Predicting Bed Scour for Toe Protection Design in Bank Stabilization Projects

Workshop Presented By

David T. Williams, Ph.D., P.E., P.H., CPESC
President, WEST Consultants, Inc.

WEST CONSULTANTS, INC.

Flood Control District of Maricopa County
Phoenix, Arizona

March, 2003

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Course Outline:

I. Introduction - Need for Toe Protection 8:00 - 9:00 am

A. Generalizations
B. Four techniques to prevent undermining of toe
C. Illustrations of toe protection

II. Channel Stability (Instability) 9:00 - 9:45 am

A. Observations
B. Analytical methods

9:45 - 10:00 am - Break

III. Scour Concepts 10:00 - 10:45 am

A. General characteristics
B. Alluvial streams
C. Non-alluvial streams
D. Some scour generalizations

IV. Total Scour - Vertical 10:45 - 11:30 am

A. Three major components that are additive:
B. Other scour phenomenon - headcut and nickpoint
C. Information required for long-term scour analysis
D. Evaluation of long-term scour

11:30 - 12:30 pm - Lunch

back to top

V. Analytical Methods to Assess Vertical Stability 12:30 - 1:15 am

A. Incipient motion analysis
B. Armoring

VI. Lateral Movement - Meandering Streams 1:15 - 2:00 pm

A. Meandering streams move laterally and migrate downstream
B. Possible causes
C. Flow in channel bends
D. Considerations in bend design
E. Typical countermeasures for lateral shifting and instability
F. Effect of control of meander

2:00 - 2:15 pm - Break

VII. Toe Scour Estimates 2:15 - 3:30 pm

A. Total vertical adjustment comprised of:
B. Blodgett's (1986) relationship (Brown and Clyde, 1989)
C. Levee Design Criterion (L.A. County Flood Control District, 1982)
D. Corps of Engineers (EM 1110-2-1601)
E. Zeller's (1981) Formula (Simons, Li & Associates, 1985)
F. U.S. Bureau of Reclamation (1984)

VIII. Design Considerations for Toe Protection 3:30 - 4:00 pm
A. General
B. Rock toe keys (Johnson and Stypula, 1993)
C. Live Cribwall

IX. Inspection and Maintenance (Johnson and Stypula, 1993) 4:00 - 4:30 pm

A. Inspect toe protection during low water period for:
B. Monitor at least annually and after major floods
C. Maintenance

Your Instructor: David T Williams, Phd.,P.E., P.H.
and Brian J. Doeing, P.E.
Contact Information :dwilliams@westconsultants.com

TABLE OF CONTENTS

I. ***Introduction – Need for Toe Protection*** *1*

A. *Generalizations* *1*

B. *Four techniques to prevent undermining of toe* *4*

C. *Illustrations of toe protection* *7*

II. ***Channel Stability (Instability)*** *13*

A. *Observations* *13*

B. *Analytical methods* *14*

III. ***Scour Concepts*** *15*

A. *General characteristics* *15*

B. *Alluvial streams* *15*

C. *Non-alluvial streams* *16*

D. *Some scour generalizations* *16*

IV. ***Total Scour – Vertical*** *18*

A. *Three major components that are additive:* *18*

B. *Other scour phenomenon - headcut and nickpoint* *20*

C. *Information required for long-term scour analysis* *22*

D. *Evaluation of long-term scour* *23*

V. ***Analytical Methods to Assess Vertical Stability*** *24*

A. *Incipient motion analysis* *24*

B. *Armoring* *27*

VI. ***Lateral Movement – Meandering Streams*** *29*

A. *Meandering streams move laterally and migrate downstream* *29*

B. *Possible causes* *29*

C. *Flow in channel bends* *30*

D. *Considerations in bend design* *34*

E. *Typical countermeasures for lateral shifting and instability* *39*

F. *Effect of control of meander* *39*

VII. ***Toe Scour Estimates*** *40*

A. *Components of total vertical scour* *40*

B. *Blodgett's (1986) relationship (Brown and Clyde, 1989)* *42*

C. *Levee design criterion (Los Angeles County Flood Control District, 1982)* *46*

D. *Corps of Engineers (EM 1110-2-1601)* *50*

E. *Zeller's (1981) bend scour formula (Simons, Li & Associates, 1985)* *52*

F. *U.S. Bureau of Reclamation (Pemberton and Lara, 1984)* *53*

VIII. ***Design Considerations for Toe Protection*** ***62***

A. *General* *62*

B. *Rock toe keys (Johnson and Stypula, 1993)* *64*

C. *Live cribwall* *65*

IX. ***Inspection and Maintenance (Johnson and Stypula, 1993)*** ***67***

A. *Inspect toe protection during low water period* *67*

B. *Monitor at least annually and after major floods* *67*

C. *Maintain and repair as needed* *67*

X. ***References*** ***68***

XI. ***Acknowledgements*** ***71***

APPENDIX A Metric System, Conversion Factors, and Water Properties

APPENDIX B Summary Example Problem

I. Introduction – Need for Toe Protection

A. Generalizations

1. Toe: "The break in slope at the foot of a streambank where the bank meets the bed" (Johnson and Stypula, 1993)

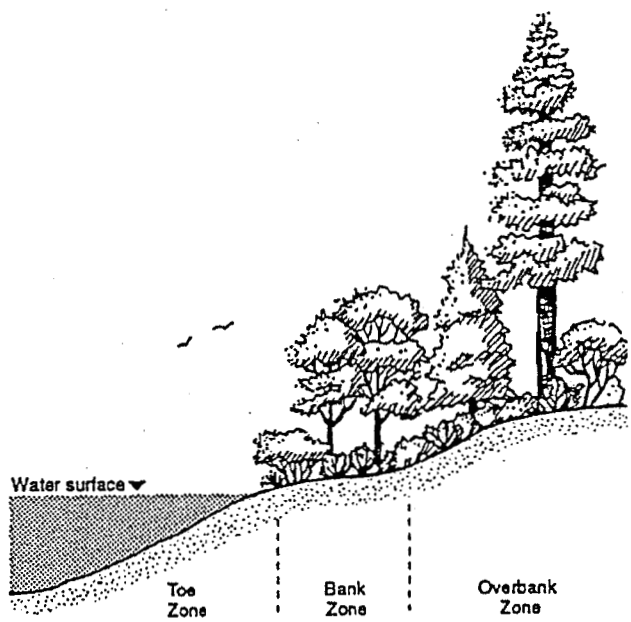


Figure I-1 Section of streambank zones in natural channels (Johnson and Stypula, 1993, p. 3-1)

2. Revetment: "A facing of stone, wood, or other materials placed on a bank as protection against wave action or currents."

