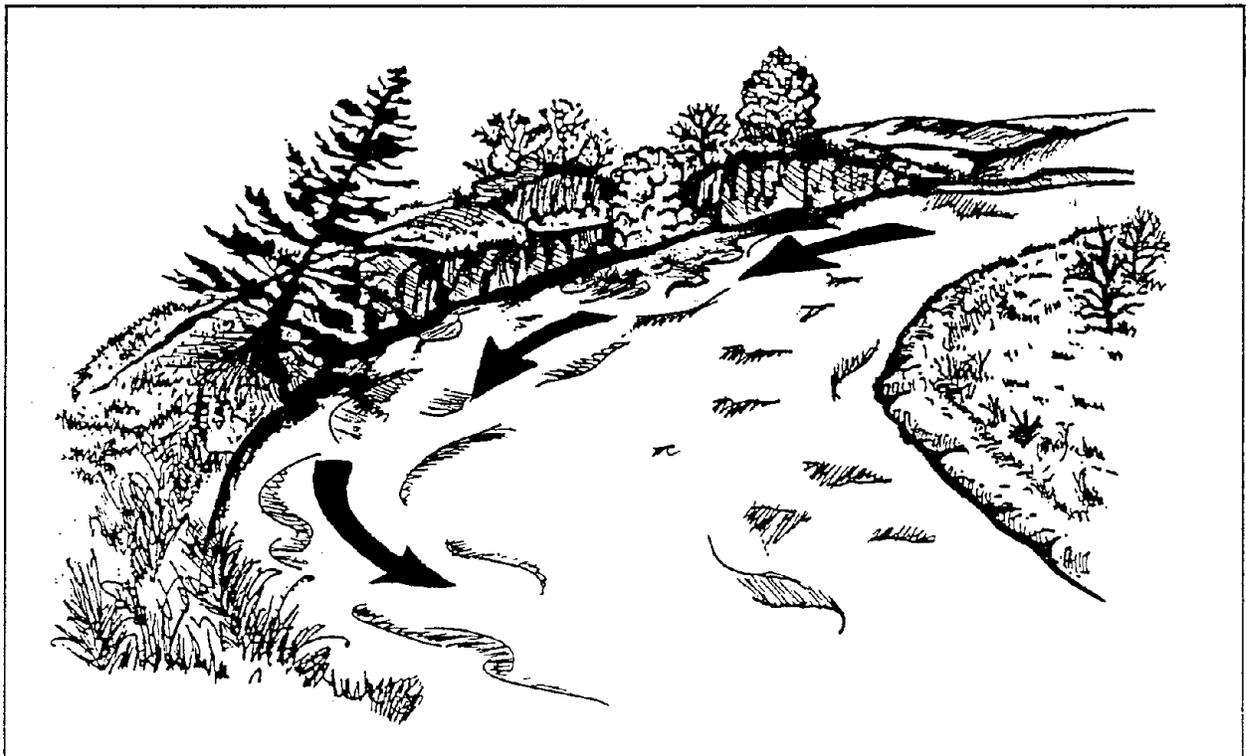


Figure 3. Active bank erosion illustrated by vertical cut banks, slump blocks, and falling vegetation.

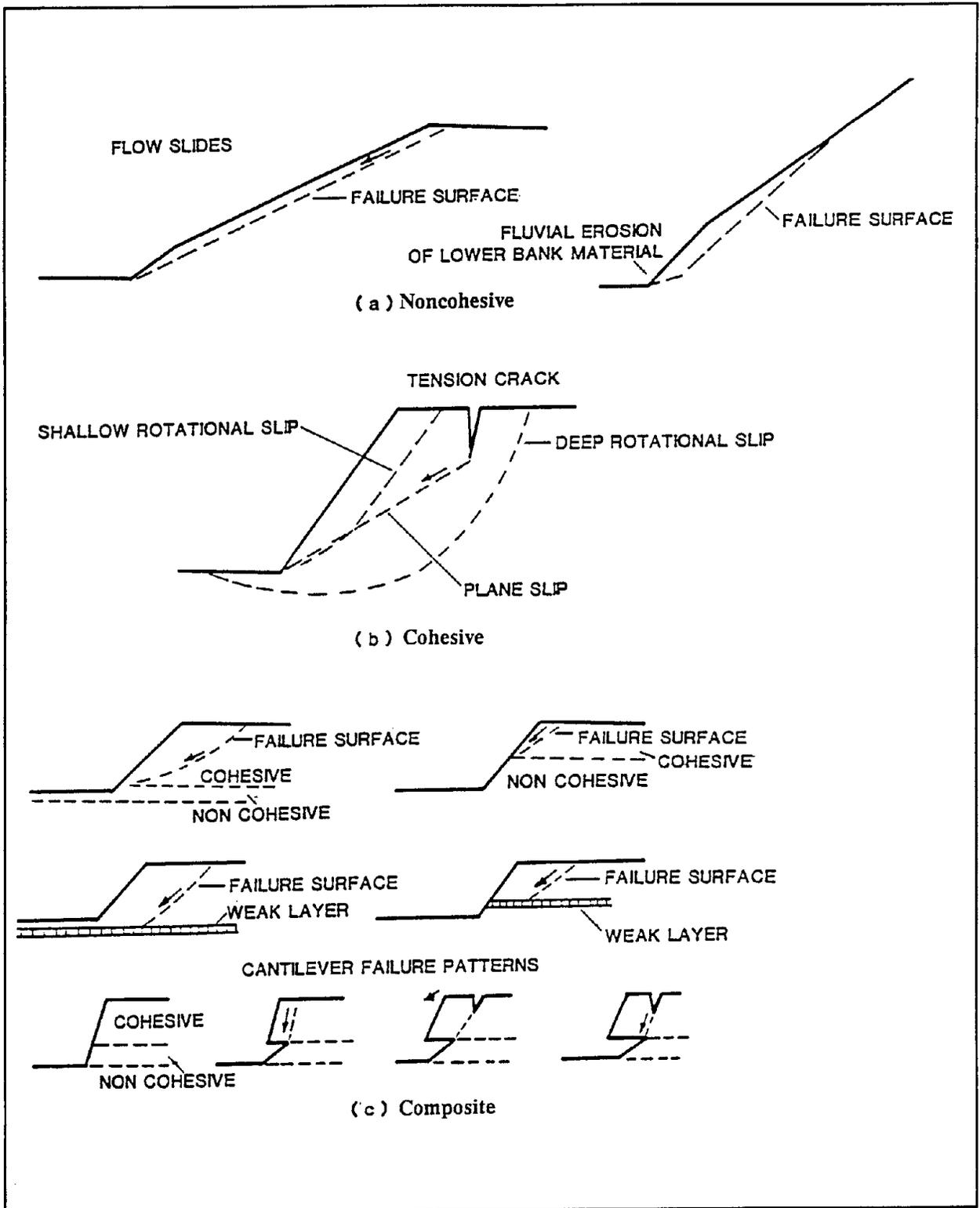


Figure 4. Typical bank failure surfaces: (a) noncohesive, (b) cohesive, and (c) composite (after Brown).<sup>(6)</sup>

- Noncohesive bank material tends to be removed grain by grain from the bank. The rate of particle removal, and particle movement, and hence the rate of bank erosion, is affected by factors such as particle size, bank slope, the direction and magnitude of the velocity adjacent to the bank, turbulent velocity fluctuations, the magnitude of and fluctuations in the shear stress exerted on the banks, seepage force, piping, and wave forces. Figure 4(a) illustrates failure of banks of noncohesive material from flow slides resulting from a loss of shear strength because of saturation, and failure from sloughing resulting from the removal of materials in the lower portion of the bank.
- Cohesive material is more resistant to surface erosion and has low permeability, which reduces the effects of seepage, piping, frost heaving, and subsurface flow on the stability of the banks. However, when undercut and/or saturated, such banks are more likely to fail due to mass wasting processes. Failure mechanisms for cohesive banks are illustrated in figure 4(b).
- Composite or stratified banks consist of layers of materials of various sizes, permeability, and cohesion. The layers of noncohesive material are subject to surface erosion, but may be partly protected by adjacent layers of cohesive material. This type of bank is also vulnerable to erosion and sliding as a consequence of subsurface flows and piping. Typical failure modes are illustrated in figure 4(c).

**Piping.** Piping is a phenomenon common to alluvial streambanks. With stratified banks, flow is induced in more permeable layers by changes in stream stage and by waves. If flow through the permeable lenses is capable of dislodging and transporting particles, the material is slowly removed, undermining portions of the bank. Without this foundation material to support the overlying layers, a block of bank material drops down and results in the development of tension cracks as sketched in figure 4(c). These cracks allow surface flows to enter, further reducing the stability of the affected block of bank material. Bank erosion may continue on a grain-by-grain basis or the block of bank material may ultimately slide downward and outward into the channel, with bank failure resulting from a combination of seepage forces, piping, and mass wasting.

**Mass Wasting.** Local mass wasting is another form of bank failure. If a bank becomes saturated and possibly undercut by flowing water, blocks of the bank may slump or slide into the channel. Mass wasting may be caused or aggravated by the construction of homes on river banks, operation of equipment adjacent to the banks, added gravitational force resulting from tree growth, location of roads that cause unfavorable drainage conditions, agricultural uses on adjacent floodplain, saturation of banks by leach fields from septic tanks, and increased infiltration of water into the floodplain as a result of changing land-use practices.

Various forces are involved in mass wasting. Landslides, the downslope movement of earth and organic materials, result from an imbalance of forces. These forces are associated with the downslope gravity component of the slope mass. Resisting these downslope forces are the shear strength of the materials and any contribution from vegetation via root strength or man's slope reinforcement activities. When the toe of a slope is removed, as by a stream, the slope materials may move downward into the void in order to establish a new equilibrium. Oftentimes, this equilibrium is a slope configuration with less than original surface gradient. The toe of the failed mass then provides a new buttress against further movements. Erosion of the toe of the slope then begins the process over again.

### 2.2.9 Sinuosity

Sinuosity is the ratio of the length of a stream reach measured along its centerline, to the length measured along the valley centerline or along a straight line connecting the ends of the reach. The valley centerline is preferable when the valley itself is curved. Sometimes, sinuosity is defined as the ratio of valley slope to stream slope or, more commonly, the ratio of the thalweg length to the valley length. Straight stream reaches have a sinuosity of one, and the maximum value of sinuosity for natural streams is about four. Inasmuch as the sinuosity of a stream is rarely constant from one reach to the next, no very refined measurement of sinuosity is warranted. The four classes of sinuosity in figure 1 are arbitrary.

A straight stream, or one that directly follows the valley centerline, sometimes has the same slope as the valley. As the sinuosity of the stream increases, its slope decreases in direct proportion. Similarly, if a sinuous channel is straightened, the slope increases in direct proportion to the change in length.

The size, form, and regularity of meander loops are aspects of sinuosity. Symmetrical meander loops are not very common, and a sequence of two or three identical symmetrical loops is even less common. In addition, meander loops are rarely of uniform size. The largest is commonly about twice the diameter of the smallest. Statistically, the size-frequency distribution of loop radii tends to have a normal distribution.

There is little relation between degree of sinuosity and lateral stream stability. A highly meandering stream may have a lower rate of lateral migration than a sinuous stream of similar size (figure 1). Stability is largely dependent on other properties, especially bar development and the variability of channel width.

Streams are broadly classified as straight, meandering or braided. Any change imposed on a stream system may change its planform geometry.

Straight Streams. A straight stream has small sinuosity at bankfull stage. At low stage, the channel develops alternate sandbars, and the thalweg meanders around the sandbars in a sinuous fashion. Straight streams are considered a transitional stage to meandering, since straight channels are relatively stable only where sediment size and load are small, gradient, velocities, and flow variability are low, and the channel width-depth ratio is relatively low. Straight channel reaches of more than 10 channel widths are not common in nature.

Meandering Streams. Alluvial channels of all types deviate from a straight alignment. The thalweg oscillates transversely and initiates the formation of bends. In a straight stream, alternate bars and the thalweg are continually changing; thus, the current is not uniformly distributed through the cross section, but is deflected toward one bank and then the other. Sloughing of the banks, nonuniform deposition of bed load, debris such as trees, and the Coriolis force due to the Earth's rotation have been cited as causes for the meandering of streams. When the current is directed toward a bank, the bank is eroded in the area of impingement, and the current is deflected and impinges on the opposite bank farther downstream. The angle of deflection of the current is affected by the curvature formed in the eroding bank and the lateral depth of erosion. Figure 5 shows bars, pools, and crossings typical of a meandering channel and the effects on water surface profiles.

Sinuuous, meandering, and highly meandering streams have more or less regular inflections that are sinuous in plan, consisting of a series of bends connected by crossings. In the bends, deep pools are carved adjacent to the concave bank by the relatively high velocities. Because velocities are lower on the inside of bends, sediments are deposited in this region, forming point bars. Also, the centrifugal force in the bend causes a transverse water surface slope and helicoidal flow with a bottom velocity away from the outer bank toward the point bar. These transverse velocities enhance point bar building by sweeping the heavier concentrations of bed load toward the convex bank where they are deposited to form the point bar. Some transverse currents have a magnitude of about 15 percent of the average channel velocity.

The bends in meandering streams are connected by crossings (short straight reaches) which are quite shallow compared to the pools in the bendways. At low flow, large sandbars form in the crossings if the channel is not well confined. Scour in the bend causes the bend to migrate downstream and sometimes laterally. Lateral movements as large as 750 m/yr have been observed in large alluvial rivers. Much of the sediment eroded from the outside bank is deposited in the crossing and on the point bar in the next bend downstream. The variability of bank materials and the fact that the stream encounters and produces such features as clay plugs causes a wide variety of river forms. The meander belt formed is often fifteen to twenty times the channel width.

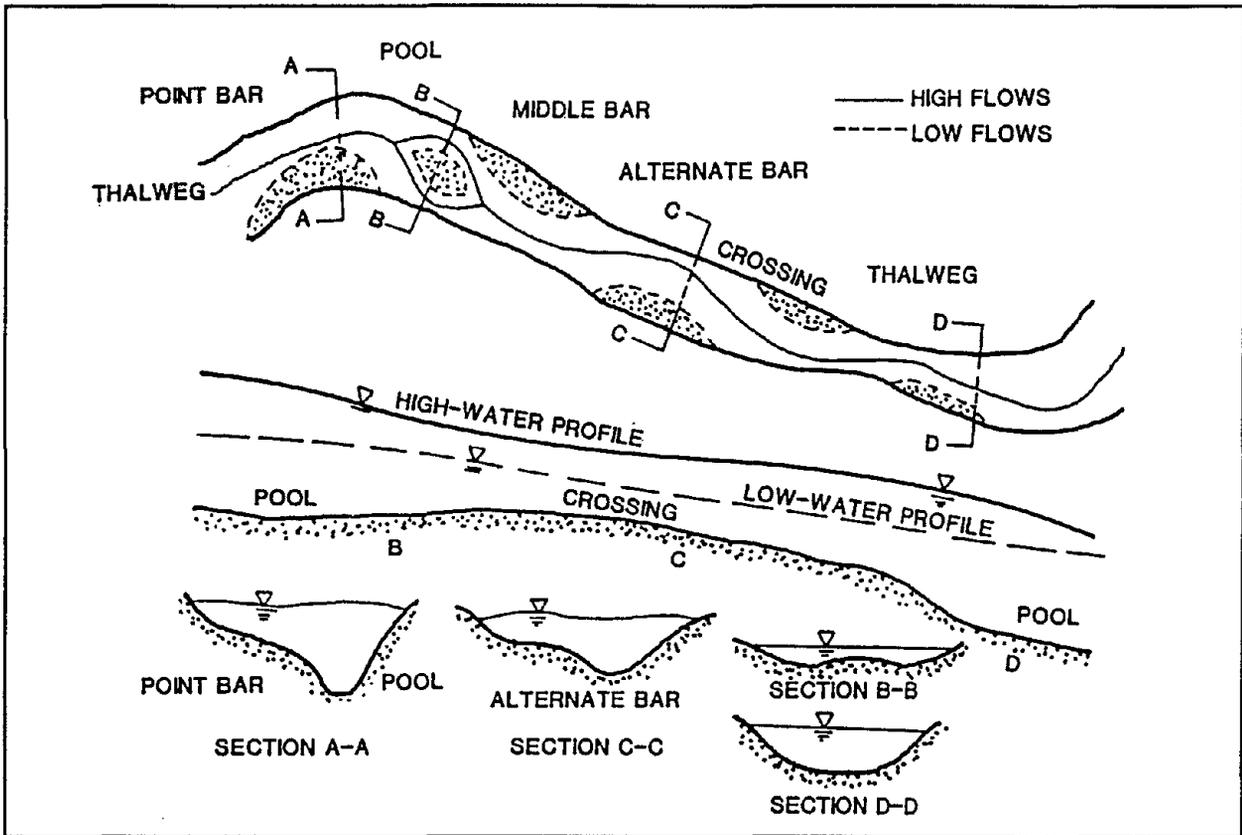


Figure 5. Plan view and cross section of a meandering stream (after HIRE).<sup>(4)</sup>

On a laterally unstable channel, or at actively migrating bends on an otherwise stable channel, point bars are usually wide and unvegetated and the opposite bank is cut and often scalloped by erosion. The crescent-shaped scars of slumping may be visible from place to place along the bank line. The presence of a cut bank opposite a point bar is evidence of instability. Sand or gravel on the bar appears as a light tone on aerial photographs. The unvegetated condition of the point bar is attributed to a rate of outbuilding that is too rapid for vegetation to become established. However, the establishment of vegetation on a point bar is dependent on factors other than the rate of growth of the point bar, such as climate and the timing of floods. Therefore, the presence of vegetation on a point bar is not conclusive evidence of stability. If the width of an unvegetated point bar is considered as part of the channel width, the channel tends to be wider at bends.

As a meandering stream system moves laterally and longitudinally, meander loops move at unequal rates because of unequal erodibility of the banks. This causes the channel to appear as a slowly developing bulb-form. Channel geometry depends upon the local slope, bank material, and the geometry of adjacent bends. Years may be required before a configuration characteristic of average conditions in the stream is attained.

If the proposed highway or highway stream crossing is located near a meander loop, it is useful to have some insight into the probable way in which the loop will migrate or develop, as well as its rate of growth. No two meanders will behave in exactly the same way, but the meanders on a particular stream reach tend to conform to one of the several modes of behavior illustrated in figure 6, which is based on a study of about 200 sinuous or meandering stream reaches.<sup>(1)</sup>

Mode a (figure 6) represents the typical development of a loop of low amplitude, which decreases in radius as it extends slightly in a downstream direction. Mode b rarely occurs unless meanders are confined by artificial levees or by valley sides on a narrow floodplain. Well developed meanders on streams that have moderately unstable banks are likely to follow Mode c. Mode d applies mainly to larger loops on meandering or

highly meandering streams. The meander has become too large in relation to stream size and flow, and secondary meanders develop, converting it to a compound loop. Mode e also applies to meandering or highly meandering streams, usually of the equiwidth, point-bar type. The banks have been sufficiently stable for an elongated loop to form without being cut off, but the neck of the loop is gradually being closed and cutoff will eventually occur at the neck. Modes f and g apply mainly to locally braided, sinuous, or meandering streams having unstable banks. Loops are cut off by chutes that break diagonally or directly across the neck.

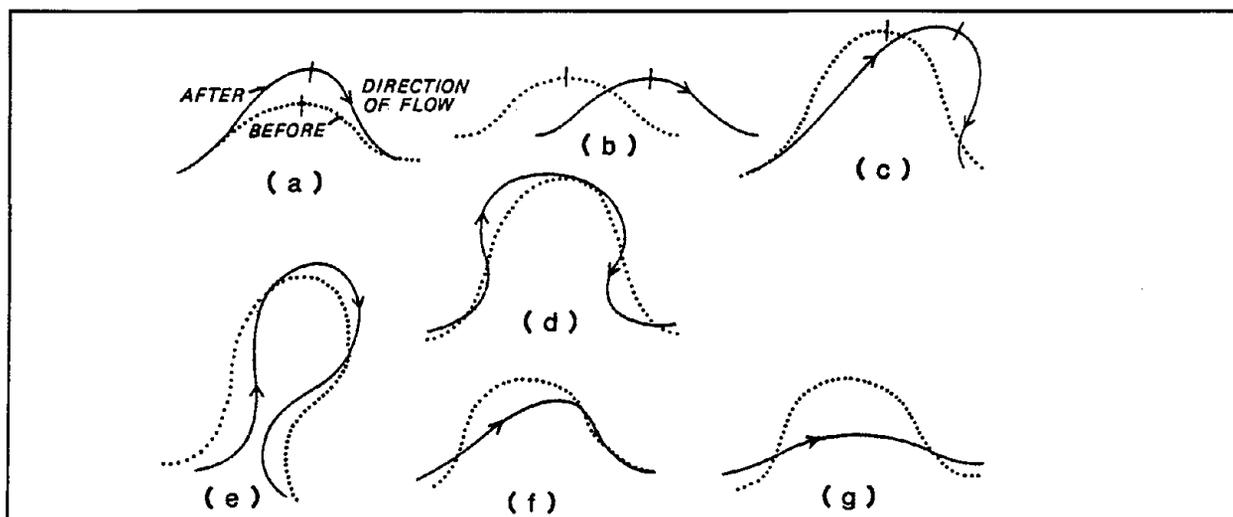


Figure 6. Modes of meander loop development: (a) extension; (b) translation; (c) rotation; (d) conversion to a compound loop; (e) neck cutoff by closure; (f) diagonal cutoff by chute; and (g) neck cutoff by chute (after Brice and Blodgett).<sup>(1)</sup>

Oxbow lakes are formed by the cutoff of meander loops, which occurs either by gradual closure of the neck (neck cutoffs) or by a chute that cuts across the neck (chute cutoffs). Neck cutoffs are associated with relatively stable channels, and chute cutoffs with relatively unstable channels. Recently formed oxbow lakes along a channel are evidence of recent lateral migration. Commonly, a new meander loop soon forms at the point of cutoff and grows in the same direction as the previous meander. Cutoffs tend to induce rapid bank erosion at adjacent meander loops. The presence of abundant oxbow lakes on a floodplain does not necessarily indicate a rapid channel migration rate because an oxbow lake may persist for hundreds of years.

Usually the upstream end of the oxbow lake fills quickly to bank height. Overflow during floods and overland flow entering the oxbow lake carry fine materials into the oxbow lake area. The lower end of the oxbow remains open and drainage entering the system can flow out from the lower end. The oxbow gradually fills with fine silts and clays which are plastic and cohesive. As the stream channel meanders, old bendways filled with cohesive materials (referred to as clay plugs) are sufficiently resistant to erosion to serve as semipermanent geologic controls which can drastically affect planform geometry.

The local increase in channel slope due to cutoff usually results in an increase in the growth rate of adjoining meanders, and an increase in channel width at the point of cutoff. On a typical wide-bend point-bar stream, the effects of cutoff do not extend very far upstream or downstream. The consequences of cutoffs are an abruptly steeper stream gradient at the point of the cutoff, scour at the cutoff, and a propagation of the scour in an upstream direction. Downstream of a cutoff, the gradient of the channel is not changed and, therefore, the increased sediment load caused by upstream scour will usually be deposited at the site of the cutoff or below it, forming a large bar.

In summary, there is little relation between degree of sinuosity, as considered apart from other properties, and lateral stream stability.<sup>(1)</sup> A highly meandering stream may have a lower rate of lateral migration

than a sinuous stream of similar size. Assessment of stability is based mainly on additional properties, especially on bar development and the variability of channel width. However, many hydraulic problems are associated with the location of highway crossings at a meander or bend. These include the shift of flow direction at flood stage, shift of thalweg toward piers or abutments, development of point bars in the bridge reach, and lateral channel erosion at piers, abutments, or approaches.

Since random factors seem to be involved in the migration of meanders, the exact rate or place of erosion is probably not predictable. However, the most rapid bank erosion is generally at the outside of meanders, downstream from the apex of the loop.

The cutoff of a meander, whether done artificially or naturally, causes a local increase in channel slope and a more rapid growth rate of adjoining meanders. Adjustment of the channel to increase in slope seems to be largely accomplished by increase in channel width (wetted perimeter) at and near the point of cutoff.

Some generalizations can be made, from general knowledge of stream behavior, about the probable consequences of controlling or halting the development of a meander loop by the use of countermeasures. The most probable consequences relate to change in flow alignment (or lack of change, if the position of a naturally eroding bank is held constant). The development of a meander is affected by the alignment of the flow that enters it. Any artificial influence on flow alignment is likely to affect meander form. Downstream bank erosion rates are not likely to be increased, but the points at which bank erosion occurs are likely to be changed. In the case where flow is deflected directly at a bank, an increase in erosion rates would be expected. The recent failure of a major bridge on the Hatchie River near Covington, Tennessee has been attributed, in part, to lateral migration of the channel in the bridge reach.

#### **2.2.10 Braided Streams**

A braided stream is one that consists of multiple and interlacing channels (figure 1). In general, a braided channel has a large slope, a large bed-material load in comparison with its suspended load, and relatively small amounts of silts and clays in the bed and banks. The magnitude of the bed load is more important than its size. If the flow is overloaded with sediment, deposition occurs, the bed aggrades, and the slope of the channel increases in an effort to obtain a graded state. As the channel steepens, velocity increases, and multiple channels develop. Multiple channels are generally formed as bars of sediment and deposited within the main channel, causing the overall channel system to widen. However, braided streams may occur with a graded state that is neither aggrading nor degrading.

The formation of multiple, mid channel islands and bars is characteristic of streams that transport large bed loads. The presence of bars obstructs flow and scour occurs, either lateral erosion of banks on both sides of the bar, scour of the channels surrounding the bar, or both. This erosion will enlarge the channel and, with reduced water levels, an island may form at the site of a gravel or sand bar. The worst case will be where major bar or island forms at a bridge site. This can produce erosion of both banks of the stream and bed scour along both sides of the island. Reduction in the flow capacity beneath the bridge can result as a vegetated island forms under the bridge. An island or bar that forms upstream or downstream of a bridge can change flow alignment and create bank erosion or scour problems at the bridge site.

Island shift is easily identified because active erosion at one location and active deposition at another on the edge of an island can be recognized in the field. Also, the development or abandonment of flood channels and the joining together of islands can be detected by observing vegetational differences and patterns of erosion and deposition.

The degree of channel braiding is indicated by the percent of reach length that is divided by bars and islands, as shown in figure 1. Braided streams tend to be common in arid and semiarid parts of the western United States and regions having active glaciers.

Braided streams may present difficulties for highway construction because they are unstable, change alignment rapidly, carry large quantities of sediment, are very wide and shallow even at flood flow and are, in general, unpredictable. Deep scour holes can develop downstream of a gravel bar or island where the flow from two channels comes together.

Braided streams generally require long bridges if the full channel width is crossed or effective flow-control measures if the channel is constricted. The banks are likely to be easily erodible, and unusual care must be taken to prevent lateral erosion at or near abutments. The position of braids is likely to shift during floods, resulting in unexpected velocities, angle of attack, and depths of flow at individual piers. Lateral migration of braided streams takes place by lateral shift of a braid against the bank, but available information indicates that lateral migration rates are generally less than for meandering streams. Along braided streams, however, migration is not confined to the outside of bends but can take place at any point by the lateral shift of individual braids.

### **2.2.11 Anabranching Streams**

An anabranching stream differs from a braided stream in that the flow is divided by islands rather than bars, and the islands are large relative to channel width. The anabranches, or individual channels, are more widely and distinctly separated and more fixed in position than the braids of a braided stream. An anabranch does not necessarily transmit flow at normal stage, but it is an active and well-defined channel, not blocked by vegetation. The degree of anabranching is arbitrarily categorized in figure 1 in the same way as the degree of braiding was described.

Although the distinction between braiding and anabranching may seem academic, it has real significance for engineering purposes. Inasmuch as anabranches are relatively permanent channels that may convey substantial flow, diversion and confinement of an anabranching stream is likely to be more difficult than for a braided stream. Problems associated with crossings on anabranching streams can be avoided if a site where the channel is not anabranching can be chosen. If not, the designer may be faced with a choice of either building more than one bridge, building a long bridge, or diverting anabranches into a single channel. Problems with flow alignment may occur if a bridge is built at or near the junction of anabranches. Where anabranches are crossed by separate bridges, the design discharge for the bridges may be difficult to estimate. If one anabranch should become partly blocked, as by floating debris or ice, an unexpected amount of flow may be diverted to the other.

### **2.2.12 Variability of Width and Development of Bars**

The variability of unvegetated channel width is a useful indication of the lateral stability of a channel. The visual impression of unvegetated channel width on aerial photographs depends on the relatively dark tones of vegetation as contrasted with the lighter tones of sediment or water. A channel is considered to be of uniform width (equiwidth) if the unvegetated width at bends is not more than 1.5 times the average width at the narrowest places.

The relationship between width variability and lateral stability is based on the rate of development of point bars and alternate bars. If the concave bank at a bend is eroding slowly, the point bar will grow slowly and vegetation will become established on it. The unvegetated part of the bar will appear as a narrow crescent. If the bank is eroding rapidly, the unvegetated part of the rapidly growing point bar will be wide and conspicuous. A point bar with an unvegetated width greater than the width of flowing water at the bend is considered to be wider than average. Lateral erosion rates are probably high in stream reaches where bare point bars tend to exceed average width. In areas where vegetation is quickly established, as in rainy southern climates, cut banks at bends may be a more reliable indication of instability than the unvegetated width of point bars.

Three categories of width variability are distinguished in figure 1, but the relative lateral stability of these must be assessed in connection with bar development and other properties. In general, equiwidth streams having narrow point bars are the most stable laterally, and random-width streams having wide, irregular point bars are the least stable. Vertical stability, or the tendency to scour, cannot be assessed from these properties. Scour may occur in any alluvial channel. In fact, the greatest potential for deep scour might be expected in laterally stable equiwidth channels, which tend to have relatively deep and narrow cross sections and bed material in the size range of silt and sand.

### 2.3 LANE RELATION AND OTHER GEOMORPHIC CONCEPTS

The major complicating factors in river mechanics are: (1) the large number of interrelated variables that can simultaneously respond to natural or imposed changes in a stream system, and (2) the continual evolution of stream channel patterns, channel geometry, bars and forms of bed roughness with changing water and sediment discharge. In order to understand the responses of a stream to the actions of man and nature, a few simple geomorphic concepts are presented here.

The dependence of stream form on slope, which may be imposed independent of other stream characteristics, is illustrated schematically in figure 7. Any natural or artificial change which alters channel slope can result in modifications to the existing stream pattern. For example, a cutoff of a meander loop increases channel slope. Referring to figure 7, this shift in the plotting position to the right could result in a shift from a relatively tranquil, meandering pattern toward a braided pattern that varies rapidly with time, has high velocities, is subdivided by sandbars, and carries relatively large quantities of sediment. Conversely, it is possible that a slight decrease in slope could change an unstable braided stream into a meandering one.

The significantly different channel dimensions, shapes, and patterns associated with different quantities of discharge and amounts of sediment load indicate that as these independent variables change, major adjustments of channel morphology can be anticipated. Further, a change in hydrology may cause changes in stream sinuosity, meander wave length, and channel width and depth. A long period of channel instability with considerable bank erosion and lateral shifting of the channel may be required for the stream to compensate for the hydrologic change. The reaction of a channel to changes in discharge and sediment load may result in channel dimension changes contrary to those indicated by many regime equations. For example, it is conceivable that a decrease in discharge together with an increase in sediment load could cause a decrease in depth and an increase in width.

Figure 8 illustrates the dependence of sand-bed stream form on channel slope and discharge. According to Lane, a sand-bed channel meanders where:<sup>(7)</sup>

$$SQ^{0.25} \leq 0.00070 \tag{1}$$

Similarly, a sand-bed channel is braided where:

$$SQ^{0.25} \geq 0.0041 \tag{2}$$

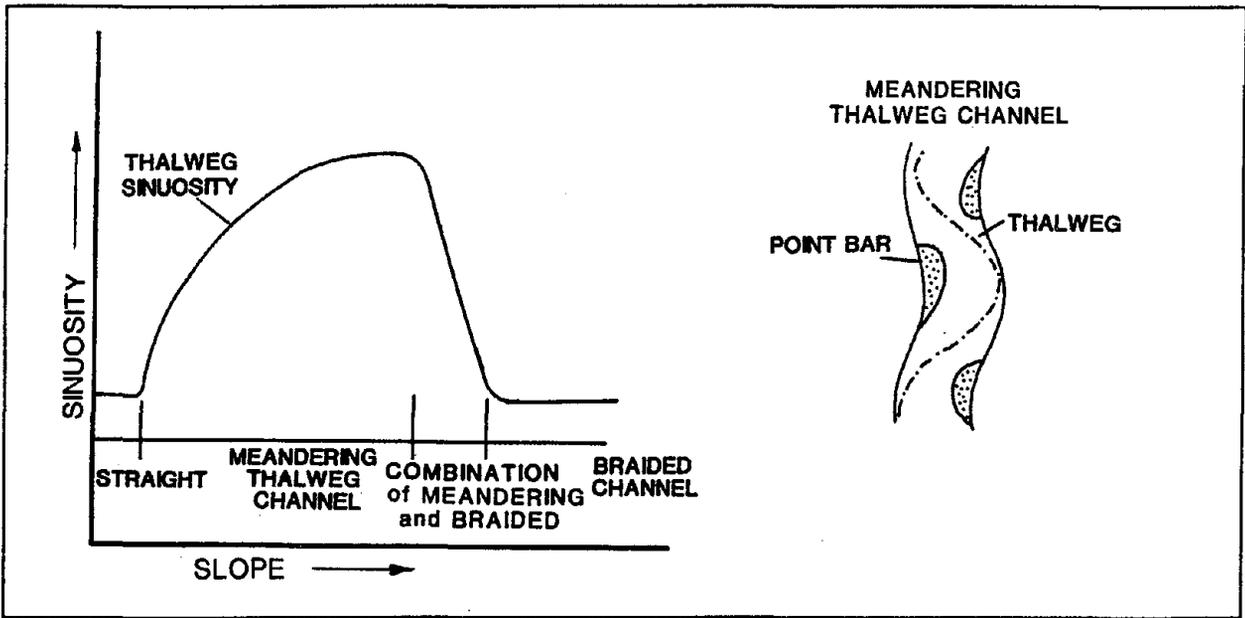


Figure 7. Sinuosity vs. slope with constant discharge (after HIRE).<sup>(4)</sup>

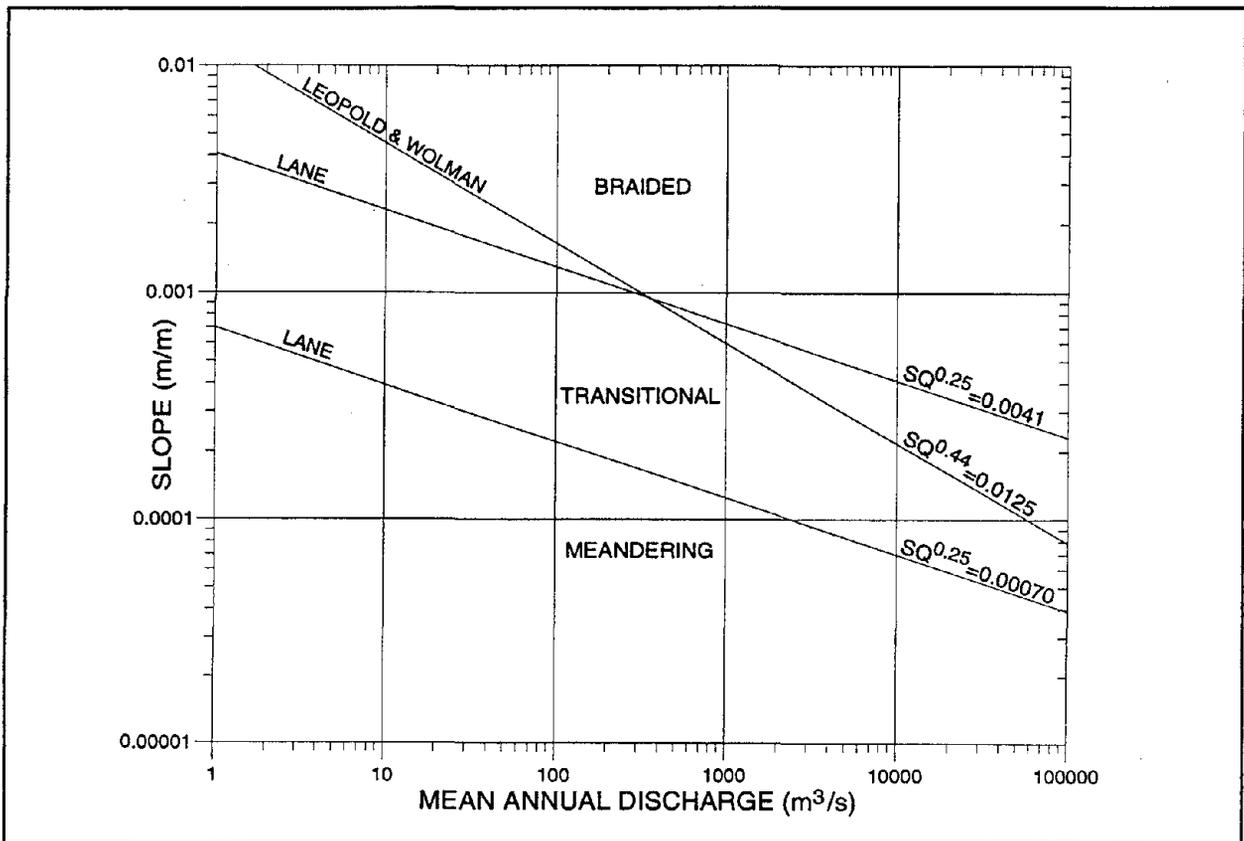


Figure 8. Slope-discharge relationship for braiding or meandering in sand-bed streams (after Lane).<sup>(7)</sup>

where:

S = channel bed slope, m/m

Q = mean discharge, m<sup>3</sup>/s

The zone between the lines defining braided streams and meandering streams in figure 8 is the transitional range, i.e., the range in which a stream can change readily from one stream form to the other.

Many United States rivers, classified as intermediate sand-bed streams, plot in this zone between the limiting curves defining meandering and braided stream. If a stream is meandering but its discharge and slope borders on the transitional zone, a relatively small increase in channel slope may cause it to change, with time, to a transitional or braided stream.

Leopold and Wolman plotted slope and discharge for a variety of natural streams.<sup>(8)</sup> They observed that a line could separate meandering from braided streams. The equation of this line is:

$$SQ^{0.44} = 0.0125 \quad (3)$$

Streams classified as meandering by Leopold and Wolman are those whose sinuosity is greater than 1.5. Braided streams are those which have relatively stable alluvial islands and, therefore, two or more channels. They note that sediment size is related to slope and channel pattern but do not try to account for the effect of sediment size on the morphology of streams. They further note that braided and meandering streams can be differentiated based on combinations of slope, discharge, and width/depth ratio, but regard width as a variable dependent mainly on discharge.

Long reaches of many streams have achieved a state of equilibrium, for practical engineering purposes. These stable reaches are called "graded" streams by geologists and "poised" streams by engineers. However, this condition does not preclude significant changes over a short period of time or over a period of years. Conversely, many streams contain long reaches that are actively aggrading or degrading. These aggrading and degrading channels pose definite hazards to highway crossings and encroachments, as compared with poised streams.

Regardless of the degree of channel stability, man's activities may produce major changes in stream characteristics locally and throughout an entire reach. All too frequently, the net result of a stream "improvement" is a greater departure from equilibrium than existed prior to "improvement." Designers of stream channel modifications should invariably seek to enhance the natural tendency of the stream toward equilibrium and a stable condition. This requires an understanding of the direction and magnitude of change in channel characteristics which will result from the actions of man and nature. This understanding can be obtained by: (1) studying the stream in a natural condition, (2) having knowledge of the sediment and water discharge, (3) being able to predict the effects and magnitude of man's future activities, and (4) applying to these a knowledge of geology, soils, hydrology, and hydraulics of alluvial rivers.

Predicting the response to channel modifications is a very complex task. There are large numbers of variables involved in the analysis that are interrelated and can respond to changes in a stream system in the continual evolution of stream form. The channel geometry, bars, and forms of bed roughness all change with changing water and sediment discharges. Because such a prediction is necessary, useful methods have been developed to qualitatively and quantitatively predict the response of channel systems to changes.

Quantitative prediction of response can be made if all of the required data are known with sufficient accuracy. However, available data are usually not sufficient for quantitative estimates, and only qualitative estimates are possible. Examples of studies that have been undertaken by various investigators for qualitative estimates follow. Lane studied the changes in stream morphology caused by modifications of water and sediment discharges.<sup>(9)</sup> Similar but more comprehensive treatments of channel response to changing conditions

in streams have been presented by Leopold and Maddock, Schumm, and Santos-Cayado.<sup>(10,11,12)</sup> All research results support the relationship originally proposed by Lane:

$$QS \propto Q_s D_{50} \quad (4)$$

where:

Q = discharge  
S = energy slope  
Q<sub>s</sub> = sediment discharge  
D<sub>50</sub> = median sediment size

Equation 4 is very useful to predict qualitatively channel response to climatological changes, stream modifications, or both. The geomorphic relation expressed is only an initial step in analyzing long-term channel response problems. However, this initial step is useful because it warns of possible future difficulties related to channel modifications. Examples of its use are given in section 2.4.4 and in HIRE.<sup>(4)</sup>

## 2.4 AGGRADATION/DEGRADATION AND THE SEDIMENT CONTINUITY CONCEPT

### 2.4.1 Aggradation/Degradation

Aggradation and degradation are the vertical raising and lowering, respectively, of the streambed over relatively long distances and time frames. Such changes can be the result of both natural and man-induced changes in the watershed. The sediment continuity concept is the primary principle applied in both qualitative and quantitative analysis of bed elevation changes. After an introduction to the concept of sediment continuity, some factors causing a bed elevation change are reviewed.

### 2.4.2 Overview of the Sediment Continuity Concept

The amount of material transported, eroded, or deposited in an alluvial channel is a function of sediment supply and channel transport capacity. Sediment supply is provided from the tributary watershed and from any erosion occurring in the upstream channel. Sediment transport capacity is a function of the size of sediment, the discharge of the stream, and the geometric and hydraulic properties of the channel. When the transport capacity (sediment outflow) equals sediment supply (sediment inflow), a state of equilibrium exists.

Application of the sediment continuity concept to a single channel reach illustrates the relationship between sediment supply and transport capacity. Technically, the sediment continuity concept states that the sediment inflow minus the sediment outflow equals the time rate of change of sediment volume in a given reach. More simply stated, during a given time period the amount of sediment coming into the reach minus the amount leaving the downstream end of the reach equals the change in the amount of sediment stored in that reach (see figure 9). The sediment inflow to a given reach is defined by the sediment supply from the watershed (upstream of the study reach plus any significant lateral input directly to the study reach). The transport capacity of the channel within the given reach defines the sediment outflow. Changes in the sediment volume within the reach occur when the total input to the reach (sediment supply) is not equal to the downstream output (sediment transport capacity). When the sediment supply is less than the transport capacity, erosion (degradation) will occur in the reach so that the transport capacity at the outlet is satisfied, unless controls exist that limit erosion. Conversely, when the sediment supply is greater than the transport capacity, deposition (aggradation) will occur in the reach.

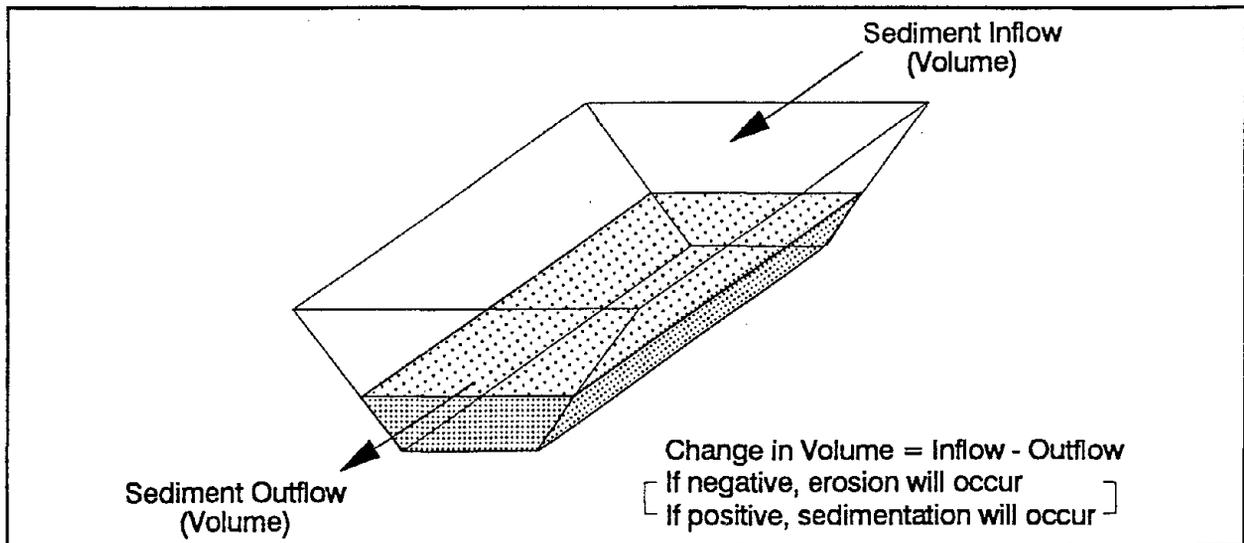


Figure 9. Definition sketch of sediment continuity concept applied to a given channel reach over a given time period.

Controls that limit erosion may either be man made or natural. Man-made controls included bank protection works, grade control structures, and stabilized bridge crossings. Natural controls can be geologic, such as outcroppings, or the presence of significant coarse sediment material in the channel. The presence of coarse material can result in the formation of a surface armor layer of larger sediments that are not transported by average flow conditions.

#### 2.4.3 Factors Initiating Bed Elevation Changes

Man-induced Changes. Man's activities are the major cause of streambed elevation changes. Very few bed elevation changes are due to natural causes, although some may be the result of both natural and man-induced causes. The most common activities which result in bed elevation changes caused by man are channel alterations, streambed mining, dams and reservoirs, and land-use changes. Highway construction, including the construction of bridges and channel alterations of limited extent, usually affect stream vertical stability only locally.

Channel Alterations. Dredging, channelization, straightening, the construction of cutoffs to shorten the flow path of a stream, and clearing and snagging to increase channel capacity are the major causes of streambed elevation changes. An increase in slope resulting from a shorter flow path, or an increase in flow capacity results in increased velocities and a corresponding increase in sediment transport capacity. If the stream was previously in equilibrium (supply equal to transport capacity) the channel may adjust, either by increasing its length or by reducing its slope by degradation, in order to reestablish equilibrium. The most frequent response is a degrading streambed followed by bank erosion and a new meander pattern.

Constrictions in a stream channel, as in river control projects to maintain a navigation channel or highway crossings, also increase velocities and the sediment transport capacity in the constricted reach. The resulting degradation can be considered local, but it may extend through a considerable reach of stream, depending on the extent of the river control project. Constrictions may also cause local aggradation problems downstream.

The response to an increased sediment load in a stream that was near equilibrium conditions (i.e., supply now greater than transport capacity) is normally deposition in the channel downstream of the alteration. The result is an increase in flood stages and overbank flooding in downstream reaches. In time, the aggradation will

progress both upstream and downstream of the end of the altered channel, and the stream reach may become locally braided as it seeks a new balance between sediment supply and sediment transport capacity.

Streambed Mining. Streambed mining for sand or gravel can be beneficial or detrimental, depending on the balance between sediment supply and transport capacity. Where the sediment supply exceeds the stream's transport capacity because of man's activities in the watershed or from natural causes, controlled removal of gravel bars and limited mining may enhance both lateral and vertical stability of the stream.

The usual result of streambed mining is an imbalance between sediment supply and transport capacity. Upstream of the operation, the water surface slope may be increased and bank erosion and headcutting or a nick point may result. The extent of the damage that can result is a function of the volume and depth of the sand and gravel pit relative to the size of the stream, bed material size, flood hydrographs, upstream sediment transport, and the location of the pit. If the size of the borrow pit is sufficiently large, a substantial quantity of the sediment inflow will be trapped in the pit and degradation will occur downstream. If bank erosion and headcutting upstream of the pit produce a sediment supply greater than the trap capacity of the pit and the transport capacity downstream, aggradation could occur. However, this circumstance is unlikely and streambed mining generally causes degradation upstream and downstream of the pit.

Dams and Reservoirs. Storage and flood control reservoirs produce a stream response both upstream and downstream of the reservoir. A stream flowing into a reservoir forms a delta as the sediment load is deposited in the ponded water. This deposition reduces the stream gradient upstream of the reservoir and causes aggradation in the channel. Aggradation can extend many kilometers upstream.

Downstream of reservoirs, stream channel stability is affected because of the changed flow characteristics and because flow releases are relatively sediment-free. Clear water releases pick up a new sediment load and degradation can result. The stream channel and stream gradient that existed prior to the construction of the dam was the cumulative result of past floods of various sizes and subject to change with each flood. Post-construction flows are usually of lesser magnitude and longer duration and the stream will establish a new balance in time consistent with the new flow characteristics.

It is possible for aggradation to occur downstream of a reservoir if flow releases are insufficient to transport the size or volume of sediment brought in by tributary streams. Streamflow regulation, which is an objective in dam construction and reservoir operation, is sometimes overlooked in assessing stream system response to this activity by man. The reduction in flood magnitude and stage downstream of dams as a result of reservoir operation can result in greatly increased hydraulic gradients and degradation in tributaries downstream of the dam. A notorious bridge failure on the Big Sioux River was, in part, attributable to such a condition.

Land Use Changes. Agricultural activities, urbanization, commercial development, and construction activities also contribute to bed elevation problems in streams. Clear cutting of forests, and the destruction of grasslands by overgrazing, burning and cultivation can accelerate erosion, causing streams draining these areas to become overloaded with sediment (i.e., excess sediment supply). As the overload persists, the stream system aggrades and increases its slope to increase its sediment transport capacity.

Construction and developing urban and commercial areas can affect stream gradient stability. Fully developed urban areas are low sediment producers because of impervious areas and lawns, but tend to increase the magnitude of runoff events and reduce their duration. The response of a small stream system to these changes is degradation, changes in planform (e.g., increased sinuosity), and channel widening downstream of the urbanized area. However, if the urbanized area is small relative to the basin of the stream in which it is located, the net effect will probably be small.

Natural Changes. Natural causes of stream gradient instability are primarily natural channel alterations, earthquake, tectonic and volcanic activities, climatic change, fire, and channel bed and bank material erodibility.

Cutoffs and chute development associated with channel straightening are the most common natural channel alterations. This results in a shorter flow path, a steeper channel gradient, and an increase in sediment

transport capacity. Significant bank erosion and degradation progressing to an upstream control can result. Downstream of the cutoff, aggradation will occur.

Severe landslides, mud flows, uplifts and lateral shifts in terrain, and liquefaction of otherwise semi-stable materials are associated with earthquakes and tectonic activities. The response to these activities include channel changes, scour or deposition locally or system-wide, headcutting and bank instability.

Alluvial fans, discussed under Valley Setting, are among the most common naturally occurring cases of channel aggradation.

#### 2.4.4 Stream System Response

Streambed aggradation or degradation affects not only the stream in which a bed elevation change is initiated, but also tributaries to the stream and the stream to which it is tributary. Thus, the stream system is in an imbalanced sediment supply-sediment transport capacity condition, and it will seek a new state of equilibrium. A few examples are cited to illustrate the system-wide response to gradation changes. These examples also illustrate the use of several geomorphic concepts introduced in section 2.3 and the discussion of section 2.4.3.

Example 1. A degrading principal stream channel will cause tributaries to the stream to degrade, thus contributing additional sediment load to the degrading stream. This larger sediment load will slow the rate of degradation in the principal stream channel and may halt or reverse it for a period of time if the contribution is large enough or if a tributary transports material which armors the bed of the degrading stream.

Using equation 4, the basic response of the principal stream can be expressed as:

$$QS^+ \propto Q_s^+ D_{50}$$

Here, it is assumed that water discharge ( $Q$ ) and sediment size ( $D_{50}$ ) remain unchanged. (Note: When neither + or - appears as a superscript in the Lane relationship, conditions remain unchanged). Thus, the increase in sediment discharge ( $Q_s^+$ ) derived from the tributary stream must result in an increase in slope ( $S^+$ ) on the master stream if the geomorphic balance expressed by the Lane relationship is to hold. This increase in slope on the principal stream then slows or reverses the original degradation of the principal stream which initiated the stream system response.

Example 2. The sediment supply available for transport by a reach of stream may be reduced by changes in the watershed which reduce erosion, mining of sand and gravel from the streambed upstream of the reach, or the construction of a dam to impound water upstream of the reach. In general, for the two latter cases, sediment transported by the stream is trapped in the mined areas or reservoir and mostly clear water is released downstream. Figure 10 illustrates the principle by use of the example of a dam. Referring to equation 4, a decrease in sediment discharge will cause a decrease in slope, if the discharge and median sediment size remain constant, or:

$$QS^- \propto Q_s^- D_{50}$$

The original equilibrium channel gradient (figure 10) is represented by the line CA. A new equilibrium grade represented by C'A will result from a decrease in sediment supply. The dam is a control in the channel which prevents the effects from extending upstream. Except for the channel control formed by the dam, similar effects are experienced at any location which undergoes a reduction in sediment supply.

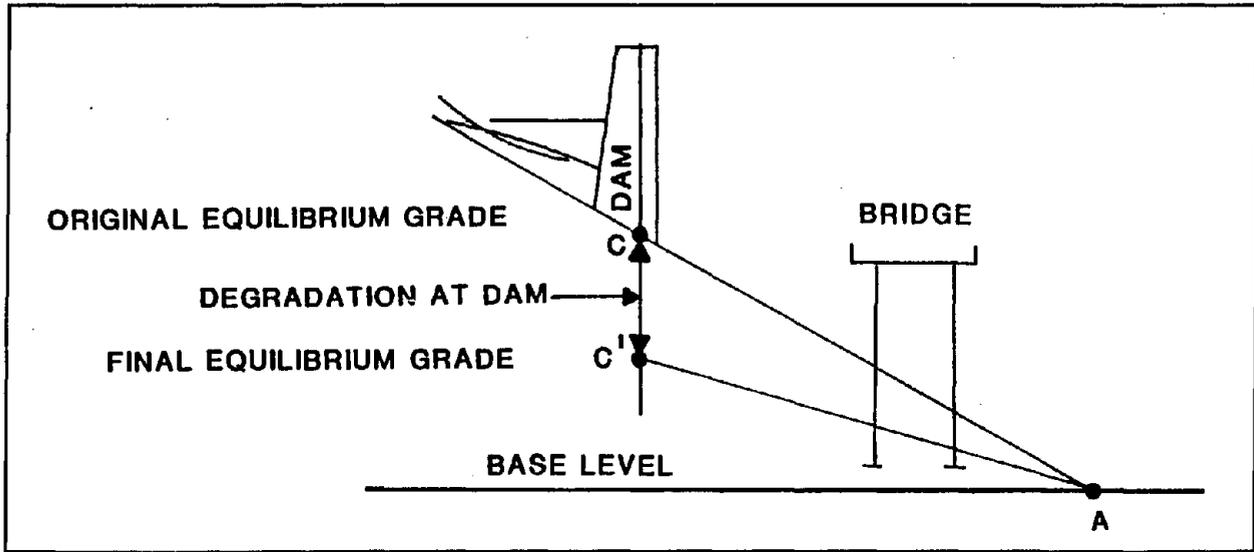
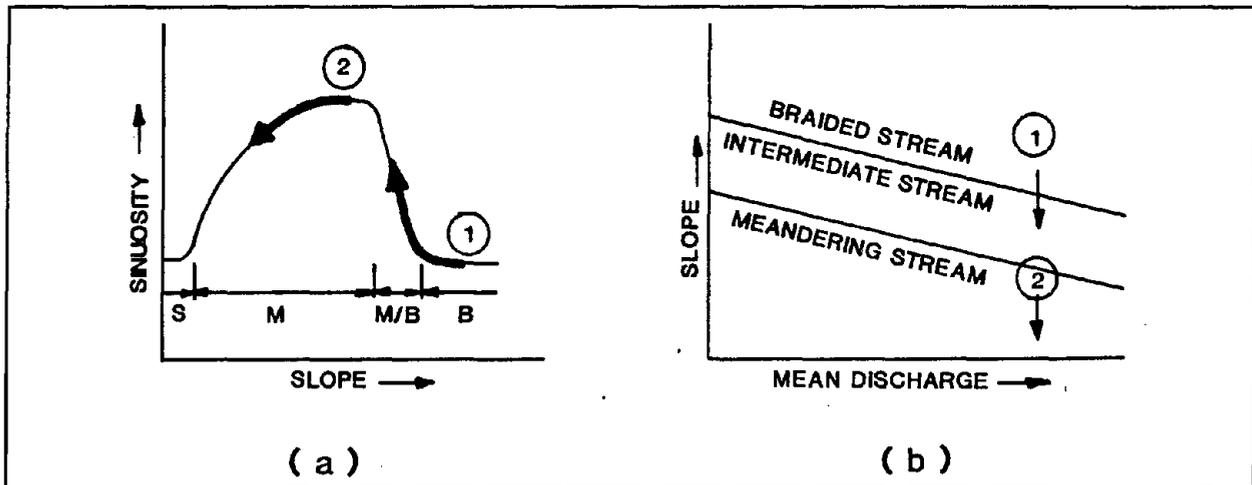


Figure 10. Changes in channel slope in response to a decrease in sediment supply at point C.

Referring to figure 7, for a low sinuosity braided stream, this decrease in slope below the dam could result in an increase in sinuosity and a change in planform toward a combination meandering/braided stream. If the stream below the dam were initially a meandering stream at near maximum sinuosity for the original slope, the decrease in slope below the dam could shift the planform of the stream toward a reduced sinuosity, meandering thalweg channel. These changes in plotting position are illustrated as (1) and (2), respectively, on figure 11a.

A similar result can be derived from figure 8. For an initially braided channel pattern below the dam [(1) on figure 11b], a decrease in slope below the dam could indicate a tendency to shift the stream's plotting position downward, possibly into the intermediate stream range (i.e., a combination of meandering and braided as on figure 11a). For an initially meandering stream [(2) on figure 11b], the decrease in slope below the dam could indicate a tendency toward a less meandering channel (as on figure 11a). It should be noted that both of these cases have assumed a constant discharge ( $Q$ ).



Figures 11a and b. Use of geomorphic relationships of figures 7 and 8 in a qualitative analysis.

As discussed in section 2.4.3, the effects downstream of a dam are more complex than a simple reduction in sediment supply. If the reservoir is relatively small and water flow rates downstream are little affected, degradation may occur downstream initially and aggradation may then occur after the reservoir fills

with sediments. Except for local scour downstream of the dam, the new equilibrium grade may approach line CA (figure 10) over the long term. This could apply to a diversion dam or other small dam in a stream.

Dams constructed to impound water for flood control or water supply usually have provisions for sediment storage. Over the economic life of the project, essentially clear water is released downstream. For practical purposes, the sediment supply to downstream reaches is permanently reduced. Reservoirs developed for these purposes, however, also reduce the water flow rates downstream. Referring to equation 4, a reduction in discharge  $Q$  may have a moderating effect on the reduction in slope  $S$  and, consequently, on degradation at the dam CC' in figure 10. If sediment discharge or sediment size remain constant below the dam (e.g., a tributary downstream continues to bring in a large sediment discharge), this would be expressed as:

$$Q^{-}S^{+} \propto Q_s D_{50}$$

Considering the more likely scenario of stream response to a dam, both water discharge ( $Q$ ) and sediment discharge ( $Q_s$ ) would decrease. It is also possible that sediment size ( $D_{50}$ ) in the reach below the dam would increase due to armoring or tributary sediment inflow. Using equation 4, this complex result could be expressed as:

$$Q^{-}S^{\pm} \propto Q_s^{-} D_{50}^{+}$$

Here, the resulting response in slope ( $S^{\pm}$ ) would depend on the relative magnitude of changes in the other variables in the relationship.

## CHAPTER 3

### HYDRAULIC FACTORS AND PRINCIPLES

#### 3.1 INTRODUCTION

The design of highway stream crossings and countermeasures to prevent damage from streamflow requires assessment of factors that characterize streamflow and channel conditions at the bridge site. The importance of hydraulic or flow factors in the crossing design process is influenced by the importance of the bridge and by land use on the floodplain, among other things. Each of the hydraulic factors listed in the left column of figure 12 has an effect on stream stability at a bridge crossing. Since the geometry and location of the bridge crossing can also affect stream stability, the most significant factors related to bends, confluences, alignment, and highway profile are summarized in figure 12. Hydraulic factors are discussed in the following section. This is followed by a discussion of the geometry and location of the highway stream crossings, and some general concepts related to the hydraulic design of bridges.

#### 3.2 HYDRAULIC FACTORS AFFECTING STREAM STABILITY

##### 3.2.1 Magnitude and Frequency of Floods

The hydrologic analysis for a stream crossing consists of establishing peak flow-frequency relationships and such flow-duration hydrographs as may be necessary. Flood-frequency relationships are generally defined on the basis of a regional analysis of flood records, a gaging station analysis, or both. Regional analyses have been completed for all states by the USGS, and the results are generally applicable to watersheds which are unchanged by man. Flood-frequency relationships at gaged sites can be established from station records which are of sufficient length to be representative of the total population of flood events on that particular stream. The Pearson Type III distribution with log transformation of flood data is recommended by the Water Resources Council for station flood data analysis.<sup>(13)</sup> Where flood estimates by regional analysis vary from estimates by station analysis, factors such as gaging station record length and the applicability of the regional analysis to that specific site should be considered, as well as high water information, flood data, and information of floods at existing bridges on the stream.

The term "design flood" is purposely avoided in the above discussion because of the implication that a stream crossing can be designed for a unique flood event. In reality, a range of events should be examined to determine which design condition is most advantageous, insofar as costs and risks are concerned. If a design flood is designated for purposes of stream stability analysis, it probably should be that event which causes the greatest stress to the highway stream crossing system, that is, the flood magnitude and stage which is at incipient overtopping of the highway.

Hydrologic analysis establishes the probability of occurrence of a flood of given magnitude in any one year period. It also is the first step in establishing the probability of occurrence of the flood event which will pass through bridge waterways in the highway-stream crossing system without overtopping the highway. FHWA's HDS-2 should be referred to for more detailed information and guidelines on hydrologic analysis.<sup>(14)</sup> The second step is the determination of the stage-discharge relationship, flow and velocity distributions, backwater, scour, etc., (i.e., the hydraulics of the crossing system, as discussed in the remainder of this section).

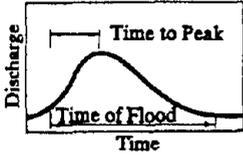
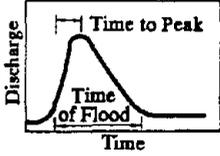
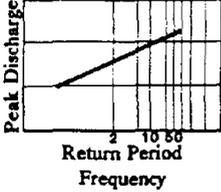
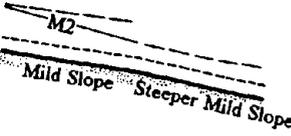
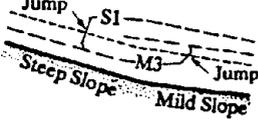
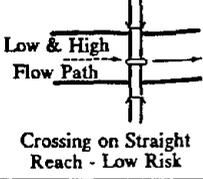
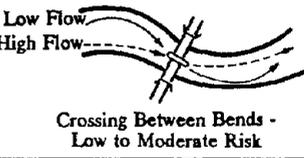
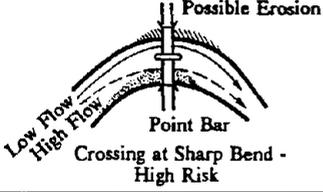
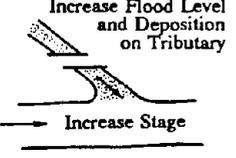
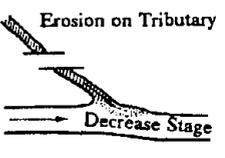
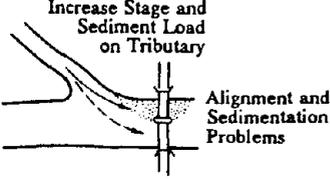
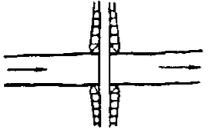
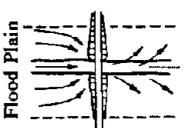
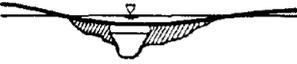
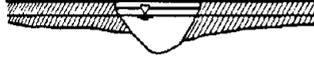
Hydraulic Factors	MAGNITUDE AND FREQUENCY OF FLOODS (SECT. 3.2.1)					
	BED CONFIGURATION IN SAND BED STREAMS (SECT. 3.2.2)					
	RESISTANCE TO FLOW (SECT. 3.2.3)	Lower Regime n .014-.040	Transition n .010-.013	Upper Regime n .012-.020		
	WATER SURFACE PROFILES (SECT. 3.2.4)					
Location Factors	PROBLEMS AT BENDS (SECT. 3.3.1)					
	PROBLEMS AT CONFLUENCES (SECT. 3.3.2)					
	BACKWATER EFFECTS OF ALIGNMENT AND LOCATION (SECT. 3.3.3)					
	EFFECTS OF HIGHWAY PROFILE (SECT. 3.3.4)					
Design Factors	BRIDGE DESIGN (SECT. 3.4)	Scour	Abutments	Piers	Foundations	Superstructures

Figure 12. Hydraulic and location factors that affect stream stability.

### 3.2.2 Bed Configurations in Sand-Bed Streams

In sand-bed streams, sand material is easily eroded and is continually being moved and shaped by the flow. The interaction between the flow of the water-sediment mixture and the sand-bed creates different bed configurations which change the resistance to flow, velocity, water surface elevation and sediment transport. Consequently, an understanding of the different types of bed forms that may occur and a knowledge of the resistance to flow and sediment transport associated with each bed form can help in analyzing flow in an alluvial channel. More specific to this discussion, it is necessary to understand what bed forms will be present so that the resistance to flow can be estimated and flood stages and water surface profiles can be computed.

Flow Regime. Flow in alluvial sand-bed channels is divided into two regimes separated by a transition zone.<sup>(4)</sup> Forms of bed roughness in sand channels are shown in figure 13a, while figure 13b shows the relationships between water surface and bed configuration. The flow regimes are:

- The lower flow regime, where resistance to flow is large and sediment transport is small. The bed form is either ripples or dunes or some combination of the two. Water-surface undulations are out of phase with the bed surface, and there is a relatively large separation zone downstream from the crest of each ripple or dune. The velocity of the downstream movement of the ripples or dunes depends on their height and the velocity of the grains moving up their backs.
- The transition zone, where the bed configuration may range from that typical of the lower flow regime to that typical of the upper flow regime, depending mainly on antecedent conditions. If the antecedent bed configuration is dunes, the depth or slope can be increased to values more consistent with those of the upper flow regime without changing the bed form; or, conversely, if the antecedent bed is plane, depth and slope can be decreased to values more consistent with those of the lower flow regime without changing the bed form.
- Resistance to flow and sediment transport also have the same variability as the bed configuration in the transition. This phenomenon can be explained by the changes in resistance to flow and, consequently, the changes in depth and slope as the bed form changes.
- The upper flow regime, in which resistance to flow is small and sediment transport is large. The usual bed forms are plane bed or antidunes. The water surface is in phase with the bed surface except when an antidune breaks, and normally the fluid does not separate from the boundary.
- There is no direct relationship between the classification of upper and lower flow regime and Froude Number (supercritical/subcritical flow).

Effects of Bed Forms at Stream Crossings. At high flows, most sand-bed stream channels shift from a dune bed to a transition or a plane bed configuration. The resistance to flow is then decreased to one-half to one-third of that preceding the shift in bed form. The increase in velocity and corresponding decrease in depth may increase scour around bridge piers, abutments, spur dikes or banks and may increase the required size of riprap. However, maximum scour depth with a plane bed can be less than with dunes because of the absence of dune troughs. On the other hand, the decrease in stage resulting from planing out of the bed will decrease the required elevation of the bridge, the height of embankments across the floodplain, the height of any dikes, and the height of any channel control works that may be needed. The converse is also true.

Another effect of bed forms on highway crossings is that with dunes on the bed, there is a fluctuating pattern of scour on the bed and around piers. The average height of dunes is approximately one-third to one-half of the average depth of flow, and the maximum height of a dune may approach the average depth of flow. If the average depth of flow is 3 m, maximum dune height may be on the order of 3 m, half of which would be below the mean elevation of the bed. With the passage of a dune through a bridge opening, an increase in local scour would be anticipated when the trough of the dune arrives at the bridge. It has been determined experimentally that local scour increases by 30 percent or more over equilibrium scour depth with the passage of a large dune trough (see HEC-18).<sup>(15)</sup>

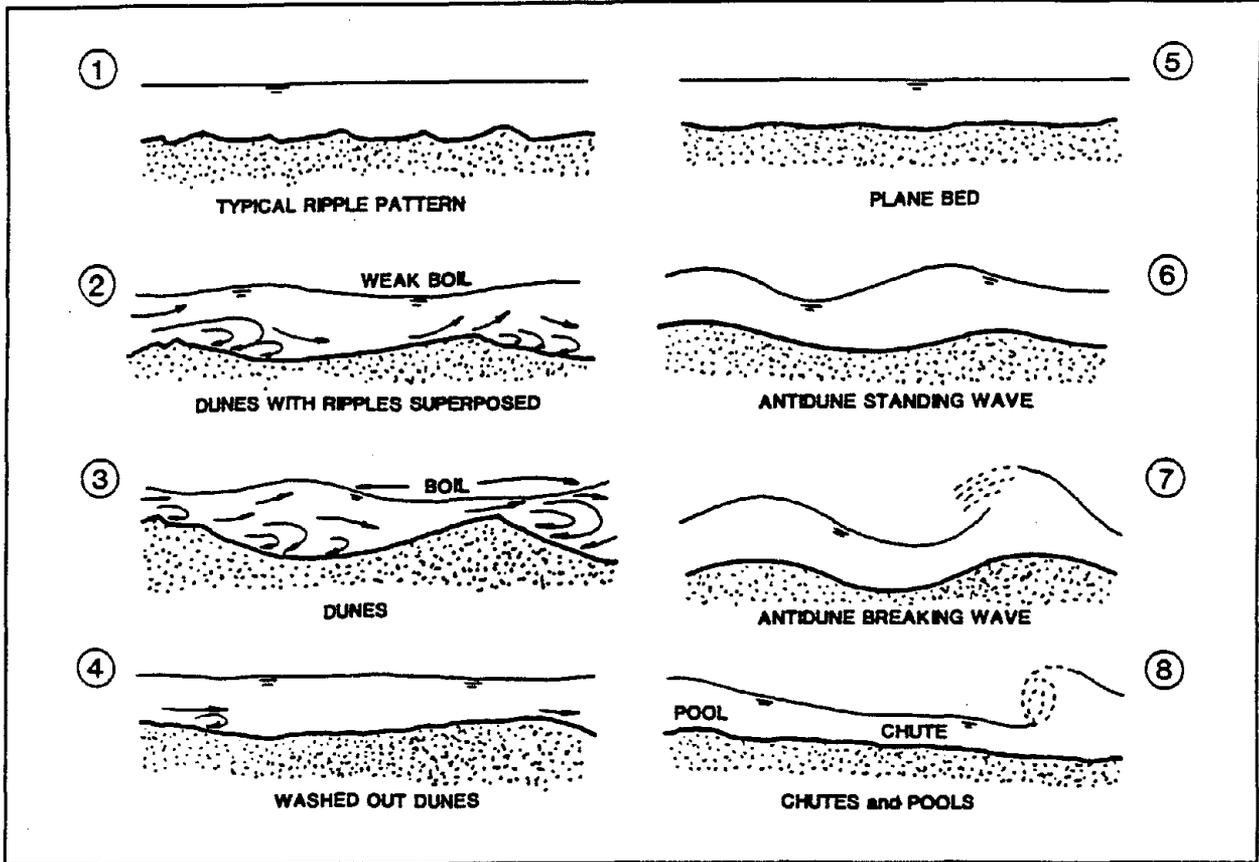


Figure 13(a). Forms of bed roughness in sand channels (after HIRE).<sup>(4)</sup>

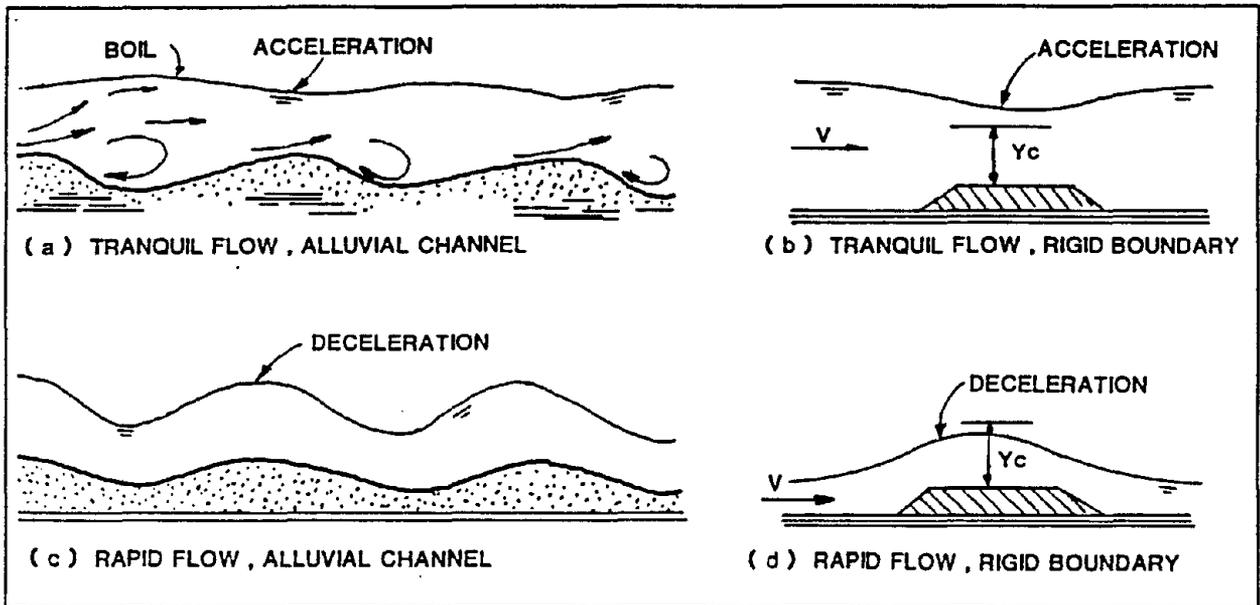


Figure 13(b). Relation between water surface and bed configuration (after HIRE).<sup>(4)</sup>

A very important effect of bed forms and bars is the change of flow direction in channels. At low flow, the bars can be residual and cause high velocity flow along or at a pier or other structures in the streambed, causing deeper than anticipated scour.

Care must be used in analyzing crossings of sand-bed streams in order to anticipate changes that may occur in bed forms and the impact of these changes on the resistance to flow, sediment transport, and the stability of the reach and highway structures. As described in section 3.2.3, with a dune bed, the Manning's  $n$  could be as large as 0.040. Whereas, with a plane bed, the  $n$  value could be as low as 0.010. A change from a dune bed to a plane bed, or the reverse, can have an appreciable effect on depth and velocity. In the design of a bridge or a stream stability or scour countermeasure, it is good engineering practice to assume a dune bed (large  $n$  value) when establishing the water surface elevations, and a plane bed (low  $n$  value) for calculations involving velocity.

### 3.2.3 Resistance to Flow

Use of the Manning's equation to compute flow in open channels and floodplains assumes one-dimensional flow. Procedures for summing the results of computations for subsections to obtain results for the total cross section involve use of the following assumptions: (1) mean velocity in each subsection is the same, (2) the total force resisting flow is equal to the sum of forces in the subsections, and (3) total flow in the cross section is equal to the sum of the flows in the subsections. This implies that the slope of the energy grade line is the same for each subsection. Assumption (3) is the basis for computing total conveyance for a cross section by adding conveyances of subsections.

Resistance to Flow in Channels. The general approach for estimating the resistance to flow in a stream channel is to select a base  $n$  value for materials in the channel boundaries assuming a straight, uniform channel, and then to make corrections to the base  $n$  value to account for channel irregularities, sinuosity, and other factors which affect the resistance to flow.<sup>(4,16)</sup> Equation 5 is used to compute the equivalent material roughness coefficient " $n$ " for a channel:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \quad (5)$$

where:

- $n_b$  = Base value for straight, uniform channel,
- $n_1$  = Value for surface irregularities in the cross section,
- $n_2$  = Value for variations in shape and size of the channel,
- $n_3$  = Value for obstructions,
- $n_4$  = Value for vegetation and flow conditions, and
- $m$  = Correction factor for sinuosity of the channel

Table 2 provides base  $n$  values for stable channels and sand channels, while table 3 provides adjustment factors for use in equation 5. Richardson et al. and Arcement and Schneider provide more detailed descriptions of conditions that affect the selection of appropriate values.<sup>(4,17)</sup>

Resistance to Flow in Sand-Bed Channels. The value of  $n$  varies greatly in sand-bed channels because of the varying bed forms that occur with lower and upper flow regimes. Figure 14 shows the relative resistance to flow in channels in lower regime, transition, and upper regime flow and the bed forms which exist for each regime.

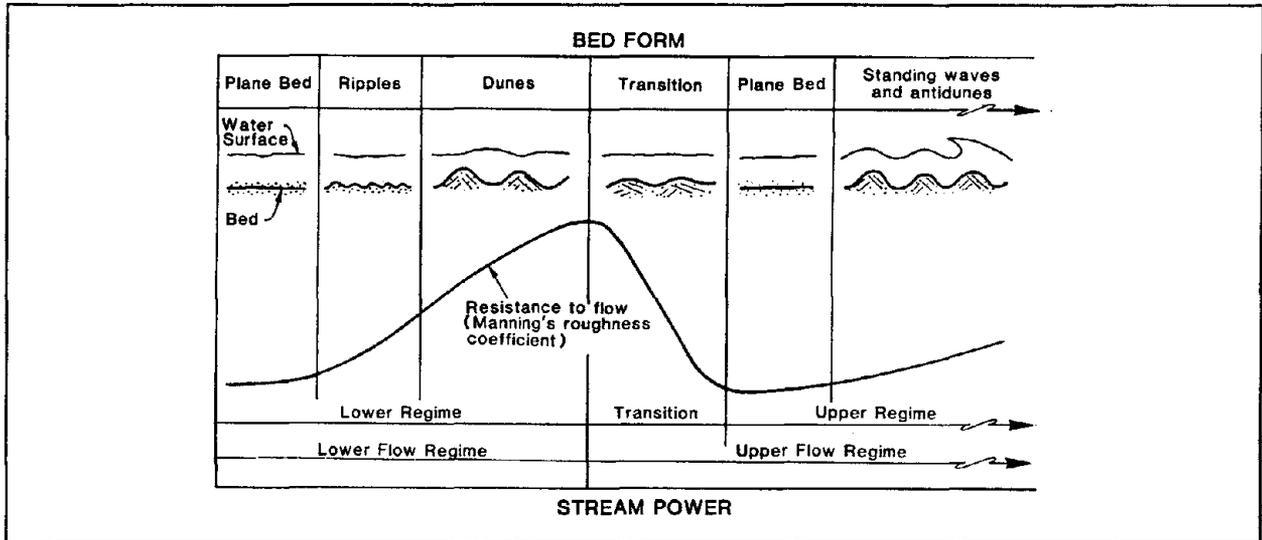


Figure 14. Relative resistance to flow in sand-bed channels (after Arcement and Schneider).<sup>(17)</sup>

Channel or Floodplain Type	Median Size, Bed Material		Base $n$ Value	
	Millimeters (mm)	Inches (in)	Benson and Dalrymple	Chow
<u>Sand Channels</u> (Only for upper regime flow where grain roughness is predominant.)	0.2	--	0.012	--
	.3	--	0.017	--
	.4	--	0.020	--
	.5	--	0.022	--
	.6	--	0.023	--
	.8	--	0.025	--
	1.0	--	0.026	--
<b>Stable Channels and Floodplains</b>				
Concrete	--	--	0.012 - 0.018	0.011
Rock cut	--	--	--	0.025
Firm soil	--	--	0.025 - 0.032	0.020
Coarse sand	1 - 2	--	0.026 - 0.035	--
Fine gravel	--	--	--	0.024
Gravel	2 - 64	0.08 - 2.5	0.028 - 0.035	--
Coarse gravel	--	--	--	0.026
Cobble	64 - 256	2.5 - 10.1	0.030 - 0.050	--
Boulder	> 256	> 10.1	0.040 - 0.070	--

Table 3. Adjustment Factors for the Determination of n Values for Channels.			
	Conditions	n Value	Remarks
<sup>n</sup> <sub>1</sub>	Smooth	0	Smoothest channel
	Minor	0.001-0.005	Slightly eroded side slopes
	Moderate	0.006-0.010	Moderately rough bed and banks
	Severe	0.011-0.020	Badly sloughed and scalloped banks
<sup>n</sup> <sub>2</sub>	Gradual	0	Gradual Changes
	Alternating Occasionally	0.001-0.005	Occasional Shifts From Large to small sections
	Alternating Frequently	0.010-0.015	Frequent changes in cross-sectional shape
<sup>n</sup> <sub>3</sub>	Negligible	0-0.004	Obstructions < 5% of cross-section area
	Minor	0.005-0.015	Obstruction < 15% of cross-section area
	Appreciable	0.020-0.030	Obstruction 15-50% of cross-section area
	Severe	0.040-0.060	Obstruction > 50% of cross-section area
<sup>n</sup> <sub>4</sub>	Small	0.002-0.010	Flow depth > 2 x vegetation height
	Medium	0.010-0.025	Flow depth > vegetation height
	Large	0.025-0.050	Flow depth < vegetation height
	Very Large	0.050-0.100	Flow depth < 0.5 vegetation height
<sup>m</sup>	Minor	1.00	Sinuosity < 1.2
	Appreciable	1.15	1.2 < Sinuosity < 1.5
	Severe	1.30	Sinuosity > 1.5

Sand-bed channels with bed materials having a median diameter from 0.14 to 0.4 mm usually plane out during high flows. Manning's  $n$  values change from as large as 0.040 at low flows to as small as 0.010 at high flow. Table 4 provides typical ranges of  $n$  values for sand-bed channels.

Resistance to Flow in Coarse Material Channels. A coarse-material channel may range from a gravel bed channel up to the cobble-boulder channels typical of mountainous regions. The latter type channels may have bed material that is only partly submerged making it difficult to determine the channel roughness. However, for gravel and small cobble and boulder-bed channels analysis of data from many rivers, canals and flumes shows that channel roughness can be predicted by the equation:<sup>(18)</sup>

$$n = 0.0152 D_{50}^{1/6} \quad (6)$$

where:

$D_{50}$  is measured in mm. A constant of 0.0481 is used for  $D_{50}$  expressed in m.

Alternately, Limerinos developed equation (7) from samples on streams having bed materials ranging in size from small gravel to medium size boulders.<sup>(19)</sup>

$$n = \frac{0.113 R^{1/6}}{1.16 + 2.03 \log \left[ \frac{R}{D_{84}} \right]} \quad (7)$$

where:

$R$  = Hydraulic radius, m  
 $D_{84}$  = 84th percentile (percent finer) size of bed material, m

All dimensions are in m. Flow depth,  $Y$ , may be substituted for the hydraulic radius,  $R$  in wide channels ( $W/Y > 10$ ). Note that equation 7 also applies to sand-bed channels in upper regime flow.<sup>(17)</sup>

The alternative to use of equations 6 or 7 for gravel-bed streams is to select a value of  $n$  from table 2. Because of the range of values in the table, it would be advisable to verify the selected value by use of one of the above equations if flow depth or velocities will significantly affect a design. HIRE also gives equations for this case.<sup>(4)</sup>

Resistance to Flow on Floodplains. Arcement and Schneider modified equation 5 for channels to make it applicable for the estimation of  $n$  values for floodplains.<sup>(16)</sup> The correction factor for sinuosity,  $m$ , becomes 1.0 for floodplains, and the value for variations in size and shape,  $n_2$ , is assumed equal to zero. Equation 5, adapted for use on floodplains, becomes:

$$n = n_b + n_1 + n_3 + n_4 \quad (8)$$

where:

$n_b$  = Base value of  $n$  for a bare soil surface  
 $n_1$  = Value to correct for surface irregularities  
 $n_3$  = Value for obstructions  
 $n_4$  = Value for vegetation

Selection of the base  $n$  value for floodplains is the same as for channels. Arcement and Schneider is recommended for a detailed discussion of factors which affect flow resistance in floodplains.<sup>(17)</sup>

Table 4. Manning's n Roughness Coefficients for Alluvial Sand-bed Channels (no vegetation <sup>1</sup> ).	
<b>Lower Flow Regime</b>	
Plane bed	0.014 - 0.020
Ripples	0.018 - 0.030
Dunes	0.020 - 0.040
<b>Transition</b>	
Washed out dunes	0.014 - 0.025
<b>Upper Flow Regime</b>	
Plane bed	0.010 - 0.013
Standing Waves	0.012 - 0.015
Antidunes	0.012 - 0.020
<sup>1</sup> Data are limited to sand channels with $D_{50} < 1.0$ mm.	

### 3.2.4 Water Surface Profiles

The water surface profile in a stream or river is a combination of gradually varied flow over long distances, and rapidly varied flow over short distances. Due to various obstructions in the flow, such as bridges, the actual flow depth over longer reaches is either larger or smaller than the normal depth defined by Manning's uniform flow equation. In the immediate vicinity of the obstruction, the flow can be rapidly varied.

**Gradually Varied Flow.** In gradually varied flow, changes in depth and velocity take place slowly over a large distance, resistance to flow dominates and acceleration forces are neglected. The calculation of a gradually varied flow profile is well defined by analytical procedures (e.g., see HIRE), which can be implemented manually or more commonly by computer programs such as the FHWA WSPRO program, or the U.S. Army Corps of Engineers (USACOE) HEC-2 program, or the new HEC River Analysis System (RAS).<sup>(4,20,21,58)</sup> A qualitative analysis of the general characteristics of the backwater curve is often useful prior to quantitative evaluation. Such an analysis requires locating control points, determining the type of profile upstream and downstream of the control points, and then sketching the backwater curves. For example, figure 12 illustrates several typical profiles that would result from a control represented by a change in bed slope. HIRE provides a detailed discussion of water surface profiles for gradually varied flow.<sup>(4)</sup>

**Rapidly Varied Flow.** In rapidly varied flow, changes in depth and velocity take place over short distances, acceleration forces dominate and resistance to flow may be neglected. The calculation of certain types of rapidly varied flow are well defined by analytical procedures, such as the analysis of hydraulic jumps, but analysis of other types of rapidly varied flow, such as flow through bridge openings (see figure 15) are a combination of analytical and empirical relationships. The FHWA document *Hydraulics of Bridge Waterways*, provides a procedure for manual calculation of the backwater created by certain types of flow conditions at bridge openings.<sup>(22)</sup> Gradually varied flow computer programs, such as WSPRO and HEC-2 include analysis of bridge backwater, but do not calculate undular jump conditions or the flow through the bridge when flow accelerations are large, that is, large change in velocity either in magnitude or direction.<sup>(20,21)</sup>

**Superelevation of Water Surface at Bends.** Because of the change in flow direction which results in centrifugal forces, there is a superelevation of the water surface in bends. The water surface is higher at the concave bank than at the convex bank (figure 16). The total super elevation is measured from water edge to water edge. Half this amount is added to the average water surface elevation to obtain the water surface

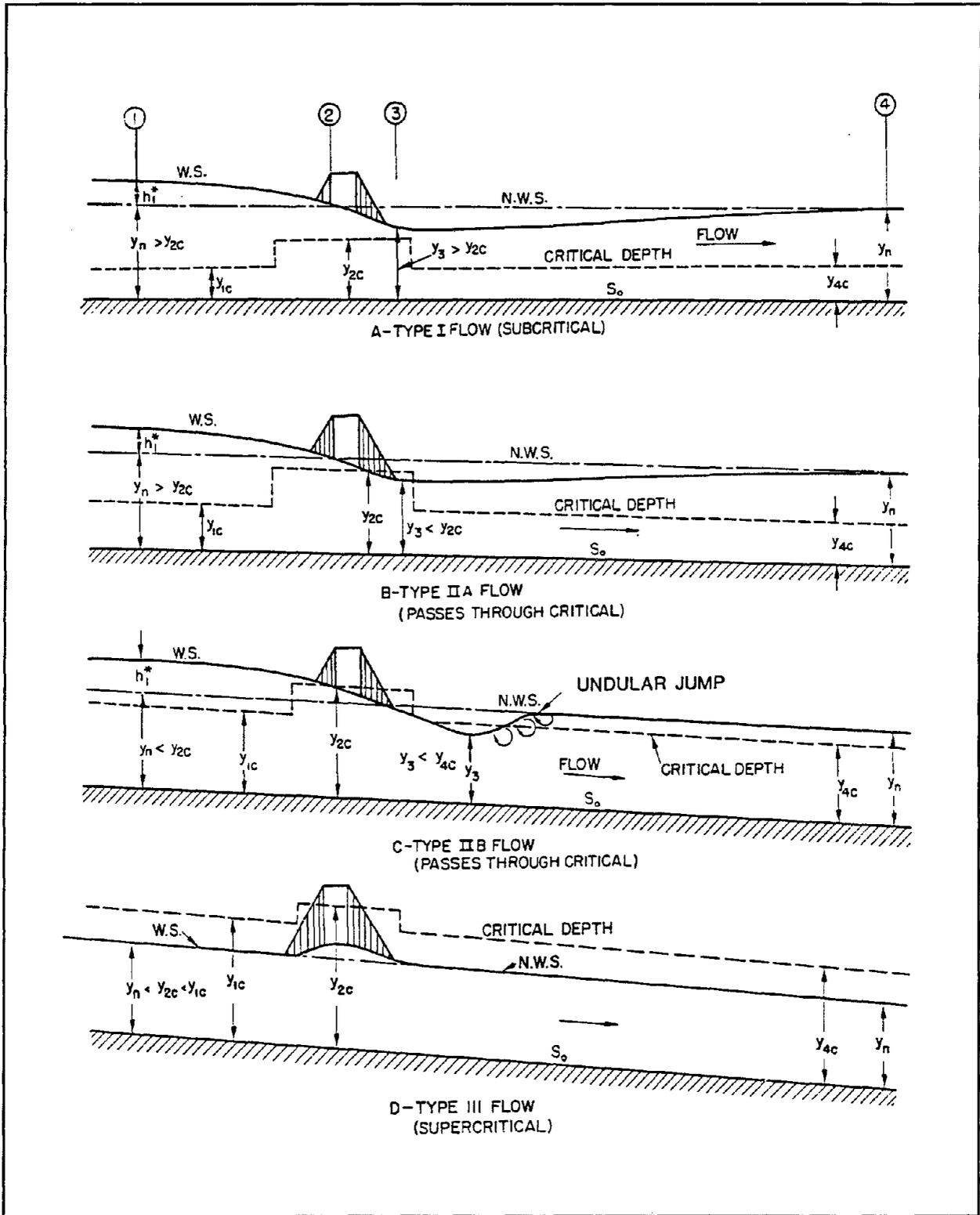


Figure 15. Types of water surface profiles through bridge openings (after Bradley).<sup>(22)</sup>

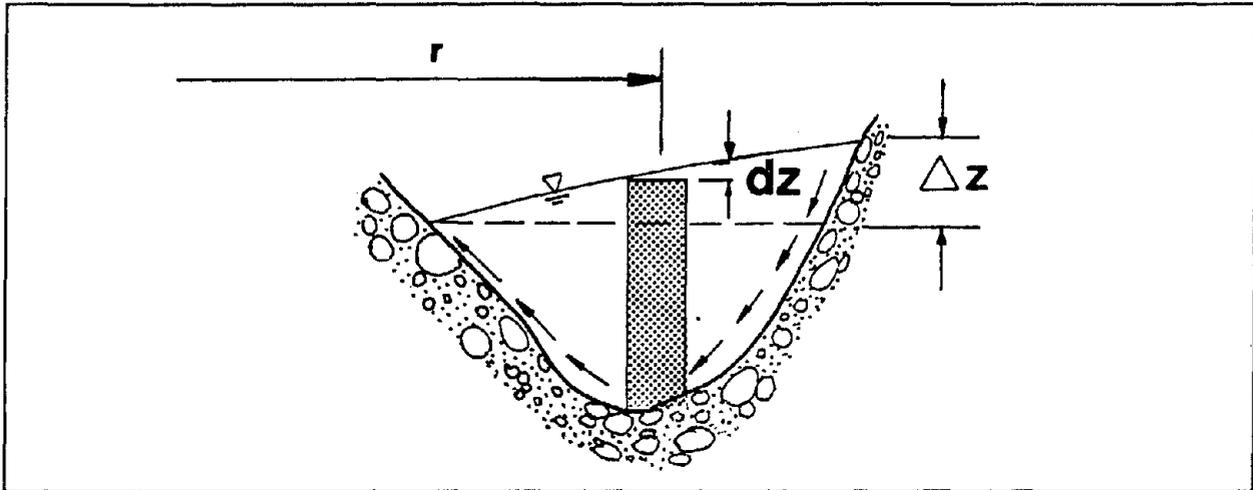


Figure 16. Superelevation of water surface in a bend.

elevation at the concave (outside) bank. The resulting transverse slope can be evaluated quantitatively. By assuming velocity equal to average velocity, the following equation was derived for superelevation for subcritical flow:<sup>(23)</sup> Other equations for superelevation are given in HIRE<sup>(4)</sup>.

$$\Delta Z = \frac{V^2}{gr_c} (r_o - r_i) \quad (9)$$

where:

- g = Acceleration of gravity, m/s<sup>2</sup>
- r<sub>o</sub> = Radius of the outside bank at the bend, m
- r<sub>i</sub> = Radius of the inside bank, m
- r<sub>c</sub> = Radius of the center of the stream, m
- ΔZ = Difference in water surface elevation between the concave and convex banks, m
- V = Average velocity, m/s

### 3.3 GEOMETRY AND LOCATION OF HIGHWAY STREAM CROSSINGS

#### 3.3.1 Problems at Bends

The location of a highway stream crossing is important because of the inherent instability of streams at some locations (See, for example, chapter 2) and because the crossing system can contribute to instability. In general, a crossing on a straight reach is preferred because stability problems are usually minor. Low-flow and high-flow paths (thalwegs) are generally similar for a straight reach, reducing the risk of problems related to alignment and orientation of bridge piers and superstructures (see figure 12).

For a relatively stable meandering stream, a bridge crossing at the inflection point between bends generally reduces the risk of instability problems. At the inflection point, the low-flow and high-flow paths are comparable (as shown in figure 12) and the crossing is in a zone where deposition and erosion are usually moderate. However, countermeasures against meander migration may still be required.

More hydraulic problems occur at alluvial stream crossings at or near bends than at all other locations because bends are naturally unstable. In addition, ice and floating debris tend to be greater problems in bends than in straight reaches. Other problems at bends include the shifting of the thalweg which can result in

unanticipated scour at piers because of changes in flow direction and velocities, and nonuniform velocity distribution which could cause scour of the bed and bank at the outside of the bend and deposition in the inside of the bend (see figure 12). The high velocities at the outside of the bend or downstream of the bend can contribute substantially to local scour on abutments and piers.

### 3.3.2 Problems at Confluences

Hydraulic problems may also be experienced at crossings near stream confluences. Crossings of tributary streams are affected by the stage of the main stream (See chapter 2). Aggradation of the channel of the tributary may occur if the stage of the main stream is high during a flood on the tributary, and scour in the tributary may occur if the stage in the main stream is low. Similarly, problems at a crossing of the larger stream can result from varying flow distribution and flow direction at various stages in the stream and its tributary, and from sediment deposited in the stream by the tributary (see figure 12). Tributaries entering the main channel upstream of a main channel bridge can also cause varying flow distribution and direction at various stages (flows) in the main channel and the tributary.

### 3.3.3 Backwater Effects of Alignment and Location

As flow passes through a channel constriction, most of the energy losses occur as expansion losses downstream of the contraction. This loss of energy is reflected by a rise in the water surface and the energy line upstream from the constriction. Upstream of bridges, the rise in water level above the normal water surface (that which would exist without the bridge) is referred to as the bridge backwater (see figure 15). However, many bridges do not cause backwater even at high flows even though they constrict the flows.<sup>(4)</sup> Hydraulic engineers are concerned with backwater with respect to flooding upstream of the bridge; backwater elevation with respect to the highway profile; and the effects on sediment deposition upstream, scour around embankments, contraction scour due to the constriction, and local scour at piers.

The effects of highway-stream crossing alignments on backwater conditions shown in figure 17 are based on:

- Backwater resulting from a long skewed or curved roadway embankment (figure 17a) may be quite large for wide floodplains. In effect, the bridge opening is located up-valley from one end of the embankment and the water level at the downstream extreme of the approach roadway, as at point A in figure 17a, can be significantly higher than at the bridge.
- Backwater in an incised stream channel without substantial overbank flow (figure 17b) is seldom large, but contraction and local scour may be severe. Backwater results from encroachment in the channel by approach embankments and from piers located in the channel.
- Backwater resulting from a normal crossing of the valley where road approach embankments block overbank flow (figure 17c) may be significant. General and local scour may be severe if a significant quantity of flow is diverted from the floodplain to the bridge waterway.

### 3.3.4 Effects of Highway Profile

A highway stream crossing is a system consisting of the stream and its floodplain, the bridge(s) and the approach roadways on the floodplain. All floods which occur during the life of the crossing system will pass either through the bridge waterways provided or through the waterways and over the highway. The highway profile and alignment control the quantity of flow which must pass through waterway openings. Flood frequency should be considered in the design of bridge components and may influence highway profile and alignment.

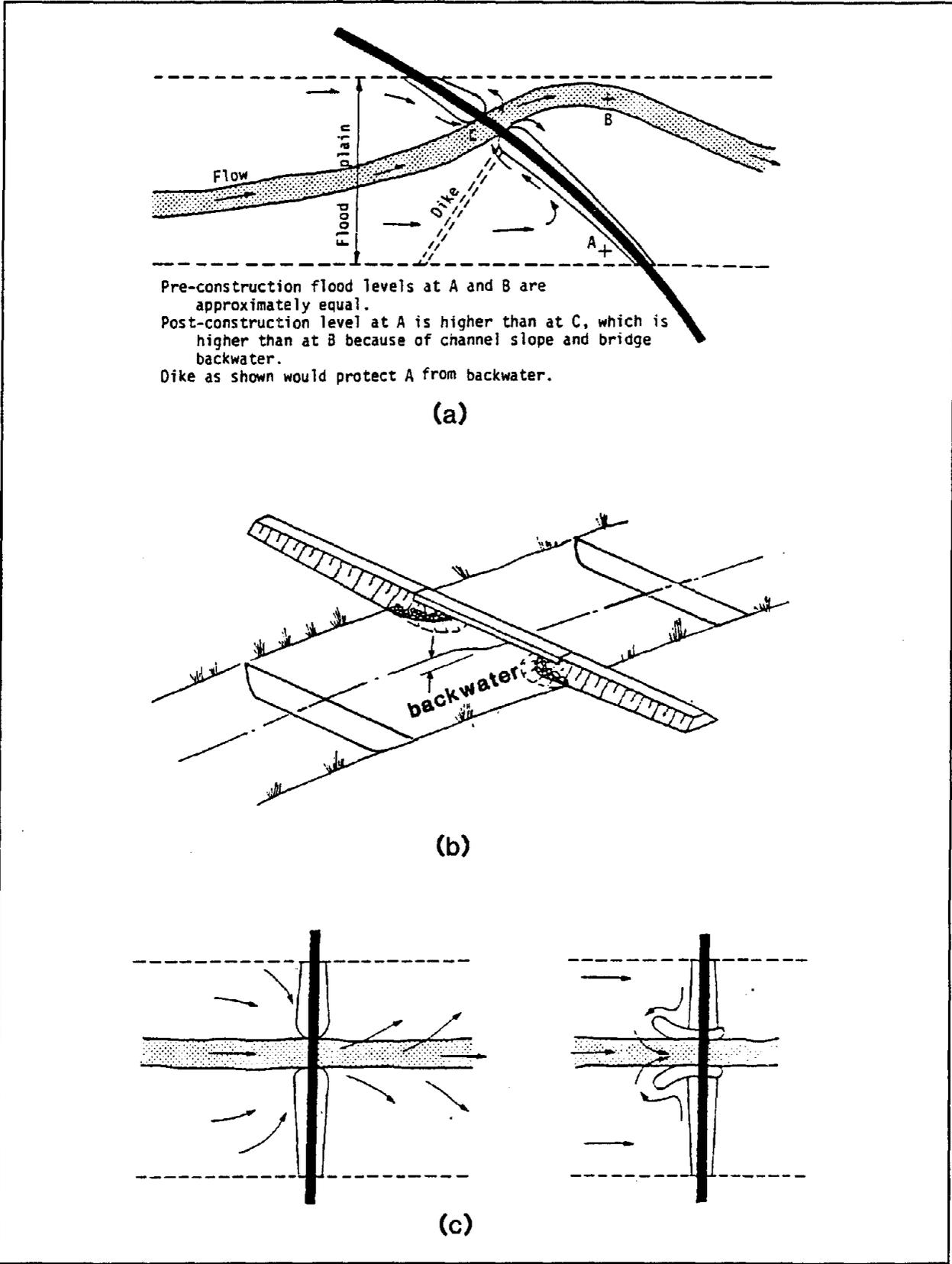


Figure 17. Backwater effect associated with three types of stream crossings: (a) a skewed alignment across a floodplain, (b) constriction of channel flow, and (c) constriction of overbank flow (after Neill).<sup>(24)</sup>

The stage-discharge relationship for the stream and backwater associated with a crossing design are the hydraulic considerations for establishing the highway profile. Profile alternatives are dependent on site topography and other site constraints, such as land use, traffic requirements, and flood damage potential. Figures 18a, b, and c illustrate profile alternatives, namely, a sag vertical curve, a crest vertical curve on the bridge or a rolling profile, and a level profile. A distinctive aspect of the sag vertical curve, as depicted in figure 18a, is the certainty that the bridge structure will be submerged before overflow of the roadway will occur. Therefore, the magnitude and probability of occurrence of such a flood event should be considered in the design of the waterway opening and bridge components. A variation of the sag vertical curve where the low point of the curve is located on a floodplain rather than on the bridge affords relief to the bridge waterway. Bridges on level profiles and sag vertical curves are susceptible to debris accumulation on the superstructure, impact forces, buoyant forces, and accentuated contraction and local scour.

The crest vertical profile illustrated in figure 18b provides protection to the bridge in that flood events exceeding the stage of the low point in the sag vertical curve will, in part, flow over the roadway. This relieves the bridge and the bridge waterway of stresses to which bridges on sag vertical curves and level profiles are subjected.

When this superstructure is submerged (pressure flow through the bridge), pier scour is increased. In some cases the local scour with pressure flow will be two times deeper than for free flow.<sup>(15)</sup>

### **3.4 BRIDGE DESIGN**

The design of bridge components must consider the effects on the local stability of a stream because of scour that is attributable to the encroachment on the stream. It is prudent to utilize designs which minimize undesirable stream response, to the extent practicable. This applies to component design as well as to the design of the total crossing system, including countermeasures against stream instability. The term countermeasure, as used here, is not necessarily an appurtenance to the highway stream crossing, but may be an integral part of the highway or bridge.

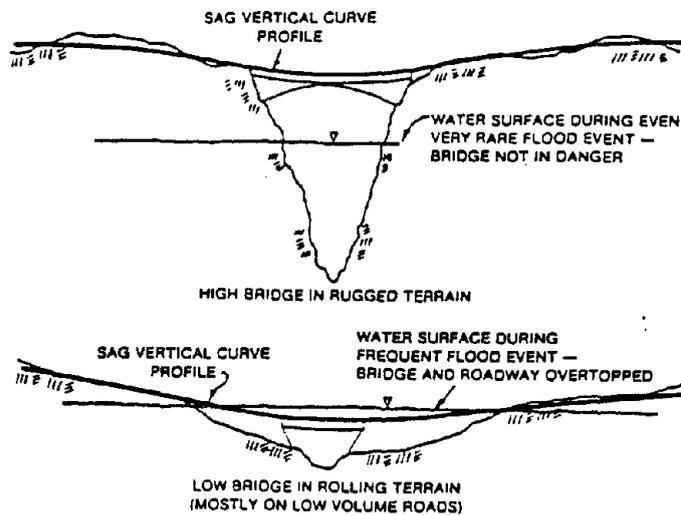
The location and size of bridge openings influence stream stability. Encroachment in the stream channel by abutments and piers reduces the channel section and may cause significant contraction scour. Severe constriction of floodplain flow may cause approach embankment failures and serious contraction scour in the bridge waterway. Auxiliary (relief) openings should be carefully designed to avoid excessive diversion of floodplain flow to main channel bridge openings on wide floodplains and at skewed crossings of floodplains.