3. Undermining of toe protection is one of the primary mechanisms of revetment failure

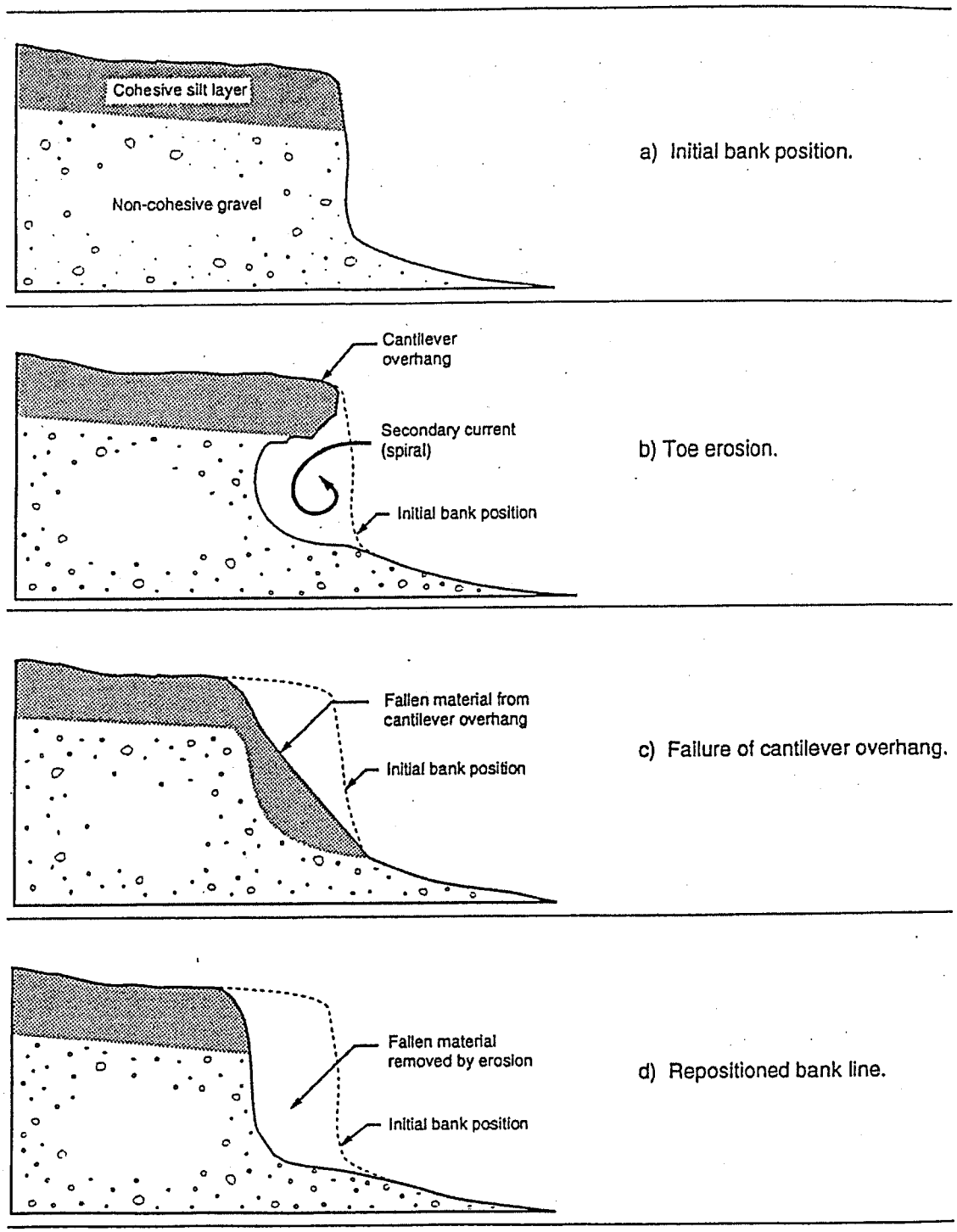


Figure I-2 Undercutting of a composite bank (Johnson and Stypula, 1993, p. 3-5; adapted from Thorne and Lewin, 1979)

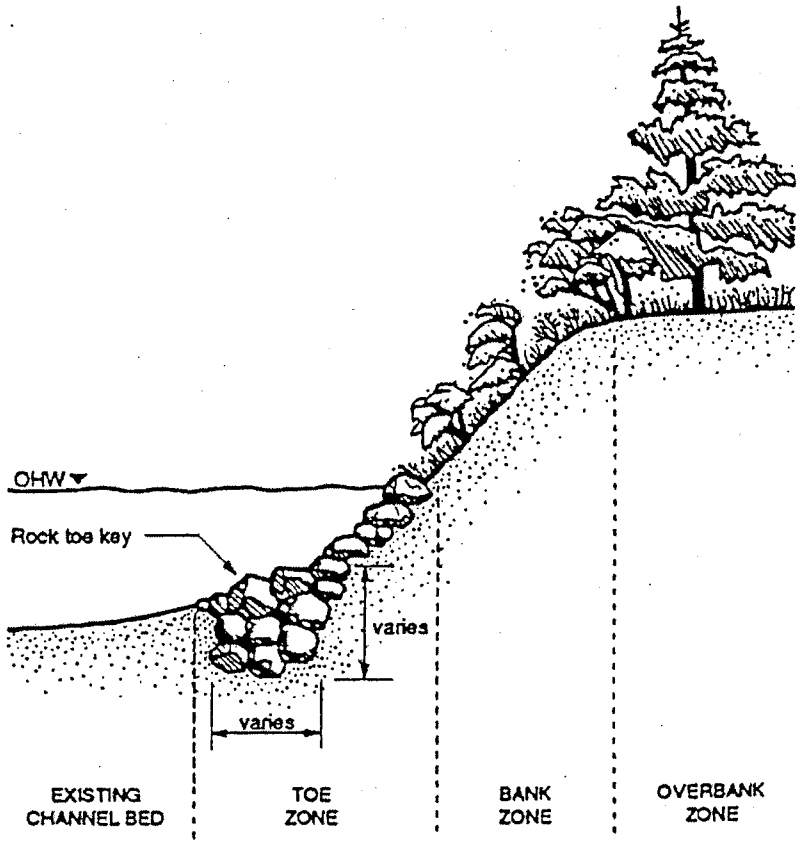


Figure I-3 A bank stabilization project with a rock toe key
(Johnson and Stypula, 1993, p. 7-1)

4. **Estimates of depth of scour needed so protection layer is placed low enough in streambed to prevent undermining**

5. **Ultimate depth of scour must consider channel degradation as well as natural scour and fill process**

B. Four techniques to prevent undermining of toe

1. **Excavate and continue revetment to nonerodible material or below depth of scour**

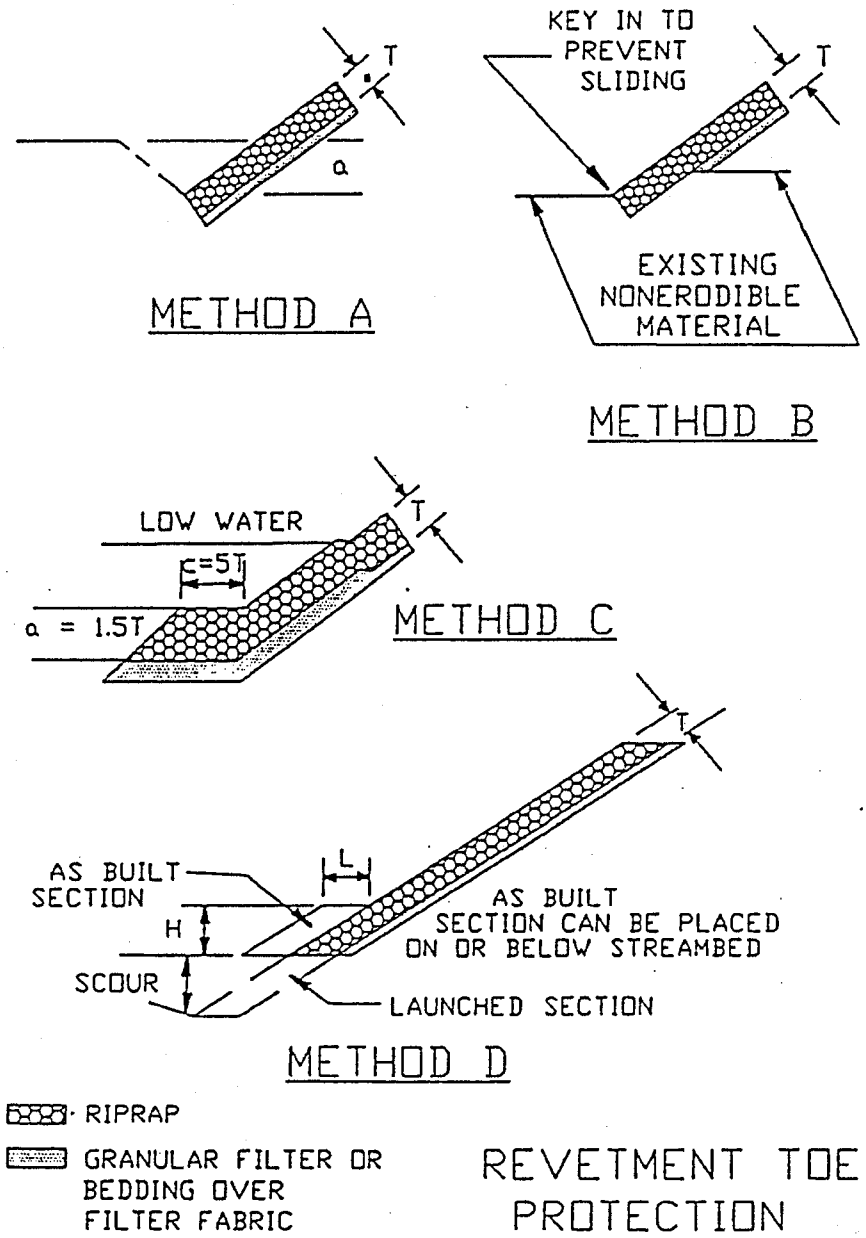


Figure I-4 Revetment toe protection (EM 1110-2-1601 30 Jun 94, plate B-43)