#### **3.4.1 Scour at Bridges**

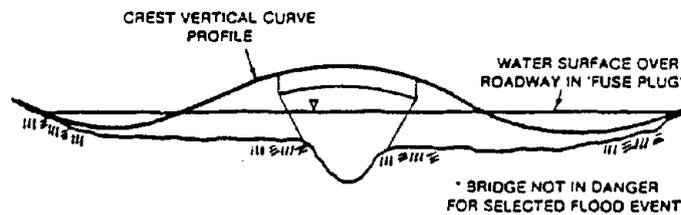
Scour at bridges consists of three components: (1) long-term aggradation or degradation of the stream channel (natural or man-induced), (2) contraction scour due to constriction or the location of the bridge, and (3) local scour. In general, the three components are additive.

Scour can be related to the following factors: (1) channel slope and alignment, (2) channel shifting, (3) bed sediment size distribution, (4) antecedent floods and surging phenomena, (5) accumulation of debris, logs, or ice, (6) flow contraction, flow alignment, and flow depth, (7) pier and abutment geometry and location, (8) type of foundation, (9) natural or man-induced modification of the stream, and (10) failure of a nearby structure.

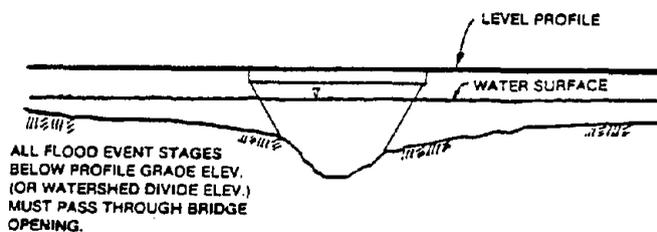
The rate of scour depends on the erosive forces exerted on the channel boundary and the resistance of the material to erosion. Resistance to erosion in fine cohesive material results from molecular forces. Resistance in noncohesive material depends primarily on bed sediment size distribution and density.



(a) Sag-vertical curves



(b) Crest-vertical curve



(c) Level profile

Figure 18. Various highway profiles: (a) sag-vertical curves, (b) crest-vertical curve, and (c) level profile.<sup>(25)</sup>

Under steady flow conditions, scour processes gradually approach an equilibrium condition; however, equilibrium scour conditions are not necessarily attained during a single flow event. Bridge crossings are generally subjected to unsteady flow conditions, and a series of events are often required to reach equilibrium or maximum scour depth. During a typical flood hydrograph, experiments indicated that scour tends to lag behind discharge and maximum scour depth occurs after the flood peak. Deposition often occurs during the recession of the hydrograph, and the maximum scour depth measured after the flood is generally less than the maximum depth of scour reached during the flood event.

Gravel mining in the streambed can cause severe stream instability. Therefore, it is essential to monitor sand and gravel mining so that countermeasures can be installed to stabilize the stream in the vicinity of a highway facility. Where possible, mining should be managed so that instabilities in the stream system will be minimized (see additional discussion in section 2.4.3).

Methods and equations for determining scour at piers and abutments are given in HEC-18.<sup>(15,4,26)</sup>

### 3.4.2 Abutments

Bridge abutments are classified as spillthrough, vertical wall, or vertical wall with wingwalls. Abutments are susceptible to damage by scour depending on flow distribution, foundation materials, velocities and other factors. However, scour at spillthrough abutments is about 50 percent smaller than at vertical wall abutments subjected to the same scouring actions.

In addition to the effects of abutment shape, scour at abutments is affected by the skew of approach flow at the abutment, soils materials, encroachment on the floodplain and in the channel, and the amount of overbank flow diverted to the bridge waterway by approach fills to the bridge. Equations and methods for computing abutment scour are presented in HEC-18.<sup>(15)</sup> Countermeasures for abutment scour are discussed in chapters 5 and 6 and HEC-18.<sup>(15)</sup>

### 3.4.3 Piers

The number of piers in any stream channel should be limited to a practical minimum and, if possible, piers should not be located in the channel of small streams. Piers properly oriented with the flow do not contribute significantly to bridge backwater, but they can contribute to contraction scour. Piers should be aligned with flow direction at flood stage in order to minimize the opportunity for debris collection, to reduce the contraction effect of piers in the waterway, to minimize ice forces and the possibility of ice dams forming at the bridge, and to minimize backwater and local scour.

Pier orientation is difficult where flow direction changes with stage or time. Cylindrical piers or some variation thereof, are probably the best alternative if orientation at other than flood stage is critical. Raudkivi reported that a row of cylindrical columns will produce shallower scour than a solid pier when the angle of attack is greater than 5 degrees.<sup>(27)</sup> A solid pier will not collect as much debris as a pile bent or a multiple-column bent. Rounding or streamlining the leading edges of piers helps to decrease the accumulation of debris and reduces local scour. Recent studies have provided additional data on the effects of footings and the behavior of pile groups.<sup>(15,28)</sup> Guidance pertaining to pier foundations is presented in HEC-18.<sup>(15)</sup>

Piers located on a bank or in the stream channel near the bank are likely to cause lateral erosion of the bank. Piers located near the streambank on the floodplain are vulnerable to undermining by bank scour and meander migration. Piers which must be placed in such locations should be founded at elevations safe from undermining or otherwise protected.<sup>(15)</sup>

### 3.4.4 Bridge Foundations

The types of foundations used for bridges include piles, piles with pile caps, spread footings, footings on piles or drilled shafts, drilled shafts, and caissons. Spread footings are used where sound rock is relatively shallow, but failures have occurred where spread footings were set in erodible rock.

Piling usually are dependent on the surrounding material for skin friction and lateral stability. In some locations, they can be carried to bedrock or other dense materials for bearing capacity. Tip elevation for piling should be based on estimates of potential scour depths as well as bearing in order to avoid losing lateral support and load carrying capacity after scour. Pile bearing capacity derived from driving records has little validity if the material through which the piles were driven is scoured away during a flood.

Caissons are used in large rivers and are usually sunk to dense material by excavation inside the caisson. Founding depths are such that scour is not usually a problem after construction is completed; however, severe contraction scour has developed at some bridges, because of contraction of flow from the large piers.

Attention should be given to potential scour resulting from channel shifts in designing foundations on floodplains. Also, the thalweg in channels should not be considered to be in a fixed location. Consideration should be given, therefore, to duplicating the foundation elevations of the main channel piers on adjacent floodplain piers. The history of stream channel activity can be very useful in establishing foundation elevations (see chapter 2).

### 3.4.5 Superstructures

Hydraulic forces that should be considered in the design of a bridge superstructure include buoyancy, drag, and impact from ice and floating debris. The configuration of the superstructure should be influenced by the highway profile, the probability of submergence, expected problems with ice and debris, and flow velocities, as well as the usual economic, structural and geometric considerations. Superstructures should be made a structurally integral part of the piers and abutments to provide structural redundancy, that is, alternate load paths in case of failure of one bridge element.

Buoyancy. The weight of a submerged or partially submerged bridge superstructure is the weight of the superstructure less the weight of the volume of water displaced. The volume of water displaced may be much greater than the volume of the superstructure components if air is trapped between girders. Also, solid parapet rails and curbs on the bridge deck can increase the volume of water displaced and increase buoyant forces. The volume of air trapped under the superstructure can be reduced by providing holes (vents) through the deck between structural members. Superstructures should be anchored to piers to counter buoyant forces and to resist drag forces. Continuous span designs are also less susceptible to failure from buoyancy than simple span designs.

Drag Forces. Drag forces on a submerged or partially submerged superstructure can be calculated by equation 10:

$$F_d = C_d \rho H \frac{V^2}{2} \quad (10)$$

where:

- $F_d$  = Drag force per unit of length of bridge, N/m
- $C_d$  = Coefficient of drag (2.0 to 2.2)
- $\rho$  = Density of water, 1000 kg/m<sup>3</sup>
- $H$  = Depth of submergence, m
- $V$  = Velocity of flow, m/s

Floating Debris and Ice. Where bridges are destroyed by debris and ice, it usually is due to accumulations against bridge components. Waterways may be partially or totally blocked by ice and debris, creating hydraulic conditions that cause or increase scour at pier foundations and bridge abutments, structural damage from impact and uplift, and overtopping of roadways and bridges. Floating debris is a hydraulic problem at highway stream crossings on a nation-wide basis. Debris hazards occur more frequently in unstable streams where bank erosion is active and in streams with mild to moderate slopes, as contrasted with headwater streams. Debris hazards are often associated with large floods, and most debris is derived locally along the streambanks upstream from the bridge. After being mobilized, debris typically moves as individual logs which tend to concentrate in the thalweg of the stream. It is possible to evaluate the abundance of debris upstream of a bridge crossing and then to implement mitigation measures, such as removal and or containment, to minimize potential problems during a major flood.

Ice Forces. Superstructures may be subjected to impact forces from floating ice, static pressure from thermal movements or ice jams, or uplift from adhering ice in water of fluctuating levels. The latter is usually associated with relatively large bodies of water and superstructures in these locations should normally be high enough to be unaffected. Research is needed to define the static and dynamic loads that can be expected from ice under various conditions of ice strength and streamflow.

In addition to forces imposed on bridge superstructures by ice loads, ice jams at bridges can cause exaggerated backwater and a sluicing action under the ice. There are numerous examples of foundation failures from this orifice flow under ice as well as superstructure damage and failure from ice forces. Accumulations of ice or drift may substantially increase local pier and abutment scour especially if they are allowed to extend down to near the channel bed. Ice also has serious effects on bank stability. For example, ice may form in bank stabilization materials, and large quantities of rock and other material embedded in the ice may be floated downstream and dumped randomly when the ice breaks up. Banks are subjected to piping forces during the drawdown of water surface elevation after the breakup.

Debris Forces. Information regarding methods for computing forces imposed on bridge superstructures by floating debris is also lacking despite the fact that debris causes or contributes to many failures. Floating debris may consist of logs, trees, house trailers, automobiles, storage tanks, lumber, houses, and many other items representative of floodplain usage. This complicates the task of computing impact forces since the mass and the resistance to crushing of the debris contribute to the impact force.

The equation for computing impact forces is:

$$F = M \, dv/dt = \frac{MV^2}{2S} \quad (11)$$

where:

- F = Impact imparted by the debris, N
- M = Mass of the debris, kg
- S = Stopping distance, m
- V = Velocity of the floating debris prior to impact, m/s

In addition to impact forces, a buildup of debris increases the effective depth of the superstructure and the drag coefficient may also be increased. Perhaps the most hazardous result of debris buildup is partial or total clogging of the waterway. This can result in a sluicing action of flow under the debris which can result in scour and foundation failure or a shift in the channel location from under the bridge.

## CHAPTER 4

### ANALYSIS PROCEDURE

#### 4.1 PROBLEM STATEMENT

A stable channel does not change in size, form, or position with time; however, all alluvial channels change to some extent and are somewhat unstable. For highway engineering purposes, a stream channel can be considered unstable if the rate or magnitude of change is great enough that the planning, location, design, or maintenance considerations for a highway encroachment are significantly affected. The kinds of changes that are of concern are: (1) lateral bank erosion, including the erosion that occurs from meander migration; (2) aggradation or degradation of the streambed that progresses with time; and (3) short-term fluctuations in streambed elevation that are usually associated with the passage of a flood (scour and fill). These changes are associated with instability in a stream system or in an extensive reach of stream.

Local instability caused by the construction of a highway crossing or encroachment on a stream is also of concern. This includes general scour caused by contraction of the flow, and local scour due to the disturbance of streamlines at an object in the flow, such as at a pier or an abutment. The purpose of this section is to outline the analysis procedures that may be utilized to evaluate stream instability.

#### 4.2 GENERAL SOLUTION PROCEDURE

The analysis of any complex problem should begin with an overview or general evaluation, including a qualitative assessment of the problem and its solution. This fundamental initial step should be directed towards providing insight and understanding of significant physical processes, without being too concerned with the specifics of any given component of the problem. The understanding generated from such analyses assures that subsequent detailed analyses are properly designed.

The progression to more detailed analyses should begin with application of basic principles, followed as required, with more complex solution techniques. This solution approach, beginning with qualitative analysis, proceeding through basic quantitative principles and then utilizing, as required, more complex or state-of-the-art solution procedures assures that accurate and reasonable results are obtained while minimizing the expenditure of time and effort.

The inherent complexities of a stream stability analysis, further complicated by highway stream crossings, require such a solution procedure. The evaluation and design of a highway stream crossing or encroachment should begin with a qualitative assessment of stream stability. This involves application of geomorphic concepts to identify potential problems and alternative solutions. This analysis should be followed with quantitative analysis using basic hydrologic, hydraulic and sediment transport engineering concepts. Such analyses could include evaluation of flood history, channel hydraulic conditions (up to and including, for example, water surface profile analysis) and basic sediment transport analyses such as evaluation of watershed sediment yield, incipient motion analysis and scour calculations. This analysis can be considered adequate for many locations if the problems are resolved and the relationships between different factors affecting stability are adequately explained. If not, a more complex quantitative analysis based on detailed mathematical modeling and/or physical hydraulic models should be considered.

In summary, the general solution procedure for analyzing stream stability could involve the following three levels of analysis:

- Level 1: Application of Simple Geomorphic Concepts and other Qualitative Analyses
- Level 2: Application of Basic Hydrologic, Hydraulic and Sediment Transport Engineering Concepts
- Level 3: Application of Mathematical or Physical Modeling Studies

### **4.3 DATA NEEDS**

The types and detail of data required to analyze a highway crossing or encroachment on a stream are highly dependent on the relative instability of the stream and the depth of study required to obtain adequate resolution of potential problems. More detailed data are needed where quantitative analyses are necessary, and data from an extensive reach of stream may be required to resolve problems in complex and high risk situations.

#### **4.3.1 Level 1: Qualitative and Other Geomorphic Analyses**

The data required for preliminary stability analyses include maps, aerial photographs, notes and photographs from field inspections, historic channel profile data, information on man's activities, and changes in stream hydrology and hydraulics over time.

The National Bridge Inspection Standards (NBIS) Program involves inspections on a two-year cycle of the 575 000 bridges on the National Bridge Inventory. The FHWA December 1988 publication "The Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" specifies the bridge and channel hydraulics and scour data that are evaluated and reported within the NBIS. Item 60, substructure, Item 61, Channel and Channel Protection, Item 71, Waterway Adequacy, and Item 113, Scour Critical Bridges, are included. Typically, a cross section of the bridge waterway at the time of each inspection will provide a chronological picture of the bridge waterway.

Area, vicinity, site, geologic, soils, and land use maps each provide essential information. Unstable stream systems upstream or downstream of the encroachment site can cause instability at the site. Area maps are needed to locate unstable reaches of streams relative to the site. Vicinity maps help to identify more localized problems. They should include a sufficient reach of stream to permit identification of stream classification, and to locate bars, braids, and channel controls. Site maps are needed to determine factors that influence local stability and flow alignment, such as bars and tributaries. Geologic maps provide information on deposits and rock formations and outcrops that control stream stability. Soils and land use maps provide information on soil types, vegetative cover, and land use which affect the character and availability of sediment supply.

Aerial photographs record much more ground detail than maps and are frequently available at five-year intervals. This permits measurement of the rate of progress of bend migration and other stream changes that cannot be measured from maps made less frequently. A highway agency should periodically obtain aerial photographs of actively unstable streams that threaten highway facilities, including immediately after major floods. However, aerial photographs taken after the passage of an ice jam or immediately after a major flood must be interpreted with care and may provide misleading information regarding the rate of change.

Notes and photographs from field inspections are important to gaining an understanding of stream stability problems, particularly local stability. Field inspections should be made during high- and low-flow periods to record the location of bank cutting or slumping and deposition in the channel. Flow directions should be sketched, signs of aggradation or degradation noted, properties of bed and bank materials estimated or measured, and the locations and implications of impacting activities recorded.

If historic stream profile data are available, it will provide information on channel stability. Stage trends at stream gaging stations and comparisons of streambed elevations with elevations before construction at structures will provide information on changes in stream profile. As-built bridge data and cross sections are frequently useful. Structure-induced scour should be taken into consideration where such comparisons are made.

Man's activities in a watershed are frequently the cause of stream instability. Information on urbanization, land clearing, snagging in stream channels, channelization, bend cutoffs, streambed mining, dam construction, reservoir operations, navigation projects, and other activities, either existing or planned, are necessary to evaluate the impact on stream stability.

Data on changes in morphology are important because change in a stream is rarely at a constant rate. Stream instability can often be associated with an event, such as an extreme flood or a particular activity in the watershed or stream channel. If association is possible, the rate of change can be more accurately assessed.

Similarly, information on changes in hydrology or hydraulics can sometimes be associated with activities that caused the change. Where changes in stream hydraulics are associated with an activity, changes in stream morphology are also likely to have occurred.

#### **4.3.2 Level 2: Basic Engineering Analyses**

Data requirements for basic hydrologic, hydraulic and sediment transport engineering analysis are dependent the types of analysis that must be completed. Hydrologic data needs include dominant discharge (or bankfull flow), flow duration curves, and flow frequency curves. Discussion of hydrologic methods is beyond the scope of this manual; however, information can be obtained from HDS-2 and State Highway Agency manuals.<sup>(14)</sup> Hydraulic data needs include cross sections, channel and bank roughness estimates, channel alignment, and other data for computing channel hydraulics, up to and including water surface profiles calculations. Analysis of basic sediment transport conditions requires information on land use, soils, and geologic conditions, sediment sizes in the watershed and channel, and available measured sediment transport rates (e.g., from USGS gaging stations).

More detailed quantitative analyses require data on the properties of bed and bank materials and, at times, field data on bed-load and suspended-load transport rates. Properties of bed and bank materials that are important to a study of sediment transport include size, shape, fall velocity, cohesion, density, and angle of repose.

#### **4.3.3 Level 3: Mathematical and Physical Model Studies**

Application of mathematical and physical model studies requires the same basic data as a Level 2 analysis, but typically in much greater detail. For example, water and sediment routing by mathematical models (e.g., BRI-STARS or HEC-6), and construction of a physical model, would both require detailed channel cross-sectional data.<sup>(29,30)</sup> The more extensive data requirements for either mathematical or physical model studies, combined with the additional level of effort needed to complete such studies, results in a relatively large scope of work.

### **4.4 DATA SOURCES**

Preliminary stability data may be available from government agencies such as the USACOE, Natural Resources Conservation Service (formerly Soil Conservation Service, SCS), USGS, local river basin commissions, and local watershed districts. These agencies may have information on historic streambed profiles, stage-discharge relationships, and sediment load characteristics. They may also have information on past and planned activities that affect stream stability. Table 5 provides a list of sources for the various data needed to assess stream stability at a site.

### **4.5 LEVEL 1: QUALITATIVE AND OTHER GEOMORPHIC ANALYSES**

A flow chart of the typical steps in qualitative and other geomorphic analyses is provided in figure 19. The six steps are generally applicable to most stream stability problems. These steps are discussed in more detail in the following paragraphs. As shown on figure 19, the qualitative evaluation leads to a conclusion regarding the need for more detailed (Level 2) analysis or a decision to proceed directly to bridge scour evaluation or selection and design of countermeasures based only on the qualitative and other geomorphic analyses. Selection and design of countermeasures are discussed in chapters 5 and 6, respectively. A Level 1 qualitative analysis is a prerequisite for a Level 2 engineering analysis for bridge design or rehabilitation.

Table 5. List of Data Sources (after FHWA).<sup>(26)</sup>

<b>Topographic Maps:</b>	
(1)	Quadrangle maps - U.S. Department of the Interior, Geological Survey, Topographic Division; and U.S. Department of the Army, Army Map Service.
(2)	River plans and profiles - U.S. Department of the Interior, Geological Survey, Conservation Division.
(3)	National parks and monuments - U.S. Department of the Interior, National Park Service.
(4)	Federal reclamation project maps - U.S. Department of the Interior, Bureau of Reclamation.
(5)	Local areas - commercial aerial mapping firms.
(6)	American Society of Photogrammetry.
<b>Planimetric Maps:</b>	
(1)	Plats of public land surveys - U.S. Department of the Interior, Bureau of Land Management
(2)	National forest maps - U.S. Department of Agriculture, Forest Service.
(3)	County maps - State Highway Agency.
(4)	City plats - city or county recorder.
(5)	Federal reclamation project maps - U.S. Department of the Interior, Bureau of Reclamation.
(6)	American Society of Photogrammetry.
(7)	ASCE Journal - Surveying and Mapping Division.

Table continues

Table 5. List of Data Sources (after FHWA).<sup>(26)</sup> continued

<b>Aerial Photographs:</b>	
(1)	The following agencies have aerial photographs of portions of the United States: U.S. Department of the Interior, Geological Survey, Topographic Division; U.S. Department of Agriculture, Commodity Stabilization Service, Soil Conservation Service and Forest Service; U.S. Air Force; various state agencies; commercial aerial survey; National Oceanic and Atmospheric Administration; and mapping firms.
(2)	American Society of Photogrammetry.
(3)	Photogrammetric Engineering.
(4)	Earth Resources Observation System (EROS) - Photographs from Gemini, Apollo, Earth Resources Technology Satellite (ERTS) and Skylab.
<b>Transportation Maps:</b>	
(1)	State Highway Agency.
<b>Triangulation and Benchmarks:</b>	
(1)	State Engineer.
(2)	State Highway Agency.
<b>Geologic Maps:</b>	
(1)	U.S. Department of the Interior, Geological Survey, Geologic Division; and state geological surveys or departments. (Note - some regular quadrangle maps show geological data also).
<b>Soils Data:</b>	
(1)	County soil survey reports - U.S. Department of Agriculture, Soil Conservation Service.
(2)	Land use capability surveys - U.S. Department of Agriculture, Soil Conservation Service.
(3)	Land classification reports - U.S. Department of the Interior, Bureau of Reclamation.
(4)	Hydraulic laboratory reports - U.S. Department of the Interior, Bureau of Reclamation.
Table continues	

Table 5. List of Data Sources (after FHWA).<sup>(26)</sup> continued

<b>Climatological Data:</b>	
(1)	National Weather Service Data Center.
(2)	Hydrologic bulletin - U.S. Department of Commerce, National Oceanic and Atmospheric Administration.
(3)	Technical papers - U.S. Department of Commerce, National Oceanic and Atmospheric Administration.
(4)	Hydrometeorological reports - U.S. Department of Commerce, National Oceanic and Atmospheric Administration; and U.S. Department of the Army, Corps of Engineers.
(5)	Cooperative study reports - U.S. Department of Commerce, National Oceanic and Atmospheric Administration; and U.S. Department of the Interior, Bureau of Reclamation.
<b>Streamflow Data:</b>	
(1)	Water supply papers - U.S. Department of the Interior; Geological Survey, Water Resources Division.
(2)	Reports of state engineers.
(3)	Annual reports - International Boundary and Water Commission, United States and Mexico.
(4)	Annual reports - various interstate compact commissions.
(5)	Hydraulic laboratory reports - U.S. Department of the Interior, Bureau of Reclamation.
(6)	Bureau of Reclamation.
(7)	U.S. Army Corps of Engineers, Flood control studies.
<b>Sedimentation Data:</b>	
(1)	Water supply papers - U.S. Department of the Interior, Geological Survey, Quality of Water Branch.
(2)	Reports - U.S. Department of the Interior, Bureau of Reclamation; and U.S. Department of Agriculture, Soil Conservation Service.
(3)	Geological Survey Circulars - U.S. Department of the Interior, Geological Survey.
Table continues	

Table 5. List of Data Sources (after FHWA).<sup>(26)</sup> continued

**Quality of Water Reports:**

- (1) Water supply papers - U.S. Department of the Interior, Geological Survey, Quality of Water Branch.
- (2) Reports - U.S. Department of Health, Education, and Welfare, Public Health Service.
- (3) Reports - state public health departments
- (4) Water resources publications - U.S. Department of the Interior, Bureau of Reclamation.
- (5) Environmental Protection Agency, regional offices.
- (6) State water quality agency.

**Irrigation and Drainage Data:**

- (1) Agriculture census reports - U.S. Department of Commerce, Bureau of the Census.
- (2) Agricultural statistics - U.S. Department of Agriculture, Agricultural Marketing Service.
- (3) Federal reclamation projects - U.S. Department of the Interior, Bureau of Reclamation.
- (4) Reports and progress reports - U.S. Department of the Interior, Bureau of Reclamation.

**Power Data:**

- (1) Directory of Electric Utilities - McGraw Hill Publishing Co.
- (2) Directory of Electric and Gas Utilities in the United States - Federal Power Commission.
- (3) Reports - various power companies, public utilities, state power commissions, etc.

**Basin and Project Reports and Special Reports**

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

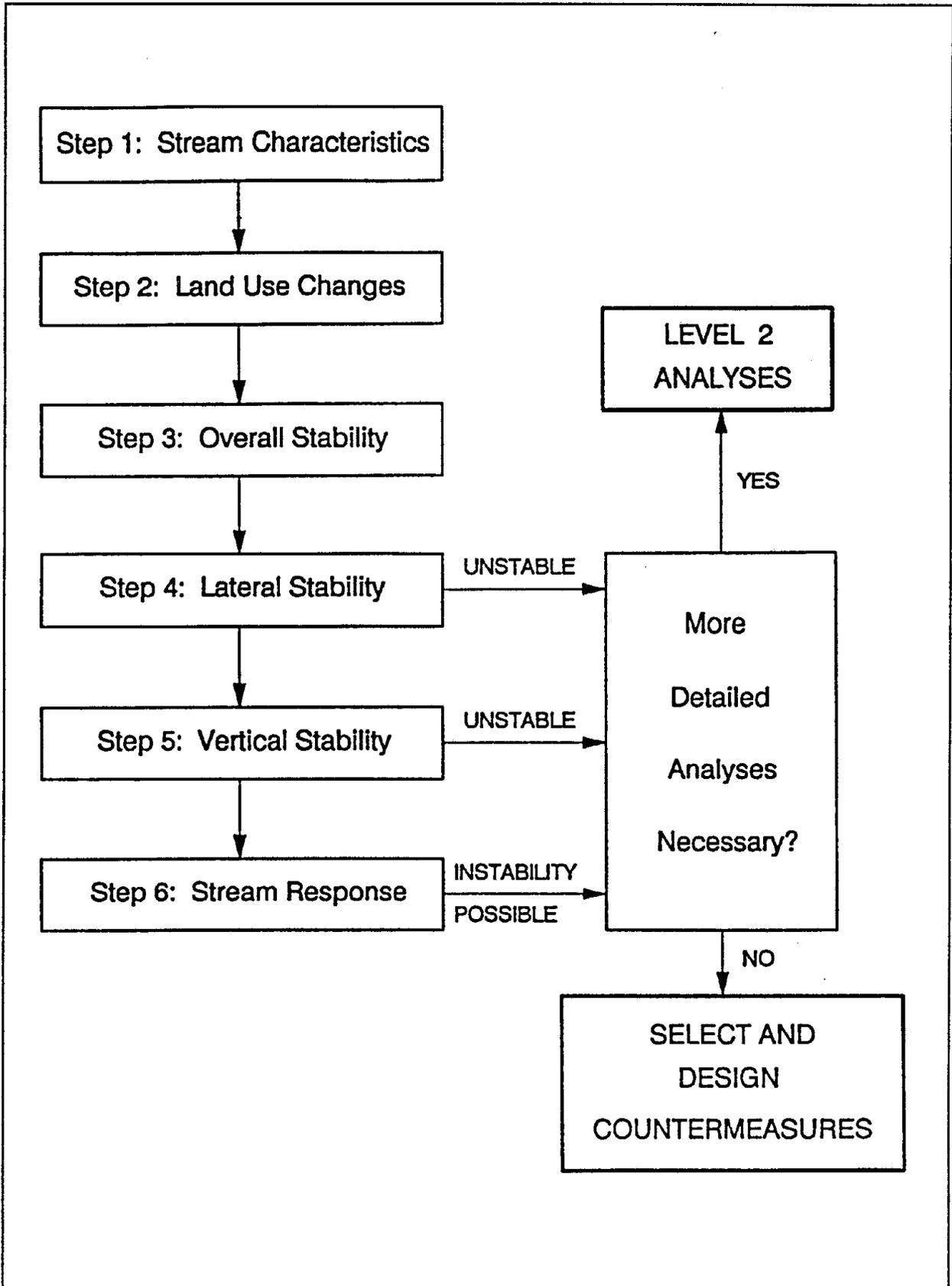


Figure 19. Flow chart for level 1: Qualitative Analyses.

#### 4.5.1 Step 1. Define Stream Characteristics

The first step in stability analysis is to identify stream characteristics according to the factors discussed in chapter 2, Geomorphic Factors and Principles. Defining the various characteristics of the stream according to this scheme provides insight into stream behavior and response, and information on impacting activities in the watershed.

#### 4.5.2 Step 2. Evaluate Land Use Changes

Water and sediment yield from a watershed is a function of land-use practices. Thus, knowledge of the land use and historical changes in land use is essential to understanding conditions of stream stability and potential stream response to natural and man-induced changes.

The presence or absence of vegetative growth can have a significant influence on the runoff and erosional response of a fluvial system. Large scale changes in vegetation resulting from fire, logging, land conversion and urbanization can either increase or decrease the total water and sediment yield from a watershed. For example, fire and logging tend to increase water and sediment yield, while urbanization promotes increased water yield and peak flows, but decreased sediment yield from the watershed. Urbanization may increase sediment yield from the channel.

Information on land use history and trends can be found in Federal, State and Local government documents and reports (i.e., census information, zoning maps, future development plans, etc.). Additionally, analysis of historical aerial photographs can provide significant insight on land use changes. Land use change due to urbanization can be classified based on estimated changes in pervious and impervious cover. Changes in vegetative cover can be classified as simply as no change, vegetation increasing, vegetation damaged and vegetation destroyed. The relationship or correlation between changes in channel stability and land use changes can contribute to a qualitative understanding of system response mechanisms.

#### 4.5.3 Step 3. Assess Overall Stream Stability

Table 6 summarizes possible channel stability interpretations according to stream characteristics discussed in chapter 2 (figure 1), as well as additional factors that commonly influence stream stability. Figure 20 is also useful in making a qualitative assessment of stream stability based on stream characteristics. It shows that straight channels are relatively stable only where flow velocities and sediment load are low. As these variables increase, flow meanders in the channel causing the formation of alternate bars and the initiation of a meandering channel pattern. Similarly, meandering channels are progressively less stable with increasing velocity and bed load. At high values of these variables, the channel becomes braided. The presence and size of point bars and middle bars are indications of the relative lateral stability of a stream channel.

Bed material transport is directly related to stream power, and relative stability decreases as stream power increases as shown by figure 20. Stream power is the product of shear stress at the bed and the average velocity in the channel section. Shear stress can be determined from the gross shear stress equation ( $\gamma RS$ ) where  $\gamma$  is the specific weight of water,  $R$  is the hydraulic radius, and  $S$  is the slope of the energy grade line.

#### 4.5.4 Step 4. Evaluate Lateral Stability

The effects of lateral instability of a stream at a bridge are dependent on the extent of the bank erosion and the design of the bridge. Bank erosion can undermine piers and abutments located outside the channel and erode abutment spill slopes or breach approach fills. Where bank failure is by a rotational slip, lateral pressures on piers located within the slip zone may cause cracks in piers or piling or displacement of pier foundations. Migration of a bend through a bridge opening changes the direction of flow through the opening so that a pier designed and constructed with a round-nose acts as a blunt-nosed, enlarged obstruction in the flow, thus accentuating local and contraction scour. Also, the development of a point bar on the inside of the migrating bend can increase contraction at the bridge if the outside bank is constrained from eroding. Figure 21 illustrates some of the problems of lateral erosion at bridges.

Table 6. Interpretation of Observed Data (after Keefer et al.). <sup>(31)</sup>				
Observed Condition	Channel Response			
	Stable	Unstable	Degrading	Aggrading
Alluvial Fan <sup>1</sup>				
Upstream		X		X
Downstream		X	X	
Dam and Reservoir				
Upstream		X		X
Downstream		X	X	
River Form				
Meandering	X	X	Unknown	Unknown
Straight		X	Unknown	Unknown
Braided		X	Unknown	Unknown
Bank Erosion		X	Unknown	Unknown
Vegetated Banks	X		Unknown	Unknown
Head Cuts		X	X	
Diversion				
Clear water diversion		X		X
Overloaded w/sediment		X	X	
Channel Straightened		X	X	
Deforest Watershed		X		X
Drought Period	X			X
Wet Period		X	X	
Bed Material Size				
Increase		X		X
Decrease		X	Unknown	X
<sup>1</sup> The observed condition refers to location of the bridge on the alluvial fan, i.e., on the upstream or downstream portion of the fan.				

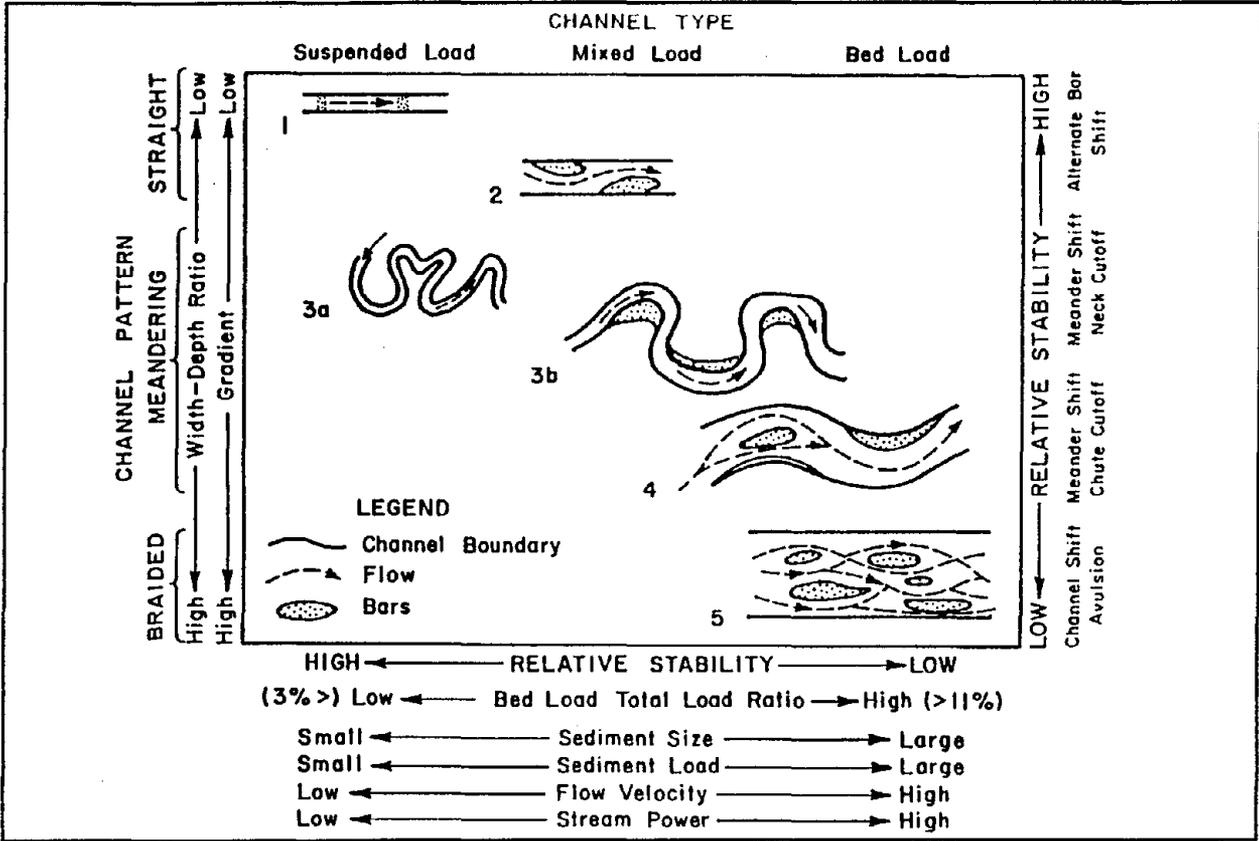


Figure 20. Channel classification and relative stability as hydraulic factors are varied (after Shen et al.).<sup>(5)</sup>

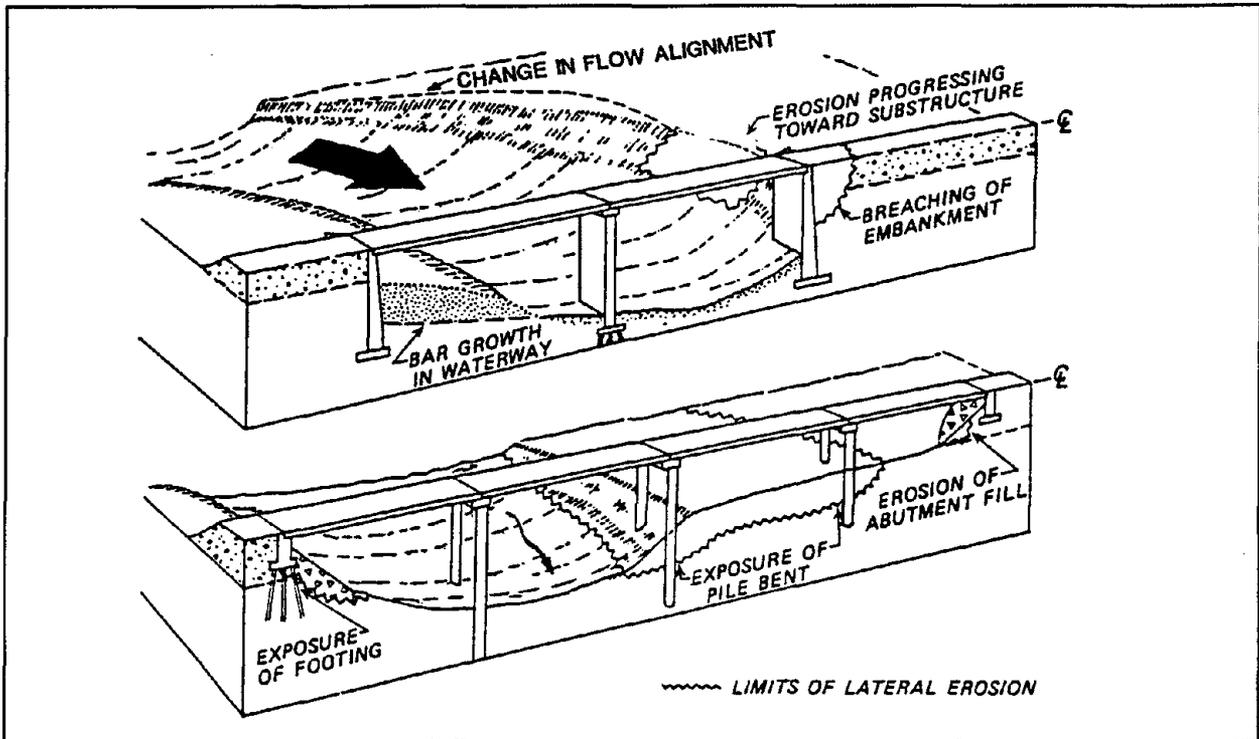


Figure 21. Hydraulic problems at bridges attributed to erosion at a bend or to lateral migration of the channel (after Brice and Blodgett).<sup>(1,2)</sup>

A field inspection is a critical component of a qualitative assessment of lateral stability. A comparison of observed field conditions with the descriptions of stable and unstable channel banks presented in section 2.2.8 helps qualify bank stability. Similarly, field observations of bank material, composition and existing failure modes can provide insight on bank stability, based on the descriptions of cohesive, non-cohesive and composite banks given in section 2.2.8. An evaluation of lateral stability in conjunction with the design of a bridge should take the performance of existing nearby bridges into account. The experience of such structures which have been subjected to the impacts of the stream can provide insight into response at a nearby structure.

Lateral stability assessment can also be completed from records of the position of a bend at two or more different times; aerial photographs or maps are usually the only records available. Surveyed cross sections are extremely useful although rarely available. Some progress is being made on the numerical prediction of loop deformation and bend migration (Level 3 type analyses). At present, however, the best available estimates are based on past rates of lateral migration at a particular reach. In using the estimates, it should be recognized that erosion rates may fluctuate substantially from one period of years to the next.

Measurements of bank erosion on two time-sequential aerial photographs (or maps) require the identification of reference points which are common to both. Useful reference points include roads, buildings, irrigation canals, bridges and fence corners. This analysis of lateral stability is greatly facilitated by a drawing of changes in bank line position with time. To prepare such a drawing, aerial photographs are matched in scale and the photographs are superimposed holding the reference points fixed.

A site of potential avulsion (channel shifting to new flow path) in the vicinity of a highway stream crossing should be identified so that steps can be taken to mitigate the effects of avulsion when it occurs. A careful study of aerial photographs will show where overbank flooding has been taking place consistently and where a channel exists that can capture the flow in the existing channel. In addition, topographic maps and special surveys may show that the channel is indeed perched above the surrounding alluvial surface, with the inevitability of avulsion. Generally, avulsion, as the term is used here, will only be a hazard on alluvial fans, alluvial plains, deltas, and wide alluvial valleys. In a progressively aggrading situation, as on an alluvial fan, the stream will build itself out of its channel and be very susceptible to avulsion. In other words, in a cross profile on an alluvial fan or plain, it may be found that the river is flowing between natural levees at a level somewhat higher than the surrounding area. In this case, avulsion is inevitable.

#### **4.5.5 Step 5. Evaluate Vertical Stability**

The typical effects associated with bed elevation changes at highway bridges are erosion at abutments and the exposure and undermining of foundations from degradation, and a reduction in flow area from aggradation under bridges resulting in more frequent flow over the highway. Bank caving associated with degradation poses the same problems at bridges as lateral erosion from bend migration, but the problems may be more severe because of the lower elevation of the streambed. Aggrading stream channels also tend to become wider as aggradation progresses, eroding floodplain areas and highway embankments on the floodplain. The location of the bridge crossing upstream, downstream, or on tributaries may cause bed elevation problems.

Brown et al., reported that their study indicated that there are serious problems at about three degradation sites for every aggradation site.<sup>(32)</sup> This is a reflection of the fact that degradation is more common than aggradation, and also the fact that aggradation does not endanger the bridge foundation. It is not an indication that aggradation is not a serious problem in some areas of the United States.

Problems other than those most commonly associated with degrading channels include the undermining of cutoff walls, other flow-control structures, and bank protection. Bank sloughing because of degradation often greatly increases the amount of debris carried by the stream and increases the potential for blocked waterway openings and increased scour at bridges. The hazard of local scour becomes greater in a degrading stream because of the lower streambed elevation.

Aggradation in a stream channel increases the frequency of backwater that can cause damage. Bridge decks and approach roadways become inundated more frequently, disrupting traffic, subjecting the superstructure of the bridge to hydraulic forces that can cause failure, and subjecting approach roadways to overflow that can

erode and cause failure of the embankment. Where lateral erosion or increased flood stages accompanying aggradation increases the debris load in a stream, the hazards of clogged bridge waterways and hydraulic forces on bridge superstructures are increased.

Data records for at least several years are usually needed to detect bed elevation problems. This is due to the fact that the channel bottom often is not visible and changes in flow depth may indicate changes in the rate of flow rather than bed elevation changes. Bed elevation changes develop over long periods of time even though rapid change can occur during an extreme flood event. The data needed to assess bed elevation changes include historic streambed profiles, and long-term trends in stage-discharge relationships. Occasionally, information on bed elevation changes can be gained from a series of maps prepared at different times. Bed elevations at railroad, highway and pipeline crossings monitored over time may also be useful. On many large streams, the long-term trends have been analyzed and documented by agencies such as the USGS and the USACOE.

#### **4.5.6 Step 6. Evaluate Channel Response to Change**

The knowledge and insight developed from evaluation of present and historical channel and watershed conditions, as developed above through Steps 1 through 5, provides an understanding of potential channel response to previous impacts and/or proposed changes, such as construction of a bridge. Additionally, the application of simple, predictive geomorphic relationships, such as the Lane relationship (see section 2.3) can assist in evaluating channel response mechanisms. Section 2.4.4 illustrated the evaluation of stream response based on geomorphic and other qualitative considerations. Additional applications of Level 1 analyses techniques to bridge related stream stability problems can be found in chapter VIII of HIRE.<sup>(4)</sup>

### **4.6 LEVEL 2: BASIC ENGINEERING ANALYSES**

A flow chart of the typical steps in basic engineering analyses is provided in figure 22. The flow chart illustrates the typical steps to be followed if a Level 1 qualitative analysis resulted in a decision that Level 2 analyses were required (figure 19). The eight basic engineering steps are generally applicable to most stream stability problems and are discussed in more detail in the paragraphs which follow. The basic engineering analysis steps lead to a conclusion regarding the need for more detailed (Level 3) analysis or a decision to proceed to bridge design, scour evaluation, or selection and design of countermeasures without more complex studies. Selection and design of countermeasures are discussed in chapters 5 and 6, respectively.

#### **4.6.1 Step 1. Evaluate Flood History and Rainfall-Runoff Relations**

Detailed discussion of hydrologic analysis techniques, in particular the analysis of flood magnitude and frequency, is presented in HDS-2 and will not be repeated here.<sup>(14)</sup> However, several hydrologic concepts of particular significance to evaluation of stream stability are summarized.

Consideration of flood history is an integral step in attempting to characterize watershed response and morphologic evolution. Analysis of flood history is of particular importance to understanding arid region stream characteristics. Many dryland streams flow only during the spring and immediately after major storms. For example, Leopold, et al. found that arroyos near Santa Fe, New Mexico, flow only about three times a year.<sup>(33)</sup> As a consequence, dryland stream response can be considered to be more hydrologically dependent than streams located in a humid environment. Whereas the simple passage of time may be sufficient to cause change in a stream located in a humid environment, time alone, at least in the short term, may not necessarily cause change in a dryland system due to the infrequency of hydrologically significant events. Thus, the absence of significant morphological changes in a dryland stream or river, even over a period of years, should not necessarily be construed as an indication of system stability.

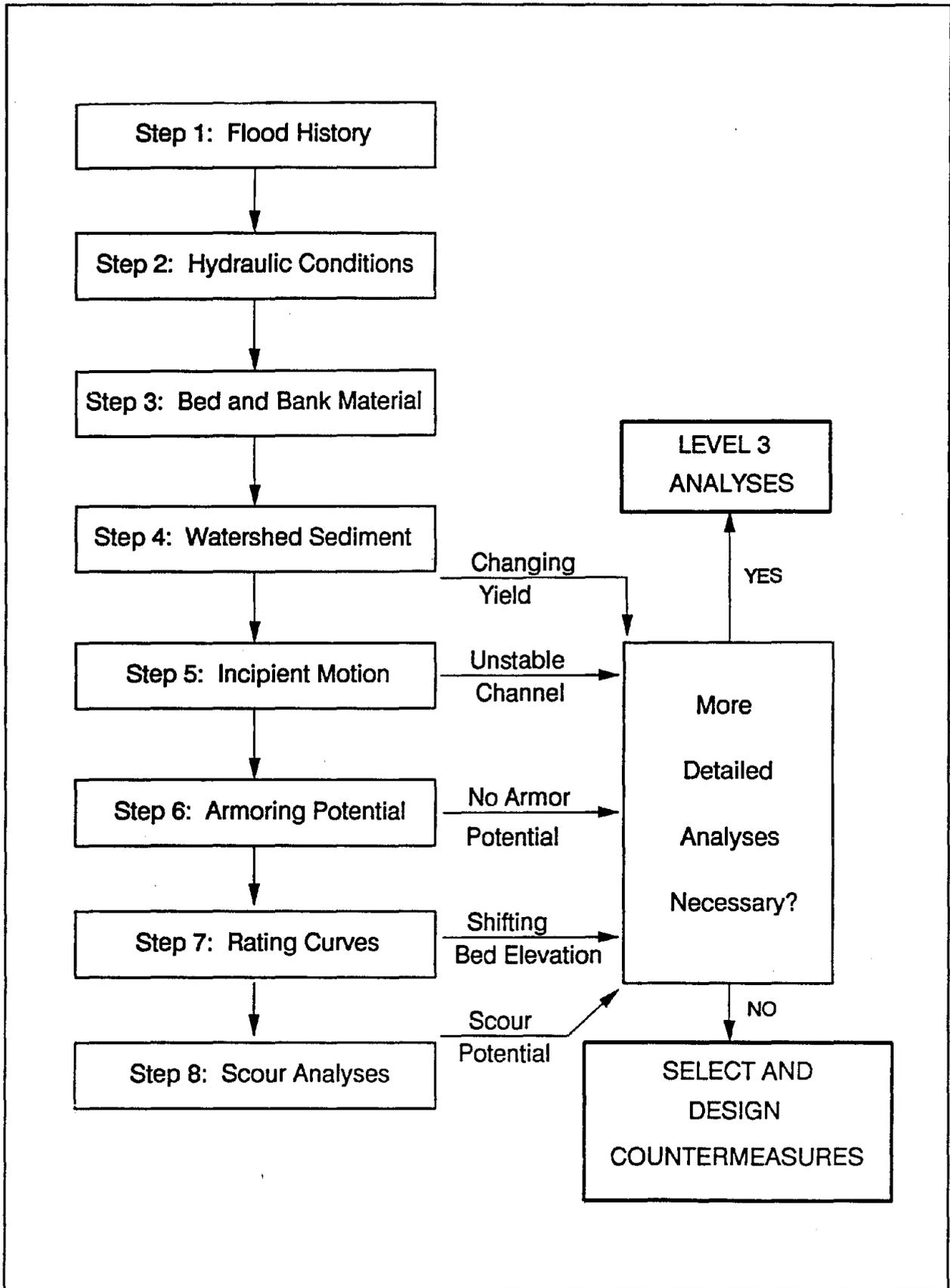


Figure 22. Flow chart for level 2: Basic Engineering Analyses.

Although the occurrence of single large storms can often be directly related to system change in any region of the country, this is not always the case. In particular, the succession of morphologic change may be linked to the concept of geomorphic thresholds as proposed by Schumm.<sup>(3)</sup> Under this concept, although a single major storm may trigger an erosional event in a system, the occurrence of such an event may be the result of a cumulative process leading to an unstable geomorphic condition.

Where available, the study of flood records and corresponding system responses, as indicated by time-sequenced aerial photography or other physical information, may help determine the relationship between morphological change and flood magnitude and frequency. Evaluation of wet-dry cycles can also be beneficial to an understanding of historical system response. Observable historical change may be found to be better correlated with the occurrence of a sequence of events during a period of above average rainfall and runoff than with the single large event. The study of historical wet-dry trends may explain certain aspects of system response. For example, a large storm preceded by a period of above-average precipitation may result in less erosion, due to better vegetative cover, than a comparable storm occurring under dry antecedent conditions; however, runoff volumes might be greater due to saturated soil conditions.

A good method to evaluate wet-dry cycles is to plot annual rainfall amounts, runoff volumes and maximum annual mean daily discharge for the period of record. A comparison of these graphs will provide insight to wet-dry cycles and flood occurrences. Additionally, a plot of the ratio of rainfall to runoff is a good indicator of watershed characteristics and historical changes in watershed condition.

#### **4.6.2 Step 2. Evaluate Hydraulic Conditions**

Knowledge of basic hydraulic conditions, such as velocity, flow depth and top width, etc., for given flood events is essential for completion of Level 2 stream stability analysis. Incipient motion analysis, scour analysis, assessment of sediment transport capacity, etc. all require basic hydraulic information. Hydraulic information is sometimes required for both the main channel and overbank areas, such as in the analysis of contraction scour.

Evaluation of hydraulic conditions is based on the factors and principles reviewed in chapter 3. For many river systems, particularly near urban areas, hydraulic information may be readily available from previous studies, such as flood insurance studies, channel improvement projects, etc., and complete re-analysis may not be necessary. However, in other areas, hydraulic analysis based on appropriate analytical techniques will be required prior to completing other quantitative analyses in a Level 2 stream stability assessment. The most common computer models for analysis of water surface profiles and hydraulic conditions are the Corps of Engineers HEC-2 or the new HEC River Analysis System (RAS) and the Federal Highway Administration WSPRO.<sup>(20,21,58)</sup> For the analysis and design of bridge crossings, WSPRO is generally considered a better model. The computational procedure in WSPRO for evaluating bridge loss is superior to that utilized in other models, and the input structure of the model has been specifically developed to facilitate bridge design.

#### **4.6.3 Step 3. Bed and Bank Material Analysis**

Bed material is the sediment mixture of which the streambed is composed. Bed material ranges in size from huge boulders to fine clay particles. The erodibility or stability of a channel largely depends on the size of the particles in the bed. Additionally, knowledge of bed sediment is necessary for most sediment transport analyses, including evaluation of incipient motion, armoring potential, sediment transport capacity and scour calculations. Many of these analyses require knowledge of particle size gradation, and not just the median ( $D_{50}$ ) sediment size.

Bank material usually consists of particles the same size as, or smaller than, bed particles. Thus, banks are often more easily eroded than the bed, unless protected by vegetation, cohesion, or some type of man-made protection.

Of the various sediment properties, size has the greatest significance to the hydraulic engineer, not only because size is the most readily measured property, but also because other properties, such as shape and fall velocity, tend to vary with particle size. A comprehensive discussion of sediment characteristics, including sediment size and its measurement, is provided in HIRE.<sup>(4)</sup> The following information briefly discusses sediment sampling considerations.