2. Drive a "cut-off wall" of sheet piling from toe of revetment to nonerodible material or below depth of scour

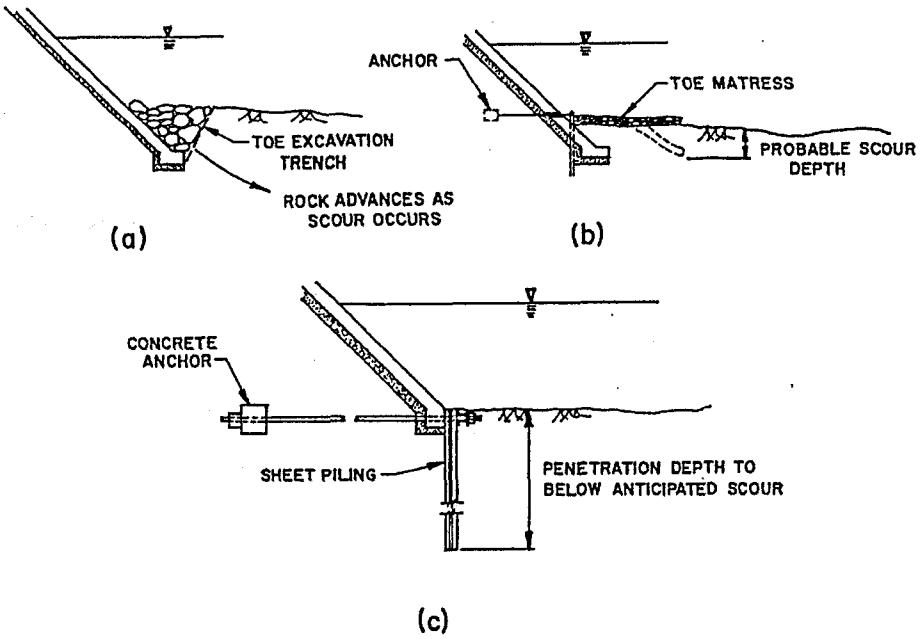


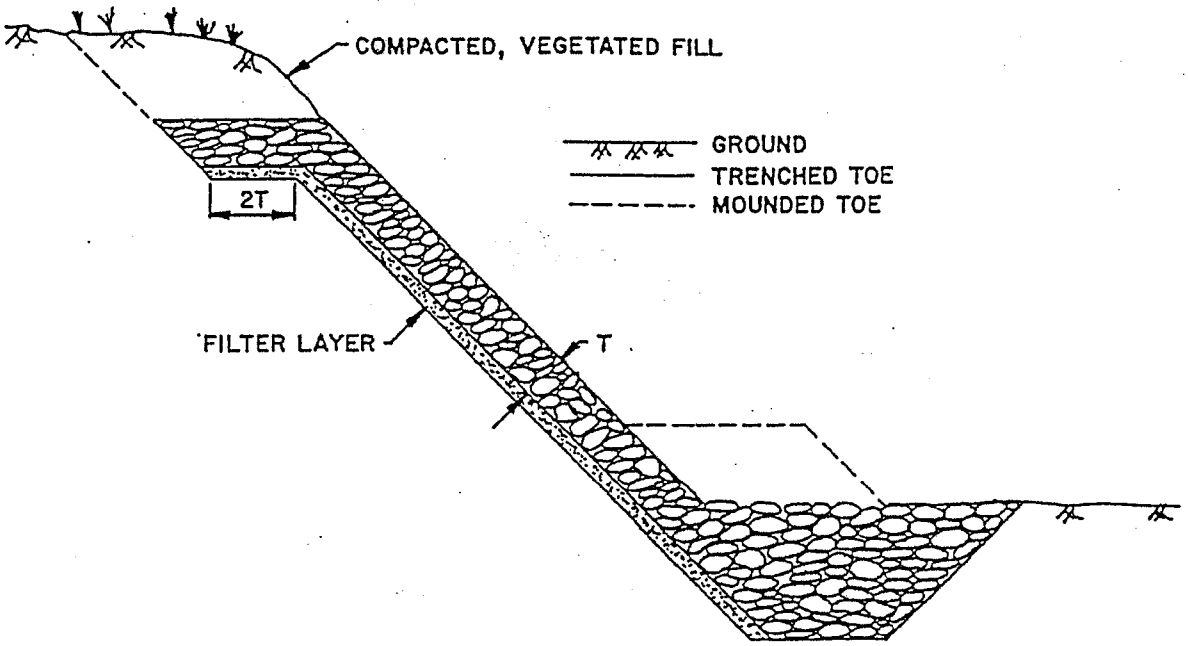
Figure I-5 Concrete pavement toe details (Brown and Clyde, 1989, p. 108)

3. Lay a flexible "launching apron" horizontally on bed at foot of revetment

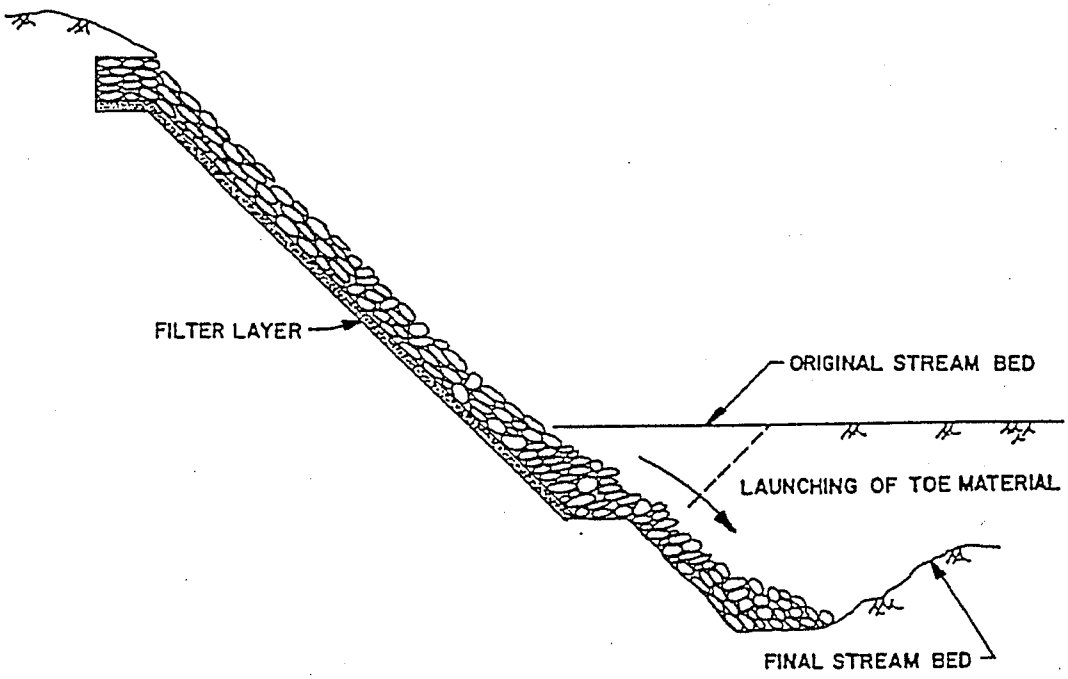
   a) Most economical for cohesionless material

   b) Applicable for deep scour

   c) Includes trench toe and mounded toe for riprap



Typical riprap installation: end view (bank protection only)

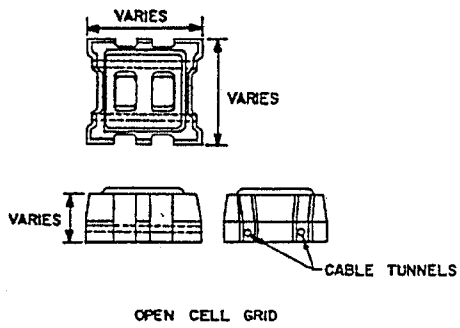


Launching of riprap toe material

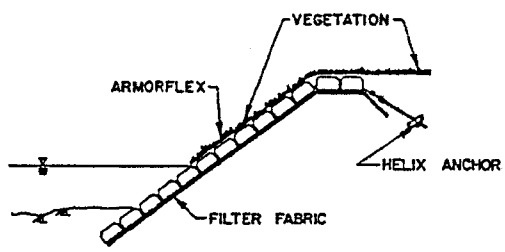
Figure I-6 Riprap toe protection (Brown and Clyde, 1989, p. 44)

4. **Pave entire bed across cross section (economical only for small streams)**

C. Illustrations of toe protection



(a)



(b)

Figure I-7 Armorflex® (a) block detail and (b) revetment configuration (Brown and Clyde, 1989, p. 95)

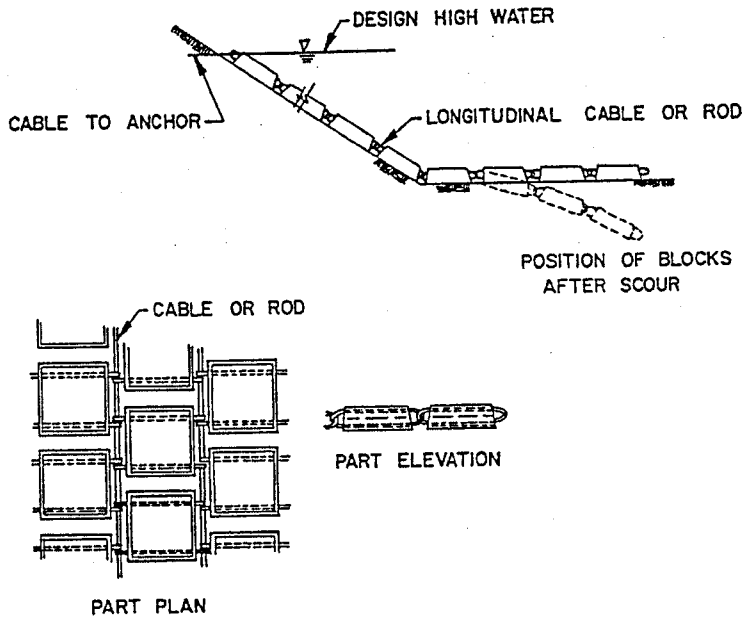


Figure I-8 Articulated concrete revetment (Brown and Clyde, 1989, p. 96)

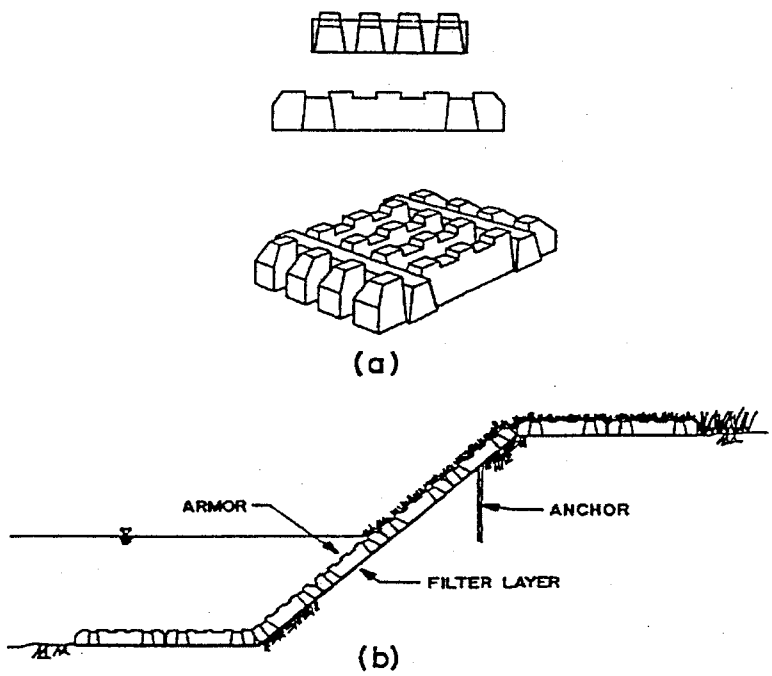


Figure I-9 Monoslab revetment (a) block detail, and (b) revetment detail (Brown and Clyde, 1989, p. 95)

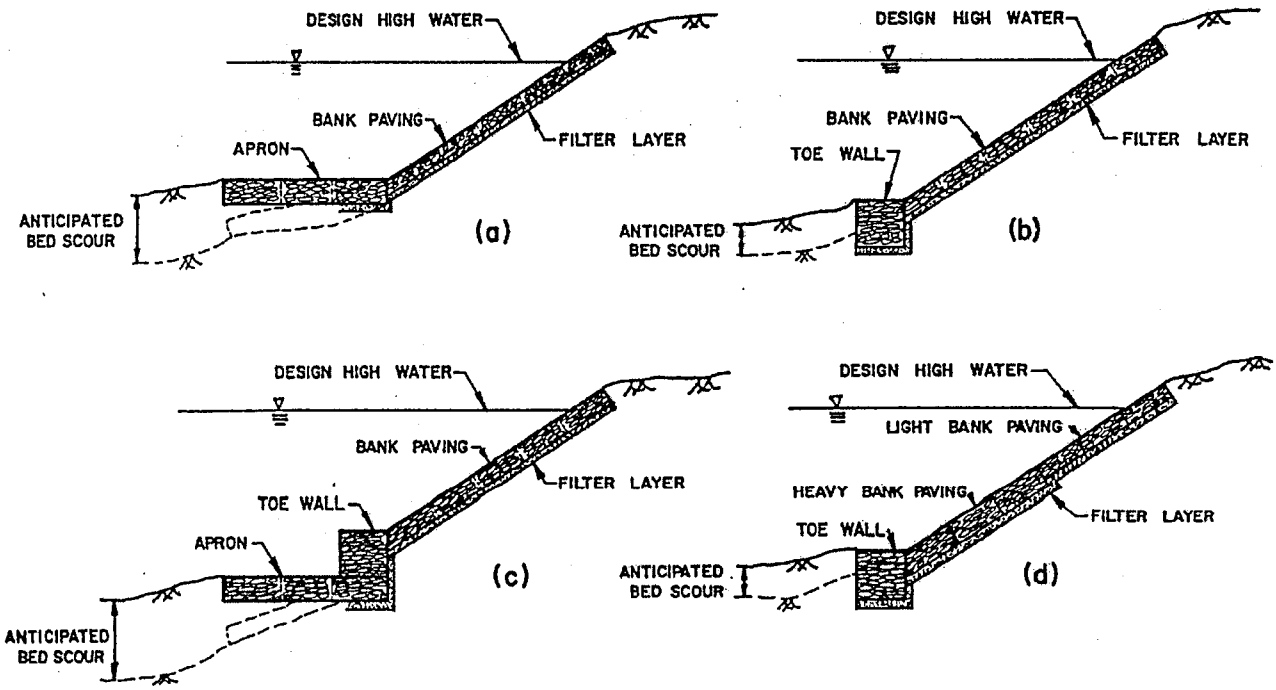


Figure I-10 Rock and wire mattress configurations (Brown and Clyde, 1989, p. 81):

(a) mattress with toe apron (length usually 1.5 to 2 times anticipated scour depth)