Important factors to consider in determining where and how many bed and bank material samples to collect include: (1) size and complexity of the study area, (2) number, lengths and drainage areas of tributaries, (3) evidence of or potential for armoring, (4) structural features that can impact or be significantly impacted by sediment transport, (5) bank failure areas, (6) high bank areas, and (7) areas exhibiting significant sediment movement or deposition (i.e., bars in channel). Tributary sediment characteristics can be very important to channel stability, since a single major tributary or tributary source area could be the predominant supplier of sediment to a system.

The depth of bed material sampling depends on the homogeneity of surface and subsurface materials. Where possible it is desirable to dig down some distance to establish bed-material characteristics. For example, in sand/gravel bed systems the potential existence of a thin surface layer of coarser sediments (armor layer) on top of relatively undisturbed subsurface material must be considered in any sediment sampling. Samples containing material from both layers would contain materials from two populations in unknown proportions, and thus it is typically more appropriate to sample each layer separately. If the purpose of the sampling is to evaluate hydraulic friction or initiation of bed movement, then the surface sample will be of most interest. Conversely, if bed-material transport during a large flood (i.e., large enough to disturb the surface layer) is important, then the underlying layer may be more significant. Methods of analysis are given in HIRE.<sup>(4)</sup>

#### 4.6.4 Step 4. Evaluate Watershed Sediment Yield

Evaluation of watershed sediment yield, and in particular, the relative increase in yield as a result of some disturbance, can be an important factor in stream stability assessment. Sediment eroded from the land surface can cause silting problems in stream channels resulting in increased flood stage and damage. Conversely, a reduction in sediment supply can also cause adverse impacts to river systems by reducing the supply of incoming sediment, thus promoting channel degradation and headcutting. A radical change in sediment yield as a result of some disturbance, such as a recent fire or long term land use changes, would suggest that stream instability conditions either already exist, or might readily develop.

Assessment of watershed sediment yield first requires understanding the sediment sources in the watershed and the types of erosion that are most prevalent. The physical processes causing erosion can be classified as sheet erosion, rilling, gullying and stream channel erosion. Other types of erosional processes are classified under the category of mass movement, e.g., soil creep, mudflows, landslides, etc. Data from publications and maps produced by the Natural Resources Conservation Service and the USGS can be used along with field observations to evaluate the area of interest.

Quantification of sediment yield is at best an imprecise science. The most useful information is typically obtained not from analysis of absolute magnitude of sediment yield, but rather the relative changes in yield as a result of a given disturbance. One useful approach to evaluating sediment yield from a watershed was developed by the Pacific Southwest Interagency Committee.<sup>(34)</sup> This method, which was designed as an aid for broad planning purposes only, consists of a numerical rating of nine factors affecting sediment production in a watershed, which then defines ranges of annual sediment yield. The nine factors are surficial geology, soil climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion and transport.

Other approaches to quantifying sediment yield are based on regression equations, as typified by the Universal Soil Loss Equation (USLE). The USLE is an empirical formula for predicting annual soil loss due to sheet and rill erosion, and is perhaps the most widely recognized method for predicting soil erosion. Wischmeier and Smith provide detailed descriptions of this equation and its terms.<sup>(35)</sup>

#### 4.6.5 Step 5. Incipient Motion Analysis

An evaluation of relative channel stability can be made by evaluating incipient motion parameters. The definition of incipient motion is based on the critical or threshold conditions where hydrodynamic forces acting on one grain of sediment have reached a value that, if increased even slightly, will move the grain. Under critical conditions, or at the point of incipient motion, the hydrodynamic forces acting on the grain are just balanced by the resisting forces of the particle.

The Shields diagram may be used to evaluate the particle size at incipient motion for a given discharge (see HIRE).<sup>(4)</sup> For most river flow conditions the following equation, derived from the Shields diagram, is appropriate for evaluation of incipient motion:

$$D_c = \frac{\tau}{0.047 (\gamma_s - \gamma)} \quad (12)$$

where:

- $D_c$  = Diameter of the sediment particle at incipient motion conditions, m
- $\tau$  = Boundary shear stress (see HIRE) for equations defining the boundary shear stress), Pa ( $\text{N/m}^2$ )<sup>(4)</sup>
- $\gamma_s$  and  $\gamma$  = Specific weights of sediment and water, respectively,  $\text{N/m}^3$
- 0.047 = Dimensionless coefficient often referred to as the Shields parameter.

As originally proposed the Shields parameter was 0.06 for flow conditions in the turbulent range. The value of 0.047 was suggested by Meyer-Peter and Muller, and further supported by Gessler.<sup>(36,37)</sup> Recent research has indicated that this coefficient is not constant (values range from 0.02 to 0.10), and equations have been derived as a function of surface and subsurface particle size. However, the use of 0.047 in sand-bed channels should provide reasonable results in most situations.

Evaluation of the incipient motion size for various discharge conditions provides insight on channel stability and what flood might potentially disrupt channel stability. The results of such an analysis are generally more useful for analysis of gravel or cobble-bed systems. When applied to a sand-bed channel, incipient motion results usually indicate that all particles in the bed material are capable of being moved for even very small discharges, a physically realistic result.

#### 4.6.6 Step 6. Evaluate Armoring Potential

The armoring process begins as the non-moving coarser particles segregate from the finer material in transport. The coarser particles are gradually worked down into the bed, where they accumulate in a sublayer. Fine bed material is leached up through this coarse sublayer to augment the material in transport. As sediment movement continues and degradation progresses, an increasing number of non-moving particles accumulate in the sublayer. Eventually, enough coarse particles can accumulate to shield, or "armor" the entire bed surface.

An armor layer sufficient to protect the bed against moderate discharges can be disrupted during high flow, but may be restored as flows diminish. Therefore, as in any hydraulic design, the analysis must be based on a certain design event. If the armor layer is stable for that design event, it is reasonable to conclude that no degradation will occur under design conditions. However, flows exceeding the design event may disrupt the armor layer, resulting in further degradation. While armoring of the bed by the coarser material size fraction can temporarily reduce the rate of degradation and stabilize the stream system, armoring cannot be counted on as a long-term solution.

Potential for development of an armor layer can be assessed using incipient motion analysis and a representative bed-material composition. In this case the representative bed-material composition is that which is typical of the depth of anticipated degradation. For given hydraulic conditions the incipient motion particle size can be computed as given above in Step 5. If no sediment of the computed size or larger is present in significant quantities in the bed, armoring will not occur.

The  $D_{90}$  or  $D_{95}$  size of the representative bed material is frequently found to be the size "paving the channel" when degradation is arrested. Within practical limits of planning and design, the  $D_{95}$  size is considered to be about the maximum size for pavement formation.<sup>(38)</sup> Therefore, armoring is probable when the computed incipient motion size is equal to or smaller than the  $D_{95}$  size in the bed material.

By observing the percentage of the bed material equal to or larger than the armor particle size ( $D_c$ ) the depth of scour necessary to establish an armor layer can be calculated:<sup>(39)</sup>

$$Y_s = Y_a \left[ \frac{1}{P_c} - 1 \right] \quad (13)$$

where:

$Y_a$  = Thickness of the armoring layer  
 $P_c$  = Decimal fraction of material coarser than the armoring size.

The thickness of the armoring layer ( $Y_a$ ) ranges from one to three times the armor particle size ( $D_c$ ), depending on the value of  $D_c$ . Field observations suggest that a relatively stable armoring condition requires a minimum of two layers of armoring particles.

#### 4.6.7 Step 7. Evaluation of Rating Curve Shifts

When stream gage data are available, such as that collected by the USGS, an analysis of the stage-discharge rating curve over time can provide insight on stream stability. For example, a rating curve that was very stable for many years, but suddenly shifts might indicate a change in watershed conditions causing increased channel erosion or sedimentation, or a some other change related to channel stability. Similarly, a rating curve that shifts continually would be a good indicator that channel instability exists. However, it is important to note that not all rating curve shifts are the result of channel instability. Other factors promoting a shift in a rating curve include changes in channel vegetation, ice conditions, or beaver activity.

The most common cause of rating curve shifts in natural channel control sections is generally scour and fill.<sup>(40)</sup> A positive shift in the rating curve results from scour, and the depth, and hence, the discharge are increased for a given stage. Conversely, a negative shift results from fill, and the depth and discharge will be less for a given stage.

Shifts may also be the result of changes in channel width. Channel width may increase due to bank-cutting, or decrease due to undercutting of steep streambanks. In meandering streams, changes in channel width can occur as point bars are created or destroyed.

Analysis of rating curve shifts is typically available from the agency responsible for the stream gage. If such information is not available, field inspection combined with the methods described by Rantz can be utilized to analyze observed rating curve shifts.<sup>(40)</sup> If the shifts can be traced to scour, fill or channel width changes, such information will be a reliable indicator of potential channel instability.

Gaging stations at which continuous sediment data are collected may also provide clues to the existence of gradation problems. Any changes in the long-term sediment load may indicate lateral movement of the channel, gradation changes, or a change in sediment supply from the watershed.

#### 4.6.8 Step 8. Evaluate Scour Conditions

Section 3.4.1 provided an overview of scour at bridge crossings and HEC-18 provides detailed computational procedures.<sup>(15)</sup> Figure 23 illustrates common scour related problems at bridges. These problems are attributable to the effects of obstructions to the flow (local scour) and contraction of the flow or channel deepening at the outside of a bend. Calculation of the three components of scour, local scour, contraction scour and aggradation/degradation, quantifies the potential instability at a bridge crossing. Scour susceptible bridges are those that show potentially large amounts of any one of the scour components, and/or their cumulative amount is large. Such bridges should be carefully monitored and/or countermeasures installed.

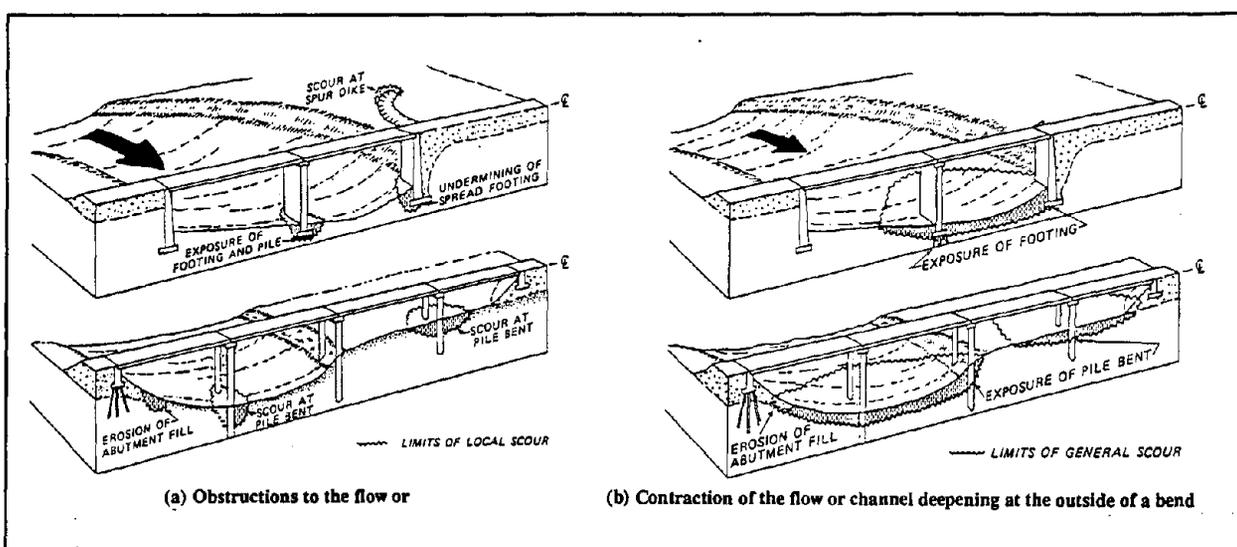


Figure 23. Local scour and contraction scour related hydraulic problems at bridges related to (a) obstructions to the flow or (b) contraction of the flow or channel deepening at the outside of a bend.<sup>(1,2)</sup>

### 4.7 LEVEL 3: MATHEMATICAL AND PHYSICAL MODEL STUDIES

Detailed evaluation and assessment of stream stability can be accomplished using either mathematical or physical model studies. A mathematical model is simply a quantitative expression of the relevant physical processes involved in stream channel stability. Various types of mathematical models are available for evaluation of sediment transport, depending on the application (watershed or channel analysis) and the level of analysis required. The use of such models can provide detailed information on erosion and sedimentation throughout a study reach, and allows evaluation of a variety of "what-if" questions.

Similarly, physical model studies completed in a hydraulics laboratory can provide detailed information on flow conditions and to some extent, sediment transport conditions, at a bridge crossing. The hydraulic laws and principles involved scaling physical model studies are well defined and understood, allowing accurate extrapolation of model results to prototype conditions. Physical model studies can often provide better information on complex flow conditions than what is readily available from mathematical models, due to the complexity of the process and the limitations of 2- and 3-dimensional mathematical models. Often the use of both physical and mathematical models can provide complementary information.

However, the need for detailed information and accuracy available from either mathematical or physical model studies must be balanced by the time and money available. As the analysis becomes more complicated, accounting for more factors, the level of effort necessary becomes proportionally larger. The decision to proceed with a Level 3 type analysis has historically been made only for high risk locations, extraordinarily complex problems, and for forensic analysis where losses and liability costs are high; however, considering the importance of stream stability to the safety and integrity of all bridges suggests that Level 3 type analyses should be completed routinely. The widespread use of personal computers and the continued development of more sophisticated software have greatly facilitated completion of Level 3 type investigations and have reduced the level of effort and cost required.

#### **4.8 ILLUSTRATIVE EXAMPLES**

The FHWA manual, "Highways in the River Environment," provides a discussion of "Design Considerations for Highway Encroachment and River Crossings" in chapter VII.<sup>(4)</sup> This discussion includes principal factors for design, procedures for evaluation and design, and conceptual examples. The procedures for evaluation and design of river crossings and encroachments parallel the three-level approach of this chapter. A series of short conceptual discussions in chapter VII of HIRE (pp. VII-13 to VII-32) illustrate the application of qualitative (Level 1) techniques, and a series of short case studies (pp. VII-33 to VII-60) provide various applications. Finally, chapter VII of HIRE presents five "Overview Examples" which illustrate various steps in the three-level approach.<sup>(4)</sup>

## CHAPTER 5

### SELECTION OF COUNTERMEASURES FOR STREAM INSTABILITY

#### 5.1 INTRODUCTION

A countermeasure is defined as a measure incorporated into a highway-stream crossing system to monitor, control, inhibit, change, delay, or minimize stream and bridge stability problems or action plan for monitoring structures during and/or after flood events. This would include river stabilizing works over a reach of the river up and downstream of the crossing. Countermeasures may be installed at the time of highway construction or retrofitted to resolve stability problems at existing crossings. Retrofitting is good economics and good engineering practice in many locations because the magnitude, location, and nature of potential stability problems are not always discernible at the design stage, and indeed, may take a period of several years to develop.

A countermeasure does not need to be a separate structure, but may be an integral part of the highway. For example, relief bridges on floodplains are countermeasures which alleviate scour from flow contraction at the bridge over the stream channel. Some features that are integral to the highway design serve as countermeasures to minimize stream stability problems. Abutments and piers oriented with the flow reduce local scour and contraction scour. Also, reducing the number of piers and/or setting back the abutments reduces contraction scour.

Countermeasures which are not integral to the highway may serve one function at one location and a different function at another. For examples, bank revetment may be installed to control bank erosion from meander migration, or it may be used to stabilize streambanks in the contracted area at a bridge. Other countermeasures are useful for one function only. This category of countermeasures includes spurs constructed in the stream channel to control meander migration.

In selecting a countermeasure it is necessary to evaluate how the stream might respond, and also how the stream may respond as the result of the activities of other parties.

A countermeasure for scour critical bridges and unknown foundations could also be monitoring a bridge during and/or after a flood event. If monitoring is selected and if the risk of scour failure is high, interim protection such as riprap or instrumentation should 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 high risk bridge should be monitored during and inspected after floods. If monitoring is selected, an action plan should be implemented which includes a notification process, flood watch procedures, a highway closure process, documentation of available detours, inspection procedures, assessment procedures, and a repair notification process (see HEC-18).<sup>(15)</sup>

This chapter provides some general criteria for the selection of countermeasures for stream instability. Then, the selection of countermeasures for specific stream instability problems is discussed. Finally, case histories of hydraulic problems at bridge sites are summarized to provide information on the relative success of various countermeasures for stream stabilization.

#### 5.2 CRITERIA FOR THE SELECTION OF COUNTERMEASURES

The selection of an appropriate countermeasure for a specific bank erosion problem is dependent on factors such as the erosion mechanism, stream characteristics, construction and maintenance requirements, potential for vandalism, and costs. Perhaps more important, however, is the effectiveness of the measure selected in performing the required function.

Protection of an existing bank line may be accomplished with revetments, spurs, retardance structures, longitudinal dikes, or bulkheads. Spurs, longitudinal dikes, and area retardance structures can be used to establish a new flow path and channel alignment, or to constrict flow in a channel. Bulkheads may be used for

any of the functions, but because of their high cost, are appropriate for use only where space is at a premium. Channel relocation may be used separately or in conjunction with other countermeasures to change the flow path and flow orientation.

### 5.2.1 Erosion Mechanism

Bank erosion mechanisms are surface erosion and/or mass wasting. Surface erosion is the removal of soil particles by the velocity and turbulence of the flowing water. Mass wasting is by slides, rotational slip, piping and block failure. In general slides, rotational slip and block failure result from the bank being under cut by the flow. Also, seepage force of the pore water in the bank is another factor that can cause surface erosion or mass wasting. The type of mechanism is determined by the magnitude of the erosive forces of the water, type of bed and bank material, vegetation, and bed elevation stability of the stream. These mechanisms are described in HIRE.<sup>(4)</sup>

### 5.2.2 Stream Characteristics

Stream characteristics that influence the selection of countermeasures include: channel width; bank height, configuration, and material; vegetative cover; channel configuration; sediment transport condition; bend radii; channel velocities and flow depth; ice and debris; and floodplains.

Channel Width. Channel width influences only the use of spur-type countermeasures. On smaller streams (<75 m), flow constriction resulting from the use of spurs may cause erosion of the opposite bank. However, spurs can be used on small channels where the purpose is to shift the location of the channel.

Bank Height. Low banks (<3 m) may be protected by any of the countermeasures, including bulkheads. Medium height banks (from 3 to 6 m) may be protected by revetment, retardance structures, spurs, and longitudinal dikes. High banks (>6 m) generally require revetments used alone or in conjunction with other measures.

Channel Configuration. Spurs and jack fields have been successfully used as a countermeasure to control the location of the channel in meandering and braided streams. Also, bulkheads, revetments, and riprap have been used to control bank erosion resulting from stream migration. On anabranching streams, revetments, riprap, and spurs have been used to control bank erosion and channel shifting. Also, channels that do not carry large flows can and have been closed off. In one case, HIRE reports that a large channel was closed off and revetment and riprap used to control erosion in the other channel.<sup>(4)</sup>

Channel Material. Spurs, revetments, riprap, jack fields, or check dams can be used in any type of channel material if they are designed correctly. However, jack fields should only be placed on streams that carry appreciable debris and sediment in order for the jacks to cause deposition and eventually be covered up.

Bank Vegetation. Vegetation such as willows can enhance the performance of structural countermeasures and may, in some cases, reduce the level of structural protection needed. Meander migration and other bank erosion mechanisms are accelerated on many streams in reaches where vegetation has been cleared.

Sediment Transport. The sediment transport conditions can be described as regime, threshold, or rigid. Regime channel beds are those which are in motion under most flow conditions, generally in sand or silt-size noncohesive materials. Threshold channel beds have no bed material transport at normal flows and become mobile at higher flows. They may be cut through cohesive or noncohesive materials, and an armor layer of coarse-grained material can develop on the channel bed. Rigid channel beds are cut through rock or boulders and rarely or never become mobile. In general, permeable structures will cause deposition of bed material in transport and are better suited for use in regime and some threshold channels than in rigid channel conditions. Impermeable structures are more effective than permeable structures in channels with little or no bed load, but impermeable structures can also be very effective in mobile bed conditions. Revetments can be effectively used with mobile or immobile channel beds.

Bend Radii. Bend radii affect the design of countermeasures. Thus, the cost per meter of bank protection provided by a specific countermeasure may differ considerably on short-radius and longer radius bends.

Channel Velocities and Flow Depth. Channel hydraulics affect countermeasure selection because structural stability and induced scour must be considered. Some of the permeable flow retardance measures may not be structurally stable and countermeasures which utilize piles may be susceptible to scour failure in high velocity environments.

Ice and Debris. Ice and debris can damage or destroy countermeasures and should always be considered during the selection process. On the other hand, the performance of some permeable spurs and area retardance structures is enhanced by debris where debris accumulation causes increased sediment deposition.

Floodplains. In selecting countermeasures for stream stability and scour, the amount of flow on the floodplain is an important factor. For example, if there is appreciable overbank flow, then guide banks to protect abutments should be considered. Also, spurs perpendicular to the approach embankment may be needed to control erosion.

### **5.2.3 Construction and Maintenance Requirements**

Standard requirements regarding construction or maintenance such as the availability of materials, construction equipment requirements, site accessibility, time of construction, contractor familiarity with construction methods, and a program of regular maintenance, inspection, and repair are applicable to the selection of appropriate countermeasures. Additional considerations for countermeasures which are located in stream channels include considerations of constructing and maintaining a structure which may be partially under water at all times, the extent of bank disturbance which may be necessary, and the desirability of preserving streambank vegetative cover to the extent practicable.

### **5.2.4 Vandalism**

Vandalism is always a maintenance concern since effective countermeasures can be made ineffective by vandals. Documented vandalism includes dismantling of devices, burning, and cutting or chopping with knives, wire cutters, and axes. Countermeasure selection or material selection for construction may be affected by concern for vandalism. For example, rock-filled baskets (gabions) may not be appropriate in some urban environments.

### **5.2.5 Costs**

Cost comparisons should be used to study alternative countermeasures with an understanding that the measures were installed under widely varying stream conditions, that the conservatism (or lack thereof) of the designer is not accounted for, that the relative effectiveness of the measures cannot be quantitatively evaluated, and that some measures included in the cost data may not have been fully tested by floods.

Figure 24 provides some insight regarding the relative costs of major countermeasure types. Although the study was done in 1985 and costs have increased, the relative cost probably has not changed. The bars represent the cost range for each countermeasure included in the comparison and the darkened portion of each bar represents the dominant range of costs. Numbers following the countermeasure type are the number of sites included in the cost analysis. The figure shows that rock spurs, horizontal wood slat spurs, rock windrow revetments, vegetation, jack retardance structures, wood-fence retardance structures, and rock toe dikes are usually the least expensive. Henson-type (vertical wood slat) spurs, cellular block revetments, and concrete-filled mats are generally the most expensive. Rock riprap revetment costs per meter of bank protection vary widely, but the dominant range of costs are not out of line with costs for other countermeasures.

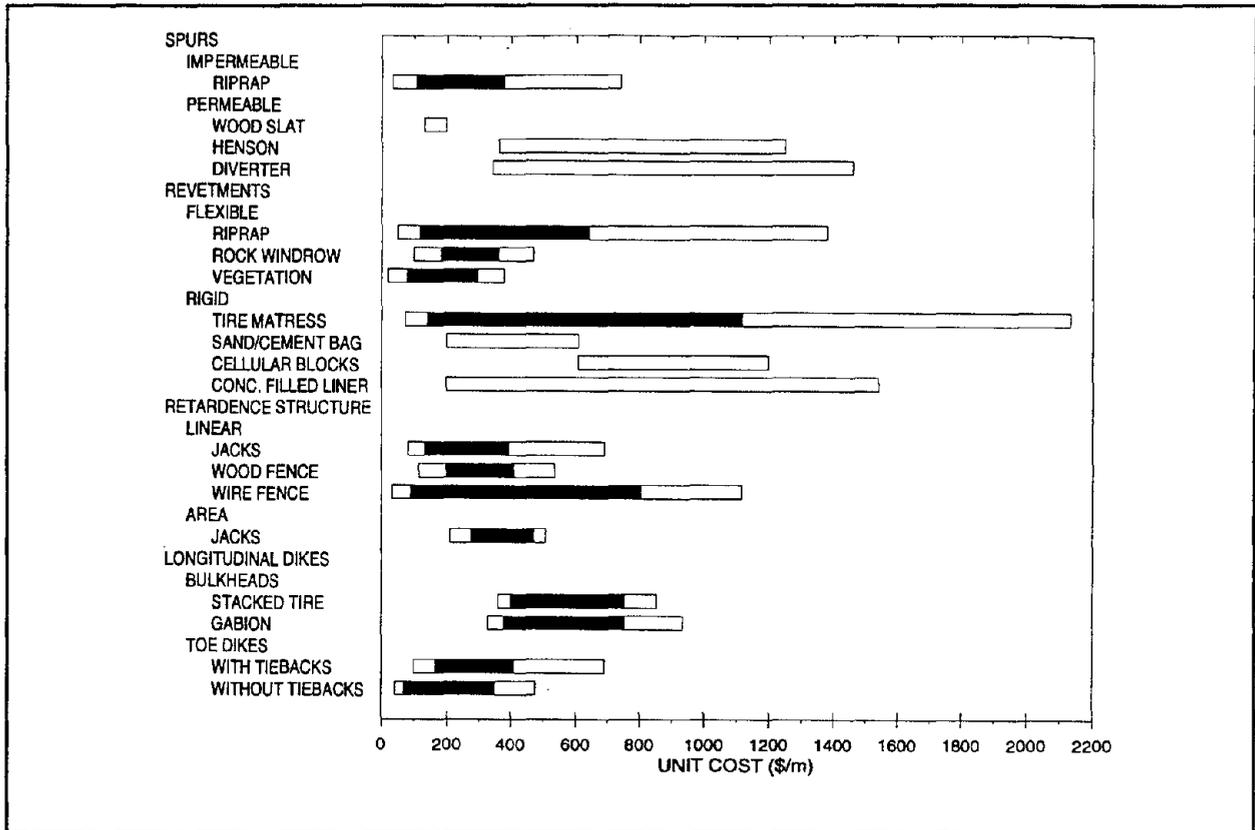


Figure 24. Countermeasure costs per meter of bank protected (after Brown).<sup>(41)</sup>

### 5.3 COUNTERMEASURES FOR MEANDER MIGRATION

The best countermeasure against meander migration is to locate the bridge crossing on a relatively straight reach of stream between bends. At many such locations, countermeasures may not be required for several years because of the time required for the bend to move to a location where it becomes threatening to the highway facility. However, bend migration rates on other streams may be at such a rate that countermeasures will be required after a few years or a few flood events and, therefore, should be installed during initial construction.

Stabilizing channel banks at a highway stream crossing can cause a change in the channel cross section and an increase in stream sinuosity upstream of the stabilized banks. Figure 25(a) illustrates a natural channel section in a bend with the deeper section at the outside of the bend and a gentle slope toward the inside bank resulting from deposition in the remainder of the section. Figure 25(b) illustrates the scour which results from stabilizing the outside bank of the channel and the steeper slope of the point bar on the inside of the bend. This effect must be considered in the design of the countermeasure and the bridge. It should also be recognized that the thalweg location and flow direction can change as sinuosity upstream increases.

Figure 26(a) illustrates meander migration in a natural stream and figure 26(b), the effects of bend stabilization on upstream sinuosity. As sinuosity increases, meander amplitude may increase, meander radii will become smaller, deposition may occur because of reduced slopes, and the channel width-depth ratio may increase as a result of bank erosion and deposition, as at the bridge location shown in figure 26(b). Ultimately, cutoffs can occur. These changes can also result in changing hydraulic problems downstream of the stabilized bend.

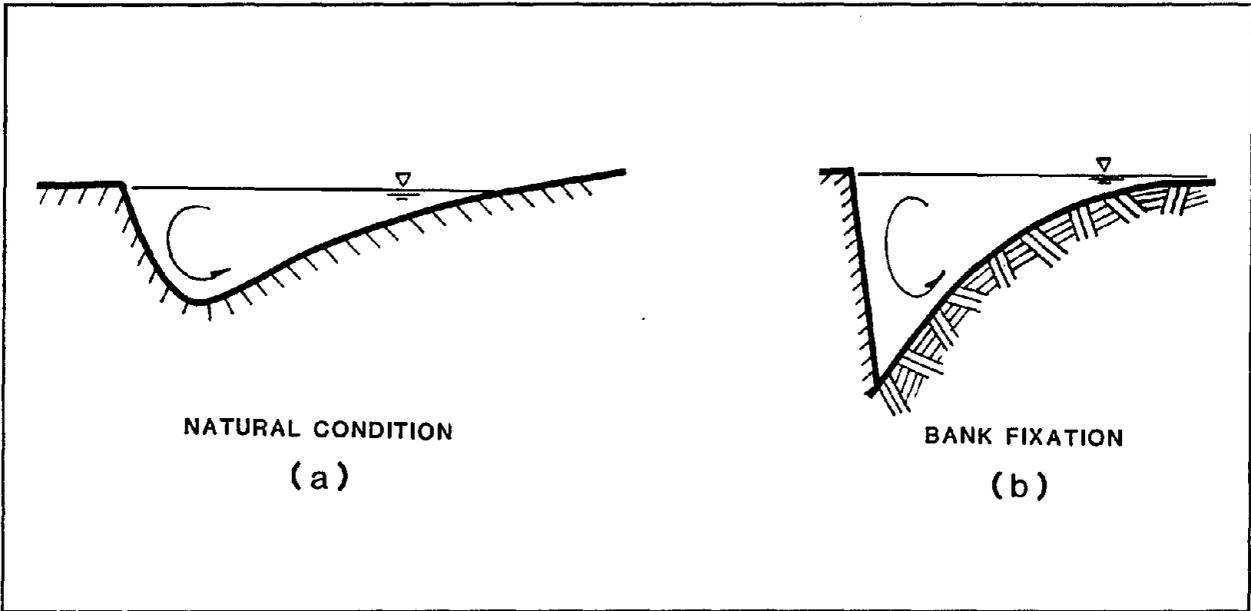


Figure 25. Comparison of channel bend cross sections (a) for natural conditions, and (b) for stabilized bend (after Brown).<sup>(41)</sup>

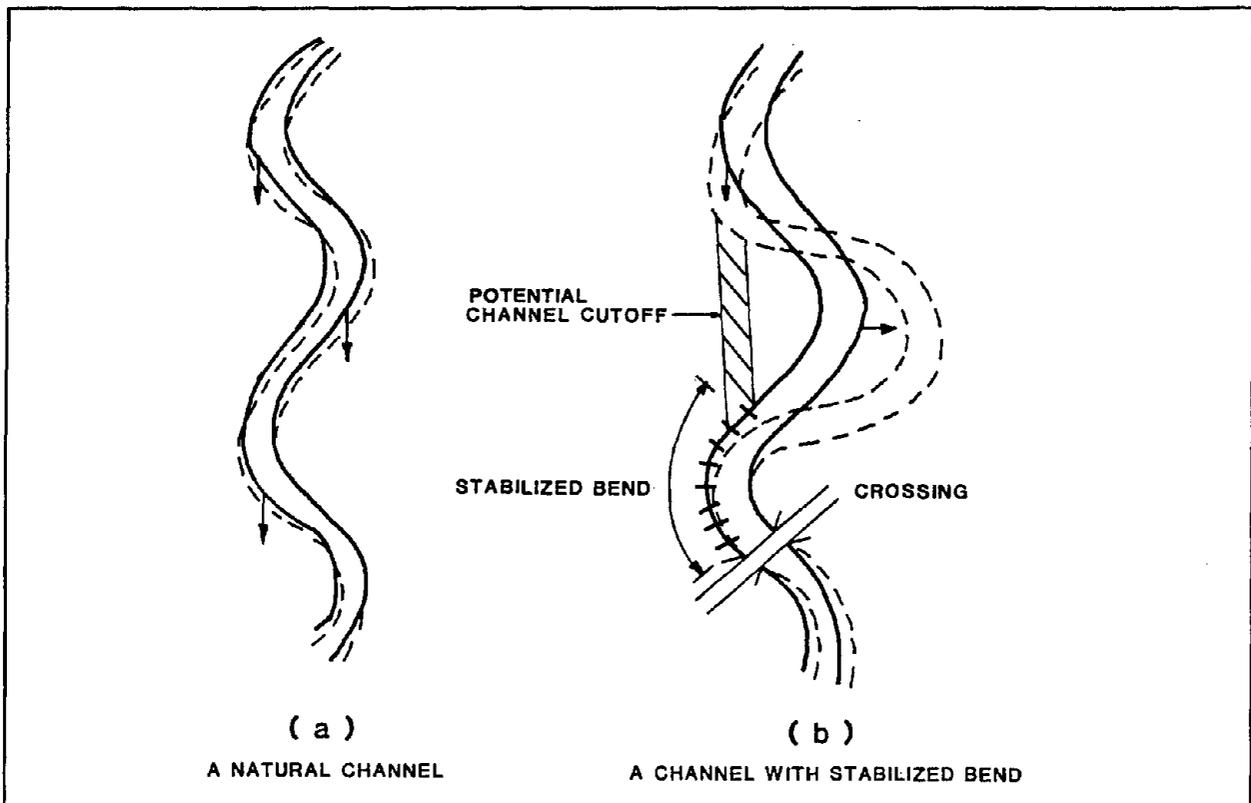


Figure 26. Meander migration in (a) a natural channel, and (b) a channel with stabilized bend (after Brown).<sup>(41)</sup>

Countermeasures for meander migration include those that:

- protect an existing bank line,
- establish a new flow line or alignment, and
- control and constrict channel flow

The classes of countermeasures identified for bank stabilization and bend control are bank revetments, spurs, retardance structures, longitudinal dikes, vane dikes, bulkheads, and channel relocations. Also, a carefully planned cutoff may be an effective way to counter problems created by meander migration. These measures may be used individually or in combination to combat meander migration at a site. Some of these countermeasures are also applicable to bank erosion from causes other than bend migration. Descriptions and design recommendations are included in chapter 6, Countermeasure Design.

#### 5.4 COUNTERMEASURES FOR SCOUR AT BRIDGES

Scour is the result of the erosive action of running water, excavating and carrying away material from the bed and banks of streams. Different materials scour at different rates. Loose granular soils are rapidly eroded under water action while cohesive or cemented soils are more scour-resistant. However, ultimate scour in cohesive or cemented soils can be as deep as scour in sand-bed streams. Scour will reach its maximum depth in sand and gravel bed materials in hours; cohesive bed materials in days; glacial tills, poorly cemented sand stones and shales in months; hard, dense and cemented sandstone or shales and limestones in years; and dense granites in centuries. Massive rock formations with few discontinuities can be highly resistant to scour and erosion during the lifetime of a typical bridge.

Designers and inspectors need to carefully study site-specific subsurface information in determining scour potential at bridges, giving particular attention to foundations on rock.

Total Scour. Total scour at a highway crossing is comprised of three components. These components are:

- Aggradation and Degradation. These are long-term streambed elevation changes due to natural or man induced causes within the reach of the river on which the bridge is located.
- Contraction Scour. This type of scour involves the removal of material from the bed and banks across all or most of the width of a channel. This scour can result from a contraction of the flow by the approach embankments to the bridge encroaching onto the floodplain and/or into the main channel, a change in downstream control of the water surface elevation, or the location of the bridge in relation to a bend. In each case, the scour is caused by an increase in transport of the bed material in the bridge cross section.
- Local Scour. This scour occurs around piers, abutments, spurs, and embankments and is caused by the acceleration of the flow and the development of vortex systems induced by these obstructions to the flow.

In addition to the types of scour mentioned above, lateral migration of the stream may also erode the approach roadway to the bridge or change the total scour by changing the angle of the flow in the waterway at the bridge crossing. Factors that affect lateral migration and the stability of a bridge are the geomorphology of the stream, location of the crossing on the stream, flood characteristics, and the characteristics of the bed and bank materials.

There are two ways by which bridges can be made fail-safe against scour, but neither is a viable alternative at many alluvial stream crossing sites. Nevertheless, where the alternative is available and practicable,

consideration can be given to making the crossing or bridge fail-safe. The first fail-safe design alternative is a one-span structure which spans streamflow at flood stage. This includes a superstructure that will not be submerged or partially submerged at flood stage. Obviously, this alternative may only be practicable for small, relatively stable, incised streams.

The second fail-safe bridge design alternative is a foundation in sound rock and a superstructure above the elevation of flood flow. Other countermeasures may be necessary to inhibit scour of streambanks, abutment spill slopes and approach fills, but the bridge will be fail-safe if adequately anchored in sound rock.

A third design alternative which is necessary for all bridges over alluvial streams is to locate the bridge foundation, pile tips or drilled shafts, at an elevation at which sufficient support will be retained after scour occurs. Where pile bearing capacity is based on skin friction, driving the piles to refusal may be inadequate. Pile tip elevation should be applied as a second criterion, and tip elevation should be based on bearing capacity after scour. HEC-18 provides detailed guidance on scour evaluations for new and existing bridges.<sup>(15)</sup>

As a practical matter, fail-safe bridge designs are usually not feasible, but strategies against scour are available. Design alternatives, in addition to the three discussed above, are integral to the highway facility. Countermeasures are appurtenances to the highway-stream crossing system. Design alternatives and countermeasures are both discussed in the following sections in regard to contraction scour and local scour problems.

#### 5.4.1 Contraction Scour

Severe contraction of flow at highway stream crossings has resulted in numerous bridge failures at abutments, approach fills, and piers from contraction scour. Lessening contraction scour can be accomplished by reducing the amount of flow contraction and by reducing the effects of flow contraction. Design alternatives to lessen contraction scour include longer bridges, relief bridges on the floodplain, superstructures at elevations above flood stages of extreme events, and a crest vertical profile on approach roadways to provide for overtopping during floods exceeding the design flood event. These design alternatives are integral features of the highway facility which reduce the contraction at bridges and, therefore, reduce the magnitude of contraction scour. Further discussion of the elevation of superstructures and the roadway profile is warranted since the impact of these features on the magnitude of scour is less obvious than the effects of other features of the design.

The elevation of bridge superstructures is recognized as important to the integrity of the bridge because of hydraulic forces that may damage the superstructure. These include buoyancy and impact forces from ice and other floating debris. Contraction scour is another consideration in setting the superstructure elevation. When the superstructure of a bridge becomes submerged or when ice or debris lodged on the superstructure cause the flow to contract, flow may be accelerated and more severe scour can occur. For this reason, where contraction scour is of concern, bridge superstructures should be located with clearance for debris, and, if practicable, above the stage of floods larger than the design flood.

Where streamflow at flood stages includes overbank flow, maximum flow through bridge waterways occurs at incipient overtopping of the roadway. As the flood stage increases, backwater and flow through bridge openings decrease, at least temporarily. Therefore, highway profiles are significant to the contraction of flow and contraction scour at stream crossings.

Another design feature which should be considered relative to contraction scour is the effective depth of the superstructure. Present day superstructures often include bridge railings which are solid parapets. These increase the effective depth of the superstructure and the importance of locating the bridge superstructure above high water with clearance for debris passage. It also increases the importance of alternate provisions for the passage of flood waters in the event of debris blockage of the waterway or superstructure submergence. Possible alternate provisions include relief bridges on the floodplain and a highway profile which provides for overtopping before the bridge superstructure begins to become submerged.

Similarly, pier design, span length, and pier location become more important contributors to contraction scour where debris can lodge on the piers and further contract flow in the waterway. In streams which carry heavy loads of debris, longer, higher spans and solid piers will help to reduce the collection of debris. Where practicable, piers should be located out of the main current in the stream, i.e., outside the thalweg at high flow. There are numerous locations where piers occupy a significant area in the stream channel and contribute to contraction scour, especially where devices to protect piers from ship traffic are provided.

The stream channel cross section under bridges is sometimes designed to increase the waterway area and thereby decrease backwater upstream of the bridge and contraction scour in the waterway. In streams which carry large sediment loads, deposition may occur in the enlarged section of channel during smaller floods and on the recession of larger floods, thus rendering the channel excavation ineffective. However, for streams which do not carry a significant sediment load and on floodplains, excavation within the bridge waterway area will compensate for some of the lateral contraction of flow and reduce contraction scour. The option of substituting excavation for scour is site-specific and may be undesirable on some floodplains because of high water tables and standing water.

Countermeasures used to reduce flow contraction include measures which retard flow along highway embankments on floodplains. Flow along highway fills usually intersects with flow within bridge openings at large angles. This causes additional contraction of the flow, vortices, and turbulence which produce local scour. The contraction of flow can be reduced by using spurs on the upstream side of the highway embankment to retard flow parallel with the highway.<sup>(22)</sup>

Guide banks (previously referred to as spur dikes) at bridge abutments serve a similar purpose in addition to the purpose of aligning flow in the bridge opening.<sup>(22)</sup> They reduce contraction scour because they increase the efficiency of the bridge opening and hence reduce flow contraction. The primary purpose of these guide banks, however, is to reduce local scour at abutments.

The principal countermeasure used for reducing the effects of contraction is revetment on channel banks and fill slopes at bridge abutments. However, guide banks may be used to reduce the effects of contraction by moving the site of local scour caused by the turbulence of intersecting flows and contraction away from the bridge abutment.

The potential for undesired effects from stabilizing all or any portion of the channel perimeter at a contraction should be considered. Stabilization of the banks may only result in exaggerated scour in the streambed near the banks or, in a relatively narrow channel, across the entire channel. Stabilization of the streambed may also result in exaggerated lateral scour in any size stream. Stabilization of the entire stream perimeter may result in downstream scour or failure of some portion of the countermeasures used on either the streambed or banks.

#### **5.4.2 Local Scour**

Local scour occurs in bridge openings at piers and abutments. In general, design alternatives against structural failure from local scour consist of measures which reduce scour depth, such as pier shape and orientation, and measures which retain their structural integrity after scour reaches its maximum depth, such as placing foundations in sound rock and using deep piling. Countermeasures which can temporarily prevent scour from occurring include riprap.

Abutments. Countermeasures for local scour at abutments consist of measures which improve flow orientation at the bridge end and move local scour away from the abutment, as well as revetments and riprap placed on spill slopes to resist erosion.

Guide banks are earth or rock embankments placed at abutments. Flow disturbances, such as eddies and cross-flow, will be eliminated where a properly designed and constructed guide bank is placed at a bridge

abutment. Guide banks also protect the highway embankment, reduce local scour at the abutment and adjacent piers, and move local scour to the end of the guide bank.

Local scour also occurs at abutments as a result of expanding flow downstream of the bridge. This is especially true of bridges on wide, wooded floodplains cleared for construction of the highway. Short guide banks extending to the tree line will move this scour away from the abutment, and the trees will retard velocities so that flow redistribution can occur with minimal scour.

The effectiveness of guide banks is a function of stream geometry, the quantity of flow on the floodplain, and the size of bridge opening. A typical guide bank at a bridge opening is shown in figure 27.

Revetments may be pervious rock or rigid concrete. Rock riprap revetment provides an effective countermeasure against erosion on spill slopes.<sup>(42)</sup> Rigid revetments have been more successful where abutments are on the floodplain rather than in stream channels because hydrostatic pressure behind the revetments is not usually a problem. Precautions against undermining of the toe and upstream terminus of all revetments are always required.

Other countermeasures have been successfully used to inhibit scour at abutments where the abutment is located at the streambank or within the stream channel. These measures include dikes to constrict the width of braided streams and retards to reduce velocities near the streambank.

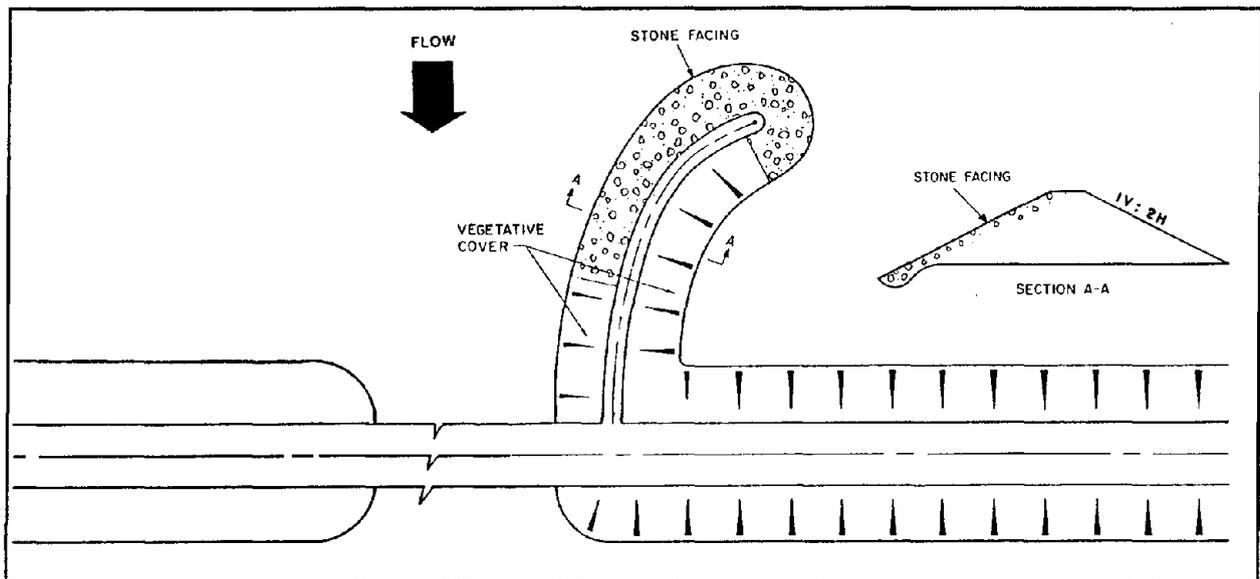


Figure 27. Typical guide bank layout and section (after Bradley).<sup>(22)</sup>

**Piers.** Three basic methods may be used to prevent damage from local scour at piers. The first method is to place the foundation of the structure at such a depth that the structural stability will not be at risk with maximum scour. This must be done on all new or replacement bridges.<sup>(15)</sup> The second (for existing bridges) is to provide protection at or below the streambed to inhibit the development of a scour hole. The third measure is to prevent erosive vortices from forming or to reduce their strength and intensity.

Streamlined pier noses decrease flow separation at the face of the pier, reducing the strength of the horseshoe vortices which form at piers. Practical application of this principle involves the use of rounded or circular shapes at the upstream and downstream faces of piers in order to reduce the flow separation. However, flow direction can and does change with time and with stage on some streams. Piers oriented with flow direction at one stage or at one point in time may be skewed with flow direction at another. Also, flow direction changes with the passage of bed forms. In general, piers should be aligned with the main flow direction and skew angles greater than 5 degrees should be avoided. Where this is not possible, a single cylindrical pier or a

row of cylindrical columns will produce a lesser depth of local scour. The tendency of a row of columns to collect debris should be considered. Debris can greatly increase scour depths. Webwalls have been used between columns to add to structural strength and to reduce the tendency to collect debris. Webwalls should be constructed at the elevation of stream flood stages which carry floating debris and extended to the elevation of the streambed.

Riprap is commonly used to inhibit local scour at piers at existing bridges. This practice is not recommended as an adequate substitute for foundations or piling located below expected scour depths for new or replacement bridges. It is recommended as a retrofit or interim measure where scour threatens the integrity of a pier. The practice of heaping stones around a pier is not recommended except as an interim measure because experience has shown that continual replacement is usually required. Success rates have been better with alluvial bed materials where the top of the riprap was placed at or below the elevation of the streambed.

Piles (sheet, H beams or concrete) have been successfully used as a retrofit measure to lower the effective foundation elevation of structures where footings or pile caps have been exposed by scour. The piling is placed around the pile footings and anchored to the pile cap or seal to retain or restore the bearing capacity of the foundation. This will, however, produce greater depth of scour.

Where sheet pile cofferdams are used during construction, the sheet piling should be removed or cut off below the level of expected contraction scour in order to avoid contributing to local scour. Cofferdams should not be much wider than the pier itself since the effect may be to greatly increase local scour depth. Leaving or removing cofferdams must be carefully evaluated because leaving a cofferdam that is higher than the contraction scour elevation may increase local scour depth. Recent work by Jones gives a method to evaluate the expected scour depths for cofferdams.<sup>(28)</sup>

#### **5.4.3 Temporary Countermeasures**

Monitoring or closing a bridge during high flows and inspection after the flood may be an effective temporary countermeasure. However, monitoring of bridges during high flow may not determine that they are about to collapse from scour. It also may not be practical to close the bridge during high flow because of traffic volume, no (or poor) alternate routes, the need for emergency vehicles to use the bridge, etc. Under these circumstances, temporary scour countermeasures such as riprap could be installed. A temporary countermeasure installed at a bridge along with monitoring during and inspection after high flows could provide for the security of the public without closing the bridge.

### **5.5 COUNTERMEASURES FOR CHANNEL BRAIDING AND ANABRANCHING**

Channel braiding occurs in streams with an overload of sediment, causing deposition and aggradation. As aggradation occurs, the slope of the channel increases, velocities increase, and multiple, interlaced channels develop. The overall channel system becomes wider and multiple channels are formed as bars of sediment are deposited in the main channel. Braiding can also occur where banks are easily eroded and there is a large range in discharge. The channel becomes wider at high flows, and low-flow forms multiple interlaced channels. In an anabranching stream, flow is divided by islands rather than bars, and the anabranches are more permanent than braided channels and generally convey more flow.

Meandering streams may change to a braided stream if slope is increased by channel straightening or the dominant discharge is increased. Lane's relation, figure 8, may be used to determine if there can be a shift from a meandering channel to a braided one.<sup>(7)</sup> If, after a change in discharge or slope the stream still plots in the meandering zone, then it will remain a meandering stream. However, if it moves closer to or into the braided zone, then the stream may become braided.

Braided channels change alignment rapidly, and are very wide and shallow even at flood flow. They present problems at bridge sites because of the high cost of bridging the complete channel system, unpredictable channel locations and flow directions, and difficulties with eroding channel banks and in maintaining bridge openings unobstructed by bars and islands.

Countermeasures used on braided and anabranching streams are usually intended to confine the multiple channels to one channel. This tends to increase sediment transport capacity in the principal channel and encourage deposition in secondary channels. These measures usually consist of dikes constructed from the limits of the multiple channels to the channel over which the bridge is constructed. Guide banks at bridge ends used in combination with revetment on highway fill slopes, riprap on highway fill slopes only, and spurs arranged in the stream channels to constrict flow to one channel have also been used successfully.

Since anabranches are permanent channels that may convey substantial flow, diversion and confinement of an anabranching stream is likely to be more difficult than for a braided stream. The designer may be faced with a choice of either building more than one bridge, building a long bridge, or diverting anabranches into a single channel.

## **5.6 COUNTERMEASURES FOR DEGRADATION AND AGGRADATION**

Bed elevation problems are common on alluvial streams. Degradation in streams can cause the loss of bridge piers in stream channels and can contribute to the loss of piers and abutments located on caving banks. Aggradation causes the loss of waterway opening in bridges and, where channels become wider because of aggrading streambeds, overbank piers and abutments can be undermined. At its worst, aggradation may cause streams to abandon their original channels and establish new flow paths which may sever highways from the existing bridge.

### **5.6.1 Countermeasures to Control Degradation**

Countermeasures used to control degradation include check dams and channel linings. Check-dams and structures which perform functions similar to check-dams include drop structures, cutoff walls, and drop flumes. A check-dam is a low dam or weir constructed across a channel to prevent degradation.

Channel linings of concrete and riprap have proved unsuccessful at stopping degradation. To protect the lining, a check-dam may have to be placed at the downstream end to key it to the channel bed. Such a scheme would provide no more protection than would a check dam alone, in which case the channel lining would be redundant.

Bank erosion is a common hydraulic hazard in degrading streams. As the channel bed degrades, bank slopes become steeper and bank caving failures occur. The USACOE found that longitudinal stone dikes, or rock toe-dikes, provided the most effective toe protection of all bank stabilization measures studied for very dynamic and/or actively degrading channels.<sup>(43)</sup>

The following is a condensed list of recommendations and guidelines for the application of countermeasures at bridge crossings experiencing degradation:

- Check-dams or drop structures are the most successful technique for halting degradation on small to medium streams.
- Channel lining alone may not be a successful countermeasure against degradation problems.
- Combinations of bulkheads and riprap revetment have been successfully used to protect abutments where steep streambanks threaten abutment fill slopes.
- Riprap on channel banks and spill slopes will fail if unanticipated channel degradation occurs.
- Successful pier protection involves providing deeper foundations at piers and pile bents.