(b) mattress with toe wall

(c) mattress with toe wall

(d) mattress of variable thickness

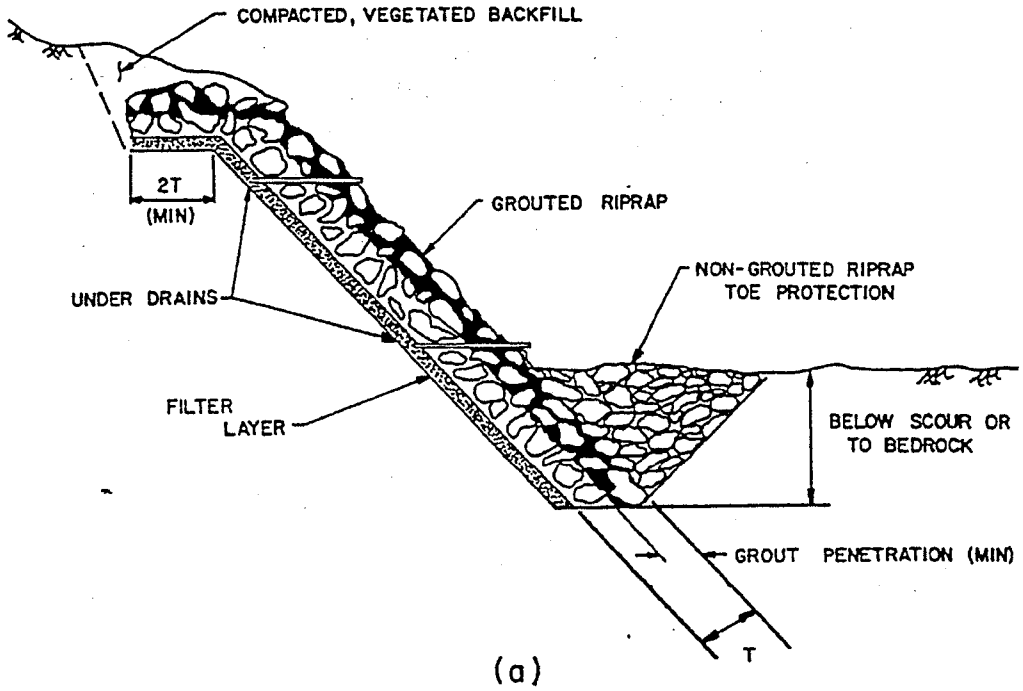


Figure I-11 Grouted riprap section (Brown and Clyde, 1989, p. 100)

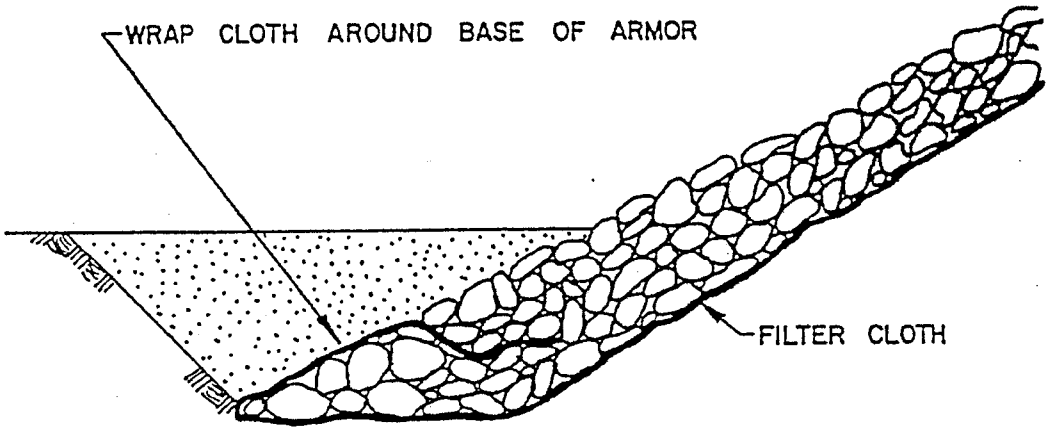


Figure I-12 Filter fabric placement (Brown and Clyde, 1989)

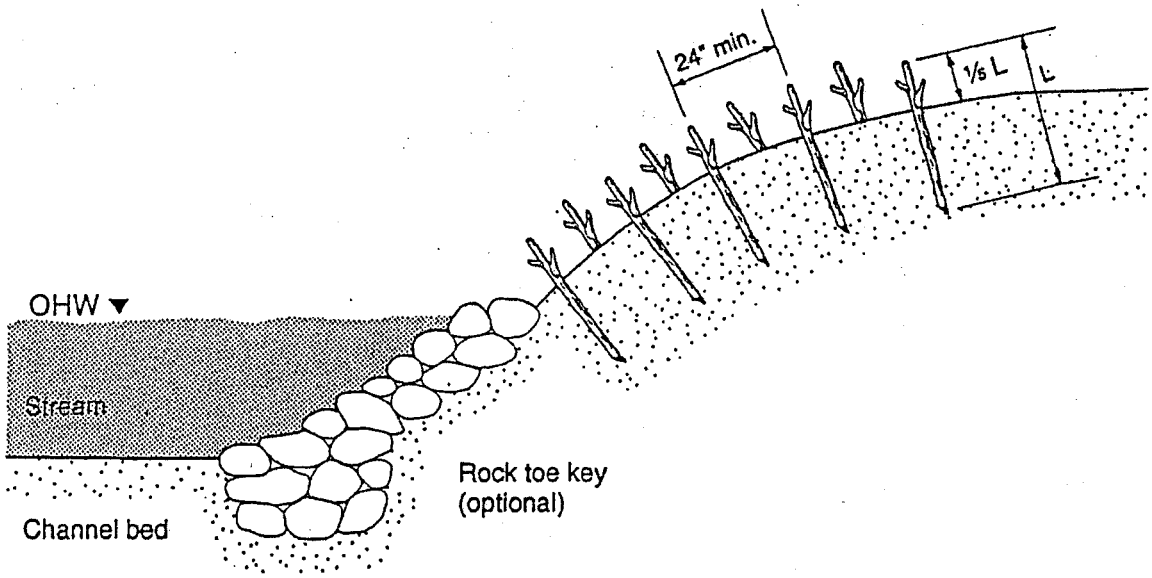


Figure I-13 Installation of live stakes shown with an optional rock toe key (Johnson and Stypula, 1993, p. 8-14)

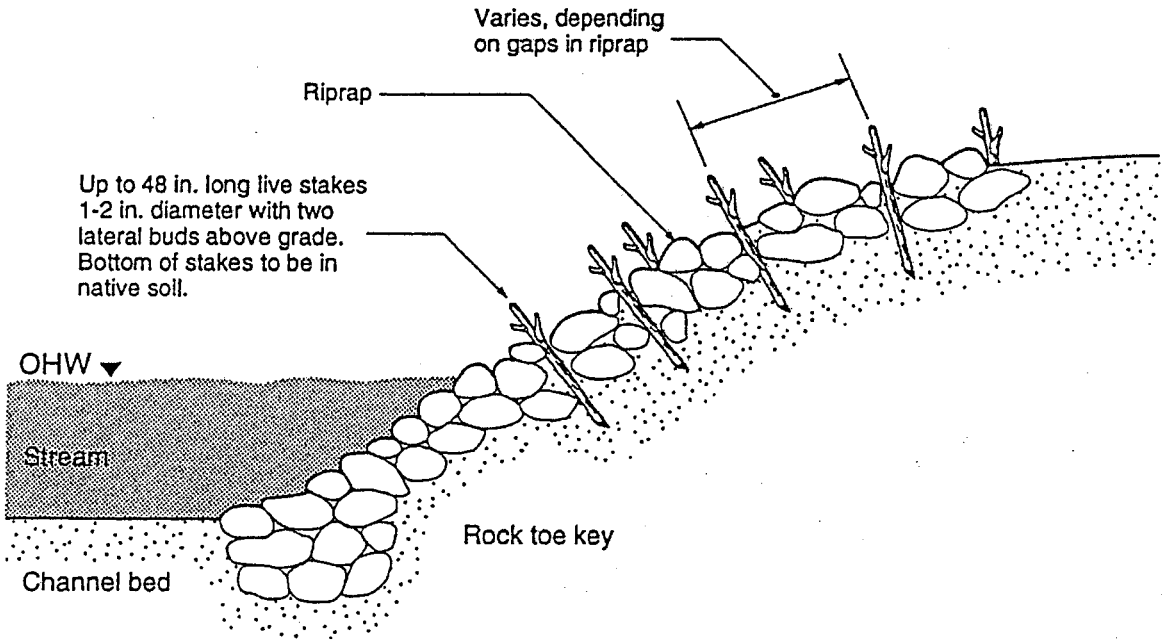


Figure I-14 Installation of joint planting (Johnson and Stypula, 1993, p. 8-19)

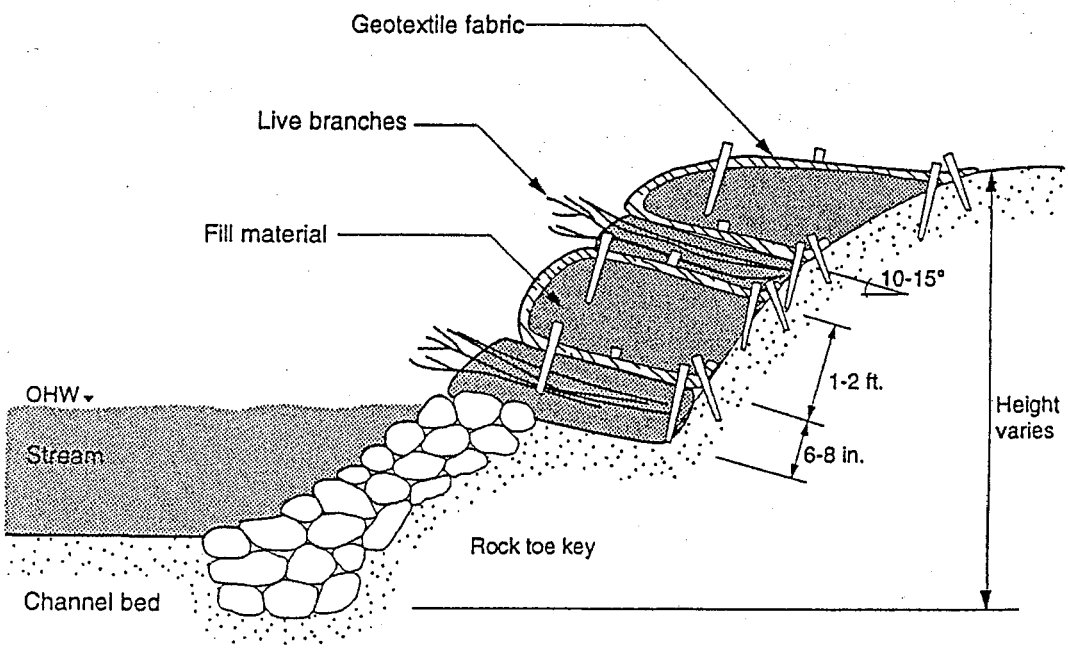


Figure I-15 Installation of vegetated geogrid with optional rock toe key (Johnson and Stypula, 1993, p. 8-20)

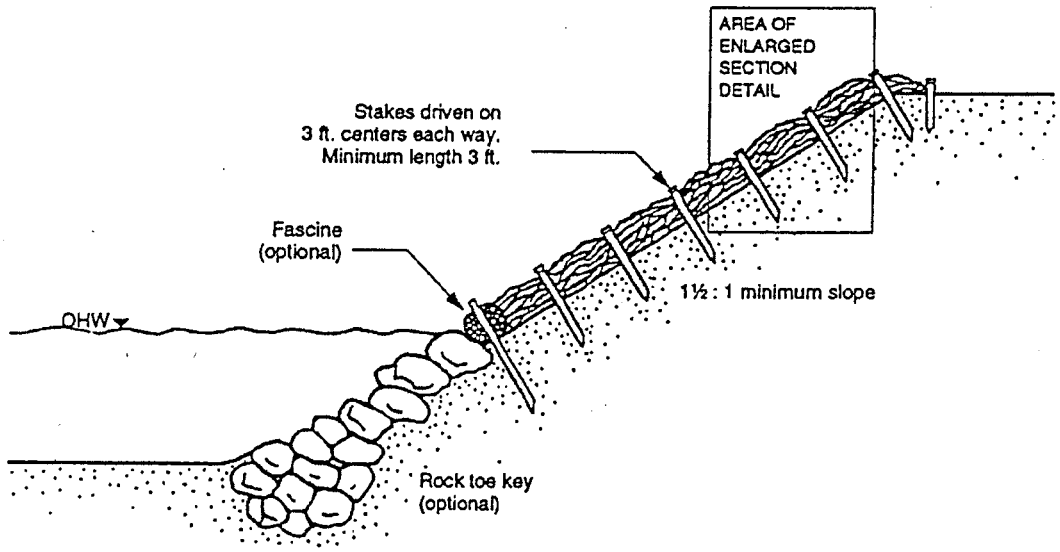


Figure I-16 Installation of a brush mattress shown with an optional fascine and rock toe key (Johnson and Stypula, 1993, p. 8-17)

II. Channel Stability (Instability)

"Channel stabilization is essential to the design of any structure in the river environment. The identification of the potential for channel bank erosion, and the subsequent need for channel stabilization, is best accomplished through observation. Analytical methods are available for the evaluation of channel stability, however, they should only be used where observed data are unavailable" (Brown and Clyde, 1989).

A. Observations

1. **Historic Information**

    a) **Aerial photographs**

    b) **Old maps and surveying notes**

    c) **Bridge design files (highway, RR, pipeline crossings)**

    d) **River survey data**

    e) **Gauging station records (rating curve shift)**

    f) **Interviews with long-time residents**

2. **Current site conditions**

    a) **Tipping and falling of vegetation along the bank**

    b) **Cracks along the bank surface**

    c) **Presence of slump blocks**

    d) **Vegetation laying in the channel near the channel banks**

    e) **Deflection of channel flows towards bank due to recent deposit or course change**

    f) **Fresh vertical face cuts along the bank**

g) Locally high velocities along the bank

h) New bar formation downstream from an eroding bank

i) Local headcuts

j) Pending or recent cutoffs

B. Analytical methods

1. Geomorphic relationships

   a) Leopold (1964), Lane (1955), Brown (1981), Richardson (1990)

2. Hydraulic relationships

   a) Analysis of site materials

   b) Channel shear stress

   c) Local flow velocities

III. Scour Concepts

A. General characteristics

1. Erosive action of flowing water
2. Dislodges and carries away material from bed and banks of stream
3. Rate of scour varies, reaching maximum depth in:
   a) Loose sand and gravel – hours
   b) Cohesive materials – days
   c) Glacial tills, sand stones, shales – months
   d) Limestones – years
   e) Dense granite – centuries

B. Alluvial streams

1. Formed in materials that have been and can be transported by the stream
2. Rule, rather than the exception:
   a) Banks will erode
   b) Sediments will be deposited
   c) Floodplains, islands and side channels will undergo modification, sometimes fairly rapidly, in time
3. Alluvial channels continually:
   a) Change position and shape
   b) Result of hydraulic forces exerted on bed and banks

c) May be gradual or rapid, natural or man-induced

C. Non-alluvial streams

1. Bed/bank very coarse material (cobbles, boulders, or even bed rock)

2. May not erode, except at extreme flood events

3. Are generally stable, but should be analyzed for plan form stability at large flows

D. Some scour generalizations

1. Section geometry for riprap design (bank only design) for hydraulic design parameters for placement

   a) Cross section data at a site during a given year (area, hydraulic radius, top width, mean depth, and maximum depth) may vary by 50% from long term mean (Blodgett, 1986)

   b) Bank stabilization has been observed to increase the maximum depth-to-average depth ratio to 1.7 (Brown and Clyde, 1989)