- Jacketing piers with steel casings or sheet piles has also proved successful where expected degradation extends only to the top of the original foundation.
- The most economical solution to degradation problems at new crossing sites on small to medium size streams is to minimize the number of piers in the flow channel and provide adequate foundation depths. Adequate setback of abutments from slumping banks is also necessary.
- Rock-and-wire mattresses are recommended for use only on small (<30 m) channels experiencing lateral instability and little or no vertical instability.
- Longitudinal stone dikes placed at the toe of channel banks are effective countermeasures for bank caving in degrading streams. Precautions to prevent outflanking, such as tiebacks to the banks, may be necessary where installations are limited to the vicinity of the highway stream crossing.

### 5.6.2 Countermeasures to Control Aggradation

Currently, measures used in attempts to alleviate aggradation problems at highways include channelization, debris basins, bridge modification, and/or continued maintenance, or combinations of these. Channelization may include excavating and clearing channels, constructing small dams to form debris basins, constructing cutoffs to increase the local slope, constructing flow control structures to reduce and control the local channel width, and constructing relief channels to improve flow capacity at the crossing. Except for debris basins and relief channels, these measures are intended to increase the sediment transport capacity of the channel, thus reducing or eliminating problems with aggradation. Cutoffs must be designed with considerable study as they can cause erosion upstream and deposition downstream. These studies would involve the use of sediment transport relations given in HIRE or the use of sediment transport models such as BRI-STARS.<sup>(4,29)</sup> The most common bridge modifications are increasing the bridge length by adding spans and increasing the effective flow area beneath the structure by raising the bridge deck.

A program of continuing maintenance has been successfully used to control problems at bridges on aggrading streams. In such a program, a monitoring system is set up to survey the affected crossing at regular intervals. When some preestablished deposition depth is reached, the bridge opening is dredged or cleared of the deposited material. In some cases, this requires opening a clearing after every major flood. This solution requires surveillance and dedication to the continued maintenance of an adequate waterway under the bridge. Otherwise, it is only a temporary solution. A debris basin or a deeper channel upstream of the bridge may be easier to maintain. Continuing maintenance is not recommended if analysis shows that other countermeasures are practicable.

Over the short term, maintenance programs prove to be very cost effective when compared with the high cost of channelization, bridge alterations, or relocations. When costs over the entire life of the structure are considered, however, maintenance programs may cost more than some of the initially more expensive measures. Also, the reliability of maintenance programs is generally low because the programs are often abandoned for budgetary or priority reasons. However, a program of regular maintenance could prove to be the most cost efficient solution if analysis of the transport characteristics and sediment supply in a stream system reveals that the aggradation problem is only temporary (perhaps the excess sediment supply is coming from a construction site) or will have only minor effects over a relatively long period of time.

An alternative similar to a maintenance program which could be used on streams with persistent aggradation problems, such as those on alluvial fans, is the use of controlled sand and gravel mining from a debris basin constructed upstream of the bridge site. Use of this alternative would require careful analysis to ensure that the gravel mining did not upset the balance of sediment and water discharges downstream of the debris basin. Excessive mining could produce a degradation profile downstream, potentially impacting the bridge or other structures.

Following is a list of guidelines regarding aggradation countermeasures:

- Extensive channelization projects have generally proven unsuccessful in alleviating general aggradation problems, although some successful cases have been documented. A sufficient increase in the sediment carrying capacity of the channel is usually not achieved to significantly reduce or eliminate the problem. Channelization should be considered only if analysis shows that the desired results will be achieved.
- Alteration or replacement of a bridge is often required to accommodate maximum aggradation depths.
- Maintenance programs have proved unreliable, but they provide the most cost-effective solution where aggradation is from a temporary source or on small channels where the problem is limited in magnitude.
- At aggrading sites on wide, shallow streams, spurs or dikes with flexible revetment have been successful in several cases in confining the flow to narrower, deeper sections.
- A debris basin and controlled sand and gravel mining might be the best solution at alluvial fans and other crossings with severe problems.

## 5.7 CASE HISTORIES

Case histories of hydraulic problems at bridge sites are used in this section to provide information on the relative success of the various countermeasures used to stabilize streams. All case histories are taken from Brice and Blodgett, Brice et al., and Brown et al.<sup>(2,44,32)</sup> Site data are from Brice and Blodgett.<sup>(2)</sup> This compilation of case histories at 224 bridge sites is recommended reference material for those responsible for selecting countermeasures for stream instability. Additional case histories are given in HIRE.<sup>(4)</sup>

### 5.7.1 Flexible Revetment

Rock Riprap. Dumped rock riprap is the most widely used revetment in the United States. Its effectiveness has been well established where it is of adequate size, of suitable size gradation, and properly installed. Brice et al. documented the use of rock riprap at 110 sites (volume 1, table 2).<sup>(1)</sup> They rated the performance at 58 sites and found satisfactory performance at 34 sites, partially satisfactory performance at 12 sites, and failure to perform satisfactorily at 12 sites. Keeley concluded that riprap used in Oklahoma performed without significant failure and provides basic and efficient bank control on the meandering streams in Oklahoma.<sup>(45)</sup>

A review of the causes of failure at the sites studied by Brice et al. is instructive (volume 1, table 3).<sup>(1)</sup> They found the absence of a filter blanket clearly the cause of the failure at a site subject to tides and wave action. The riprap was placed on a fill of sand and fine gravel which eroded through the interstices of the riprap.

Internal slope failure was the cause of failure of riprap at the abutment of bridges at two sites. At one site, failure was attributed to saturation of a high fill by impounded water in a reservoir. Wave action also probably contributed to the failure. The other site is difficult to include as a riprap failure because the rock was not placed as riprap revetment. Thirty-three freight car loads of rock were dumped as an emergency measure to stop erosion at a bridge abutment during high-flow releases from a reservoir. The rock was displaced, and the high streambanks and highway fill are still susceptible to slumps. At both sites, riprap failed to prevent slumps in high fills.

Inadequate rock size and size gradation was given as the cause of failure at eight sites. All of these sites are complex, and it is difficult to assign failure to one cause, but rock size was definitely a factor.

Channel degradation accounted for failure at three sites in Mississippi. Channel degradation at these sites is due to channel straightening and clearing by the SCS and USACOE. Riprap installations on the streambanks, at bridge abutments and in the streambed have failed to stop lateral erosion. At one site, riprap placed on the banks and bed of the stream resulted in severe bed scour and bank erosion downstream of the riprap.

Failure of riprap at one site was attributed to the steep slope on which the riprap was placed. At this site, rock riprap failed to stop slumping of the steep banks downstream of a check dam in a degrading stream.

Successful rock riprap installations at bends were found at five sites. Bank erosion was controlled at these sites by rock riprap alone. Installations rated as failing were damaged at the toe and upstream end, indicating inadequate design and/or construction, and damage to an installation of rounded boulders, indicating inadequate attention to riprap specifications. Other successful rock riprap study sites were sites where bank revetment was used in conjunction with other countermeasures, such as spurs or retards. The success of these installations was attributed more to the spurs or retards, but the contribution of the bank revetment was not discounted.

Broken Concrete. Broken concrete is commonly used in emergencies and where rock is unavailable or very expensive. No specifications were found for its use. Performance was found to be more or less unsatisfactory at three sites.

Rock-and-Wire Mattress and Gabions. The distinction made between rock-and-wire mattress and gabions is in the dimensions of the devices. Rock-and-wire mattress is usually 0.3 m or less in thickness and a gabion is thicker and nearly equidimensional. The economic use of rock-and-wire mattress is favored by an arid climate, availability of stones of cobble size, and unavailability of rock for dumped rock riprap. Corrosion of wire mesh is slow in arid climates, and ephemeral streams do not subject the wire to continuous abrasion. Where large rock is not available, the use of rock-and-wire mattress may be advantageous in spite of eventual corrosion or abrasion of the wire.

Rock-and-wire mattress performance was found to be generally satisfactory although local failure of the wire mesh and spilling out of the rock was not uncommon. Mattresses are held in place against the bank by railroad rails at sites in New Mexico and Arizona where good performance was documented. This is known locally as "railbank protection." The steel rail supported rock-and-wire mattress stays in place better than dumped rock riprap on the unstable vertical banks found on the ephemeral streams of this area. Mattress held in place by stakes has been found to be effective in Wyoming.

The use of rock-and-wire mattress has diminished in California because of the questionable service of wire mesh, the high cost of labor for installation, and the efficiency of modern methods of excavating for dumped riprap toe protection. The Los Angeles Flood Control District, however, has had installations in-place for 15 years or more with no evidence of wire corrosion. On the other hand, Montana and Maryland reported abrasion damage of wire. These experiences illustrate that economic use of countermeasures is dependent on the availability of materials, costs, and the stream environment in which the measure is placed.

Several sites were identified where gabions were installed, but the countermeasures had been tested by floods at only one site where gabions placed on the downstream slope of a roadway overflow section performed satisfactorily.

Other Flexible Revetment. Favorable performance of precast-concrete blocks at bridges was reported in Louisiana. Vegetation is reported to grow between blocks and contribute to appearance and stability.

Vegetation apparently is seldom used alone at bridges. Iowa relies on sod protection of spur dikes, but Arkansas reported failure of sod as bank protection.

### 5.7.2 Rigid Revetments

Failure of rigid revetment tends to be progressive; therefore, special precautions to prevent undermining at the toe and termini and failure from unstable soils or hydrostatic pressure are warranted.

Concrete Pavement. Well-designed concrete paving is satisfactory as fill slope revetment, as revetment on streams having low gradients, and in other circumstances where it is well protected against undermining at the toe and ends. The case histories include at least one location where riprap launching aprons were successful in preventing undermining at the toe from damaging the concrete pavement revetment.<sup>(1,2)</sup> Weep holes for relief of hydrostatic pressure are required for many situations.

Documented causes of failure in the case histories are undermining at the toe (six sites), erosion at termini (five sites), eddy action at downstream end (two sites), channel degradation (two sites), high water velocities (two sites), overtopping (two sites), and hydrostatic pressure (one site). Good success is reported with concrete slope paving in Florida, Illinois, and Texas.

Sacked Concrete. No highway agency reported a general use of sacked concrete as revetment. California was reported to regard this as an expensive revetment almost never used unless satisfactory riprap was not available. Sacked concrete revetment failures were reported from undermining of the toe (two sites), erosion at termini (one site), channel degradation (two sites), and wave action (one site).

Concrete-Grouted Riprap. Concrete-grouted riprap permits the use of smaller rock, a lesser thickness, and more latitude in gradation of rock than in dumped rock riprap. No failures of grouted riprap were documented in the case histories, but it is subject to the same types of failures as other rigid revetments.

Concrete-Filled Fabric Mat. Concrete-filled fabric mat is a patented product (Fabriform) consisting of porous, pre-assembled nylon fabric forms which are placed on the surface to be protected and then filled with high-strength mortar by injection. Variations of Fabriform and Fabricast consist of nylon bags similarly filled. Successful installations were reported by the manufacturer of Fabriform in Iowa, and North Dakota reported successful installations.

Soil Cement. In areas where any type of riprap is scarce, use of in-place soil combined with cement provides a practical alternative. The resulting mixture, soil cement, has been successfully used as bank protection in many areas of the Southwest. Unlike other types of bank revetment, where milder side slopes are desirable, soil cement in a stairstep construction can be used on steeper slopes (i.e., typically one to one), which reduces channel excavation costs. For many applications, soil cement is generally more aesthetically pleasing than other types of revetment.

### 5.7.3 Bulkheads

A bulkhead is a steep or vertical wall used to support a slope and/or protect it from erosion. Bulkheads usually project above ground, although the distinction between bulkheads and cutoff walls is not always sharp. Most bulkhead applications were found at abutments. They were found to be most useful at the following locations: (1) on braided streams with erodible sandy banks, (2) where banks or abutment fill slopes have failed by slumping, and (3) where stream alignment with the bridge opening was poor, to provide a transition between streambanks and the bridge opening. It was not clear what caused failures at five sites summarized in Brice and Blodgett, but in each case, the probable cause was undermining.<sup>(1,2)</sup>

#### 5.7.4 Spurs

Spurs are permeable or impermeable structures which project from the bank into the channel. Spurs may be used to alter flow direction, induce deposition, or reduce flow velocity. A combination of these purposes is generally served. Where spurs project from embankments to decrease flow along the embankment, they are called embankment spurs. These may project into the floodplain rather than the channel, and thus function as spurs only during overbank flow. According to a summary prepared by Richardson and Simons, spurs may protect a streambank at less cost than riprap revetment, and by deflecting current away from the bank and causing deposition, they may more effectively protect banks from erosion than revetment.<sup>(46)</sup> Uses other than bank protection include the constriction of long reaches of wide, braided streams to establish a stable channel, constriction of short reaches to establish a desired flow path and to increase sediment transport capacity, and control of flow at a bend. Where used to constrict a braided stream to a narrow flow channel, the structure may be more correctly referred to as a dike or a retard in some locations.

Several factors enter into the performance of spurs, such as permeability, orientation, spacing, height, shape, length, construction materials, and the stream environment in which the spur is placed.

Impermeable Spurs. The case histories show good success with well-designed impermeable spurs at bends and at crossings of braided stream channels (eight sites). At one site, hardpoints barely projecting into the stream and spaced at about 30 to 45 m failed to stop bank erosion at a severe bend. At another site, spurs projecting 12 m into the channel, spaced at 30 m, and constructed of rock with a maximum diameter of 0.5 m experienced erosion between spurs and erosion of the spurs. At a third site, spurs constructed of timber piling filled with rock were destroyed. Failure was attributed to the inability to get enough penetration in the sand-bed channel with timber piles and the unstable wide channel in which the thalweg wanders unpredictably. Spurs (or other countermeasures) are not likely to be effective over the long term in such an unstable channel unless well-designed, well-built, and deployed over a substantial reach of stream. Although no failures from ice damage were cited for impermeable spurs, North Dakota uses steel sheet pile enclosed earth fill spurs because of the potential for ice damage. At one site, such a spur sustained only minor damage from 0.75 m of ice.

Permeable Spurs. A wide variety of permeable spur designs were also shown to successfully control bank erosion by the case histories. Failures were experienced at a site which is highly unstable with rapid lateral migration, abundant debris, and extreme scour depths. Bank revetments of riprap and car bodies and debris deflectors at bridge piers, as well as bridges, have also failed at this site. At another site, steel H-pile spurs with wire mesh have partially failed on a degrading stream.

#### 5.7.5 Retardance Structures

A retardance structure (retard) is a permeable or impermeable linear structure in a channel, parallel with and usually at the toe of the bank. The purposes of retardance structures are to reduce flow velocity, induce deposition, or to maintain an existing flow alignment. They may be constructed of earth, rock, timber pile, sheet pile, or steel pile. Steel jacks or tetrahedrons are also used.

Most retardance structures are permeable and most have good performance records. They have proved to be useful in the following situations: (1) for alignment problems very near a bridge or roadway embankment, particularly those involving rather sharp channel bends and direct impingement of flow against a bank (ten sites), and (2) for other bank erosion problems that occur very near a bridge, particularly on streams that have a wandering thalweg or very unstable banks (seven sites).

The case histories include a site where a rock retardance structure similar to a rock toe dike was successful in protecting a bank on a highly unstable channel where spurs had failed.<sup>(1,2)</sup> There were, however, deficiencies in the design and construction of the spur installation. At another site, a rock retardance structure similar to a rock toe-dike has reversed bank erosion at a bend in a degrading stream. The USACOE reported that longitudinal rock toe dikes were the most effective bank stabilization measure studied for channels having very dynamic and/or actively degrading beds.<sup>(43)</sup>

### 5.7.6 Dikes

Dikes are impermeable linear structures for the control or containment of overbank flow. Most are in floodplains, but they may be within channels, as in braided streams or on alluvial fans. Dikes at study sites were used to prevent flood water from bypassing a bridge at four sites, or to confine channel width and maintain channel alignment at two sites. Performance of dikes at study sites was judged generally satisfactory.

### 5.7.7 Guide Banks

The major use of guide banks (formerly referred to as spur dikes) in the United States is to prevent erosion by eddy action at bridge abutments or piers where concentrated flood flow travelling along the upstream side of an approach embankment enters the main flow at the bridge. By establishing smooth parallel streamlines in the approaching flow, guide banks improve flow conditions in the bridge waterway. Scour, if it occurs, is near the upstream end of the dike away from the bridge. A guide bank differs from dikes described above in that a dike is intended to contain overbank flow while a guide bank only seeks to align overbank flow with flow through the bridge opening. An extension of the usual concept of the purpose for guide banks, but not in conflict with that concept, is the use of guide banks and highway fill to constrict braided channels to one channel. At three sites studied, guide banks only or guide banks plus revetment on the highway fill were used to constrict wide braided channels rather severely, and the installations have performed well.<sup>(1,2)</sup>

Guide bank performance was found to be generally satisfactory at all study sites. Performance is theoretically affected by construction materials, shape, orientation, and length.

Most guide banks are constructed of earth with revetment to inhibit erosion of the dike. At two sites, guide banks of concrete rubble masonry performed well. Riprap revetment is most common, but concrete revetment with rock riprap toe protection, rock-and-wire mattress, gabions, and grass sod have also performed satisfactorily. Since partial failure of a guide bank during a flood usually will not endanger the bridge, wider consideration should be given to the use of vegetative cover for protection. Partial failure of any countermeasure is usually of little significance so long as the purpose of protecting the highway stream crossing is accomplished.

Guide banks of elliptical shape, straight, and straight with curved ends performed satisfactorily at study sites, although there is evidence at one site that flow does not follow the nose of the straight guide bank. Clear evidence of the effect of guide bank orientation was not found at study sites although the conclusion by Colson and Wilson that guide banks should be oriented with valley flow for skewed crossings of wooded floodplains was cited.<sup>(47)</sup> There was evidence at one site that a guide bank may be severely tested where a large flow is diverted along the roadway embankment, as at a skewed crossing or on a wide floodplain which is severely constricted by the bridge. At these locations, embankment spurs may be advisable to protect the embankment from erosion and to reduce the potential for failure of the guide bank.

Guide banks at study sites tended to be longer than recommended by Bradley at most sites, except at five sites where they ranged from 5 to 23 m.<sup>(22)</sup> All guide banks appeared to perform satisfactorily. Not enough short guide banks were included in the study to reach conclusions regarding length.<sup>(1,2)</sup>

### 5.7.8 Check Dams

A check dam is a low weir or dam across a channel for the control of water stage or velocity, or to stop degradation from progressing upstream. They may be constructed of concrete, rock, sheet pile, rock-and-wire mattress, gabions, or concrete-filled fabric mat. They are usually used to stop degradation in the channel in order to protect the substructure foundation of bridges. At one site, however, a check dam was apparently used to inhibit contraction scour in a bridge waterway. The problem with vertical scour was resolved, but lateral scour became a problem and riprap revetment on the streambanks failed.<sup>(1,2)</sup>

Scour downstream of check dams was found to be a problem at two sites, especially lateral erosion of the channel banks. Riprap placed on the streambanks at the scour holes also failed, at least in part because of

the steep slopes on which the riprap was placed. At the time of the study, lateral erosion threatened damage to bridge abutments and highway fills. At another site, a check dam placed at the mouth of a tributary stream failed to stop degradation in the tributary and the delivery of damaging volumes of sediment to the main stream just upstream of a bridge.

No structural failure of check dams was documented in this study.<sup>(1,2)</sup> Failures are known to have occurred, however, and the absence of documented failures in this study should not be given undue weight. Failure can occur by bank erosion around the ends of the structure resulting in outflanking; by seepage or piping under or around the structure resulting in undermining and structural or functional failure; by overturning, especially after degradation of the channel downstream of the structure; by bending of sheet pile; by erosion and abrasion of wire fabric in gabions or rock-and-wire mattress; or by any number of structural causes for failure.

#### **5.7.9 Jack or Tetrahedron Fields**

Jacks and tetrahedrons function as flow control measures by reducing the water velocity along a bank, which in turn results in an accumulation of sediment and the establishment of vegetation. Steel jacks, or Kellner jacks which consist of six mutually perpendicular arms rigidly fixed at the midpoints and strung with wire are the most commonly used. Tetrahedrons apparently are not currently used by highway agencies. Jacks are usually deployed in fields consisting of rows of jacks tied together with cables.

Four sites where steel jack fields were used are included in the case histories.<sup>(1,2)</sup> At two sites, the jack fields performed satisfactorily. Jacks were buried in the streambed and rendered ineffective at one site, and jacks were damaged by ice at one site, but apparently continued to perform satisfactorily. From Keeley's observations of the performance of jack fields used in Oklahoma and findings of the study of countermeasures by Brice et al., the following conclusions were reached regarding performance:<sup>(45,1)</sup>

- The probability of satisfactory performance of jack fields is greatly enhanced if the stream transports small floating debris and sediment load in sufficient quantity to form accumulations during the first few years after construction.
- Jack fields may serve to protect an existing bank line, or to alter the course of a stream if the stream course is realigned and the former channel backfilled before the jack field is installed.
- On wide shallow channels, which are commonly braided, jack fields may serve to shift the bank line channelward if jacks of large dimensions are used.

#### **5.7.10 Special Devices for Protection of Piers**

Countermeasures at piers have been used to combat abrasion of piers, to deflect debris, to reduce local scour, and to restore structural integrity threatened by scour. Retrofit countermeasures installed after problems develop are common. The usual countermeasure against abrasion consists of steel armor on the upstream face of a pier in the area affected by bed load. At one site, a pointed, sloping nose on a massive pier, called a special "cutwater" design, and a concrete fender debris deflector has functioned to prevent debris accumulation at the pier. At another site, a steel rail debris deflector worked until channel degradation caused all countermeasures to fail.

Countermeasures for local scour at piers are discussed above, except for a measure installed on a bridge over an estuary in Florida where about 11.3 m of scour had occurred. This measure consists of flat plates installed around piers to deflect plunging currents. The plates are 2.4 m in diameter and are installed around 510 mm diameter piles. It was recommended that the plates be installed at or slightly below the elevation of the streambed, but strong tidal currents prevented underwater installation at uniform locations. Two years after installation, some deposition had occurred but performance could not be judged.

Countermeasures used to restore structural integrity of bridge foundations included in the case histories include underpinning, sheet pile driven around the pier, and grout curtain around pier foundation.

#### **5.7.11 Investment in Countermeasures**

While it is often possible to predict that bank erosion will occur at or near a given location in an alluvial stream, one can frequently be in error about the location or magnitude of potential erosion. At some locations, unexpected lateral erosion occurs because of a large flood, a shifting thalweg, or from other actions of the stream or activities of man. Therefore, where the investment in a highway crossing is not in imminent danger of being lost, it is often prudent to delay the installation of countermeasures until the magnitude and location of the problem becomes obvious. In many, if not most, of the case histories collected by Brice et al., highway agencies invested in countermeasures after a problem developed rather than in anticipation of a problem.<sup>(1,2,44)</sup>



## CHAPTER 6

### COUNTERMEASURE DESIGN

#### 6.1 INTRODUCTION

Chapters 2 through 4 of this manual discuss factors influencing stream stability and response. For stream stability problems which adversely impact highway crossings, specific countermeasure recommendations were made in chapter 5. In this chapter, the design of several specific countermeasures is discussed and references for further design guidance are provided.

This chapter discusses in detail the design of three basic countermeasures: (1) Spurs; (2) Guide Banks (often referred to as Spur Dikes); and (3) Check Dams. Respectively, these three countermeasures are used to: (1) protect banks and redirect flow in the vicinity of the highway crossing; (2) move scour away from an abutment and direct flows through the bridge opening; and (3) control degradation (either long-term or contraction scour) and maintain the bed elevation at the bridge opening. With these countermeasures, most adverse impacts on highway crossings can be controlled.

In some cases other countermeasures may be required. Therefore, a separate section for the conceptual design of other countermeasures is also presented. Details of the design of these other countermeasures are not given, but a schematic and references are provided, where available.

#### 6.2 GENERAL DESIGN GUIDELINES

The objective of highway agencies at stream crossings is to protect highway users and the investment in the highway facility, and to avoid causing damage to other properties, to the extent practicable. Countermeasures should be designed and installed to stabilize only a limited reach of stream and to ensure the structural integrity of highway components in an unstable stream environment. Countermeasures are often damaged or destroyed by the stream, and streambanks and beds often erode at locations where no countermeasure was installed, but as long as the primary objectives are achieved in the short-term as a result of countermeasure installation, the countermeasure installation can be deemed a success. Therefore, the highway agency's interest in stream stability often entails long-term protection of costly structures by committing to maintenance, reconstruction, and construction of additional countermeasures as the response of streams and rivers to natural and man-induced changes are identified.

The design of any countermeasure for the protection of highway crossings requires the designer to be cognizant of the factors which affect stream stability and the morphology of the stream. In most cases, the installation of any countermeasure will cause the bed and banks to respond to the change in hydraulic conditions imposed by the countermeasure. Thus, the analyses procedures outlined and illustrated in chapter 4 are a necessary prerequisite to the detailed design of specific countermeasures provided in this chapter. The goal in any countermeasure design is to achieve a response which is beneficial to the protection of the highway crossing and to minimize adverse effects either upstream or downstream of the highway crossing.

In many cases, a combination of two or more countermeasures could be required due to site-specific problems or as a result of changing conditions after the initial installation. The great number of possible countermeasure combinations makes it impractical to suggest design procedures for combined countermeasures. However, combined countermeasures should complement each other. That is to say that the design of one countermeasure must not adversely impact on another or the overall protection of the highway crossing. The principles of river mechanics, as discussed in HIRE and in chapters 2 through 4 of this text, coupled with sound engineering judgment should be used to design countermeasure strategies involving two or more countermeasures.<sup>(4)</sup>

## 6.3 SPURS

A spur is a pervious or impervious structure projecting from the streambank into the channel. Spurs are used to deflect flowing water away from, or to reduce flow velocities in critical zones near the streambank, 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, which in turn, encourages sediment deposition due to these reduced velocities. Increased protection of banks can be achieved over time, as more sediment is deposited behind the spurs. Because of this, spurs may protect a streambank more effectively and at less cost than revetments. Furthermore, by moving the location of any scour away from the bank, partial failure of the spur can often be repaired before damage is done to structures along and across the stream.

Spurs are generally used to halt meander migration at a bend. They are also used to channelize wide, poorly defined streams into well-defined channels. The use of spurs to establish and maintain a well-defined channel location, cross section, and alignment in braided streams can decrease the required bridge lengths, thus decreasing the cost of bridge construction and maintenance.

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

Table 7 can be used as an aid in the selection of an appropriate spur type for a given situation.<sup>(6)</sup> The primary factors influencing the selection of a specific spur type are listed across the top, and primary spur types are evaluated in terms of those selection criteria. A scale from 1 to 5 is used to indicate the applicability of a specific spur for a given condition. A value of 1 indicates a disadvantage in using that spur type for given condition, and a value of 5 indicates a definite advantage. The table can be used by summing values horizontally for given site conditions to select the best spur type for the specific site. It should be recognized however, that adherence to the results of such a procedure assigns equal weight to each of the factors listed across the top of the table and places undue reliance on the accuracy and relative merit of values given in the rating table. It is possible that assigned values of 1 should have been negative and assigned values of 5 should not be assigned quantitative significance. It is recommended that values given in the table be used only for a qualitative evaluation of expected performance. Spur type selection should be based on the results of this evaluation as well as estimated costs, availability of materials, construction and maintenance requirements, and experience with the stream in which the spur installation is to be placed.

### 6.3.1 Design Considerations

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 length, orientation, permeability, height, profile, and spacing.

Longitudinal Extent of Spur Field. The longitudinal extent of channel bank requiring protection is discussed in Brown.<sup>(41,42)</sup> Figure 28 was developed from USACOE studies of the extent of protection required at meander bends.<sup>(43)</sup> The minimum extent of bank protection determined from figure 28 should be adjusted according to field inspections to determine the limits of active scour, channel surveys at low flow, and aerial photography and field investigations at high flow. Investigators of field installations of bank protection have found that protection commonly extends farther upstream than necessary and not far enough downstream. However, such protection may have been necessary at the time of installation. The lack of a sufficient length of protection downstream is generally more serious, and the downstream movement of meander bends should be considered in establishing the downstream extent of protection.

Table 7. Spur type performance (Brown).<sup>(6)</sup>

Spur Type	Function			Erosion Mechanism				Sediment Environment			Flow Environment						Bend Radius			Ice/Debris Environment		
	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	Velocity			Stage			Large	Medium	Small	Minimal	Light Debris	Large Debris/Ice
											Low	Medium	High	Low	Medium	High						
<b>Retarder</b>																						
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
<b>Retarder/Deflector</b>																						
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
<b>Deflector</b>																						
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.																						

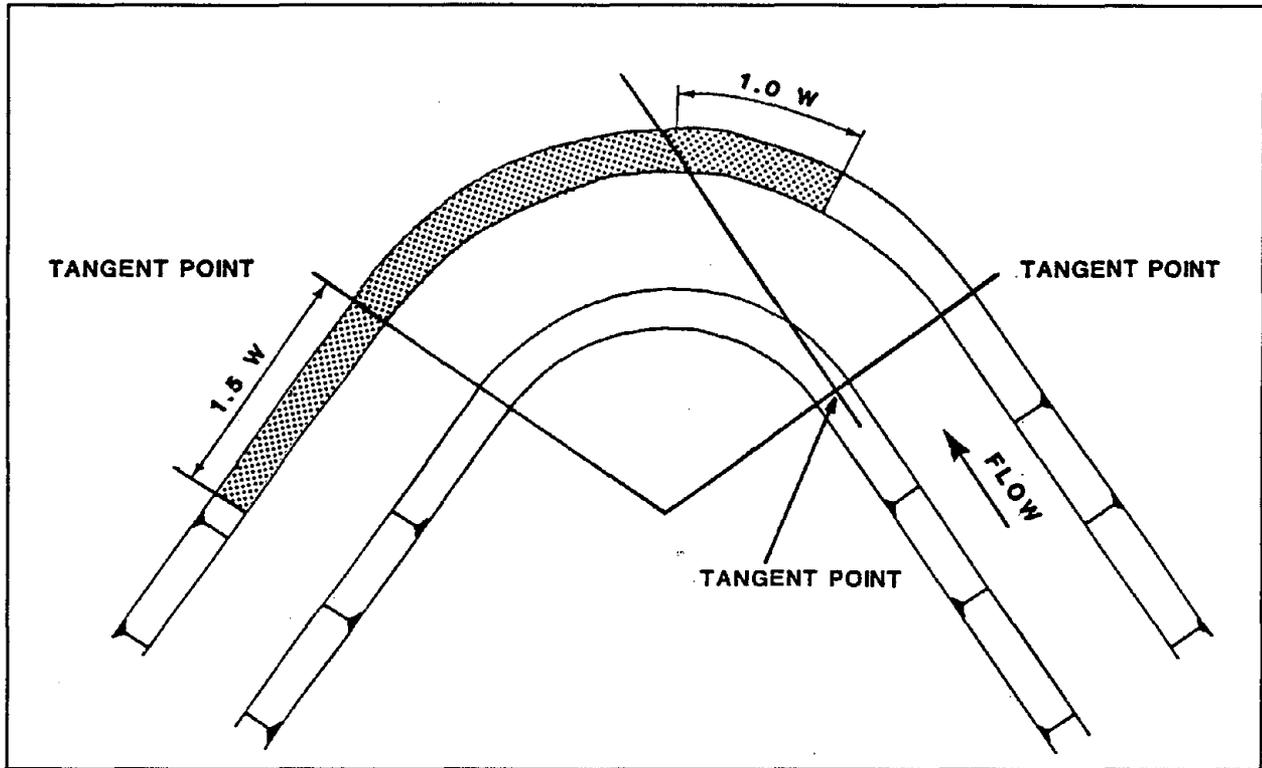


Figure 28. Extent of protection required at a channel bend (after USACOE).<sup>(43)</sup>

**Spur Length.** Spur length is taken here as the projected length of spur normal to the main flow direction or from the bank. Where the bank is irregular, spur lengths must be adjusted to provide for an even curvature of the thalweg. The length of both permeable and impermeable spurs relative to channel width affects local scour depth at the spur tip and the length of bank protected. Laboratory tests indicate that diminishing returns are realized from spur lengths greater than 20 percent of channel width. The length of bank protected measured in terms of projected spur length is essentially constant up to spur lengths of 20 percent of channel width for permeable and impermeable spurs. Field installations of spurs have been successful with lengths from 3 to 30 percent of channel width. Impermeable spurs are usually installed with lengths of less than 15 percent while permeable spurs have been successful with lengths up to 25 percent of channel width. However, only the most permeable spurs were effective at greater lengths.

The above discussion assumes that stabilization of the bend is the only objective when spur lengths are selected. It also assumes that the opposite bank will not erode. Where flow constriction or changing the flow path is also an objective, spur lengths will depend on the degree of constriction required or the length of spur required to achieve the desired change in flow path. At some locations, channel excavation on the inside of the bend may be required where spurs would constrict the flow excessively. However, it may be acceptable to allow the stream to do its own excavation if it is located in uniformly graded sand.

**Spur Orientation.** Spur orientation refers to spur orientation with respect to the direction of the main flow current in a channel. Figure 29 defines the spur angle such that an acute spur angle means that the spur is angled in an upstream direction and an angle greater than  $90^\circ$  indicates that the spur is oriented in a downstream direction.

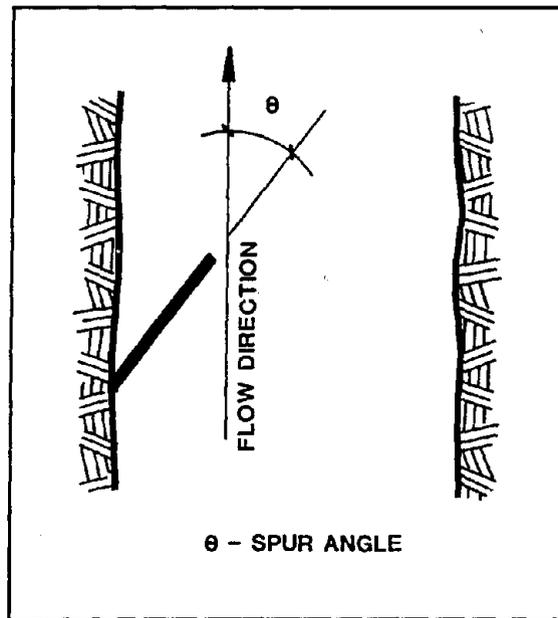


Figure 29. Definition sketch for spur angle (after Karaki).<sup>(49)</sup>

Permeable retarder spurs are usually designed to provide flow retardance near the streambank, and they perform this function equally as well without respect to the spur angle. Since spurs oriented normal to the bank and projecting a given length into the channel are shorter than those at any other orientation, all retarder spurs should be constructed at  $90^\circ$  with the bank for reasons of economy.

No consensus exists regarding the orientation of permeable retarder/deflector spurs and impermeable deflector spurs. There is some agreement that spurs oriented in an upstream direction do not protect as great a length of channel bank downstream of the spur tip, result in greater scour depth at the tip, and have a greater tendency to accumulate debris and ice. There is also some agreement that the first spur in an array should be at a spur angle of approximately  $150^\circ$  in order to provide more gradual flow transition through the bend.<sup>(48)</sup>

Spur orientation affects spur spacing, the degree of flow control achieved by the spur, and scour depth at the tip of the spur. Scour depth at the tip of impermeable spurs and retarder/deflector spurs with permeability of 35 percent or less oriented normal to the channel bank can be estimated by use of figure 30. This graph, which extends to a limiting value of  $a/y_1 < 25$  is based on laboratory studies and represents the equilibrium depth of scour for spurs oriented normal to the wall of the flume. Maximum scour depth can be as much as 30 percent greater than equilibrium scour depth. The curve representing values of  $a/y_1 > 25$  was taken from data collected at rock spurs in the Mississippi River and is believed to represent the limit in scale for scour depths. For the equations on this figure,  $y_s$  is the equilibrium scour depth measured from the mean streambed elevation,  $y_1$  is the flow depth upstream,  $Fr_1$  is the upstream Froude Number, and,  $a$  is the spur length measured normal to the wall of the flume. It should be noted that available information on the depth of scour at spurs is based on sand-bed streams. In gravel bed streams, armoring of the scour hole by selective transport of material forming the streambed will reduce the depth of scour.

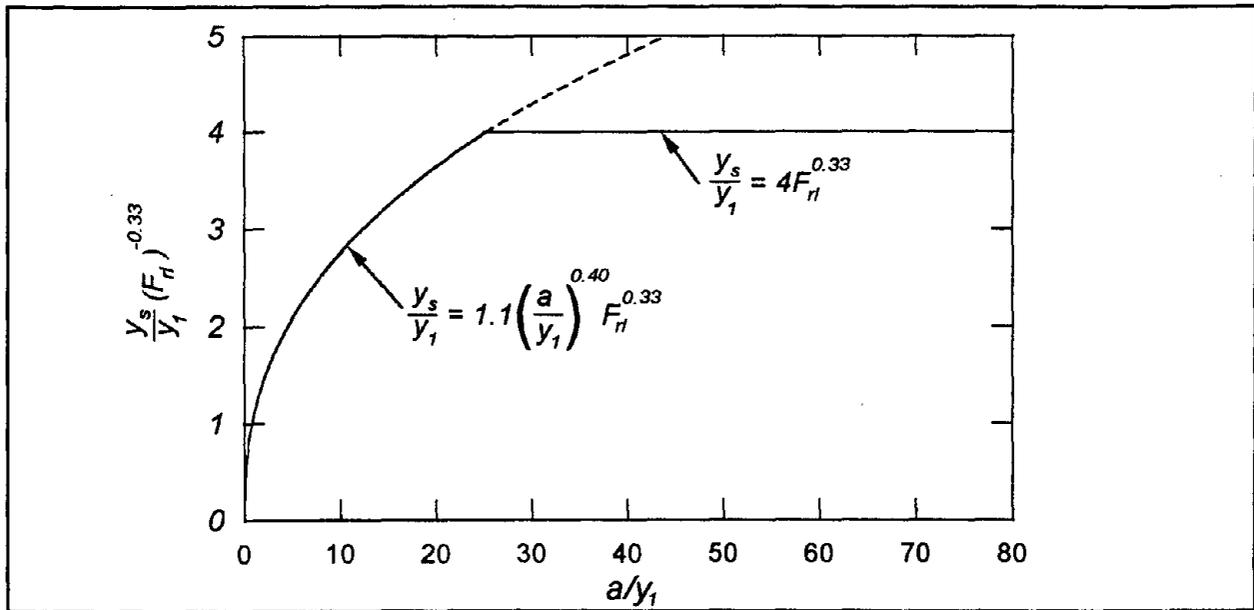


Figure 30. Recommended prediction curves for scour at the end of spurs with permeability up to about 35 percent (after HIRE).<sup>(4)</sup>

Spur orientation at approximately 90° has the effect of forcing the main flow current (thalweg) farther from the concave bank than spurs oriented in an upstream or downstream direction. Therefore, more positive flow control is achieved with spurs oriented approximately normal to the channel bank. Spurs oriented in an upstream direction cause greater scour than if oriented normal to the bank, and spurs oriented in a downstream direction cause less scour.

It is recommended that the spur furthest upstream 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 spur. Subsequent spurs downstream should all be set normal to the bank line to minimize construction costs.

Figure 31 can be used to adjust scour depth for orientation. It should be noted that permeability also affects scour depth. A method to adjust scour depth for permeability is presented in the following section.

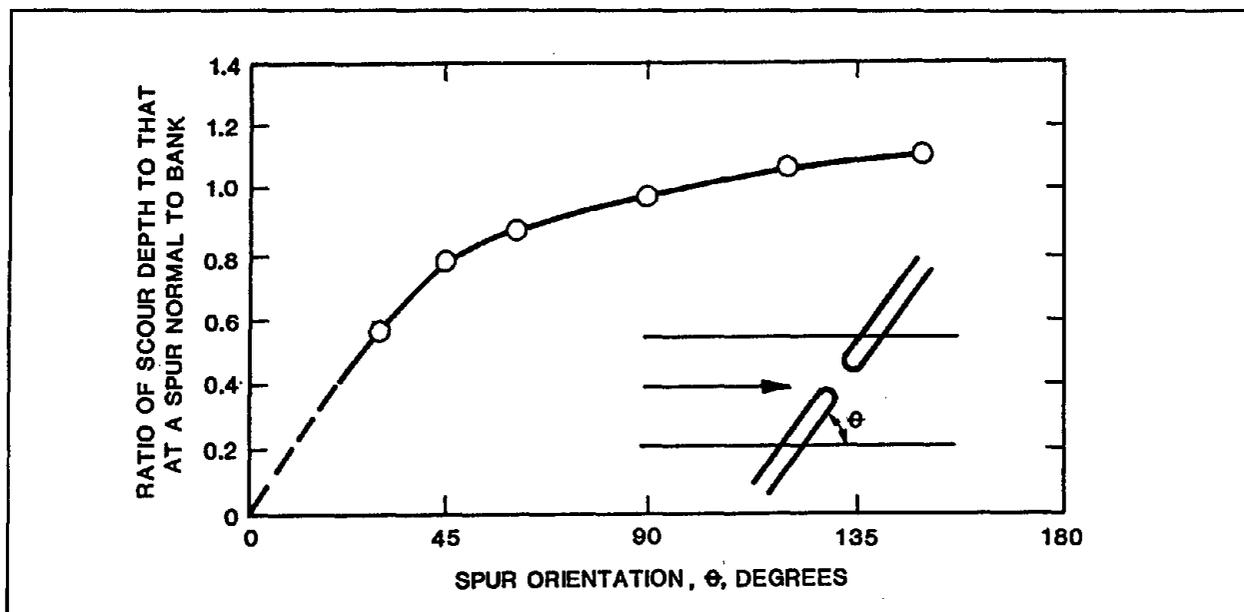


Figure 31. Scour adjustment for spur orientation (modified from HIRE).<sup>(4)</sup>

The lateral extent of scour is nearly always determinable from the depth of scour and the natural angle of repose of the bed material (see HEC-18).<sup>(15)</sup>

The expansion angle downstream of a spur, i.e., the angle of flow expansion downstream of the contraction at the spur is about  $17^\circ$  for impermeable spurs for all spur angles. The implication is that spur orientation affects the length of bank protected only because of the projected length of the spur along the channel bank.

**Spur Permeability.** The permeability of the spur depends on stream characteristics, the degree of flow retardance and velocity reduction required, and the severity of the channel bend. Impermeable spurs can be used on sharp bends to divert flow away from the outer bank. Where bends are mild and only small reductions in velocity are necessary, highly permeable retarder spurs can be used successfully. However, highly permeable spurs can also provide required bank protection under more severe conditions where vegetation and debris will reduce the permeability of the spur without destroying the spur. This is acceptable provided the bed load transport is high.

Scour along the streambank and at the spur tip are also influenced by the permeability of the spur. Impermeable spurs, in particular, can create erosion of the streambank at the spur root. This can occur if the crest of impermeable spurs are lower than the height of the bank. Under submerged conditions, flow passes over the crest of the spur generally perpendicular to the spur as illustrated in figure 32. Laboratory studies of spurs with permeability greater than about 70 percent were observed to cause very little bank erosion, while spurs with permeability of 35 percent or less caused bank erosion similar to the effect of impermeable spurs.<sup>(48)</sup>

Figure 33 illustrates the effect of spur permeability on relative scour depth at various spur orientations with the channel bank. Spur angles are measured from the bank downstream of the spur to the centerline of the spur. This graph was derived from laboratory studies which relate spur permeability to scour depth relative to depths for an impermeable spur set perpendicular to the bank.

Tests were conducted with projected spur lengths equal to 20 percent of the channel width. If the permeability of spurs is less than 35 percent, figures 30 and 31, from the previous section should be used to evaluate the scour depth. If the permeability of the spurs being designed is greater than 35 percent, figure 33 should be used to adjust scour depths obtained from figure 30 presented in the previous section.

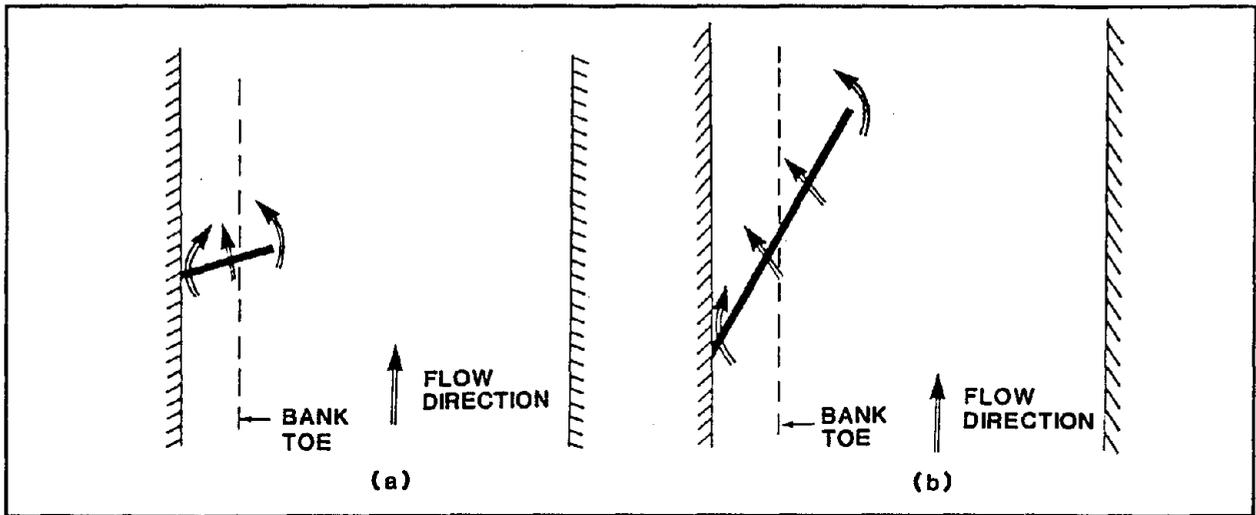


Figure 32. Flow components in the vicinity of spurs when the crest is submerged (after Brown).<sup>(48)</sup>

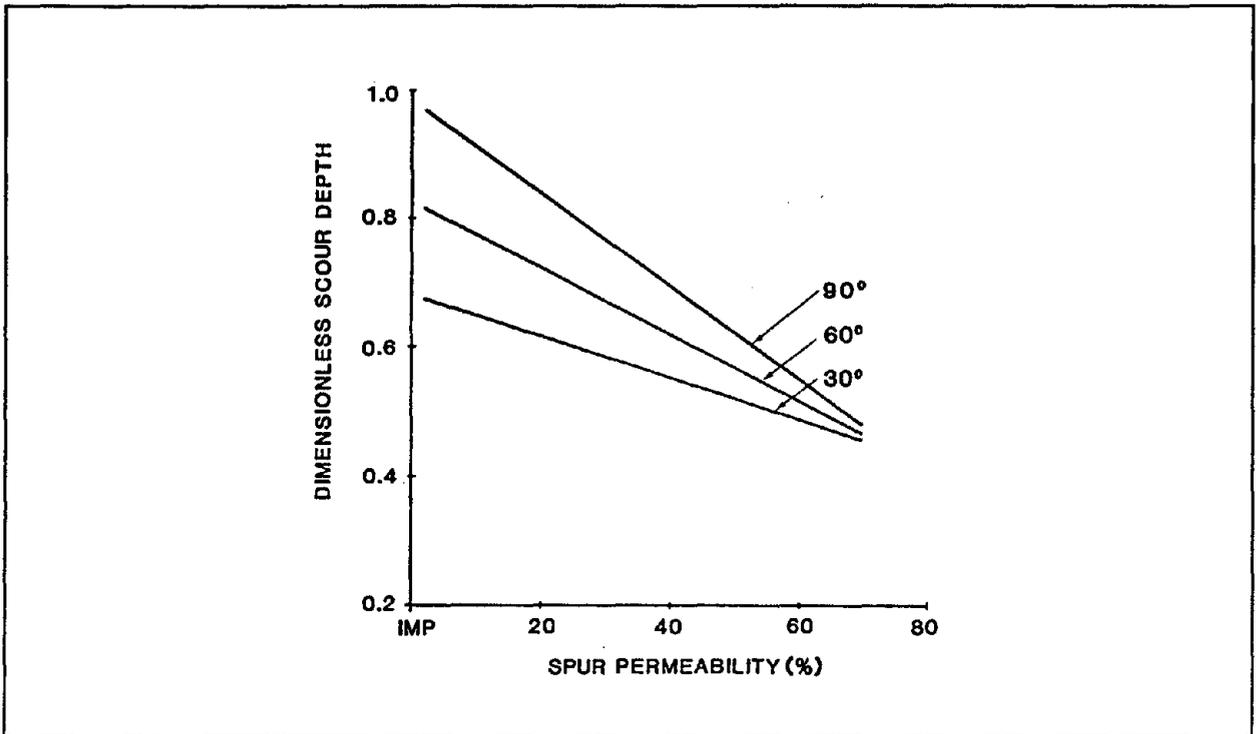


Figure 33. Plot of spur permeability and orientation vs. relative scour depth at the spur tip (after Brown).<sup>(48)</sup>

Permeability up to about 35 percent does not affect the length of channel bank protected by the spur. Above a permeability of 35 percent, the length of bank protected decreases with increasing permeability. Figure 34 shows the results of laboratory tests of the effects of permeability and orientation on the expansion angle of flow downstream of spurs. For this figure, spur lengths were 20 percent of the channel width projected normal to the bank.<sup>(48)</sup>

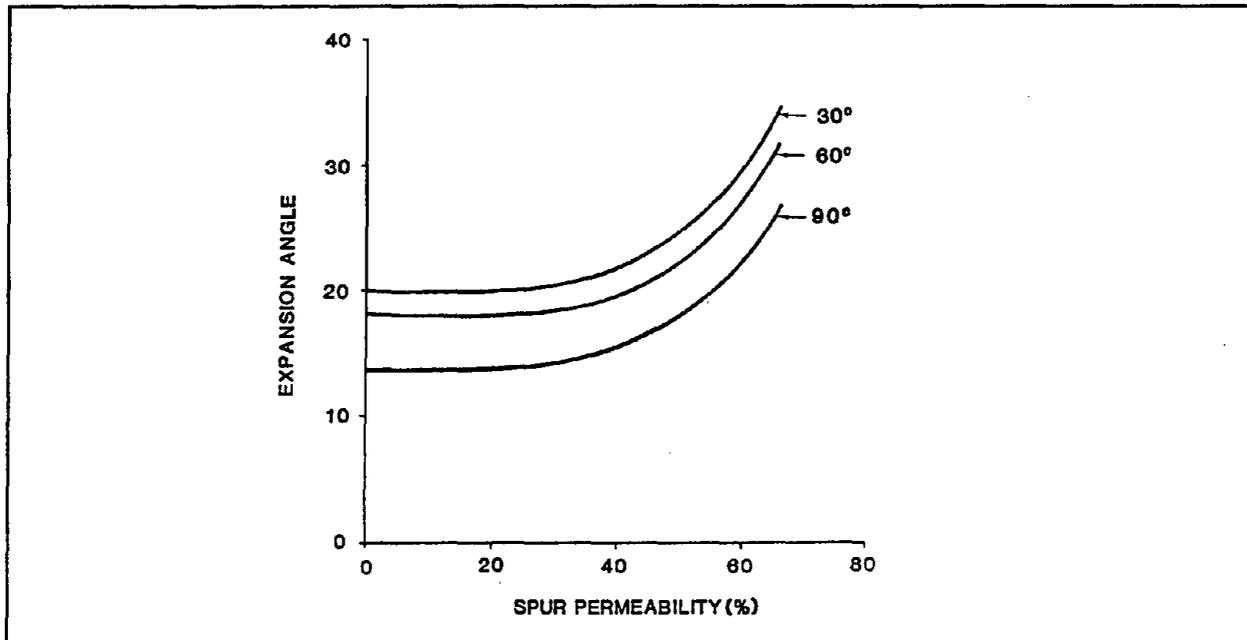


Figure 34. Spur permeability and spur orientation vs. expansion angle (after Brown).<sup>(48)</sup>

From the above discussion, it is apparent that spurs of varying permeability will provide protection against meander migration. Impermeable spurs provide more positive flow control but cause more scour at the toe of the spur and, when submerged, cause erosion of the streambank. High permeability spurs are suitable for use where only small reductions in flow velocities are necessary as on mild bends but can be used for more positive flow control where it can be assumed that clogging with small debris will occur and bed load transport is large. Spurs with permeability up to about 35 percent can be used in severe conditions but permeable spurs may be susceptible to damage from large debris and ice.

**Spur Height and Crest Profile.** Impermeable spurs are generally designed not to exceed the bank height because erosion at the end of the spur in the overbank 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. Bank erosion is more severe if the spur is oriented in the downstream direction.

The crest of impermeable spurs should slope downward away from the bank line, because it is difficult to construct and maintain a level spur of rock or gabions. Use of a sloping crest will avoid the possibility of overtopping at a low point in the spur profile, which could cause damage by particle erosion or damage to the streambank.

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.