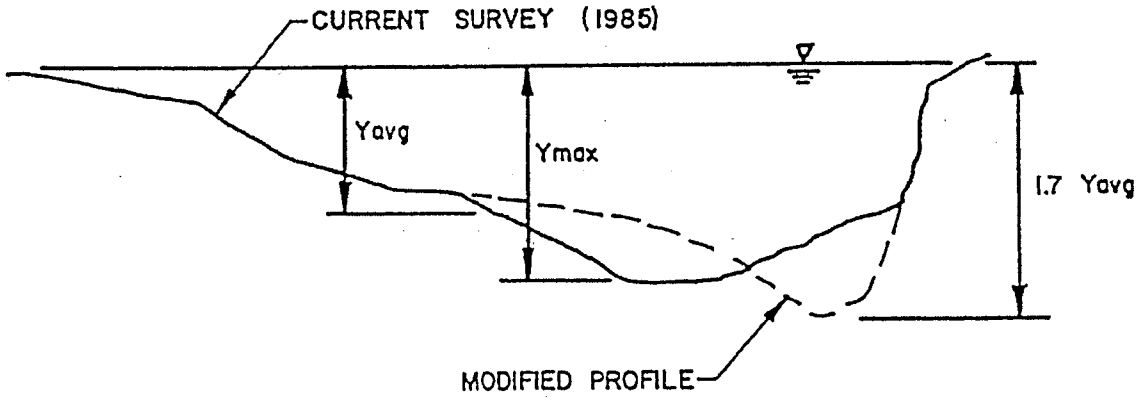


Figure III-1 Channel geometry development (Brown and Clyde, 1989, p. 22)

2. **Braided channels**

   a) **Deepest natural scour occurs when 2 channels come together or when flows come together downstream of an island or sand/gravel bar.**

   b) **Maximum scour depth observed to be 1 to 2 times average flow depth (Richardson and Davis, 1995).**

3. **Stream size**

   a) **Potential depth of scour increases with stream size (Lagasse, et al., 1995).**

   b) **Potential for lateral erosion increases with stream size. Examples (Brice and Blodgett, 1978):**

Stream	Width	Lateral shift, single major flood
Lower Mississippi River	1500 m	> 30 m
Sacramento River	300 m	< 8 m
General	30 m	< 3m

IV. Total Scour – Vertical

A. Three major components that are additive:

1. **Long-term bed elevation change**

   a) **May be natural or due to some modification of stream or watershed.**

   b) **Streambed may be aggrading, degrading, or in relative equilibrium**

   c) **May be a response to an imbalance of stream flow, sediment discharge, bed sediment size, and channel slope**

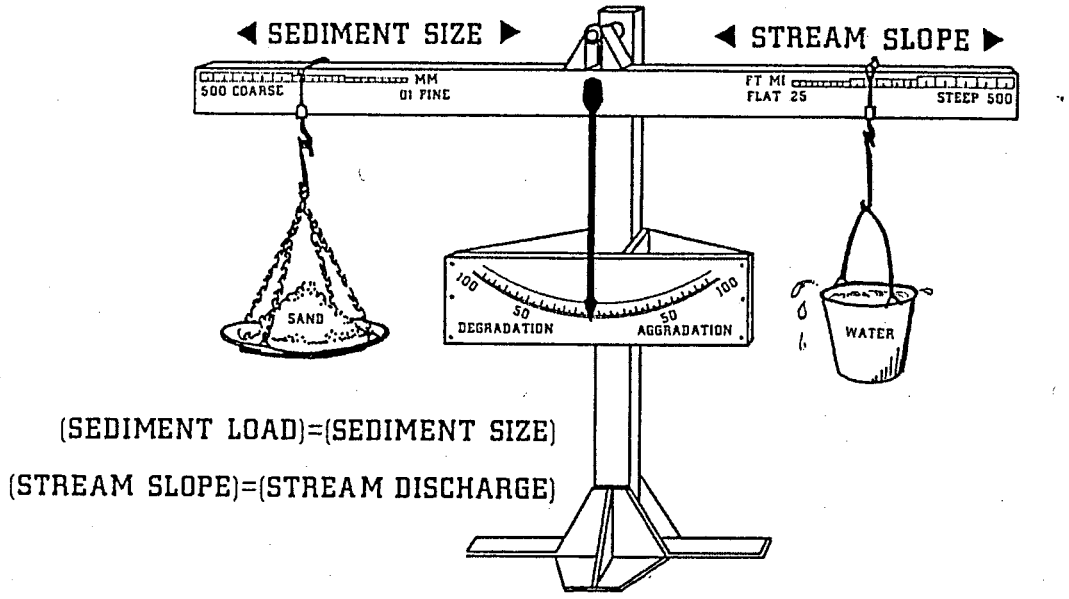


Figure IV-1 Lane's Balance, $Q_S D_{50} \propto QS$ (Biedenharn, 1983)

   d) **Does not include localized scour or deposition that might occur during runoff event (may have opposite trend)**

e) Factors that affect long term bed elevation changes:

(1) Dams and reservoirs (upstream or downstream)

(2) Change in watershed land use (urbanization, deforestation, etc.)

(3) Channelization (excavation, clearing, grubbing, etc.)

(4) Cutoffs of meander bends (natural or man made)

(5) Changes in downstream channel base level (control)

(6) Gravel mining from stream bed

(7) Diversion of water in or out of stream

(8) Natural lowering of total system

(9) Movement of a bend

(10) River geomorphology change (e.g. meandering to braided)

2. General scour and contraction scour

a) Channel adjustment based on sediment inflow, bed gradation, and sediment transport potential in a reach

b) Numerical modeling or sediment continuity calculations (see Simons, Li & Associates, 1985)

c) Equations for contraction scour (Richardson and Davis, 1995)

3. Local scour

   a) Pier scour and abutment scour (Richardson and Davis, 1995)

   b) Can be 10 times greater in magnitude than previous components

   c) Bend scour, bed forms, thalweg formation

B. Other scour phenomenon - headcut and nickpoint

1. General description

   a) Abrupt changes in longitudinal profile of the stream

   b) Moves upstream, especially during floods

   c) Result – lowering of stream bed

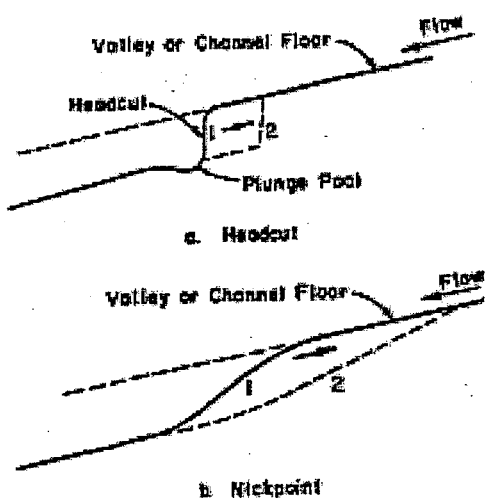


Figure IV-2 Headcuts and nickpoints (Richardson, et al., 1990, p IV-6)

2. Headcut

   a) Sharp break in profile – forms an in-channel scarp

   b) More common in fine bed material

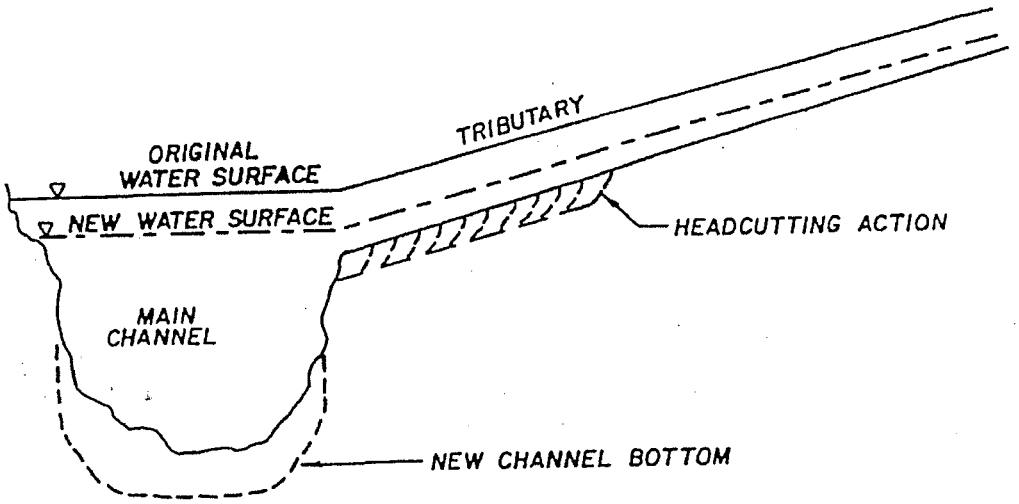


Figure IV-3 Schematic of headcut progression (Biedenharn, 1990)