Bed and Bank Contact. The most common causes of spur failure are undermining and outflanking by the stream. These problems occur primarily in highly alluvial streams that experience wide fluctuations in the channel bed. Impermeable rock riprap spurs and gabion spurs can be designed to counter erosion at the toe by providing excess material on the streambed as illustrated in figures 35 and 36. As scour occurs, excess material is launched into the scour hole, thus protecting the end of the spur. Gabion spurs are not as flexible as riprap spurs and may fail in very dynamic alluvial streams.

Permeable spurs can be similarly protected as illustrated in figure 37. The necessity for using riprap on the full length of the spur or any riprap at all is dependent on the erodibility of the streambed, the distance between the slats and the streambed, and the depth to which the piling are driven. The measure illustrated would also be appropriate as a retrofit measure at a spur that has been severely undermined, and as a design for locations at which severe erosion of the toe of the streambank is occurring.

Piles supporting permeable structures can also be protected against undermining by driving piling to depths below the estimated scour. Round piling are recommended because they minimize scour at their base.

Extending the facing material of permeable spurs below the streambed also significantly reduces scour. If the retarder spur or retarder/deflector spur performs as designed, retardance and diversion of the flow within the length of the structure should make it unnecessary to extend the facing material the full depth of anticipated scour except at the toe.

A patented Henson spur, as illustrated in figure 38, and marketed by Hold That River, Inc. of Houston, Texas maintains contact with the streambed by vertical wood slats mounted on pipes which are driven to depths secure from scour. The units slide down the pipes where undermining occurs. Additional units can be added on top as necessary.

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, or 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. This ratio is susceptible to alteration by excavation on the inside of the bend or by scour caused by the spur installation. Figure 39 indicates that the expansion angle for impermeable spurs is an almost constant 17°. 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.

As permeability increases, the expansion angle increases, and as the length of spurs relative to channel width increases, the expansion angle increases exponentially. The expansion angle varies with the spur angle, but not significantly.

Spur spacing in a bend can be established by first drawing an arc representing the desired flow alignment (see figure 40). This arc will represent the desired extreme location of the thalweg nearest the outside bank in the bend. 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 of the concave bank or reverse erosion that has already occurred. If the need is to arrest erosion, permeable retarder spurs or retarder structures may be appropriate. If the flow alignment must be altered in order to reverse erosion of the bank or to alter the flow alignment significantly, deflector spurs or retarder/deflector spurs are appropriate. The arc representing the desired flow alignment may be a compound circular curve or any curve which forms a smooth transition in flow directions.

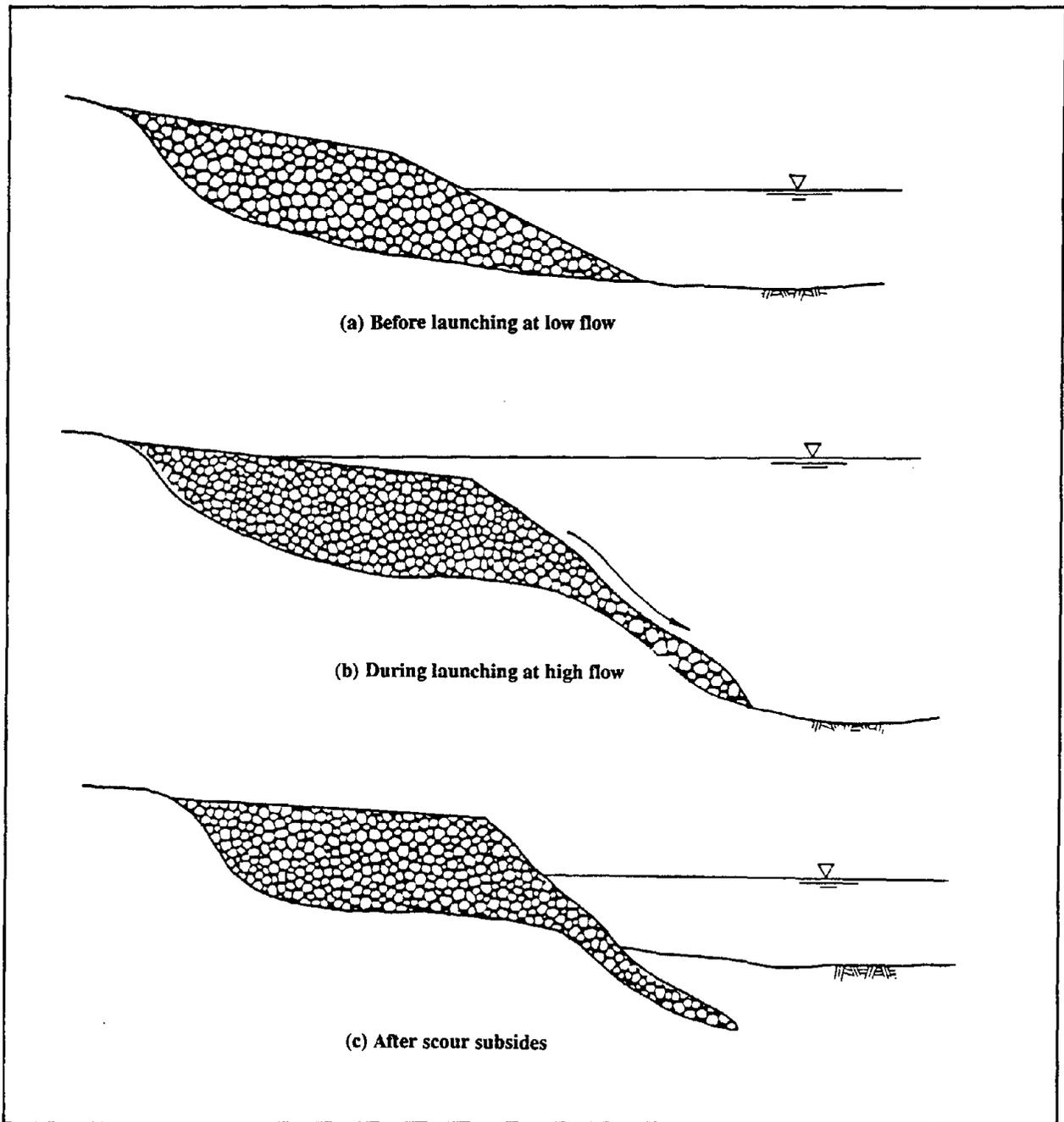


Figure 35. Launching of stone toe protection on a riprap spur: (a) before launching at low flow, (b) during launching at high flow, and (c) after scour subsides (after Brown).<sup>(48)</sup>

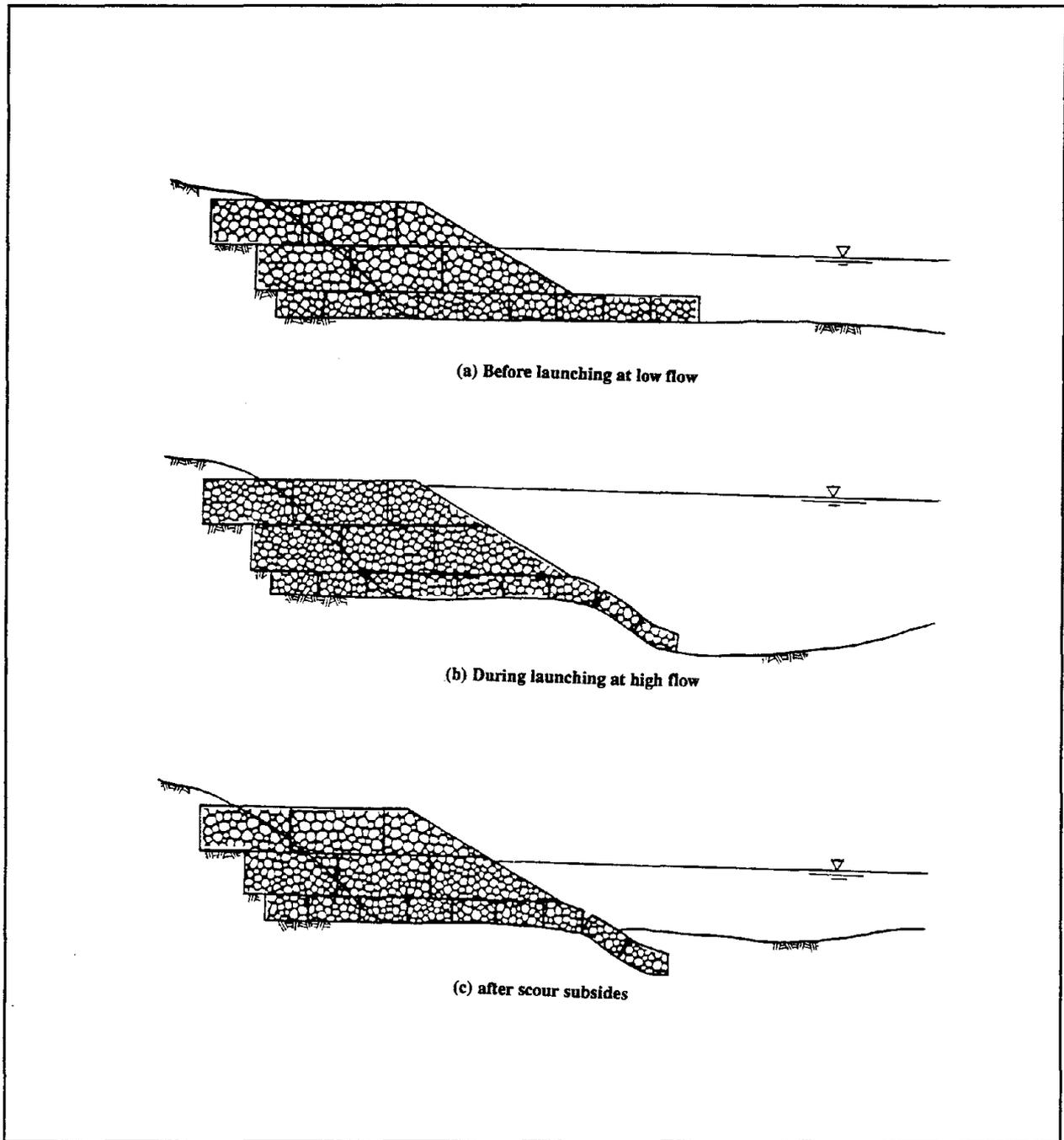


Figure 36. Gabion spur illustrating flexible mat tip protection: (a) before launching at low flow, (b) during launching at high flow, and (c) after scour subsides (after Brown).<sup>(48)</sup>

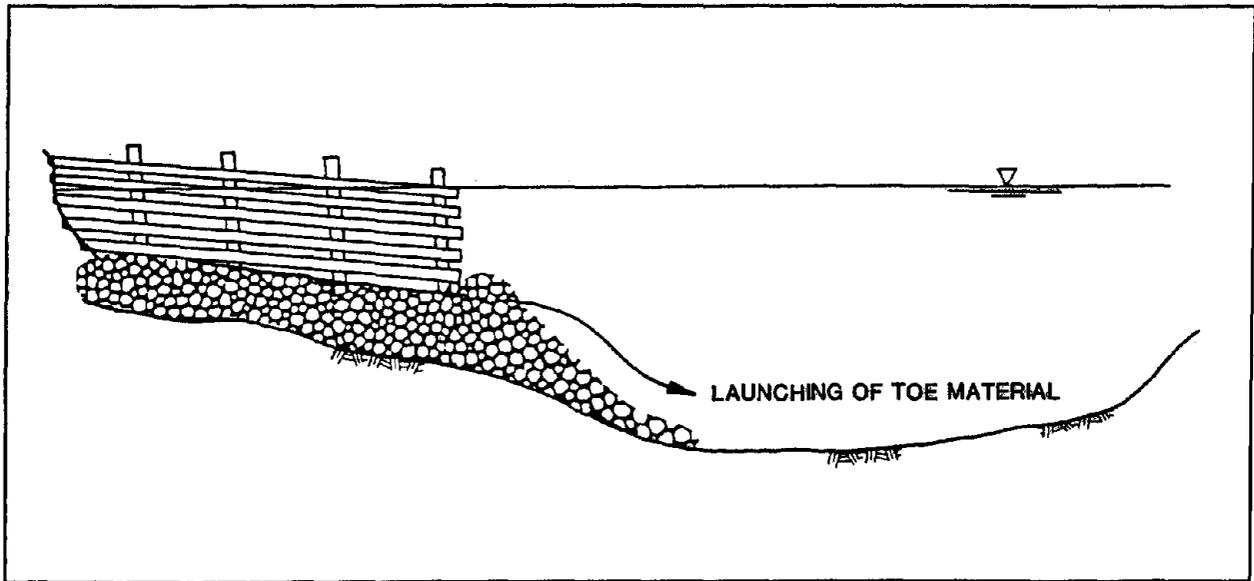


Figure 37. Permeable wood-slat fence spur showing launching of stone toe material (after Brown).<sup>(48)</sup>

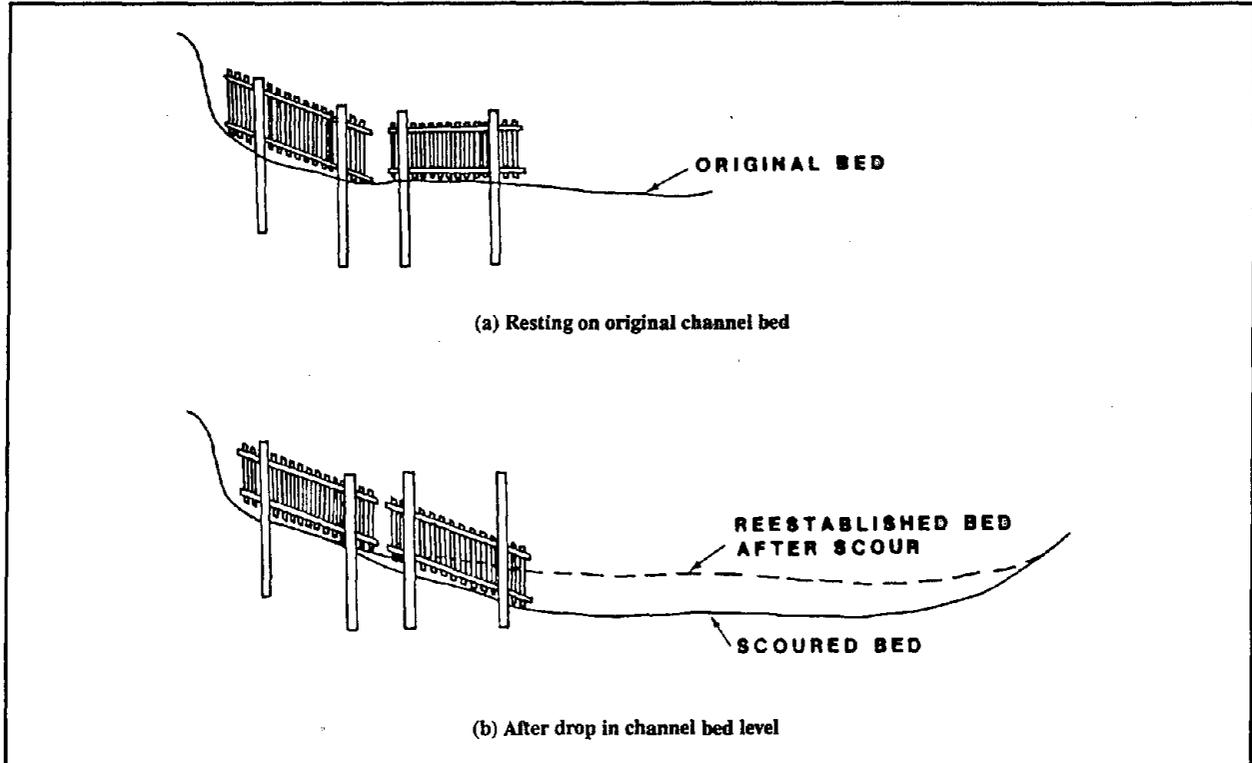


Figure 38. Henson spurs (a) resting on original channel bed, and (b) after drop in channel bed level (after Brown).<sup>(48)</sup>

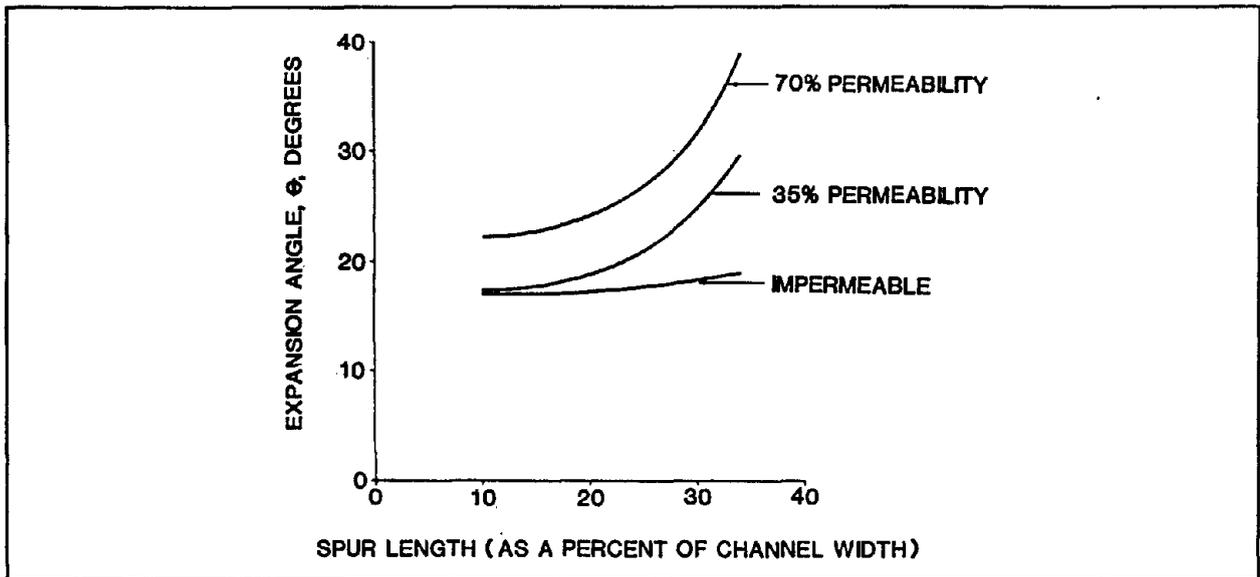


Figure 39. Relationship between spur length and expansion angle for several spur permeabilities (after Brown).<sup>(48)</sup>

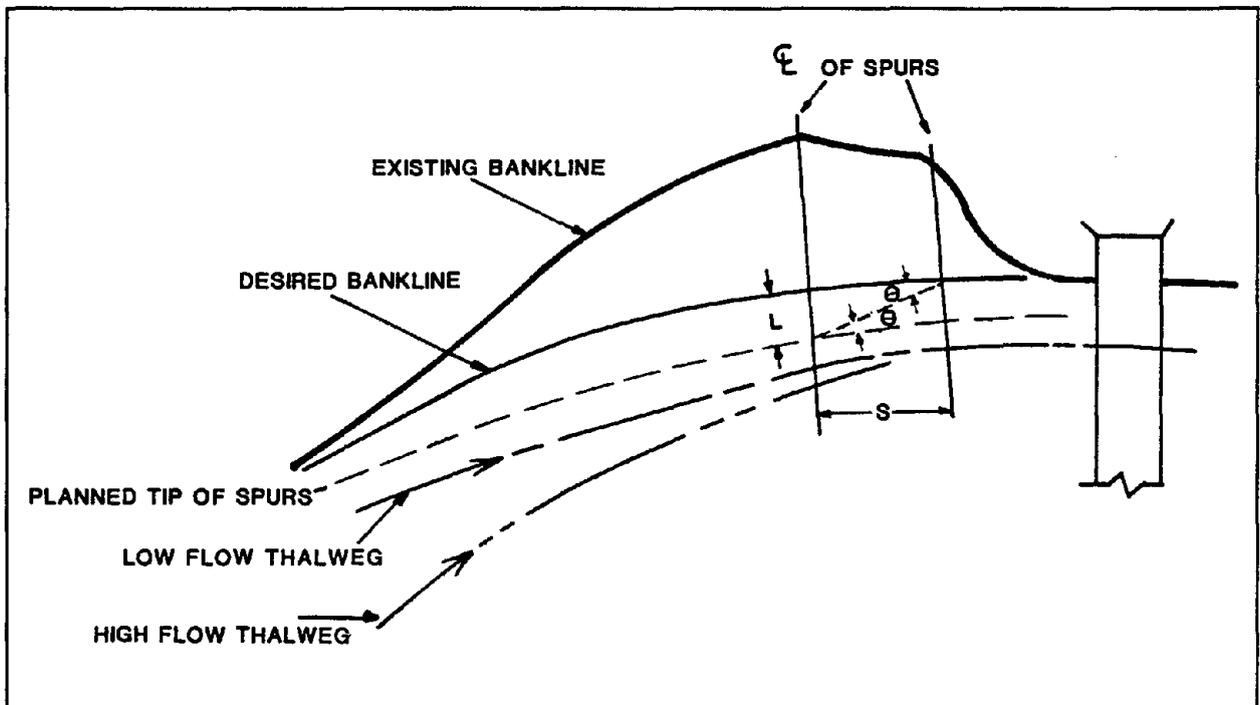


Figure 40. Spur spacing in a meander bend (after Brown).<sup>(48)</sup>

Next, draw an arc representing the desired bankline. This may approximately describe the existing concave bank or a new theoretical bankline which protects the existing bank from further erosion. Also, draw an arc connecting the nose (tip) of spurs in the installation. The distance from this arc to the arc describing the desired bank line, along with the expansion angle, fixes the spacing between spurs. The arc describing the ends of spurs projecting into the channel will be essentially concentric with the arc describing the desired flow alignment.

Establish the location of the spur at the downstream end of the installation. For a highway application, this is normally the protected abutment or guidebank at the bridge. Finally, establish the spacing between each of the remaining spurs in the installation (see figure 40). The distance between spurs is the length of spur between the arc describing the desired bank line and the nose of the spur multiplied by the cotangent of the flow expansion angle. This length is the distance between the nose of spurs measured along a chord of the arc describing spur nose location. Remaining spurs in the installation will be at the same spacing if the arcs are concentric. The procedure is illustrated by figure 40 and expressed in equation 14.

$$S = L \cot \theta \quad (14)$$

where:

- S = Spacing between spurs at the nose, m
- L = Effective length of spur, or the distance between arcs describing the toe of spurs and the desired bank line, m
- $\theta$  = Expansion angle downstream of spur nose, degrees

At less than bankfull flow rates, flow currents may approach the concave bank at angles greater than those estimated from figure 39. Therefore, spurs should be well-anchored into the existing bank, especially the spur at the upstream end of the installation, to prevent outflanking.

Shape and Size of Spurs. In general, straight spurs should be used for most bank protection. Straight spurs are more easily installed and maintained and require less material. For permeable spurs, the width depends on the type of permeable spur being used. Less permeable retarder/deflector spurs which consist of a soil or sand embankment should be straight with a round nose as shown in figure 41.

The top width of embankment spurs should be a minimum of 1 m. However, in many cases the top width will be dictated by the width of any earth moving equipment used to construct the spur. In general a top width equal to the width of a dump truck can be used. The sideslopes of the spur should be 1V:2H or flatter.

Riprap. 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 geotextile may be required (see HEC-11).<sup>(42)</sup> The designer is referred to HIRE, HEC-11, and HEC-18 for design procedures for sizing riprap at spurs.<sup>(4,42,15)</sup>

It is recommended that riprap be extended below the bed elevation to a depth as recommended in HEC-11.<sup>(42)</sup> Riprap should also extend to the crest of the spur, in cases where the spur would be submerged at design flow, or to 0.6 m above the design flow, if the spur crest is higher than the design flow depth. Additional riprap should be placed around the nose of the spur (figure 41), so that spur will be protected from scour.

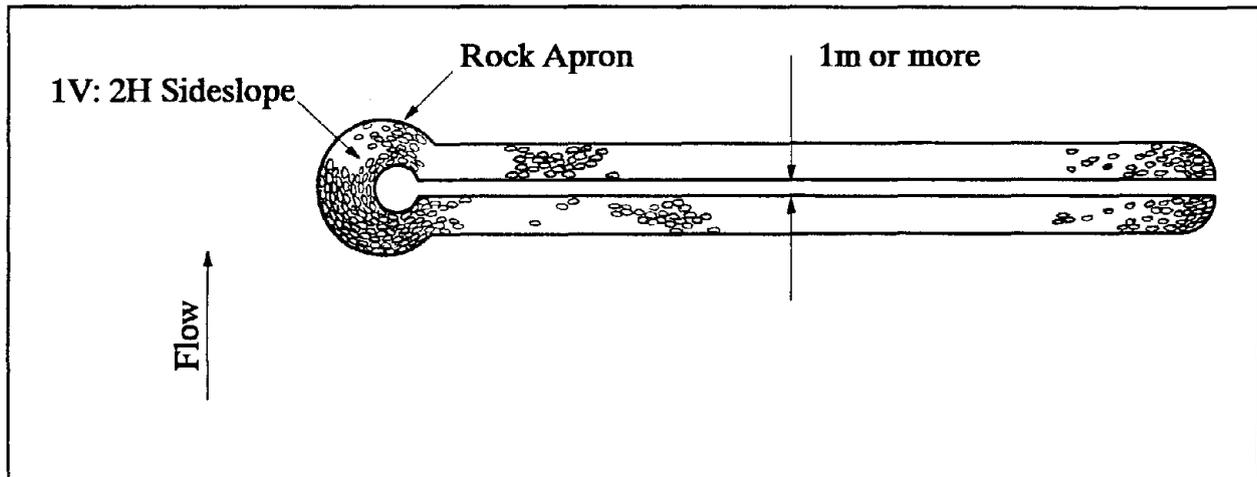


Figure 41. Typical straight, round nose spur.

### 6.3.2 Design Example of Spur Installation

Figure 42 illustrates a location at which a migrating bend threatens an existing bridge (existing conditions are shown with a solid line). Ultimately, based upon the following design example, seven spurs will be required. Although the number of spurs is not known in advance, the spurs (and other design steps) are shown as dashed lines on figure 42 as they will be specified after completing the following design example.

For this example, it is desirable to establish a different flow alignment and to reverse erosion of the concave (outside) bank. The spur installation has two objectives: (1) to stop migration of the meander before it damages the highway stream crossing, and (2) to reduce scour at the bridge abutment and piers by aligning flow in the channel with the bridge opening.

Permeable retarder/deflector spurs or impermeable deflector spurs are suitable to accomplish the objectives and the stream regime is favorable for the use of these types of countermeasure. The expansion angle for either of these spur types is approximately  $17^\circ$  for a spur length of about 20 percent of the desired channel width, as indicated in figure 39.

#### Step 1. Sketch Desired Thalweg

The first step is to sketch the desired thalweg location (flow alignment) with a smooth transition from the upstream flow direction through the curve to an approach straight through the bridge waterway (see figure 42). Visualize both the high-flow and low-flow thalwegs. For an actual location, it would be necessary to examine a greater length of stream to establish the most desirable flow alignment. Then draw an arc representing the desired bankline in relation to thalweg locations. The theoretical or desired left bank line is established as a continuation of the bridge abutment and left bank downstream through the curve, smoothly joining the left bank at the upstream extremity of eroded bank.

#### Step 2. Sketch Alignment of Spur Tips

The second step is to sketch a smooth curve through the nose (tip) locations of the spurs, concentric with the desired bankline alignment.

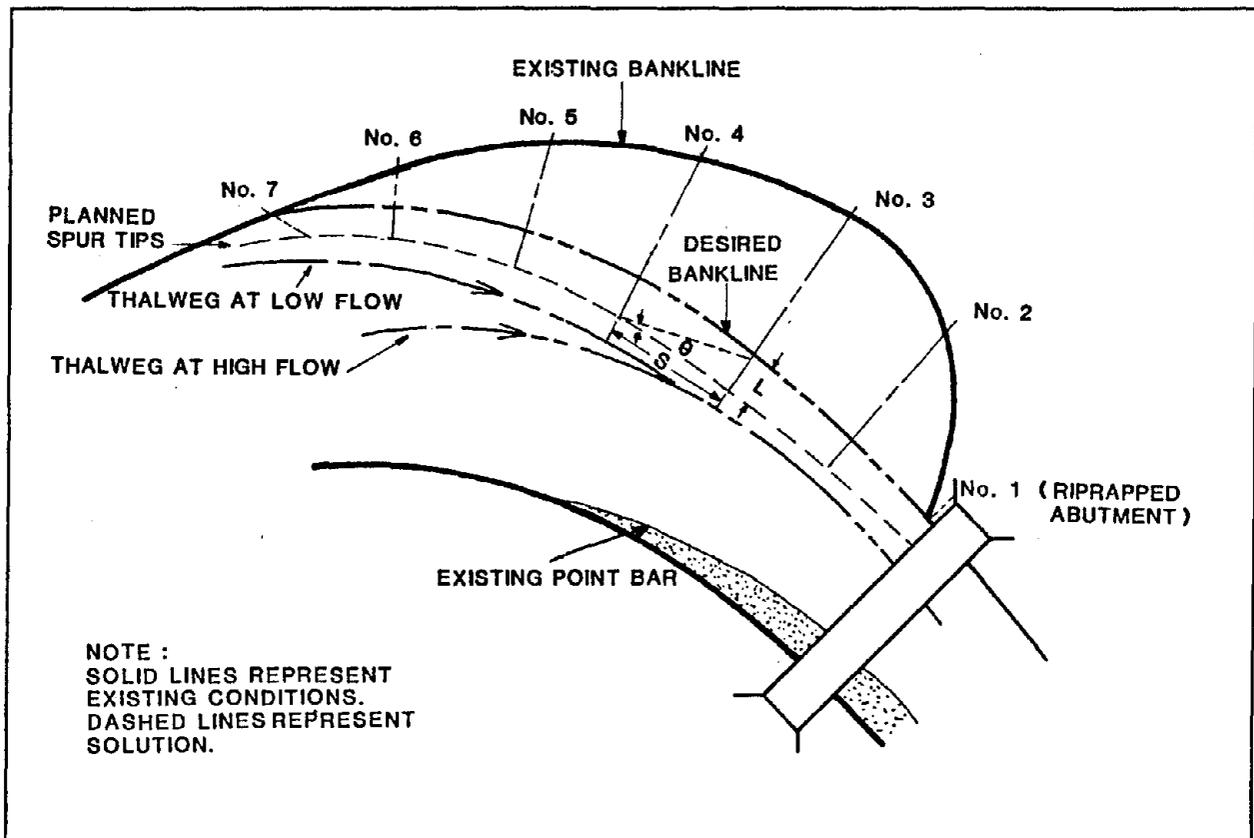


Figure 42. Example of spur design.

### Step 3. Locate First Spur

Step number three is to locate spur number 1 so that flow expansion from the nose of the spur will intersect the streambank downstream of the abutment. This is accomplished by projecting an angle of  $17^\circ$  from the abutment alignment to an intersection with the arc describing the nose of spurs in the installation or by use of equation 14. Spurs are set at  $90^\circ$  to a tangent with the arc for economy of construction. Alternatively, the first spur could be considered to be either the upstream end of the abutment or guide bank if the spur field is being installed upstream of a bridge.

It may be desirable to place riprap on the streambank at the abutment. Furthermore, the lateral size of the scour hole at the spur directly upstream of the bridge should be estimated using the procedures described in figures 30, 31, and 33. If the extent of scour at this spur overlaps local scour at the pier, total scour depth at the pier may be increased. This can be determined by extending the maximum scour depth at the spur tip, up to the existing bed elevation at the pier at the angle of repose.

### Step 4. Locate Remaining Spurs

Spurs upstream of spur number 1 are then located by use of equation 14, using dimensions as illustrated in figure 40. Using this spur spacing, deposition will be encouraged between the desired bank line and the existing eroded bank.

The seventh and last spur upstream is shown oriented in a downstream direction to provide a smooth transition of the flow approaching the spur field. This spur could have been oriented normal to the existing bank, and been shorter and more economical, but might have created excessive scour. Orienting the furthest

upstream spur at an angle in the downstream direction provides a smoother transition into the spur field, and decreases scour at the nose of the spur. Subsequent spurs downstream can be oriented normal to the intended bank line for economy.

Note that spur number 7 is somewhat downstream of the beginning of the eroded bank. This area could be protected in one of two ways. The first would be to orient spur number seven perpendicular to the planned bank and install an eighth spur, angled downstream which begins upstream of the eroded bank. The second method would be to install a hard point where the bank is beginning to erode. Hard points are discussed in the section entitled, "Other Countermeasures." In this case the hard point can be considered as a very short spur which is located at the intersection of the actual and planned bank lines. In either case, spurs or hard points should be anchored well into the bank to prevent outflanking.

## 6.4 GUIDE BANKS

### 6.4.1 Design Considerations

When embankments encroach on wide floodplains, the flows from these areas must flow parallel to the approach embankment to the bridge opening. These flows can erode the approach embankment. A severe flow contraction at the abutment can reduce the effective bridge opening, which could possibly increase the severity of abutment and pier scour.

Guide banks (also referred to as spur dikes) can be used in these cases to prevent erosion of the approach embankments by cutting off the flow adjacent to the embankment, guiding streamflow through a bridge opening, and transferring scour away from abutments to prevent damage caused by abutment scour. The two major enhancements guide banks bring to bridge design are (1) reduce the separation of flow at the upstream abutment face and thereby maximize the use of the total bridge waterway area, and (2) reduce the abutment scour due to lessening turbulence at the abutment face. 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, plan shape, upstream and downstream length, cross-sectional shape, and crest elevation. Bradley is used as the principal design reference for this section.<sup>(22)</sup>

Figure 43 presents a typical guide bank plan view. It is apparent from the figure that without this guide bank overbank flows would return to the channel at the bridge opening, which can increase the severity of contraction and scour at the abutment. Note, that with installation of guide banks the scour holes which normally would occur at the abutments of the bridge are moved upstream away from the abutments. Guide banks may be designed at each abutment, as shown, or singly, depending on the amount of overbank or floodplain flow directed to the bridge by each approach embankment.

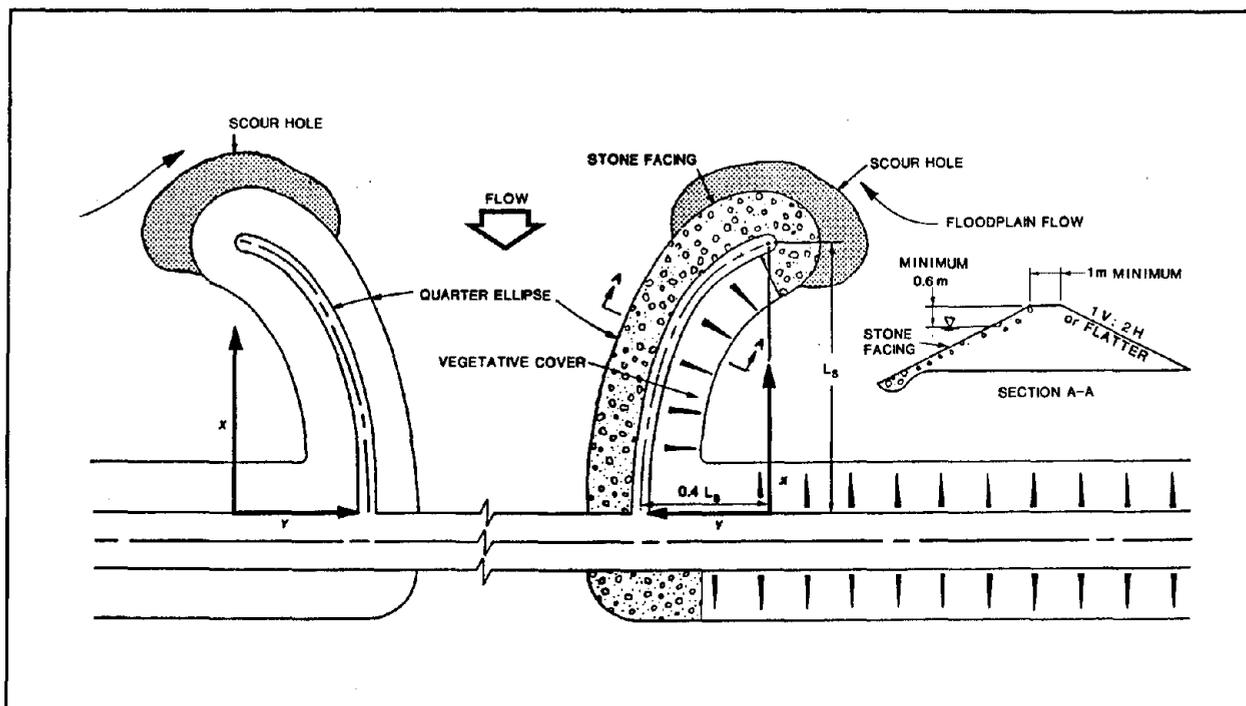


Figure 43. Typical guide bank (modified from Bradley).<sup>(22)</sup>

The goal in the design of guide banks is to provide a smooth transition and contraction of the streamflow through the bridge opening. Ideally, the flow lines through the bridge opening should be straight and parallel. As in the case with other countermeasures, the designer should consider the principles of river hydraulics and morphology, and exercise sound engineering judgment.

**Orientation.** Guide banks should start at and be set parallel to the abutment and extend upstream from the bridge opening. The distance between the guide banks at the bridge opening should be 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) of 2.5:1. This allows for a gradual constriction of the flow. Thus, if 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 roadway, should be  $0.4 L_s$ .

The plan view orientation can be determined using equation 15, which is the equation of an ellipse with origin at the nose of the guide bank. For this equation,  $X$  is the distance measured perpendicularly from the bridge approach and  $Y$  is the offset measured parallel to the approach embankment, as shown on figure 43.

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

It is important that the face of the guide bank match the abutment so that the flow is not disturbed where the guide bank meets the abutment. For new bridge construction, abutments can be sloped to the channel bed at the same angle as the guide bank. For retrofitting existing bridges modification of the abutments or wing walls may be necessary.

**Length.** For design of guide banks, the length of the guide bank,  $L_s$  must first be determined. This can be easily determined using a nomograph which was developed from laboratory tests performed at Colorado State University and from field data compiled by the USGS.<sup>(49,50,51)</sup> For design purposes the utilization of the nomograph involves the following parameters:

$Q$	=	Total discharge of the stream, $m^3/s$
$Q_f$	=	Lateral or floodplain discharge of either floodplain intercepted by the embankment, $m^3/s$
$Q_{30m}$	=	Discharge in 30 m of stream adjacent to the abutment, $m^3/s$
$b$	=	Length of the bridge opening, m
$A_{n2}$	=	Cross-sectional flow area at the bridge opening at normal stage, $m^2$
$V_{n2}$	=	$\frac{Q}{A_{n2}}$ = Average velocity through the bridge opening, m/s
$\frac{Q_f}{Q_{30m}}$	=	Guide bank discharge ratio
$L_s$	=	Projected length of guide bank, m

A nomograph is presented in figure 44 to determine the projected length of guide banks. This nomograph should be used to determine the guide bank length for designs greater than 15 m and less than 75 m. If the nomograph indicates the length required to be greater than 75 m the design should be set at 75 m. It is recommended that the minimum length of guide banks be 15 m. An example of how to use this nomograph is presented in the next section.

FHWA practice has shown that many guide banks have performed well using a standardized length of 46 m. Based on this experience, guide banks of 46 m in length should perform very well in most locations. Even shorter guide banks have been successful if the guide bank intersects the tree line.

**Crest Height.** As with deflection 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 might be generated, which could scour and undermine abutments and piers. In general, a minimum of 0.6 m of freeboard, above the design water surface elevation should be maintained.

**Shape and Size.** The cross-sectional shape and size of guide banks should be similar to deflector, or deflector/retarder spurs discussed previously. Generally, the top width is 3 to 4 m, but the minimum width is 1 m when construction is by drag line. The upstream end of the guide bank should be round nosed. Sideslopes should be 1V:2H or less.

**Downstream Extent.** In some states, highway departments extend guide banks downstream of the abutments to minimize scour due to rapid expansion of the flow at the downstream end of the abutments. These downstream guide banks are sometimes called "heels." If the expansion of the flow is too abrupt, a shorter guide bank, which usually is less than 15 m long, can be used downstream. Downstream guide banks should also start at and start parallel to the abutment and the distance between them should enlarge as the distance from the abutment of the bridge increases.

In general, downstream guide banks are a shorter version of the upstream guide banks. Riprap protection, crest height and width should be designed in the same manner as for upstream guide banks.

**Riprap.** Guide banks are constructed by forming an embankment of soil or sand extending upstream from the abutment of the bridge. To inhibit erosion of the embankment materials, guide banks must be adequately protected with riprap or stone facing.

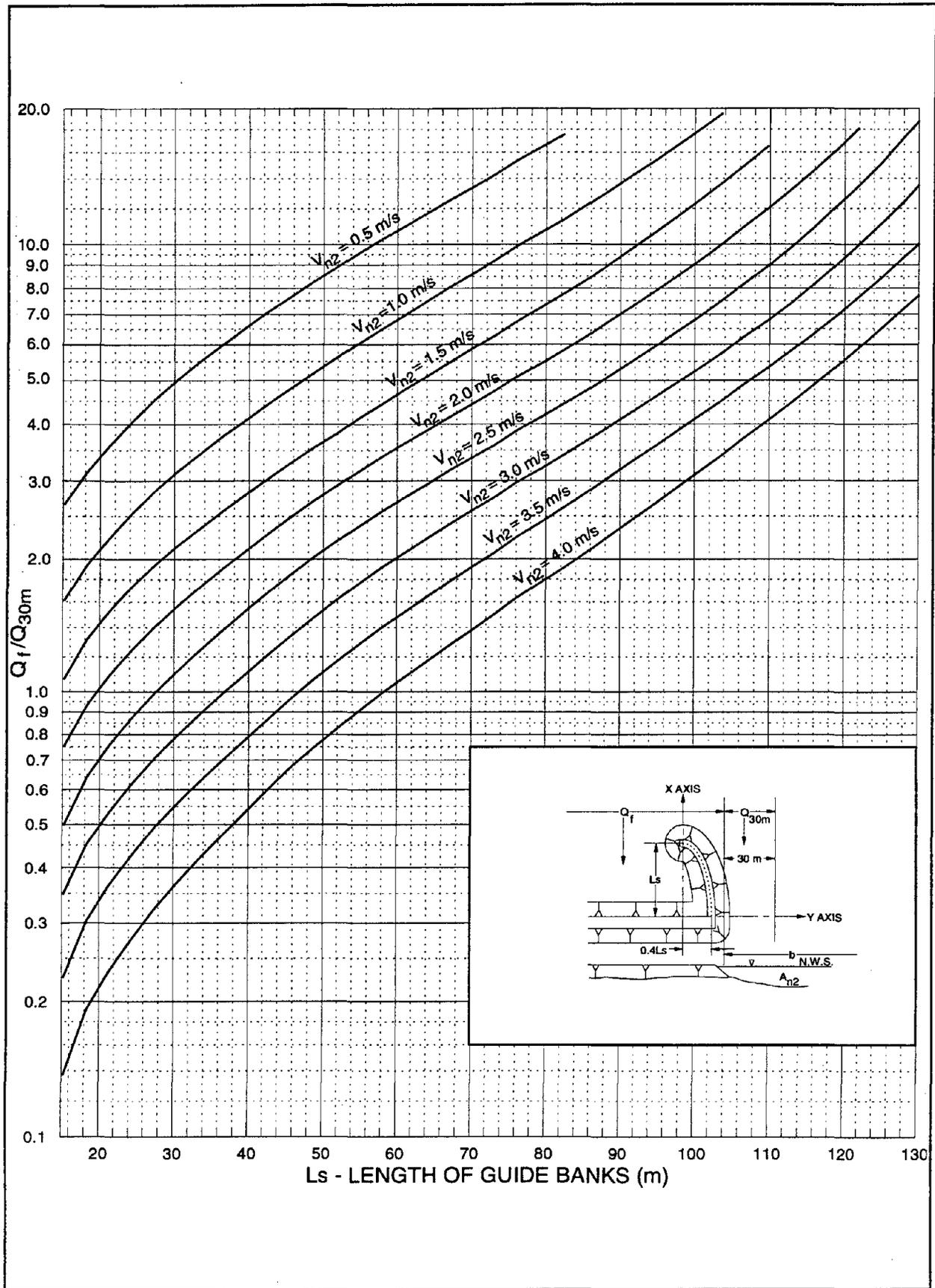


Figure 44. Nomograph to determine guide bank length (after Bradley).<sup>(22)</sup>

Rock riprap should be placed on the stream side face as well as around the end of the guide bank. It is not necessary to riprap the side of the guide bank adjacent to the highway approach embankment. As in the case of spurs, a gravel, sand, or fabric filter may be required to protect the underlying embankment material (see HEC-11).<sup>(42)</sup> The designer is referred to HIRE for design procedures for sizing riprap.<sup>(4)</sup> Riprap should be extended below the bed elevation to a depth as recommended in HEC-11 and extend up the face of the guide bank to 0.6 m above the design flow.<sup>(42)</sup> Additional riprap should be placed around the upstream end of the guide bank so to protect the embankment from scour.

As in the case of spurs, it is important to adequately tie guide banks into the approach embankment.

Guide banks on Non-symmetrical Highway Crossings. Hydraulics of Bridge Waterways states:<sup>(22)</sup>

*"From meager testing done to date, there is not sufficient evidence to warrant using longer dikes (guide banks) at either abutment on skewed bridges. Lengths obtained from [the nomograph] should be adequate for either normal or skewed crossings."*

Therefore, for skewed crossings, the length of guide banks should be set using the nomograph for the side of the bridge crossing which yields the largest guide bank length.

Other Design Concerns. In some cases, where the cost of stone riprap facing is prohibitive, the guide bank can be covered with sod or other minimal protection. If this approach is selected, the design should allow for and stipulate the repair or replacement of the guide bank after each high water occurrence.<sup>(19)</sup> Other measures which will minimize damage to approach embankments, and guide banks during high water are:

- Keep trees as close to the toe of guide bank embankments as construction will permit. Trees will increase the resistance to flow near and around the toe of the embankment, thus reducing velocities and scour potential.
- Do not allow the cutting of channels or the digging of borrow pits along the upstream side of approach embankments and near guide banks. Such practices encourage flow concentration and increases velocities and erosion rates of the embankments.
- In some cases, the area behind the guide bank may be too low to drain properly after a period of flooding. This can be a problem, especially when the guide bank is relatively impervious. Small drain pipes can be installed in the guide bank to drain this ponded water.
- In some cases, only one approach will cut off the overbank flow. This is common when one of the banks is high and well defined. In these cases, only one guide bank may be necessary.

#### **6.4.2 Design Example of Guide Bank Installation**

For the example design of a guide bank, figure 45 will be used. This figure shows the cross-section of the channel and floodplain before the bridge is constructed and the plan view of the approach, guide banks, and embankments after the design steps outlined below are completed.

##### **Step 1. Hydraulic Design Parameters**

The first step in the design of guide banks requires the computation of the depth and velocity of the design flood in the main channel and in the adjacent overbank areas. These studies are performed by using step backwater computations upstream and through the bridge opening. The computer programs WSPRO, HEC-2, or the new HEC River Analysis System (RAS) are suitable for these computations.<sup>(20,21,58)</sup> Using these programs or by using conveyance curves developed from actual data, the discharges and depths in the channel and overbank areas can be determined.

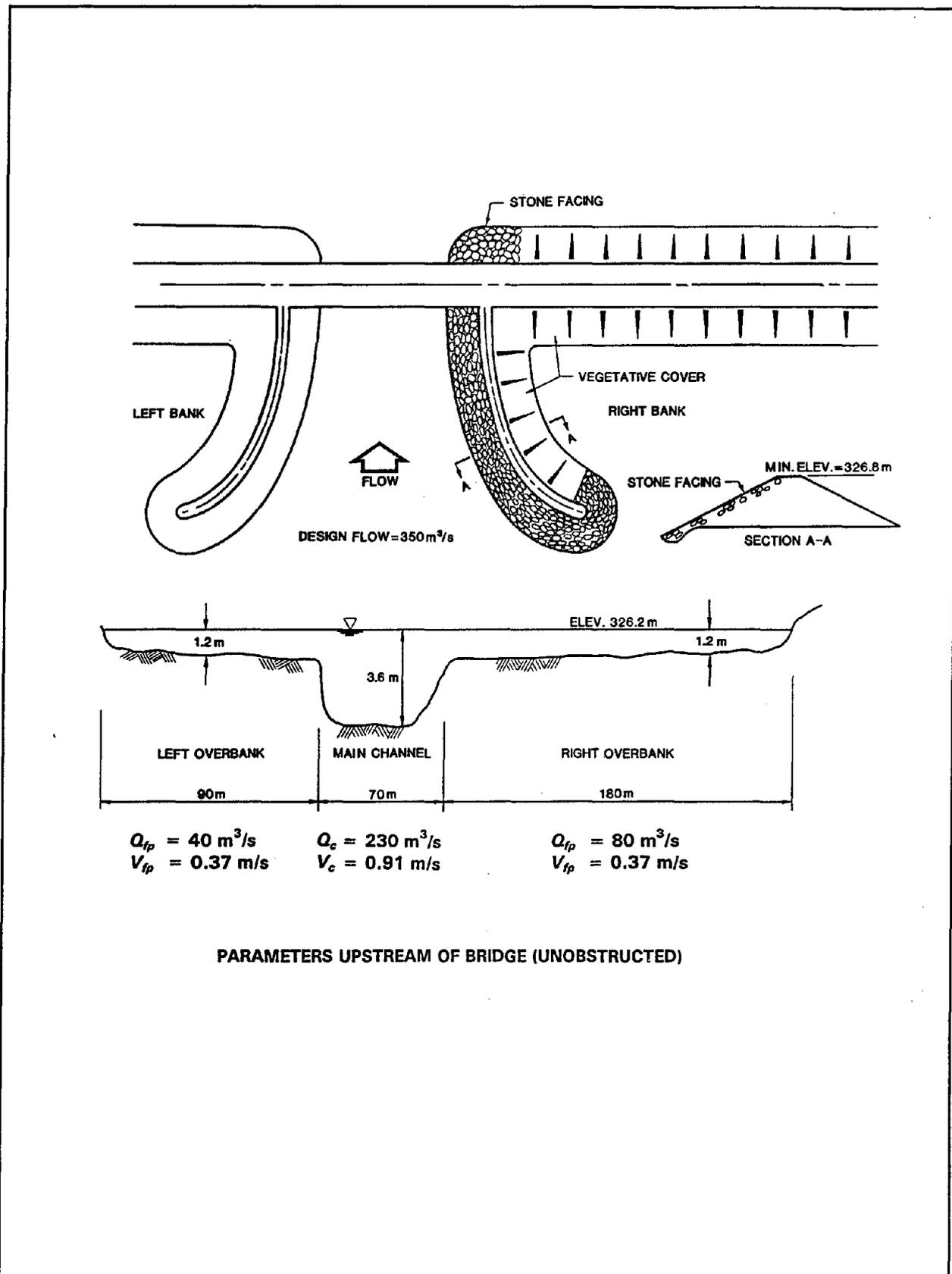


Figure 45: Example guide bank design.

To use the conveyance curve approach, the designer is referred to example problem number 4 (page 71) in *Hydraulics of Bridge Waterways* for methods to determine these discharges and areas.<sup>(22)</sup> That publication also contains another example of the design of a guide bank.

For this example, the total, overbank, and channel discharges, as well as the flow area are given. We also assume that a bridge will span a channel with a bottom width of 70 m and that the abutments will be set back 45 m from each bank of the main channel. The abutments of this bridge are spill-through with a sideslope of 1V:2H. The design discharge is 350 m<sup>3</sup>/s, which after backwater computations, results in a mean depth of 3.6 m in the main channel and a mean channel velocity of 0.91 m/s.

#### Step 2. Determine $Q_f$ in the left and right overbank

The depth in both overbank areas are 1.2 m and the width of the left and right overbank areas are 90 and 180 m, respectively. Velocity in the overbank areas (assuming no highway approach embankment) is 0.37 m/s. By noting that the discharge is the product of the velocity and the cross-sectional area in the overbank areas, the floodplain flow is equal to 40 m<sup>3</sup>/s for the left overbank and 80 m<sup>3</sup>/s for the right overbank. These flow rates would be the values of  $Q_f$  in Step 3 if the abutments were set at the channel banks. For this example, the abutments are set back 45 m from each bank. The  $Q_f$  value used in Step 3 is the overbank flow intercepted by the approach embankments. Thus, the total overbank flow should be reduced by 20 m<sup>3</sup>/s (0.37 m/s x 1.2 m deep x 45 m wide) and the values of  $Q_f$  are 20 and 60 m<sup>3</sup>/s for the left and right floodplains, respectively.

#### Step 3. Determine $Q_{30m}$ and $Q_f/Q_{30m}$ for the left and right overbank

The overbank discharge in the first 30 m of opening adjacent to the left and right abutments needs to be determined next. Since for this case the flow is of uniform depth (1.2 m) and velocity (0.37 m/s) over the entire width of the floodplain, and the abutments are set back more than 30 m from the main channel banks, the value of  $Q_{30m}$  will be 13.3 m<sup>3</sup>/s for both sides.

For the left and right overbanks the reference values of  $Q_f/Q_{30m}$  can be determined by simple division of the discharges determined in previous steps. For this example, these values are 1.5 and 4.5 for the left and right overbank, respectively. For design purposes, the largest value will result in the more conservative determination of the length of the guide banks, except where Step 4 indicates a guide bank is required for only one of the overbank areas.

#### Step 4. Determine the length of the guide bank, $L_s$

The average channel velocity through the bridge opening can be determined by dividing the total discharge of the stream  $Q$  by the cross-sectional flow area at the bridge opening  $A_{n2}$ , which in this case includes the main channel (252 m<sup>2</sup>) plus 45 m of the left and right overbank areas adjacent to the abutments at the bridge opening (108 m<sup>2</sup>). Thus, the average channel velocity  $V_{n2}$  is 0.97 m/s. For  $Q_f/Q_{30m}$  equal to 4.5 and an average channel velocity of 0.97 m/s, the length of the guide bank is determined using the nomograph presented in figure 44. For this example the length,  $L_s$  determined from the nomograph is approximately 42 m. The offset of the guide bank is determined by multiplying  $L_s$  by 0.4. These dimensions locate the end of the guide bank. The shape of the guide bank from this location to the abutment is simply an ellipse as described by equation 15. For the left overbank, a  $Q_f/Q_{30m}$  of 1.5 and  $V_{n2}$  of 0.97 m/s indicates that  $L_s$  would be less than 15 m. Thus, no guide bank is required for the left overbank for this example.

## Step 5. Miscellaneous Specifications

The crest of the guide bank must be a minimum of 0.6 m above the water surface. Therefore, the crest elevation for this example should be greater than or equal to 326.8 m. The crest width should be at least 1 m. For this example, a crest width of 3 m will be specified so that the guide bank can be easily constructed with dump trucks.

Stone or rock riprap should be placed in the locations shown on figure 45. This riprap should extend a minimum of 0.6 m above the design water surface (elevation 326.8 m) and below the intersection of the toe of the guide bank and the existing ground surface as recommended in HEC-11.<sup>(42)</sup>

## 6.5 CHECK DAMS

Check dams or channel drop structures are used downstream of highway crossings to arrest head cutting and maintain a stable streambed elevation in the vicinity of the bridge. Check dams are usually built of rock riprap, concrete, sheet piles, gabions, or treated timber piles. The material used to construct the structure depends on the availability of materials, the height of drop required, and the width of the channel. Rock riprap and timber pile construction have been most successful on channels having small drops and widths less than 30 m. Sheet piles, gabions, and concrete structures are generally used for larger drops on channels with widths ranging up to 100 m.

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 dissipators downstream of check dams can reduce the energy available to erode the channel bed and banks. In some cases it may be better to construct several consecutive drops of shorter height to minimize extensive erosion.

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, or eddy action at the banks. Bank erosion downstream of check dams can lead to erosion of bridge approach embankments and abutment foundations if lateral bank erosion causes the formation of flow channels around the ends of check dams. The usual solution to these problems is to place riprap revetments on the streambank. Riprap of the bank downstream of the check dam will be needed. The design of riprap is given in Richardson et al., Brown and Clyde, and USACOE.<sup>(4,42,43)</sup>

Erosion of the streambed can also be reduced by placing rock riprap in a preformed scour hole downstream of the drop structure. A row of sheet piling with top set at or below streambed elevation can keep the riprap from moving downstream. Because of the problems associated with check dams, the design of these countermeasures requires designing the check dams to resist scour by providing for dissipation of excess energy and protection of areas in the bed and the bank which are susceptible to erosive forces.

### 6.5.1 Bed Scour For Vertical Drop Structures

The most conservative estimate of scour downstream of channel drop structures is for vertical drops with unsubmerged flow conditions. For the purposes of design the maximum expected scour will be assumed to be equal to the scour for a vertical, unsubmerged drop, regardless of whether the drop is actually sloped or is submerged.

A typical vertical drop structure with a free overfall is diagramed in figure 46. An equation developed by the Bureau of Reclamation (USBR) is recommended to estimate the depth of scour downstream of a vertical drop:<sup>(52)</sup>

$$d_s = K H_t^{0.225} q^{0.54} - d_m \quad (16)$$

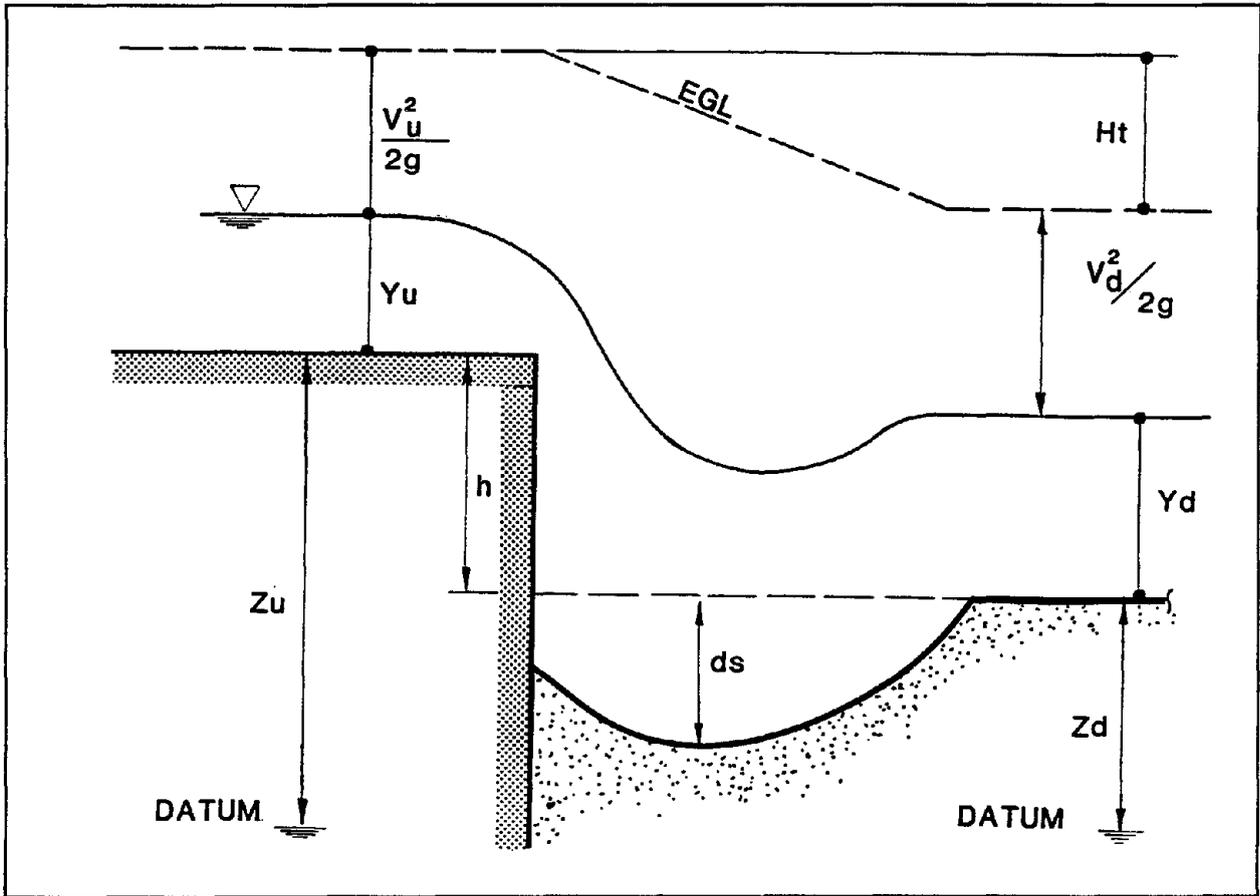


Figure 46. Schematic of a vertical drop caused by a check dam.

where:

- $d_s$  = Local scour depth for a free overfall, measured from the streambed downstream of the drop, m
- $q$  = Discharge per unit width,  $m^3/s/m$
- $H_t$  = Total drop in head, measured from the upstream to the downstream energy grade line, m
- $d_m$  = Tailwater depth, m
- $K$  = 1.90

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:

$$H_t = \left[ Y_u + \frac{V_u^2}{2g} + Z_u \right] - \left[ Y_d + \frac{V_d^2}{2g} + Z_d \right] \quad (17)$$

where:

- $Y$  = Depth, m
- $V$  = Velocity, m/s
- $Z$  = Bed elevation referenced to a common datum, m
- $g$  = Acceleration due to gravity  $9.81 \text{ m/s}^2$

The subscripts  $u$  and  $d$  refer to up- and downstream of the channel drop, respectively.

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 resistant 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 the check dam.

The drop structure 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 geotechnical and structural engineers so that the drop structure will be stable under the full scour condition. In some cases, a series of drops may be employed to minimize drop height and construction costs of foundations. Riprap or energy dissipation could be provided to limit depth of scour (see, for example, Peterka).<sup>(53)</sup>

### 6.5.2 Design Example

The following design example is based upon a comparison of scour equations presented by the USBR.<sup>(52)</sup> Background: Channel degradation is threatening bridge foundations. Increasing the bed elevation 1.4 m will stabilize the channel at the original bed level. A drop structure will raise the channel bed and reduce upstream channel slopes, resulting in greater flow depths and reduced velocity upstream of the structure. For this example, as illustrated by figure 47, the following hydraulic parameters are used:

Design Discharge	Q	= 167 m <sup>3</sup> /s
Channel Width	B	= 32 m
Upstream Water Depth	Y <sub>u</sub>	= 3.22 m
Tail Water Depth	d <sub>m</sub> , Y <sub>d</sub>	= 2.9 m
Unit Discharge	q	= 5.22 m <sup>3</sup> /s/m
Upstream Mean Velocity	V <sub>u</sub>	= 1.62 m/s
Downstream Mean Velocity	V <sub>d</sub>	= 1.80 m/s
Drop Height	h	= 1.4 m

H<sub>t</sub> is calculated from Bernoulli's equation. Using the downstream bed as the elevation datum gives:

$$H_t = \left[ 3.22 + \frac{(1.62)^2}{(2) 9.81} + 1.4 \right] - \left[ 2.9 + \frac{(1.80)^2}{(2) 9.81} + 0 \right] = 1.69 \text{ m} \quad (18)$$

Using equation (16), the estimated depth of scour below the downstream bed level is:

$$d_s = 1.90 (1.69)^{0.225} (5.22)^{0.54} - 2.9$$

$$d_s = 2.3 \text{ m} \quad (27)$$

In this case, the unsupported height of the structure is (h + d<sub>s</sub>) or 3.7 m. If, for structural reasons, this height is unacceptable, then either riprap to limit scour depth or a series of check dams could be constructed. It should be noted that if a series of drops are required, adequate distance between each drop must be maintained.<sup>(53)</sup>

### 6.5.3 Lateral Scour Downstream of Check Dams

As was mentioned, lateral scour of the banks of a stream downstream of check dams can cause the streamflow to divert around the check dam. If this occurs, a head cut may move upstream and endanger the highway crossing. To prevent this the banks of the stream must be adequately protected using riprap or other revetments. Riprap should be sized and placed in a similar fashion as for spurs and guide banks. The designer is referred to HIRE or HEC-11 for proper sizing, and placement of riprap on the banks.<sup>(4,42)</sup> Revetments are discussed in the section entitled "Other Countermeasures" in this text.

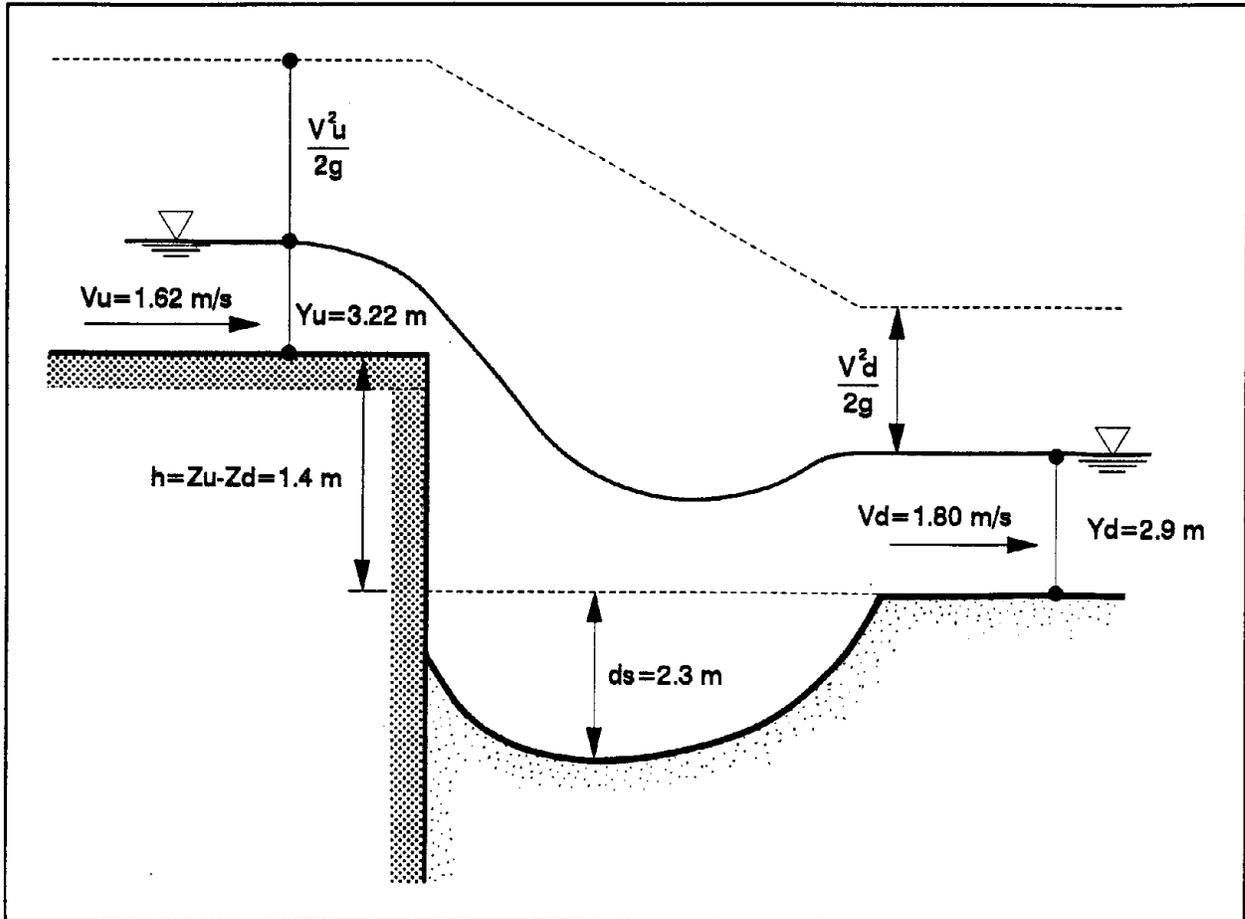


Figure 47. Design example of scour downstream of a drop structure.

## 6.6 OTHER COUNTERMEASURES

### 6.6.1 Revetments

Revetments may be flexible or rigid and can be used to counter all erosion mechanisms. They may be used to provide protection for embankments, streambanks, and streambeds. They do not significantly constrict channels or alter flow patterns. Revetments have been unsuccessful in resisting slumps in saturated streambanks and embankments and relatively unsuccessful in stabilizing streambanks and streambeds in degrading streams. Special precautions must be observed in the design of revetments for degrading channels.

**Flexible Revetments.** Flexible revetments include rock riprap, rock-and-wire mattresses, gabions, precast concrete blocks, rock-fill trenches, windrow revetments, used tire revetments, and vegetation. Rock riprap adjusts to distortions and local displacement of materials without complete failure of the revetment installation. However, flexible rock-and-wire mattress and gabions may sometimes span the displacement of underlying materials, but usually can adjust to most local distortions. Used tire mattress and precast concrete block mattresses are generally stiffer than rock riprap and gabions, and therefore, do not adjust to local displacement of underlying materials as well. References for design guidelines of flexible revetments depend on the type of flexible revetment being used and are discussed separately in the following sections.

Rock Riprap, Rock-and Wire Mattress, Gabions, and Precast Concrete Blocks. Design guidelines, design procedures, and suggested specifications for rock riprap, wire enclosed rock, stacked block gabions, and precast concrete blocks are included in HEC-11.<sup>(42)</sup>

Rock-Fill Trenches and Windrow Revetment. Rock-fill trenches are structures used to protect banks from caving caused by erosion at the toe. A trench is excavated along the toe of the bank and filled with rocks as shown in figure 48. The size of trench to hold the rock fill depends on expected depths of scour.

As the streambed adjacent to the toe is eroded, the toe trench is undermined and the rock fill slides downward to pave the bank. It is advantageous to grade the banks before placing riprap on the slope and in the toe trench. The slope should be at such an angle that the saturated bank is stable while the stream stage is falling.

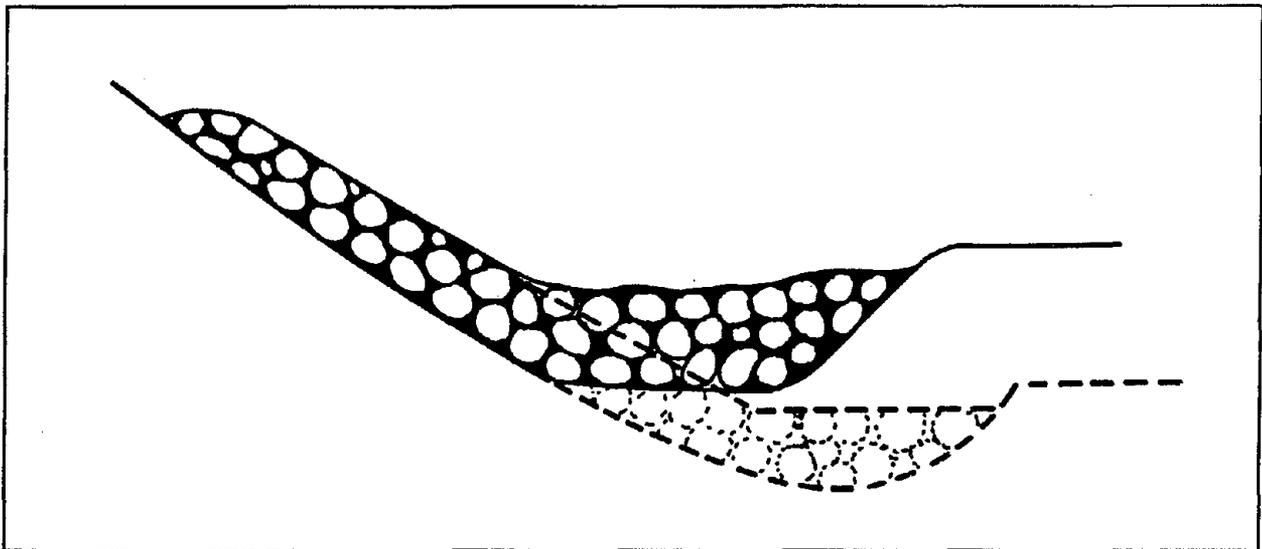


Figure 48. Rock-fill trench (after HIRE).<sup>(4)</sup>

An alternative to a rock-fill trench at the toe of the bank is to excavate a trench above the water line along the top of the bank and fill the trench with rocks. As the bank erodes, stone material in the trench is added on an as-needed basis until equilibrium is established. This method is applicable in areas of rapidly eroding banks of medium to large size streams.

Windrow revetment (figure 49) consists of a supply of rock deposited along an existing bank line at a location beyond which additional erosion is to be prevented. When bank erosion reaches and undercuts the supply of rock, it falls onto the eroding area, thus giving protection against further undercutting. The resulting bank line remains in a near natural state with an irregular appearance due to intermittent lateral erosion in the windrow location. The treatment particularly lends itself to the protection of adjacent wooded areas, or placement along stretches of presently eroding, irregular bank line.

The effect of windrow revetment on the interchange of flow between the channel and overbank areas and flood flow distribution in the flood plain should be carefully evaluated. Windrow installations will perform as guide banks or levees and may adversely affect flow distribution at bridges or cause local scour. Tying the windrow to the highway embankment at an abutment would be contrary to the purpose of the windrow since the rock is intended to fall into the channel as the bank erodes. The abutment is not intended to fall into the channel.

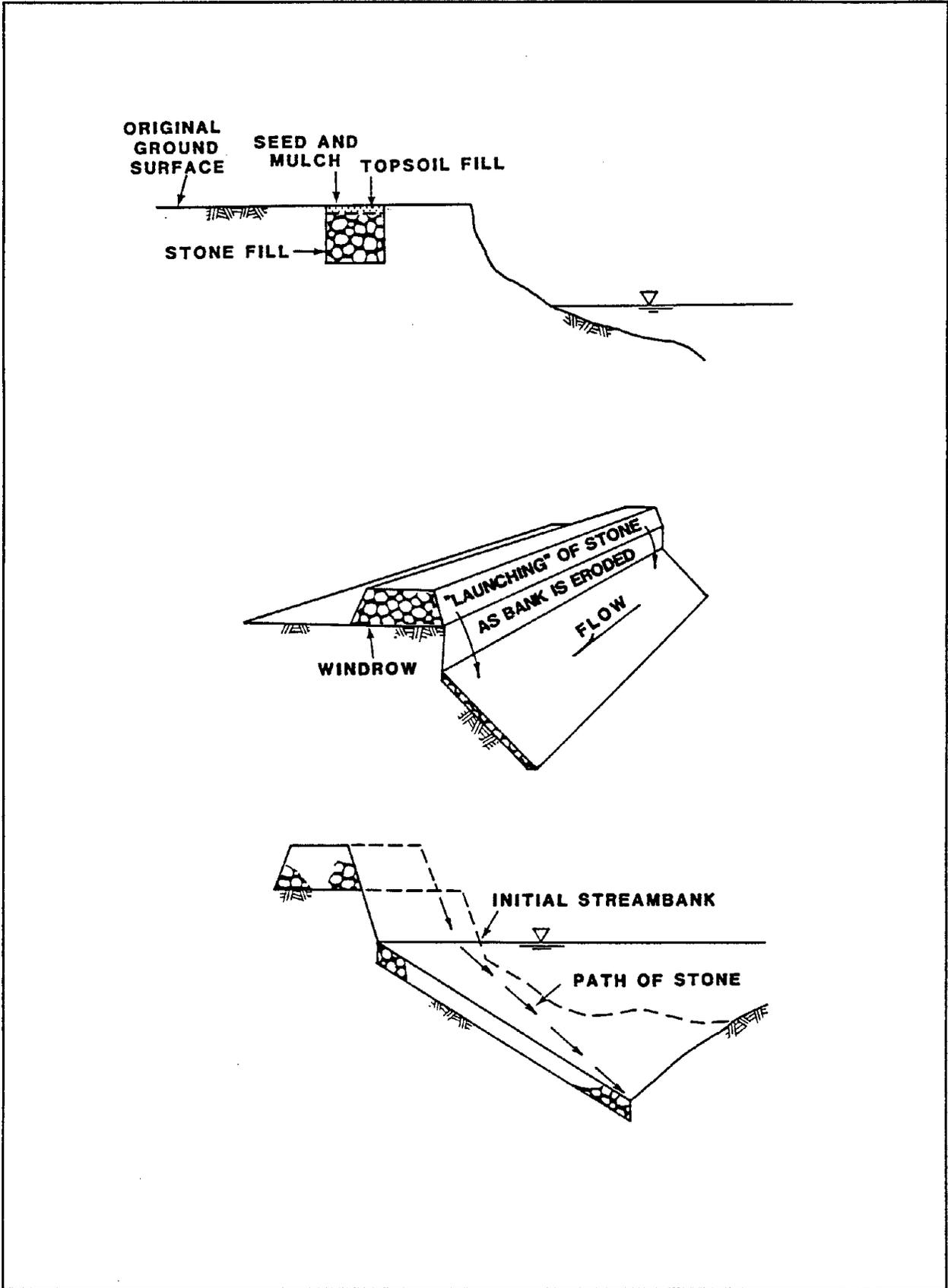


Figure 49. Windrow revetment, definition sketch (after USACOE).<sup>(43)</sup>

The following observations and conclusions from model investigations of windrow revetments and rock-fill trenches may be used as design guidance. More definitive guidance is not presently available.<sup>(43)</sup>

- The application rate of stone is a function of channel depth, bank height, material size, and estimated bed scour.
- A triangular windrow is the least desirable shape, a trapezoidal shape provides a uniform blanket of rock on an eroding bank, and a rectangular shape provides the best coverage. A rectangular shape is most easily placed in an excavated trench.
- Bank height does not significantly affect the final revetment; however, high banks tend to produce a nonuniform revetment alignment. Large segments of bank tend to break loose and rotate slightly on high banks, whereas low banks simply "melt" or slough into the stream.
- Stone size influences the thickness of the final revetment, and a smaller gradation of stone forms a more dense, closely chinked protective layer. Stones must be large enough to resist being transported by the stream, and a well-graded stone should be used to ensure that the revetment does not fail from leaching of the underlying bank material. Large stone sizes require more material than smaller stone sizes to produce the same relative thickness of revetment. In general, the greater the stream velocity, the steeper the side slope of the final revetment. The final revetment slope will be about 15 percent flatter than the initial bank slope.
- A windrow segment should be extended landward from the upstream end to reduce the possibility of outflanking of the windrow.

Used Tire Revetments. Used tire revetments have been successfully used for velocities up to 3 m/s on mild bends. They will accommodate a limited amount of bank subsidence, but usually will be damaged where substantial subsidence occurs. They are not well-suited for use where scour at the toe of the installation would undermine the revetment, but a riprap launching apron or toe trench will alleviate this problem to some extent. Used tire revetments are somewhat unsightly and vandalism has proved to be more of a problem than for other schemes of bank protection. Construction is labor-intensive and is therefore expensive.

The following precautions should be followed to ensure that the mattress will stay in place on an eroding bank:

- The tires must be banded together; alternatively, cable running the length and width of the mattress can be woven through the tires.
- The top, toe and the upstream and downstream ends of the mattress must be tied to the bank (figure 50). Riprap should be placed at the toe of the mattress for protection against scour.

While the above precautions are essential to a stable mattress, other measures can also help to ensure stability. They are:

- Cut, drill or burn holes in the tire sidewalls to prevent flotation.
- Sort the tires by size to help in fitting them together.
- Fasten the mattress to the bank at intervals with earth screw anchors (or some other type of anchor).
- Pack the tires with stone or rubble.
- Plant willows or other fast growing, thick brush inside the tires. Once established, the root system will strengthen the bank and the willows will obscure the somewhat unsightly mattress and decrease flow velocities near the bank. If willows are not readily available, other species should be planted. Possible species for use are discussed under vegetation.

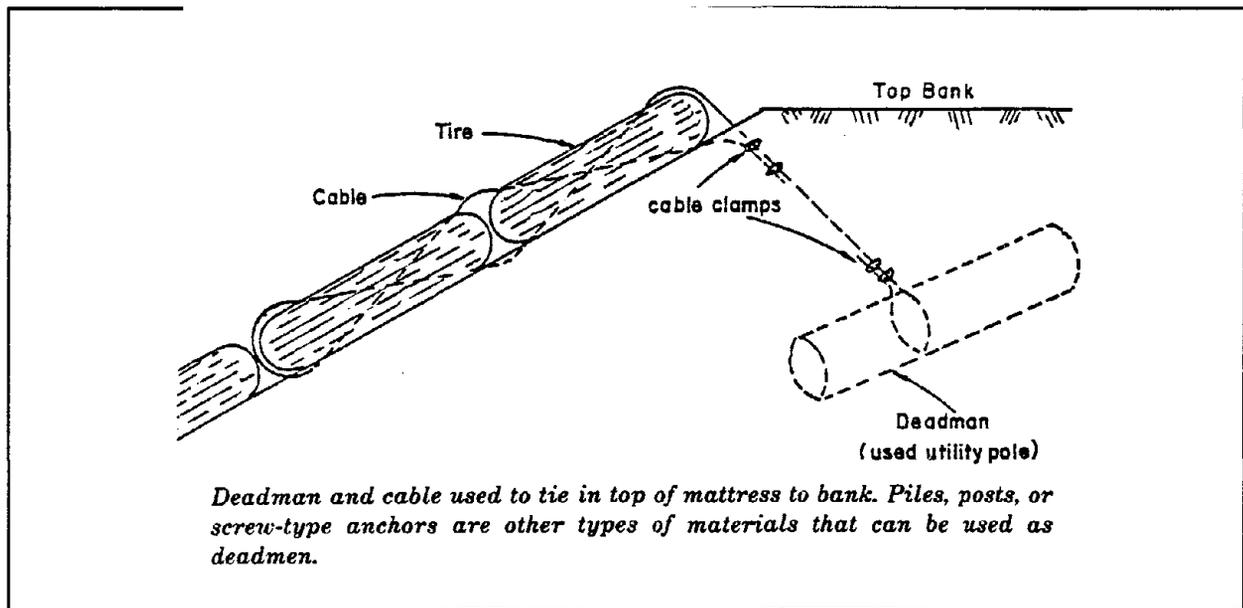


Figure 50. Used tire mattress (after Keown).<sup>(54)</sup>

If the mattress effectively controls the streambank erosion and remains intact, sediment may gradually cover the revetment. If willows have not been planted, volunteer vegetation may become established.

Vegetation. Vegetation is the most natural method for protecting streambanks because it is relatively easy to establish and maintain and is visually attractive. However, vegetation should not be seriously considered as a countermeasure against severe bank erosion where a highway facility is at risk. At such locations, vegetation can best serve to supplement other countermeasures.

Vegetation can effectively protect a bank below the water line in two ways. First, the root system helps to hold the soil together and increases overall bank stability by forming a binding network. Second, the exposed stalks, stems, branches and foliage provide resistance to flow, causing the flow to lose energy by deforming the plants rather than by removing soil particles. Above the water line, vegetation prevents surface erosion by absorbing the impact of falling raindrops and reducing the velocity of overbank flow and rainfall runoff. Further, vegetation provides additional capacity for infiltration by taking water from the soil, and may improve bank stability by water withdrawal.

Vegetation is generally divided into two broad categories: grasses and woody plants (trees and shrubs). A major factor affecting species selection is the length of time required for the plant to become established on the slope. Grasses are less costly to plant on an eroding bank and require a shorter period of time to become established. Woody plants offer greater protection against erosion because of more extensive root systems; however, under some conditions the weight of the plant will offset the advantage of the root system. On high banks, tree root systems may not penetrate to the toe of the bank. If the toe becomes eroded, the weight of the tree and its root mass may cause a bank failure.

Water-tolerant grasses such as canarygrass (*Phalaris*), reedgrass (*Calamagrostis*), cordgrass (*Spartina*), and fescue (*Festuca*) are effective in preventing erosion on upper banks which are inundated from time to time and are subject to erosion due primarily to rainfall, overland flow, and minor wave action. Along the lower bank, where erosive forces are high, vegetation is generally not effective as a protective measure; however, cattails (*Typha*), bulrushes (*Scripus*), reeds (*Phragmites*), knotweed and smartweed (*Polygonum*), rushes (*Juncus*), and mannagrass (*Glyceria*) are helpful in inducing deposition and reducing velocities in shallow water or wet areas at the bank toe and in protecting the bank in some locations. Willows (*Salix*) are among the most effective woody

plants in protecting low banks because they are resilient, are sufficiently dense to promote deposition of sediment, can withstand inundation, and easily become established.

**Rigid Revetments.** Rigid revetments include portland-cement paving, concrete filled mats, sand and cement bags, grouted riprap, and soil cement. Rigid revetments are generally smoother than flexible revetments and thus improve hydraulic efficiency and are generally highly resistant to erosion and impact damage. They are susceptible to damage from the removal of foundation support by subsidence, undermining, hydrostatic pressures, slides, and erosion at the perimeter. They are also among the most expensive streambank protection countermeasures.

**Concrete Pavement.** Concrete paving should be used only where the toe can be adequately protected from undermining and where hydrostatic pressures behind the paving will not cause failure. This might include impermeable bank materials and portions of banks which are continuously under water. Sections intermittently above water should be provided with weep holes. Refer to HEC-11 for design of concrete pavement revetment.<sup>(42)</sup>

**Soil Cement.** In areas where riprap is scarce, use of in-place soil combined with cement can sometimes provide a practical alternative. Figure 51 shows a detail of typical soil-cement construction for bank protection. For use in soil cement, soils should be easily pulverized and contain at least 5 percent, but not more than 35 percent, silt and clay (material passing the No. 200 sieve). Finer textured soils usually are difficult to pulverize and require more cement as do 100 percent granular soils which have no material passing the No. 200 sieve. Soil cement can be placed and compacted on slopes as steep as two horizontal to one vertical. Best results have been achieved on slopes no steeper than 1V:3H. However, in the arid Southwest a 1V:1H slope is generally used for stair-stepped soil cement. Where velocities exceed 1.8 to 2.4 m/s and the flow carries sufficient bed load to be abrasive, aggregates should contain at least 30 percent gravel particles retained on a No. 4 (4.75 mm) sieve.

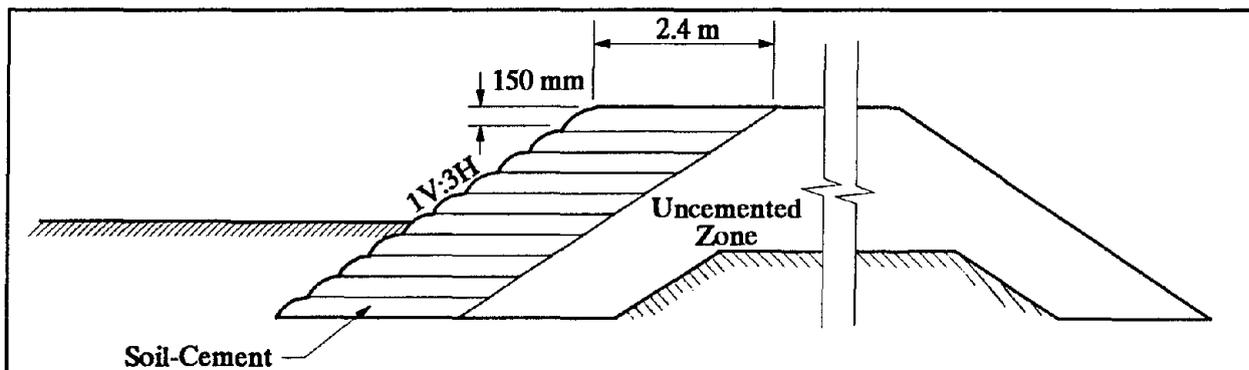


Figure 51. Typical soil-cement bank protection (after HIRE).<sup>(4)</sup>

A stair-step construction is recommended on channel banks with relatively steep slopes. Placement of small quantities of soil-cement for each layer (150 mm layers) can progress more rapidly than a large quantity of fill material. Special care should be exercised to prevent raw soil seams between successive layers of soil cement. A sheepsfoot roller should be used on the last layer at the end of a day to provide an interlock for the next layer. The completed soil-cement installation must be protected from drying out for a seven day hydration period. After completion, the material has sufficient strength to serve as a roadway along the embankment. Procedures for constructing soil-cement slope protection by the stair step method can be found in Portland Cement Association.<sup>(55,56)</sup>

A soil-cement blanket with 8 to 15 percent cement may be an economical and effective streambank protection method for use in areas where vegetation is difficult to establish and the bank material is predominantly sand. The sand can be mixed with cement by hand or mechanically to a depth of at least 100 mm. The mixture should then be wet down and allowed to set up. This method has the advantage of low cost. However, a soil-cement blanket has three major deficiencies: impermeability, low strength, and susceptibility to temperature variations. If the bank behind the blanket becomes saturated and cannot drain, failure may occur.

Also, because a sand-cement blanket is relatively brittle, very little if any vehicular, pedestrian, or livestock traffic can be sustained without cracking the thin protective veneer. In northern climates the blanket can break up during freeze-thaw cycles.

Precautions must be taken to prevent undermining at the toe and ends. Protection at the toe can be provided by extending the installation below estimated scour depth, by a riprap launching apron, or by a concrete or sheet pile cutoff-wall extending to bedrock or well below the anticipated scour elevation. Weep holes for relief of hydrostatic pressure are required for many situations.

**Sacks.** Burlap sacks filled with soil or sand-cement mixtures have long been used for emergency work along levees and streambanks during floods (figure 52). Commercially manufactured sacks (burlap, paper, plastics, etc.) have been used to protect streambanks in areas where riprap of suitable size and quality is not available at a reasonable cost. Sacks filled with sand-cement mixtures can provide long-term protection if the mixture has set up properly, even though most types of sacks are easily damaged and will eventually deteriorate. Sand-cement sack revetment construction is not economically competitive in areas where good stone is available. However, where quality riprap must be transported over long distances, sack revetment can often be placed at a lesser cost than riprap.

If a permanent revetment is to be constructed, the sacks should be filled with a mixture of 15 percent cement (minimum) and 85 percent dry sand (by weight). The filled sacks should be placed in horizontal rows like common house brick beginning at an elevation below any toe scour (alternatively, riprap can be placed at the toe to prevent undermining of the bank slope). The successive rows should be stepped back approximately one-half-bag width to a height on the bank above which no protection is needed. The slope of the completed revetment should not be steeper than 1:1. After the sacks have been placed on the bank, they can be wetted down for a quick set or the sand-cement mixture can be allowed to set up naturally through rainfall, seepage or condensation. If cement leaches through the sack material, a bond will form between the sacks and prevent free drainage. For this reason, weepholes should be included in the revetment design. The installation of weepholes will allow drainage of groundwater from behind the revetment thus helping to prevent pressure buildup that could cause revetment failure. This revetment requires the same types of toe protection as other types of rigid revetment.

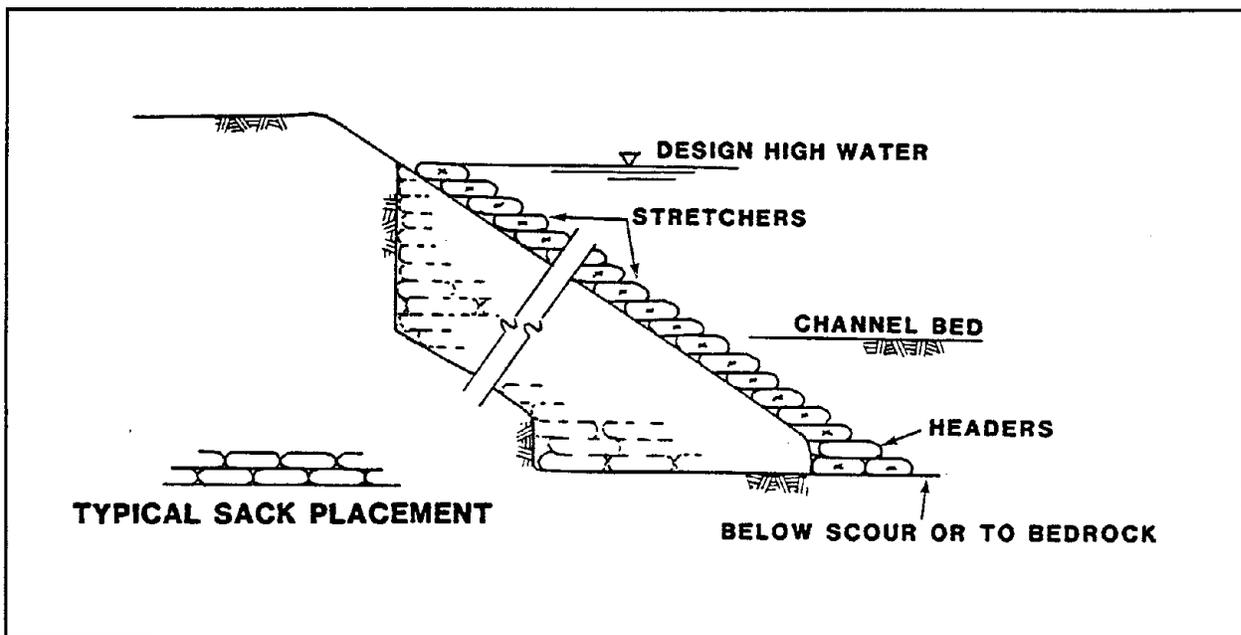


Figure 52. Typical sand-cement bag revetment (Modified from California Department of Public Works, 1970 (after Brown).<sup>(41)</sup>)

**Grouted Riprap.** Grouted riprap consists of rock slope protection with voids filled with concrete grout to form a monolithic armor. It is generally used where rock of sufficient size, gradation, or quantity is not economically available to install riprap revetment. Grouted riprap is rigid but not extremely strong; therefore, support by the streambank is essential. Precautions against failure from hydrostatic pressure behind the riprap are appropriate, as well as provisions to prevent undermining at the toe of the bank and at the termini of the installation. Refer to HEC-11 for design guidance.<sup>(42)</sup>

**Concrete-Filled Mats.** Concrete filled mats consist of fabric envelopes pumped full with sand and cement grout. This product is marketed under the names "Fabriform," "Fabricast," and "Enkamat" and are protected under various United States and foreign patents or patents pending.

Concrete-filled mats have not performed well in high-velocity environments. More experience with the use of these measures is advisable before they are used at high-risk locations.

### 6.6.2 Hardpoints

Hardpoints consist of stone fills spaced along an eroding bank line, protruding only short distances into the channel. A root section extends landward to preclude flanking. The crown elevation of hardpoints used by the USACOE at demonstration sites on the Missouri River was generally at the normal water surface elevation at the toe, sloping up at a rate of about 1 in 10 m toward the bank. Hardpoints are most effective along straight or relatively flat convex banks where the streamlines are parallel to the bank lines and velocities are not greater than 3 m/s within 15 m of the bank line. Hardpoints may be appropriate for use in long, straight reaches where bank erosion occurs mainly from a wandering thalweg at lower flow rates. They would not be effective in halting or reversing bank erosion in a meander bend unless they were closely spaced, in which case spurs, retarder structures, or bank revetment would probably cost less. Figure 53 is a perspective of a hardpoint installation. Hardpoints have been used effectively as the first "spur" in a spur field.

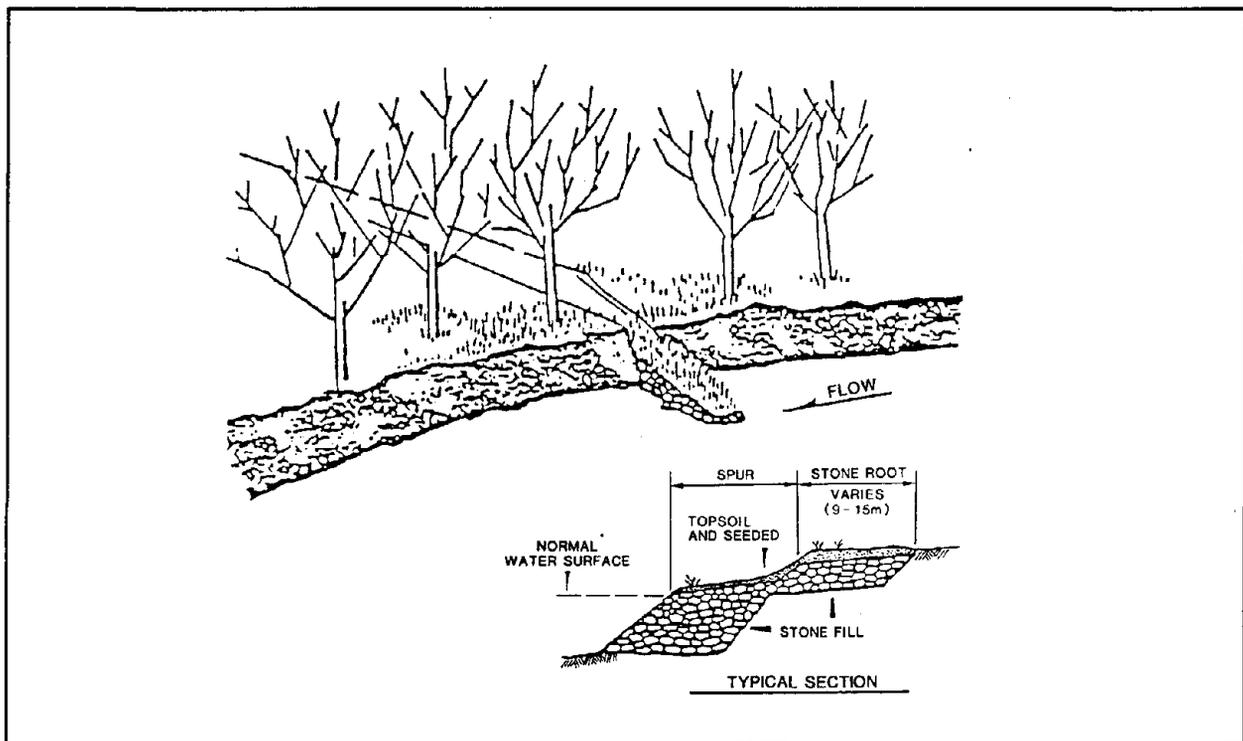


Figure 53. Perspective view of hardpoint installation with section detail (after Brown).<sup>(41)</sup>

### 6.6.3 Retarder Structures

Retarder structures are permeable devices generally placed parallel to streambanks to reduce velocities and cause deposition near the bank. They are best suited for protecting low banks or the lower portions of streambanks. Retarder structures can be used to protect an existing bank line or to establish a different flow path or alignment. Retards do not require grading of the streambank, and they create an environment which is favorable to the establishment of vegetation.

Jacks and Tetrahedrons. Jacks most commonly consist of three linear members fixed together at their midpoints so that each member is perpendicular to the other two. Wires are strung on the members to resist distortion and to collect debris. Cables are used to tie individual jacks together and for anchoring key units to deadmen. Tetrahedrons consist of six members of equal length fixed together so as to form three faces, each of which is an equilateral triangle, i.e., a tetrahedron. The tetrahedron unit may be braced as shown in figure 54 and wire mesh added to enhance flow retardance. Tetrahedrons are not as widely used as are jacks.

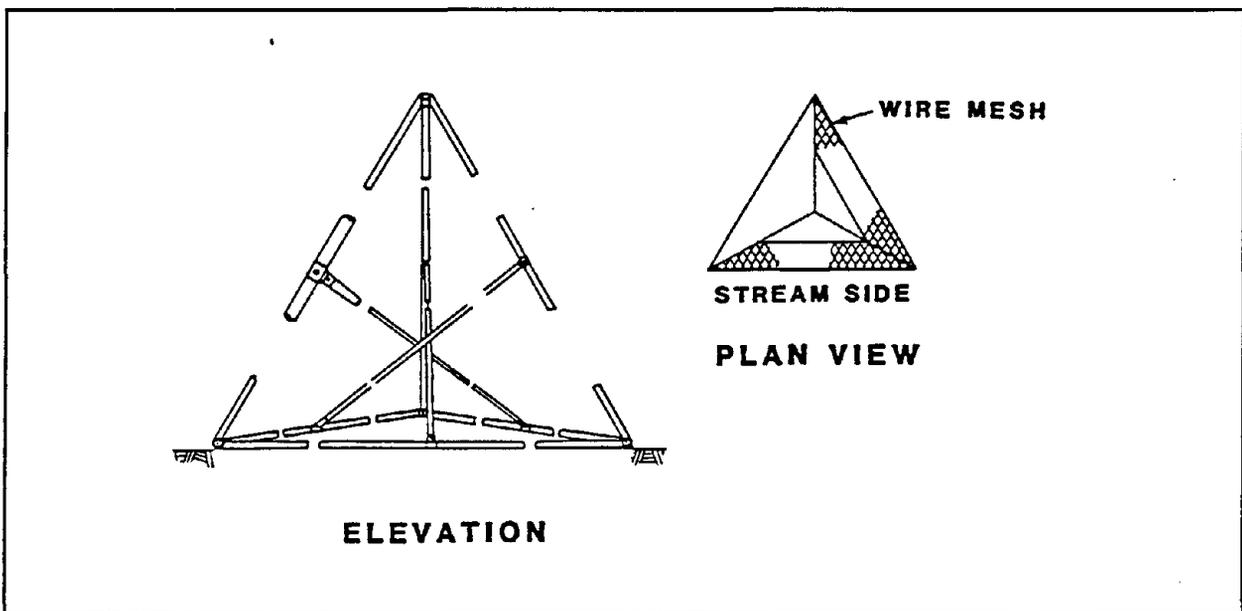


Figure 54. Typical tetrahedron design (after Brown).<sup>(41)</sup>

Jacks and tetrahedrons are effective in protecting banks from erosion only if light debris collects on the structures thereby enhancing their performance in retarding flow. However, heavy debris and ice can damage the structures severely. They are most effective on mild bends and in wide, shallow streams which carry a large sediment load.

Where jacks are used to stabilize meandering streams, both lateral and longitudinal rows are often installed to form an area retarder structure rather than a linear structure. Lateral rows of jacks are usually oriented in a downstream direction from 45° to 70°. Spacing of the lateral rows of jacks may be 15 to 75 m depending on the debris and sediment load carried by the stream. A typical jack unit is shown in figure 55 and a typical area installation is shown in figure 56.

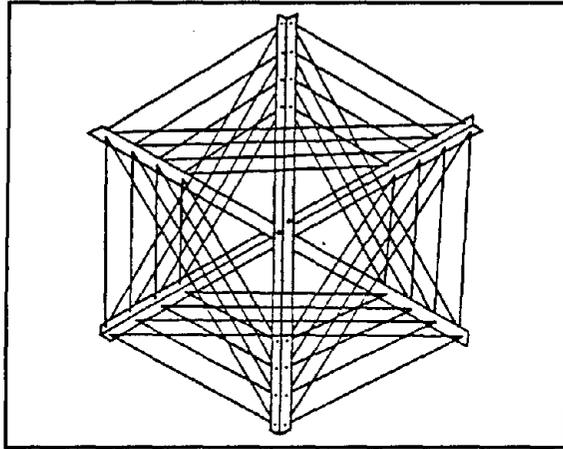


Figure 55. Typical jack unit (after Brown).<sup>(41)</sup>

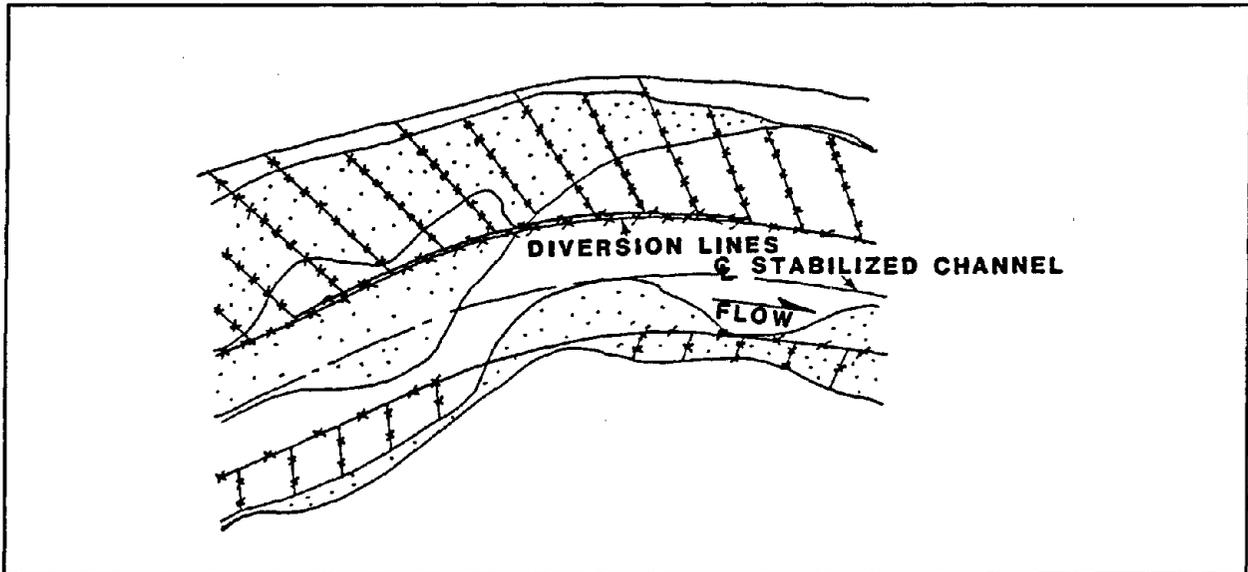


Figure 56. Retarder field schematic (after HIRE).<sup>(4)</sup>

Outflanking of jack installations is a common problem. Adequate transitions should be provided between the upstream bank and the structure, and the jack field should be extended to the overbank area to retard flow velocities and provide additional anchorage. Jacks are not recommended for use in corrosive environments or at locations where they would constitute a hazard to recreational use of the stream.

**Fence Retarder Structures.** Fence retarder structures provide protection to the lower portions of banks of relatively small streams. Posts may be of wood, steel, or concrete and fencing may be composed of wood planks or wire.

Scour and the development of flow channels behind linear structures are common causes of failure of longitudinal fences. Scour at the supporting members of the structure can be reduced by placing rock along the fence or the effects of scour can be overcome by driving supporting members to depths below expected scour. Tiebacks can be used to retard velocities between the linear structure and the streambank, thus reducing the ability of the stream to develop flow channels behind the structure.

**Timber Pile.** Timber pile retarder structures may be of a single, double, or triple row of piles with the outside of the upstream row faced with wire mesh or other fencing material. They have been found to be effective at sharp bends in the channel and where flows are directly attacking a bank. They are effective in streams which carry heavy debris and ice loads and where barges or other shipping vessels could damage other countermeasures or a bridge. As with other retarder structures, protection against scour failure is essential. Figure 57 illustrates a design.

**Wood Fence.** Wood fence retarder structures have been found to provide a more positive action in maintaining an existing flow alignment and to be more effective in preventing lateral erosion at sharp bends than other retarder structures. Figure 58 is an end view of a typical wood fence design with rock provided to protect against scour.

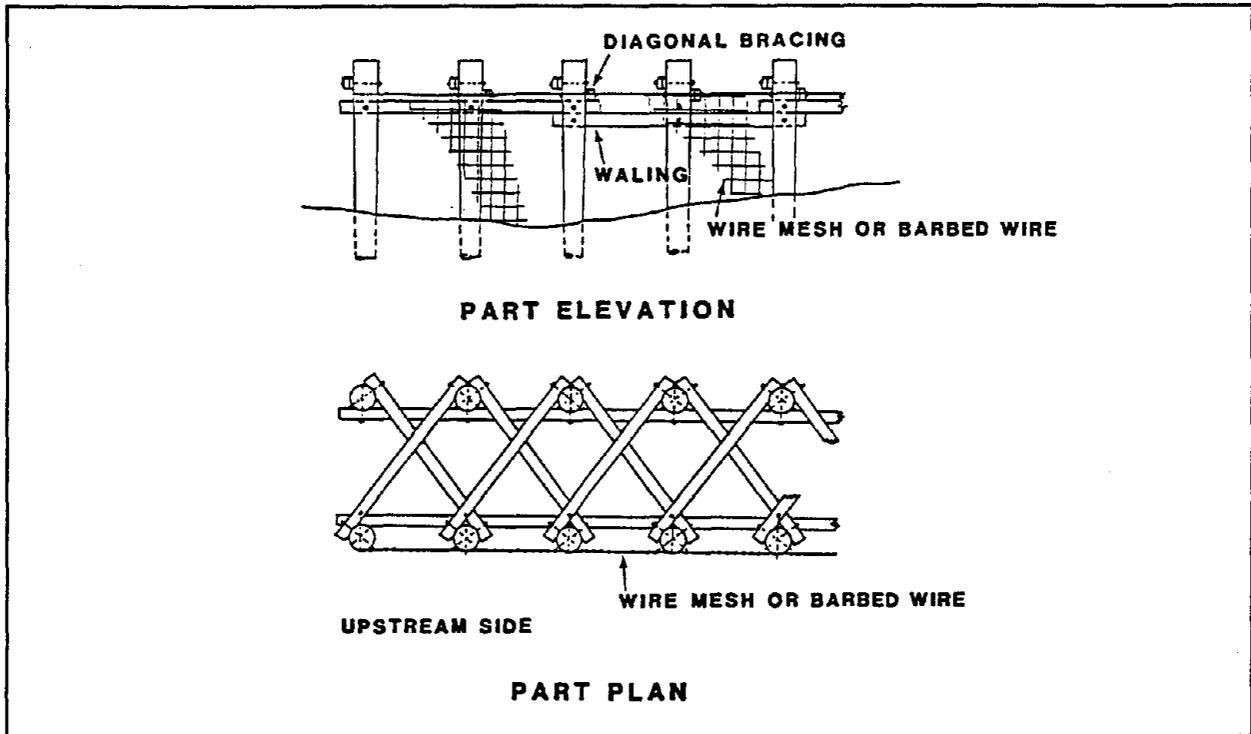


Figure 57. Timber pile bent retarder structure (Modified from California Department of Public Works, 1970 (after Brown).<sup>(41)</sup>)

Wire fence retarder structures may be of linear or area configuration, and linear configurations may be of single or multiple fence rows. Double-row fence retards are sometimes filled with brush to increase the flow retardance. Figures 59 and 60 illustrate two types of wire fence retarder structures.

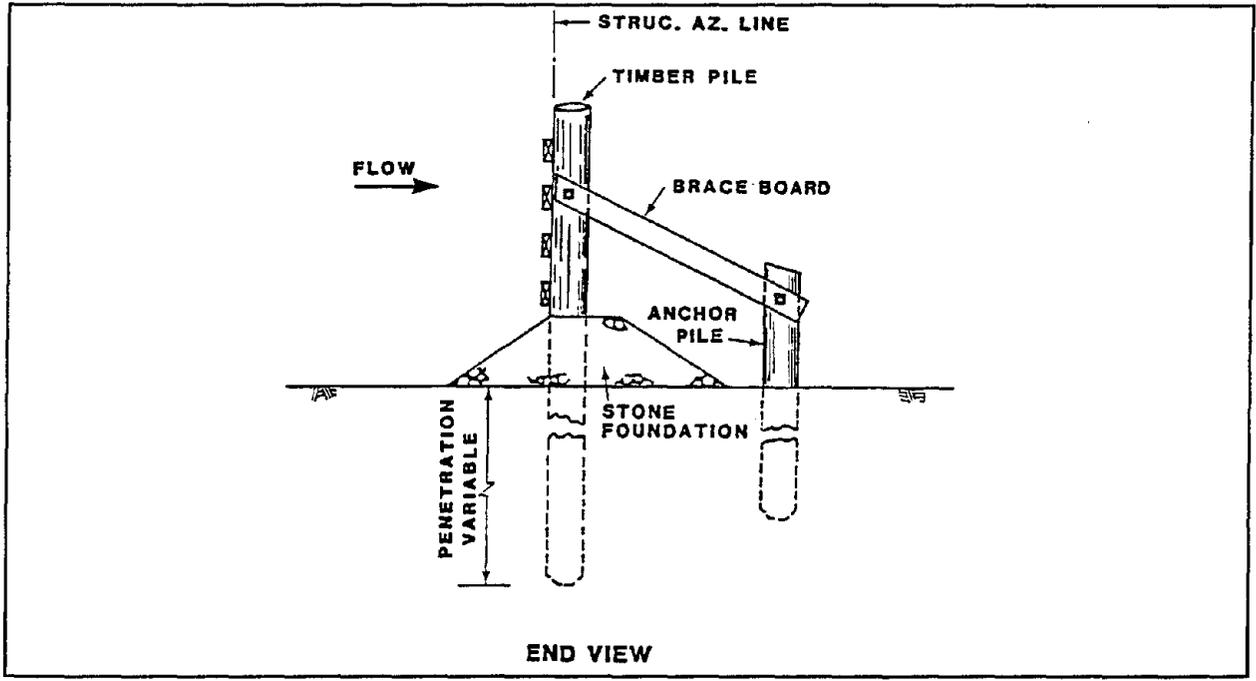


Figure 58. Typical wood fence retarder structure (modified from USACOE, 1981, after Brown).<sup>(41)</sup>

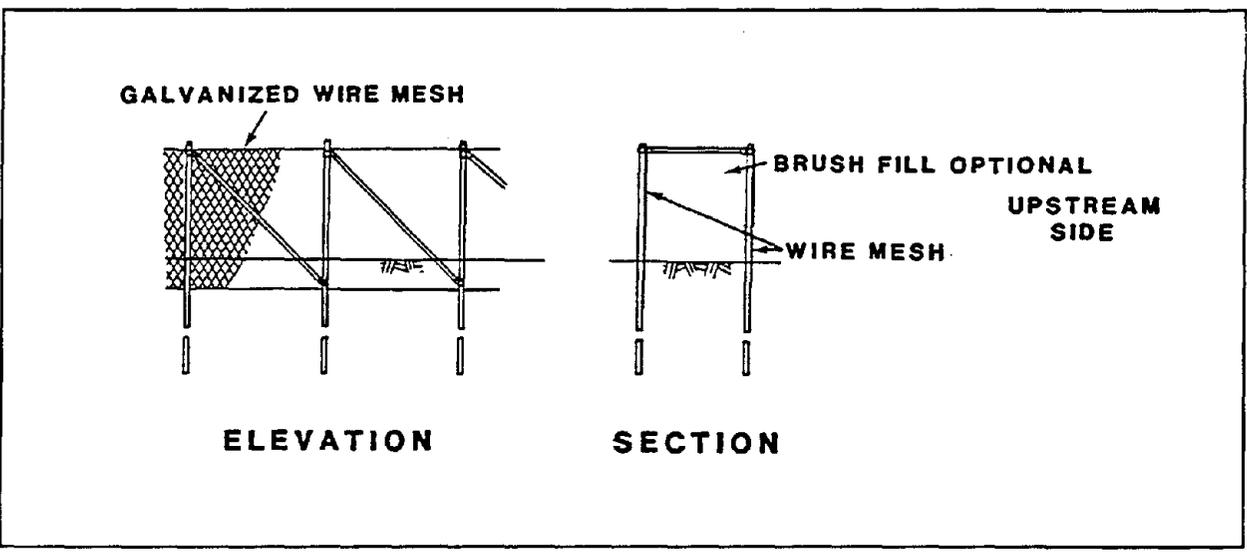


Figure 59. Light double row wire fence retarder structure (after Brown).<sup>(41)</sup>

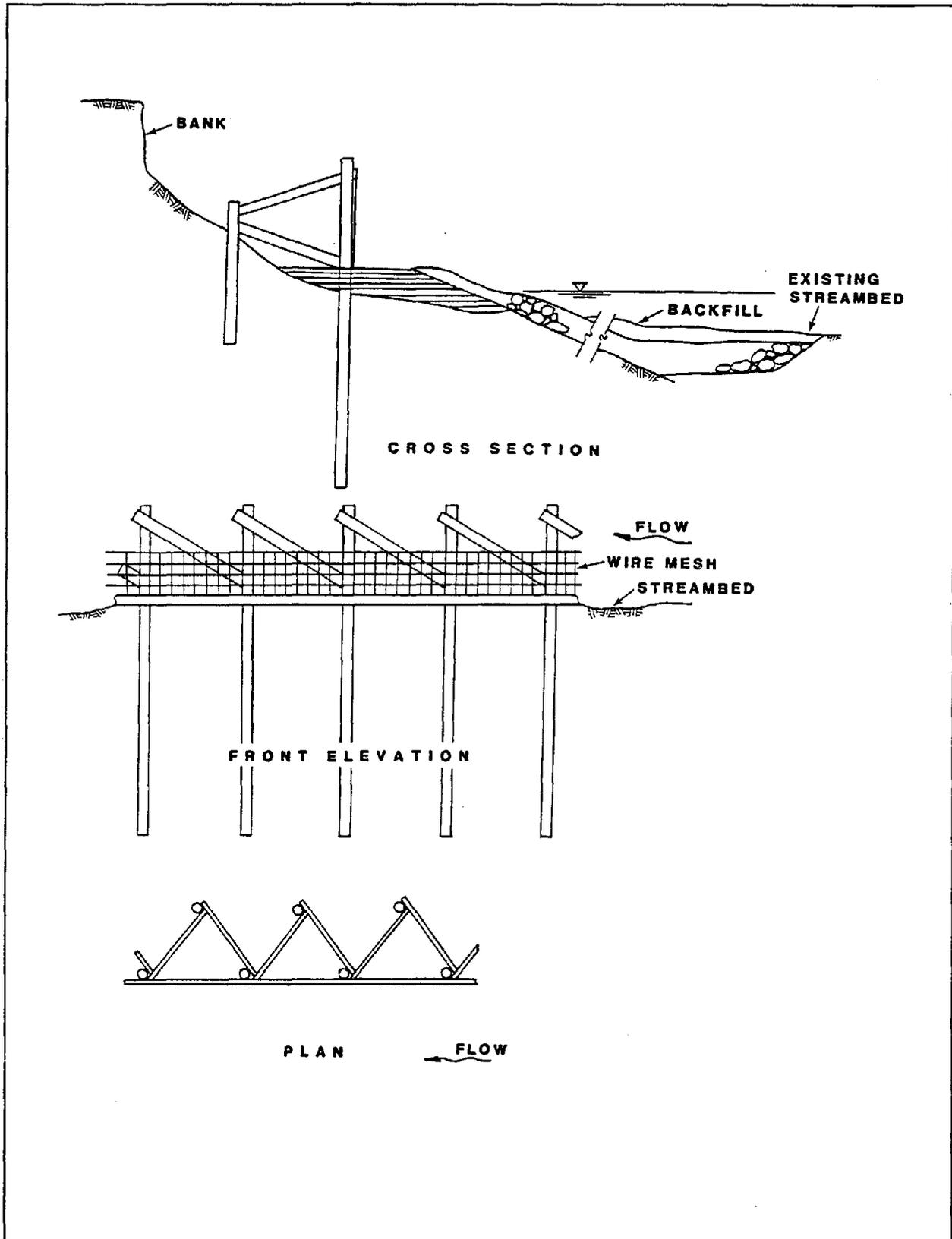


Figure 60. Heavy timber-pile and wire fence retarder structures (Modified from USACOE, after Brown).<sup>(41,43)</sup>

#### 6.6.4 Longitudinal Dikes

Longitudinal dikes are essentially impermeable linear structures constructed parallel with the streambank or along the desired flow path. They protect the streambank in a bend by moving the flow current away from the bank. Longitudinal dikes may be classified as earth or rock embankment dikes, crib dikes, or rock toe-dikes.

Earth or Rock Embankments. As the name implies, these dikes are constructed of earth with rock revetment or of rock. They are usually as high or higher than the original bank. Because of their size and cost, they are useful only for large-scale channel realignment projects.

Rock Toe-Dikes. Rock toe-dikes are low structures of rock riprap placed along the toe of a channel bank. They are useful where erosion of the toe of the channel bank is the primary cause of the loss of bank material. The USACOE has found that longitudinal stone dikes provide the most successful bank stabilization measure studied for channels which are actively degrading and for those having very dynamic beds. Where protection of higher portions of the channel bank is necessary, rock toe-dikes have been used in combination with other measures such as vegetative cover and retarder structures.

Figure 61 shows the typical placement and sections of rock toe-dikes. The volume of material required is 1.5 to 2 times the volume of material that would be required to armor the sides of the anticipated scour to a thickness of 1.5 times the diameter of the largest stone specified. Rock sizes should be similar to those specified for riprap revetments. Tiebacks are often used with rock toe-dikes to prevent flanking, as illustrated in figure 62. Tiebacks should be used if the toe-dike is not constructed at the toe of the channel bank.

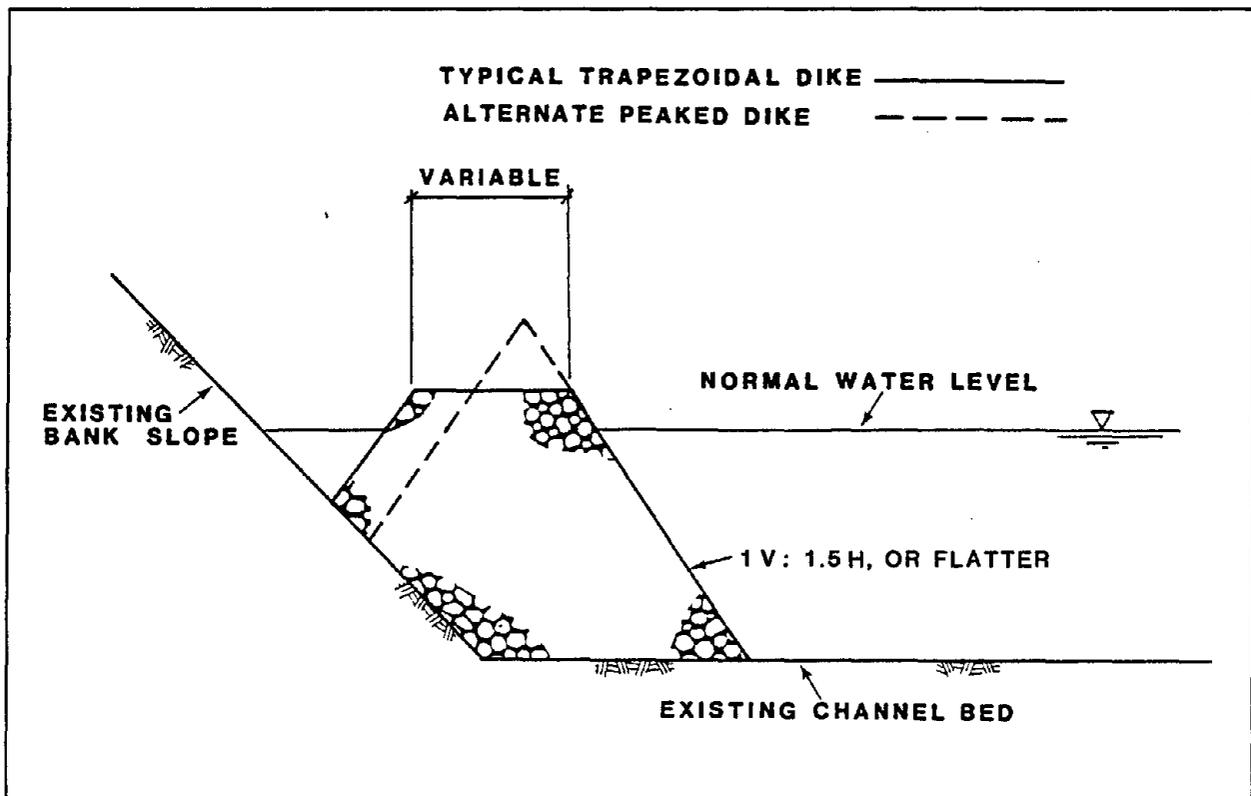


Figure 61. Typical longitudinal rock toe-dike geometries (after Brown).<sup>(41)</sup>

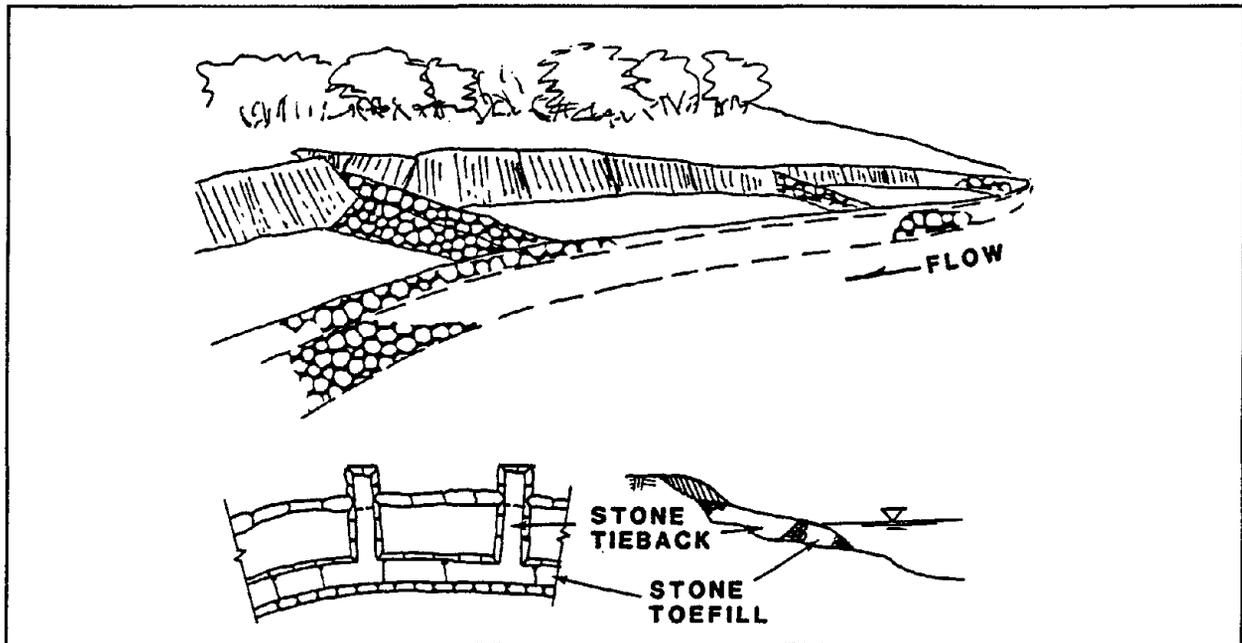


Figure 62. Longitudinal rock toe-dike tiebacks (after Brown).<sup>(41)</sup>

Rock toe-dikes are useful on channels where it is necessary to maintain as wide a conveyance channel as possible. Where this is not important, spurs could be more economical since scour is a problem only at the end projected into the channel. However, spurs may not be a viable alternative in actively degrading streams.

**Crib Dikes.** Longitudinal crib dikes consist of a linear crib structure filled with rock, straw, brush, automobile tires or other materials. They are usually used to protect low banks or the lower portions of high banks. At sharp bends, high banks would need additional protection against erosion and outflanking of the crib dike. Tiebacks can be used to counter outflanking.

Crib dikes are susceptible to undermining, causing loss of material inside the crib, thereby reducing the effectiveness of the dike in retarding flow. Figure 63 illustrates a crib dike with tiebacks and a rock toe on the stream side to prevent undermining.

#### 6.6.5 Bulkheads

Bulkheads are used for purposes of supporting the channel bank and protecting it from erosion. They are generally used as protection for the lower bank and toe, often in combination with other countermeasures that provide protection for higher portions of the bank. Bulkheads are most frequently used at bridge abutments as protection against slumping and undermining at locations where there is insufficient space for the use of other types of bank stabilization measures, and where saturated fill slopes or channel banks cannot otherwise be stabilized.

Bulkheads are classified on the basis of construction methods and materials. They may be constructed of concrete, masonry, cribs, sheet metal, piling, reinforced earth, used tires, gabions, or other materials. They must be protected against scour or supported at elevations below anticipated scour, and where sections of the installation are intermittently above water, provisions must be made for seepage through the wall. Some bulkhead types, such as crib walls and gabions, should be provided with safeguards against leaching of materials from behind the wall.

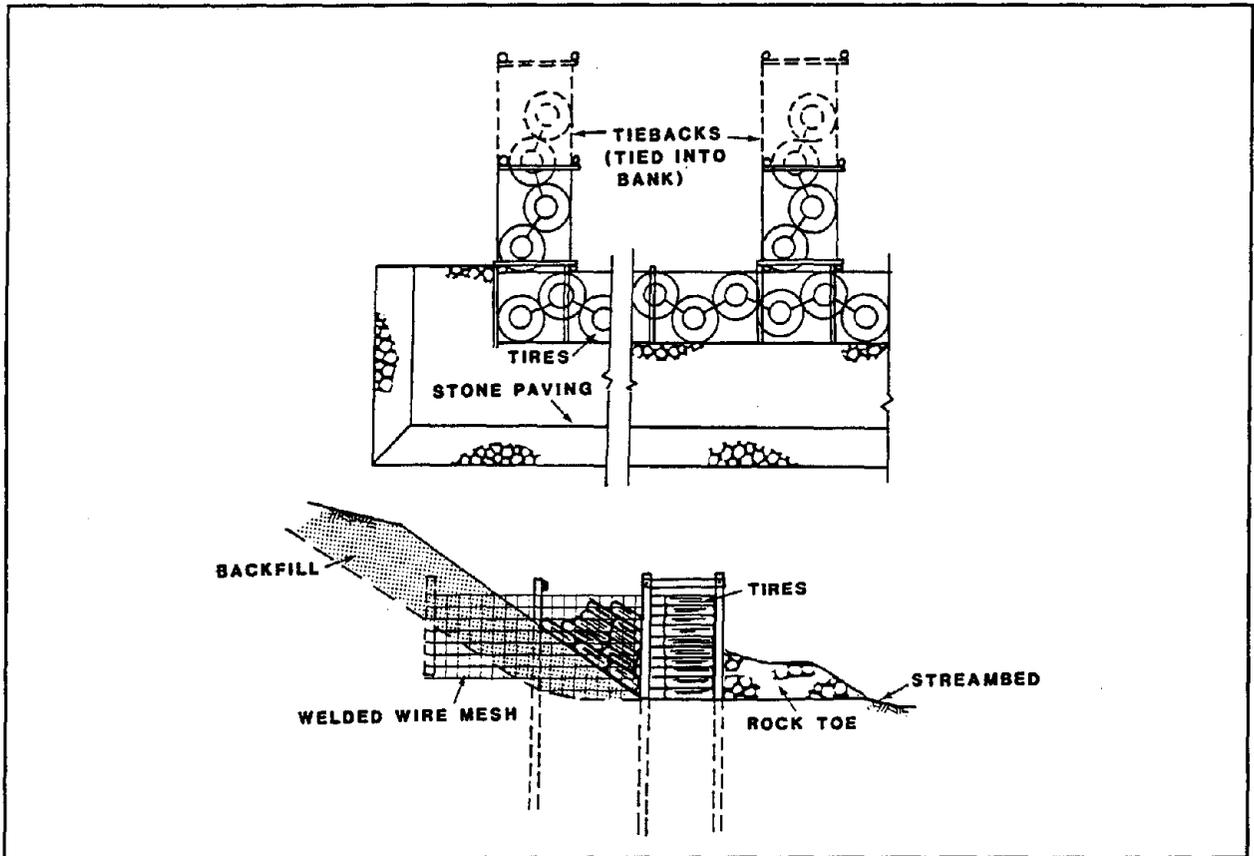


Figure 63. Timber pile, wire mesh crib dike with tiebacks (modified from USACOE, after Brown).<sup>(41,43)</sup>

Bulkheads must be designed to resist the forces of overturning, bending and sliding, either by their mass or by structural design. Figure 64 illustrates anchorage schemes for a sheetpile bulkhead. Because of costs, they should be used as countermeasures against meander migration only where space is not available to construct other types of measures.

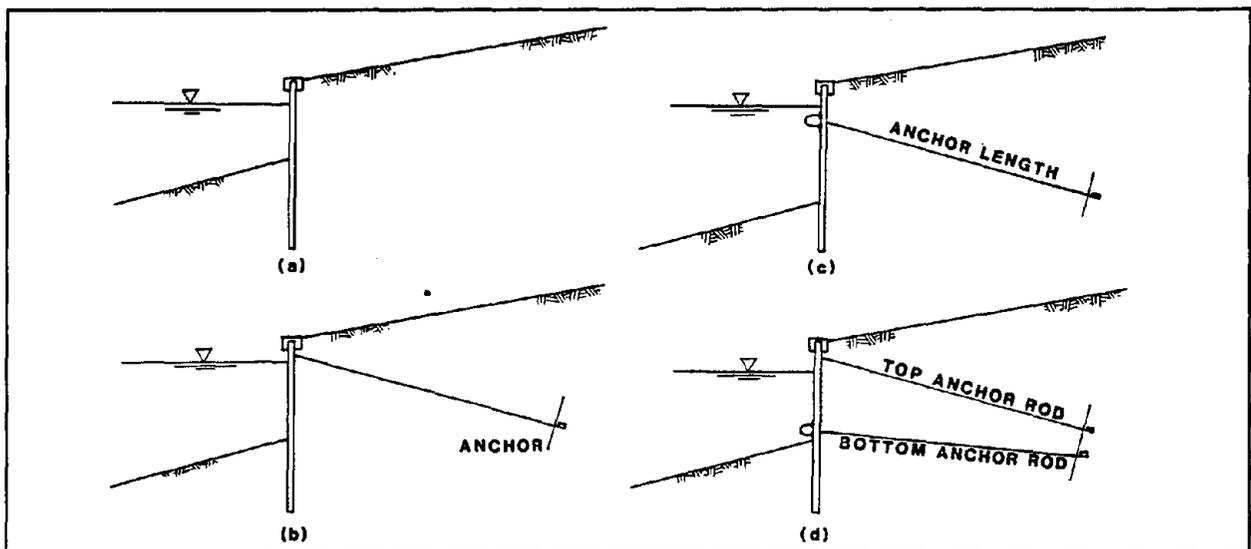


Figure 64. Anchorage schemes for a sheetpile bulkhead (after Brown).<sup>(41)</sup>

### 6.6.6 Channel Relocation

At some locations, it may be advantageous to realign a stream channel, either in combination with the use of other countermeasures against meander migration or in lieu of other countermeasures.

Figure 65 illustrates hypothetical highway locations fixed by considerations other than stream stability. To create better flow alignment with the bridge, consideration could be given to channel realignment as shown in this figure (parts a and b). Similarly, consideration for realignment of the channel would also be advisable for a hypothetical lateral encroachment of a highway as depicted in part c of the figure. In either case, criteria are needed to establish the cross-sectional dimensions.

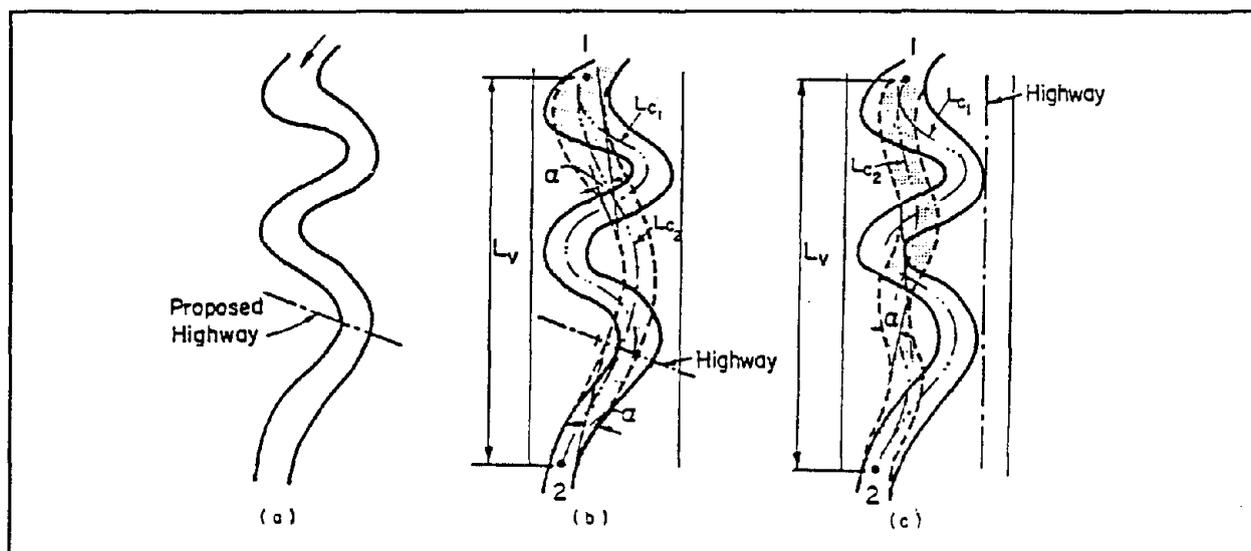


Figure 65. Encroachments on meandering streams (after HIRE).<sup>(4)</sup>

Prior to realigning a stream channel, the stability of the existing channel must be examined. The stream classification, recent and older aerial photographs, and field surveys are necessary. The realigned channel may be made straight without curves, or may include one or more curves. If curves are included, decisions regarding the radius of curvature, the number of bends, the limits of realignment (hence the length and slope of the channel) and the cross-sectional area have to be made. Different streams have different historical backgrounds and characteristics with regard to bend migration, discharge, stage, geometry, and sediment transport, and an understanding and appreciation of river hydraulics and morphology is important to decision making. It is difficult to state generalized criteria for channel relocation applicable to all streams. Knowledge about stream systems has not yet advanced to such a state as to make this possible. Nevertheless, some principles and guidelines can be provided (See chapters 2 through 4).

As the general rule, bend radii in realigned channels should be made about equal to the mean radius of bends,  $r_c$ , in extended reaches of the stream. Where the angle defined in figure 66 exceeds about  $40^\circ$ , there is a sufficient crossing length for the thalweg to shift from one side of the channel to the other. Generally, it may be necessary to stabilize the outside banks of curves in order to hold the new alignment and, depending upon crossing length, some maintenance may be necessary to remove sandbars after large floods so that the channel does not develop new meander patterns.

Sinuosity and channel bed slope are related in that the total drop in bed elevation for the old channel and the relocated channel are the same. Thus, the mean slope of the channel bed after relocation (subscript 2) is greater than the mean slope of the original channel bed (subscript 1), ( $S_2 > S_1$ ). If the larger slope,  $S_2$ , will not satisfy the equation, ( $SQ^{0.25} \leq 0.0041$ ), the possibility of the stream changing to a braided channel because of the steeper slope should be carefully evaluated (see section 2.3). With the steeper slope, there could be an increase in sediment transport which could cause degradation, and the effect

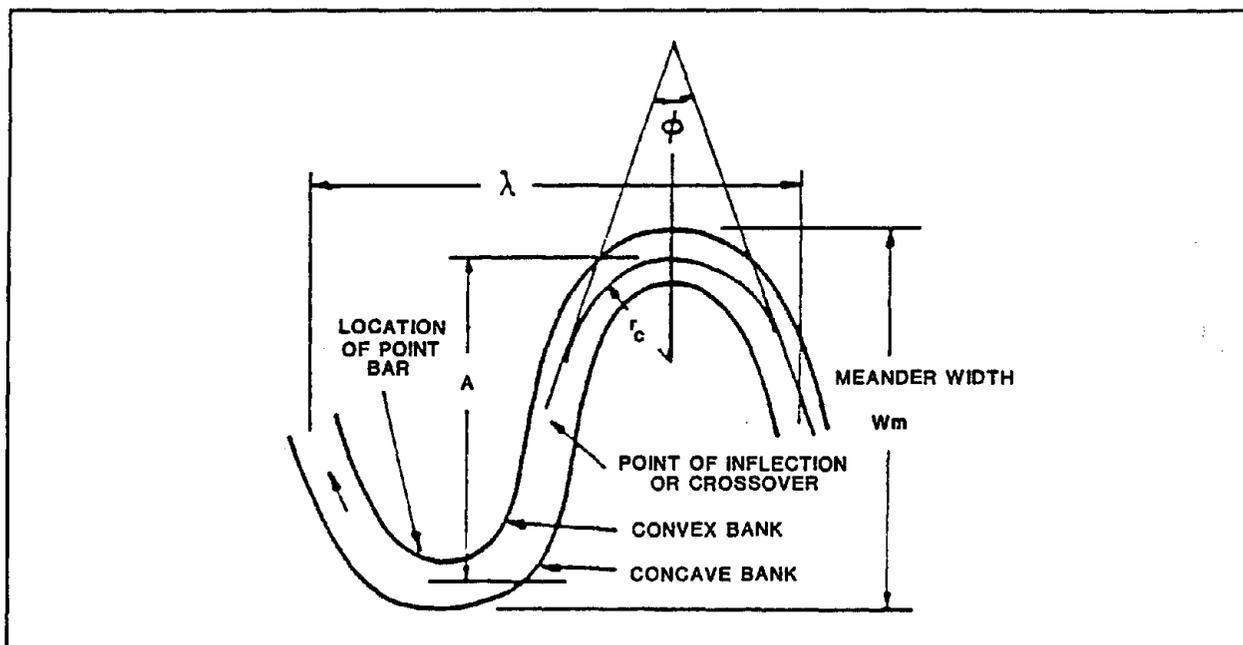


Figure 66. Definition sketch for meanders (after HIRE).<sup>(4)</sup>

would be extended both upstream and downstream of the relocated reach. Also, meander patterns could change. Considerable bank protection might be necessary to contain lateral migration which is characteristic of a braided channel, and if the slope is sufficiently steep, head cuts could develop which migrate upstream with attendant effects on the plan geometry of the channel. Even where changes in slope are not very large, a short-term adjustment of the average stream slope occurs beyond the upstream and downstream limits of channel realignment, consistent with the sediment transport rate, flow velocities and roughness.

Based on a study of the stability of relocated channels, Brice presented the following recommendations and conclusions regarding specific aspects of planning and construction of channel realignment:<sup>(57)</sup>

- Channel Stability Prior to Realignment. Assessment of the stability of a channel prior to realignment is needed to assess the risk of instability. An unstable channel is likely to respond unfavorably. Bank stability is assessed by field study and by stereoscopic examination of aerial photographs. The most useful indicators of bank instability are cut or slumped banks, fallen trees along the bank line, and exposed wide point bars. Bank recession rates are measured by comparison of time-sequential aerial photographs. Vertical instability is equally important but more difficult to determine. It is indicated by changes in channel elevation at bridges and gaging stations. Serious degradation is usually accompanied by generally cut or slumped banks along a channel and by increased debris transport.
- Erosional Resistance of Channel Boundary Materials. The stability of a channel, whether natural or relocated, is partly determined by the erosional resistance of materials that form the wetted perimeter of the channel. Resistant bedrock outcrops in the channel bottom or that lie at shallow depths will provide protection against degradation, but not all bedrock is resistant. Erosion of shale, or of other sedimentary rock types interbedded with shale, has been observed. Degradation is not a problem at most sites where bed sediment is of cobble and boulder size. However, degradation may result from the relocation of any alluvial channel, whatever the size of bed material, but the incidence of serious degradation of channels relocated by highway agencies is small in number. The erosional resistance of channel beds tends to increase with clay content. Banks of weakly cohesive sand or silt are clearly subject to rapid erosion, unless protected with vegetation. No consistent relation has been found between channel stability and the cohesion of bank materials, probably because of the effects of vegetation.

- **Length of Realignment.** The length of realignment contributes significantly to channel instability at sites where its value exceeds 250 channel widths. When the value is below 100 channel widths, the effects of length of relocation are dominated by other factors. The probability of local bank erosion at some point along a channel increases with the length of the channel. The importance of vegetation, both in appearance and in erosion control, would seem to justify a serious and possibly sustained effort to establish it as soon as possible on graded banks.
- **Bank Revetment.** Revetment makes a critical contribution to stability at many sites where it is placed at bends and along roadway embankments. Rock riprap is by far the most commonly used and effective revetment. Concrete slope paving is prone to failure. Articulated concrete block is effective where vegetation can establish in the interstices between blocks.
- **Check Dams (drop structures).** In general, check dams are effective in preventing channel degradation. The potential for erosion at a check dam depends on its design and construction, its height and the use of revetment on adjoining banks. A series of low check dams, less than about 0.5 m in height, is probably preferable to a single higher structure, because of increased safety and reduced potential for erosion and failure (see section 6.5). By simulating rapids, low check dams may add visual interest to the flow in a channel. One critical problem arising with check dams relates to improper design for large flows. Higher flows have worked around the ends of many installations to produce failure.
- **Maintenance.** Problems which could be resolved by routine maintenance were observed along relocated channels. These were problems with the growth of annual vegetation, reduction of channel conveyance by overhanging trees, local bank cutting, and bank slumping. The expense of routine maintenance or inspection of relocated channels beyond the highway right-of-way may be prohibitive; however, most of the serious problems could be detected by periodic inspection, perhaps by aerial photography, during the first five to ten years after construction. Hydraulic engineers responsible for the design of relocated stream channels should monitor their performance to gain experience and expertise.

#### **6.6.7 Scour at Bridges**

For a discussion of selection of countermeasures for scour at bridges, see section 5.4 or HEC-18.<sup>(15)</sup>

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## **APPENDIX A**

### **Use of the Metric System**



## APPENDIX A

### Use of the Metric System

The following information is summarized from the Federal Highway Administration, National Highway Institute (NHI) Course No. 12301, "Metric (SI) Training for Highway Agencies." For additional information, refer to the Participant Notebook for NHI Course No. 12301.

In SI there are seven base units, many derived units and two supplemental units (table A.1). Base units uniquely describe a property requiring measurement. One of the most common units in civil engineering is length, with a base unit of meters in SI. Decimal multiples of meter include the kilometer (1000 m), the centimeter (1 m/100) and the millimeter (1 m/1000). The second base unit relevant to highway applications is the kilogram, a measure of mass which is the inertial of an object. There is a subtle difference between mass and weight. In SI, mass is a base unit, while weight is a derived quantity related to mass and the acceleration of gravity, sometimes referred to as the force of gravity. In SI the unit of mass is the kilogram and the unit of weight/force is the newton. Table A.2 illustrates the relationship of mass and weight. The unit of time is the same in SI as in the English system (seconds). The measurement of temperature is Centigrade. The following equation converts Fahrenheit temperatures to Centigrade,  $^{\circ}\text{C} = 5/9(^{\circ}\text{F} - 32^{\circ})$ .

Derived units are formed by combining base units to express other characteristics. Common derived units in highway drainage engineering include area, volume, velocity, and density. Some derived units have special names (table A.3).

Table A.4 provides useful conversion factors from English to SI units. The abbreviations presented in this table for metric units, including the use of upper and lower case (e.g., kilometer is "km" and a newton is "N") are the standards that should be followed. Table A.5 provides the standard SI prefixes and their definitions.

Table A.6 provides physical properties of water at atmospheric pressure in SI system of units. Table A.7 gives the sediment grade scale and table A.8 gives some common equivalent hydraulic units.

Table A.1. Overview of SI.		
	Units	Symbol
Base units		
length	meter	m
mass	kilogram	kg
time	second	s
temperature*	kelvin	K
electrical current	ampere	A
luminous intensity	candela	cd
amount of material	mole	mol
Derived units	**	
Supplementary units		
angles in the plane	radian	rad
solid angles	steradian	sr
<p>* Use degrees Celsius (<math>^{\circ}\text{C}</math>), which has a more common usage than kelvin.  ** Many derived units exist; several will be discussed in this session.</p>		

Table A.2. Relationship of Mass and Weight.			
	Mass	Weight or Force of Gravity	Force
English	slug pound-mass	pound pound-force	pound pound-force
metric	kilogram	newton	newton

Table A.3. Derived Units With Special Names.			
Quantity	Name	Symbol	Expression
Frequency	hertz	Hz	$s^{-1}$
Force	newton	N	$kg \cdot m/s^2$
Pressure, stress	pascal	Pa	$N/m^2$
Energy, work, quantity of heat	joule	J	$N \cdot m$
Power, radiant flux	watt	W	$J/s$
Electric charge, quantity	coulomb	C	$A \cdot s$
Electric potential	volt	V	$W/A$
Capacitance	farad	F	$C/V$
Electric resistance	ohm	$\Omega$	$V/A$
Electric conductance	siemens	S	$A/V$
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	$Wb/m^2$
Inductance	henry	H	$Wb/A$
Luminous flux	lumen	lm	$cd \cdot sr$
Illuminance	lux	lx	$lm/m^2$

Table A.4. Useful Conversion Factors.			
Quantity	From English Units	To Metric Units	Multiplied by*
Length	mile	km	1.609
	yard	m	<u>0.9144</u>
	foot	m	<u>0.3048</u>
	inch	mm	<u>25.40</u>
Area	square mile	km <sup>2</sup>	2.590
	acre	m <sup>2</sup>	4047
	acre	hectare	0.4047
	square yard	m <sup>2</sup>	0.8361
	square foot	m <sup>2</sup>	0.092 90
	square inch	mm <sup>2</sup>	645.2
Volume	acre foot	m <sup>3</sup>	1 233
	cubic yard	m <sup>3</sup>	0.7646
	cubic foot	m <sup>3</sup>	0.028 32
	cubic foot	L (1000 cm <sup>3</sup> )	28.32
	100 board feet	m <sup>3</sup>	0.2360
	gallon	L (1000 cm <sup>3</sup> )	3.785
	cubic inch	cm <sup>3</sup>	16.39
Mass	lb	kg	0.4536
	kip (1000 lb)	metric ton (1000 kg)	0.4536
Mass/unit length	plf	kg/m	1.488
Mass/unit area	psf	kg/m <sup>2</sup>	4.882
Mass density	pcf	kg/m <sup>3</sup>	16.02
Force	lb	N	4.448
	kip	kN	4.448
Force/unit length	plf	N/m	14.59
	klf	kN/m	14.59
Pressure, stress, modulus of elasticity	psf	Pa	47.88
	ksf	kPa	47.88
	psi	kPa	6.895
	ksi	MPa	6.895
Bending moment, torque, moment of force	ft-lb	N · m	1.356
	ft-kip	kN · m	1.356
Moment of mass	lb · ft	kg · m	0.1383
Moment of inertia	lb · ft <sup>2</sup>	kg · m <sup>2</sup>	0.042 14
Second moment of area	in <sup>4</sup>	mm <sup>4</sup>	416 200
Section modulus	in <sup>3</sup>	mm <sup>3</sup>	16 390
Power	ton (refrig)	kW	3.517
	Btu/s	kW	1.054
	hp (electric)	W	745.7
	Btu/h	W	0.2931

Table A.4. Useful Conversion Factors (continued).			
Quantity	From English Units	To Metric Units	Multiplied by*
Volume rate of flow	ft <sup>3</sup> /s	m <sup>3</sup> /s	0.028 32
	cfm	m <sup>3</sup> /s	0.000 471 9
	cfm	L/s	0.4719
	mgd	m <sup>3</sup> /s	0.0438
Velocity, speed	ft/s	m/s	<u>0.3048</u>
Acceleration	f/s <sup>2</sup>	m/s <sup>2</sup>	<u>0.3048</u>
Momentum	lb · ft/sec	kg · m/s	0.1383
Angular momentum	lb · ft <sup>2</sup> /s	kg · m <sup>2</sup> /s	0.042 14
Plane angle	degree	rad	0.017 45
		mrad	17.45
* 4 significant figures; underline denotes exact conversion			

Table A.5. Prefixes.					
Submultiples			Multiples		
deci	10 <sup>-1</sup>	d	deka	10 <sup>1</sup>	da
centi	10 <sup>-2</sup>	c	hecto	10 <sup>2</sup>	h
milli	10 <sup>-3</sup>	m	kilo	10 <sup>3</sup>	k
micro	10 <sup>-6</sup>	μ	mega	10 <sup>6</sup>	M
nano	10 <sup>-9</sup>	n	giga	10 <sup>9</sup>	G
pica	10 <sup>-12</sup>	p	tera	10 <sup>12</sup>	T
femto	10 <sup>-15</sup>	f	peta	10 <sup>15</sup>	P
atto	10 <sup>-18</sup>	a	exa	10 <sup>18</sup>	E
zepto	10 <sup>-21</sup>	z	zetta	10 <sup>21</sup>	Z
yocto	10 <sup>-24</sup>	y	yotta	10 <sup>24</sup>	Y

Temperature		Density	Specific Weight	Dynamic Viscosity	Kinematic Viscosity	Vapor Pressure	Surface Tension <sup>1</sup>	Bulk Modulus
Centigrade	Fahrenheit	kg/m <sup>3</sup>	N/m <sup>3</sup>	N · s/m <sup>2</sup>	m <sup>2</sup> /s	N/m <sup>2</sup> abs.	N/m	GN/m <sup>2</sup>
0°	32°	1,000	9,810	1.79 x 10 <sup>-3</sup>	1.79 x 10 <sup>-6</sup>	611	0.0756	1.99
5°	41°	1,000	9,810	1.51 x 10 <sup>-3</sup>	1.51 x 10 <sup>-6</sup>	872	0.0749	2.05
10°	50°	1,000	9,810	1.31 x 10 <sup>-3</sup>	1.31 x 10 <sup>-6</sup>	1,230	0.0742	2.11
15°	59°	999	9,800	1.14 x 10 <sup>-3</sup>	1.14 x 10 <sup>-6</sup>	1,700	0.0735	2.16
20°	68°	998	9,790	1.00 x 10 <sup>-3</sup>	1.00 x 10 <sup>-6</sup>	2,340	0.0728	2.20
25°	77°	997	9,781	8.91 x 10 <sup>-4</sup>	8.94 x 10 <sup>-7</sup>	3,170	0.0720	2.23
30°	86°	996	9,771	7.97 x 10 <sup>-4</sup>	8.00 x 10 <sup>-7</sup>	4,250	0.0712	2.25
35°	95°	994	9,751	7.20 x 10 <sup>-4</sup>	7.24 x 10 <sup>-7</sup>	5,630	0.0704	2.27
40°	104°	992	9,732	6.53 x 10 <sup>-4</sup>	6.58 x 10 <sup>-7</sup>	7,380	0.0696	2.28
50°	122°	988	9,693	5.47 x 10 <sup>-4</sup>	5.53 x 10 <sup>-7</sup>	12,300	0.0679	
60°	140°	983	9,643	4.66 x 10 <sup>-4</sup>	4.74 x 10 <sup>-7</sup>	20,000	0.0662	
70°	158°	978	9,594	4.04 x 10 <sup>-4</sup>	4.13 x 10 <sup>-7</sup>	31,200	0.0644	
80°	176°	972	9,535	3.54 x 10 <sup>-4</sup>	3.64 x 10 <sup>-7</sup>	47,400	0.0626	
90°	194°	965	9,467	3.15 x 10 <sup>-4</sup>	3.26 x 10 <sup>-7</sup>	70,100	0.0607	
100°	212°	958	9,398	2.82 x 10 <sup>-4</sup>	2.94 x 10 <sup>-7</sup>	101,300	0.0589	

<sup>1</sup>Surface tension of water in contact with air

Table A.7. Sediment Particles Grade Scale.

Size			Inches	Approximate Sieve Mesh Openings Per Inch		Class
Millimeters	Microns	Tyler		U.S. Standard		
4000-2000	-----	-----	160-80	-----	-----	Very large boulders
2000-1000	-----	-----	80-40	-----	-----	Large boulders
1000-500	-----	-----	40-20	-----	-----	Medium boulders
500-250	-----	-----	20-10	-----	-----	Small boulders
250-130	-----	-----	10-5	-----	-----	Large cobbles
130-64	-----	-----	5-2.5	-----	-----	Small cobbles
64-32	-----	-----	2.5-1.3	-----	-----	Very coarse gravel
32-16	-----	-----	1.3-0.6	-----	-----	Coarse gravel
16-8	-----	-----	0.6-0.3	2 1/2	-----	Medium gravel
8-4	-----	-----	0.3-0.16	5	5	Fine gravel
4-2	-----	-----	0.16-0.08	9	10	Very fine gravel
2-1	2.00-1.00	2000-1000	-----	16	18	Very coarse sand
1-1/2	1.00-0.50	1000-500	-----	32	35	Coarse sand
1/2-1/4	0.50-0.25	500-250	-----	60	60	Medium sand
1/4-1/8	0.25-0.125	250-125	-----	115	120	Fine sand
1/8-1/16	0.125-0.062	125-62	-----	250	230	Very fine sand
1/16-1/32	0.062-0.031	62-31	-----	-----	-----	Coarse silt
1/32-1/64	0.031-0.016	31-16	-----	-----	-----	Medium silt
1/64-1/128	0.016-0.008	16-8	-----	-----	-----	Fine silt
1/128-1/256	0.008-0.004	8-4	-----	-----	-----	Very fine silt
1/256-1/512	0.004-0.0020	4-2	-----	-----	-----	Coarse clay
1/512-1/1024	0.0020-0.0010	2-1	-----	-----	-----	Medium clay
1/1024-1/2048	0.0010-0.0005	1-0.5	-----	-----	-----	Fine clay
1/2048-1/4096	0.0005-0.0002	0.5-0.24	-----	-----	-----	Very fine clay

Table A.8. Common Equivalent Hydraulic Units.

Volume										
Unit	Equivalent									
	Cubic Inch	Liter	U.S. Gallon	Cubic Foot	Cubic Yard	Cubic Meter	Acre-Foot	Sec-Foot-Day		
liter	61.02	1	0.264 2	0.035 31	0.001 308	0.001	810.6 E - 9	408.7 E - 9		
U.S. gallon	231.0	3.785	1	0.133 7	0.004 951	0.003 785	3.068 E - 6	1.547 E - 6		
cubic foot	1728	28.32	7.481	1	0.037 04	0.028 32	22.96 E - 6	11.57 E - 6		
cubic yard	46,660	764.6	202.0	27	1	0.746 6	619.8 E - 6	312.5 E - 6		
meter <sup>3</sup>	61,020	1000	264.2	35.31	1.308	1	810.6 E - 6	408.7 E - 6		
acre-foot	75.27 E + 6	1,233,000	325,900	43 560	1 613	1 233	1	0.504 2		
sec-foot-day	149.3 E + 6	2,447,000	646,400	86 400	3 200	2 447	1.983	1		
Discharge (Flow Rate, Volume/Time)										
Unit	Equivalent									
	gallon/minute	liter/second	acre-foot/day	foot <sup>3</sup> /sec	million gal/day	meter <sup>3</sup> /sec				
gallon/minute	1	0.063 09	0.004 419	0.002 228	0.001 440	63.09 E - 6				
liter/second	15.85	1	0.070 05	0.035 31	0.022 82	0.001				
acre-foot/day	226.3	14.28	1	0.504 2	0.325 9	0.014 28				
feet <sup>3</sup> /second	448.8	28.32	1.983	1	0.646 3	0.028 32				
meter <sup>3</sup> /second	15,850	1000	70.04	35.31	22.82	1				



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