3. Nickpoint

   a) Gradual change in elevation over greater length

   b) More common in coarse bed material

4. Example occurrence:

   Tujunga Wash, California - erosion above headwall of gravel pit led to failure of three highway bridges

C. Information required for long-term scour analysis

1. Boring logs to define geologic substrata
2. Bed material size distribution
3. Existing stream and floodplain cross sections
4. Stream plan form
5. Watershed characteristics
6. Scour data on bridges
7. Slope of energy grade line
8. History of flooding
9. Location of tributaries, bed rock controls, man-made controls
10. Character of flow in the stream (perennial, flashy, intermittent, or gradual peaks)
11. Geomorphology of site
    a) Floodplain stream
    b) Delta
    c) Youthful, mature or old-age stream
    d) Alluvial fan
    e) Meandering, straight or braided
12. Erosion history of stream
13. Development history of stream and watershed (past, present and future)
14. Sand & gravel mining (past, present and future)

D. Evaluation of long-term scour

1. Sediment routing or sediment continuity computer programs with a long-term simulation of:

    a) Actual historical flow series

    b) Continuous application of the "channel forming" discharge

        (1) Usually considered the bankfull discharge (approximately the 1.5-year flood) for perennial streams

        (2) Suggested 5-10-year flood for ephemeral streams, with bankfull discharge the upper limit (Simons, Li & Associates, 1985)

    c) Continuous application of the "average annual event" integrated in terms of runoff volume and sediment yield

2. Two examples of publicly available models:

    a) HEC-6 – "Scour and Deposition in Rivers and Reservoirs" (1-D)

    b) BRI-STARS – "Bridge Stream Tube Model for Alluvial River Simulation" (Semi 2-D)

3. Equilibrium or stable slope analysis using "channel forming discharge" (see Mussetter, et al., 1994, and Pemberton and Lara, 1984, for procedures and equations)

4. Straight line extrapolation of historical trends

5. Engineering judgment

V. Analytical Methods to Assess Vertical Stability

A. Incipient motion analysis

1. **Generally for gravel and cobble bed streams**

2. **Critical or threshold conditions preceding motion, from the Shields (1936) Diagram:**

$$Dc = \frac{\tau}{0.047\ (\gamma_S - \gamma)}$$

where:

D_C = **Diameter of the sediment particle at incipient motion conditions (ft)**

τ = **Boundary shear stress (lb/ft^2)**

γ_s = **Specific weight of sediment (lb/ft^3)**

γ = **Specific weight of water (lb/ft^3)**

0.047 = **Shields parameter, a dimensionless coefficient which typically varies between 0.02 to 0.10**

U.S. Standard Sieve					230	120	60	35	18	10	5	5/16"	5/8"	1 1/4"	2 1/2"		
Phi Value						+3	+2	+1	0	-1	-2	-3	-4	-5	-6	-7	-8
Diameter (mm)	.004	.008	.016	.031	.0625	0.125	0.25	0.5	1	2	4	8	16	32	64	128	>256

.0005	.001	.002	.004	.008	.016	.031	.0625	0.125	0.25	0.5	1	2	4	8	16	32	64	128	>256
VF	F	M	C	VF	F	M	C	VF	F	M	C	VC	VF	F	M	C	VC	Small	Large	Small
Clay Size				Silt				Sand					Gravel					Cobbles		Boulders

AMERICAN GEOPHYSICAL UNION (Lane, 1947, AGU Transactions, v. 28, no. 6)

.0005	.001	.002	.004	.008	.016	.031	.0625	0.125	0.25	0.5	1	2	4	8	16	32	64	128	>256
VF	F	M	C	VF	F	M	C	VF	F	M	C	VC	VF	F	M	C	VC	Small	Large	
Clay Size				Silt				Sand					Gravel					Cobbles		Boulders

U.S. GEOLOGICAL SURVEY (1969, Tech. of Water-Resource Investigations, Ch. C1, p. 7)

0.0039		.0625	0.125	0.25	0.5	1	2	4	64	
Clay	Silt	VF	F	M	C	VC	Granule Gravel	Pebble Gravel	Cobble Gravel	
		Sand								

WENTWORTH SCALE (1922, Journal of Geology, v. 30, p. 377-392)

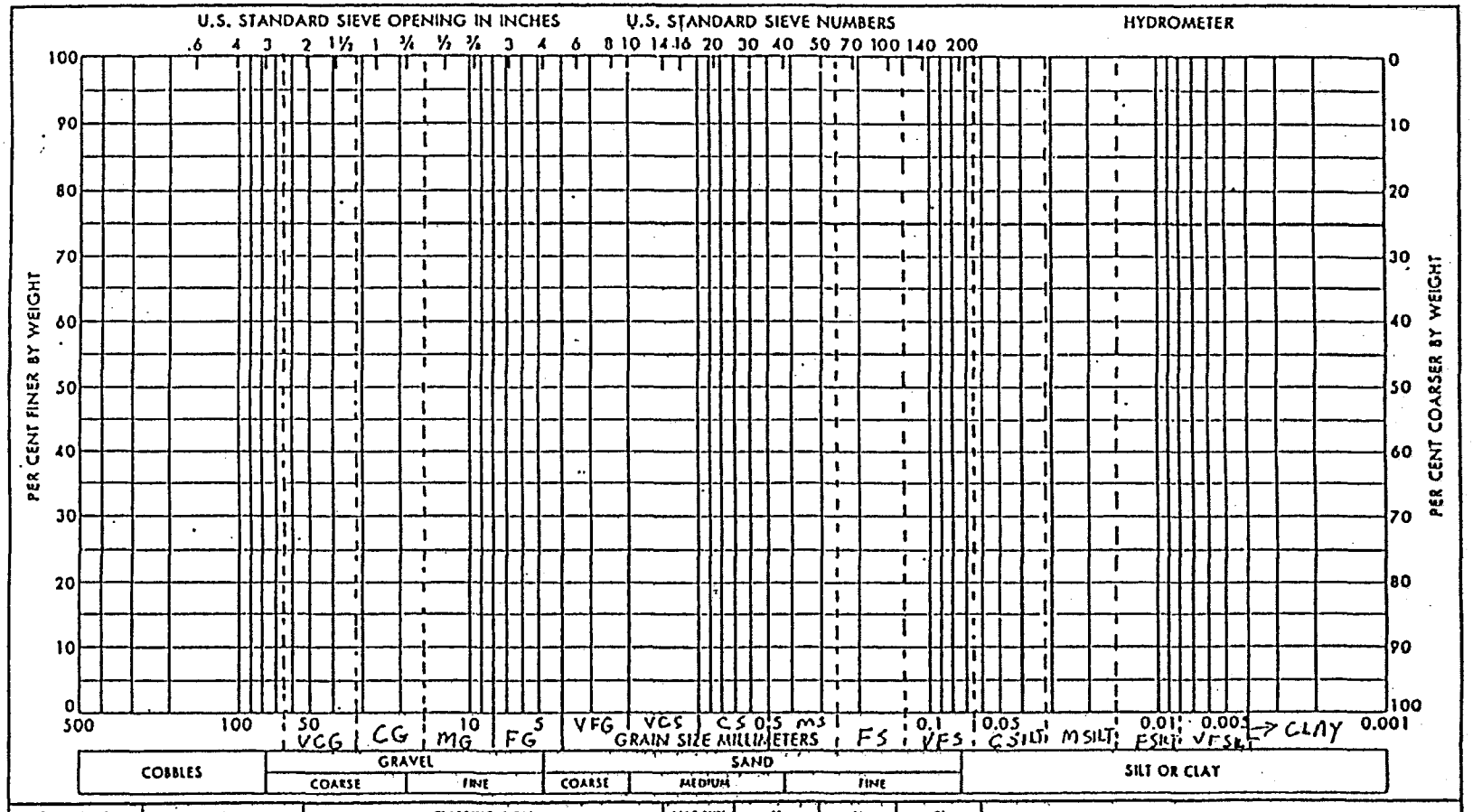
.001	.005	.074	.42	2.0	4.76	76.2	
Colloids	Clay Size	Silt Size	F	M	C	Gravel	
			Sand				

AMERICAN SOCIEY FOR TESTING AND MATERIALS 1961, ASTM Standards, p. 1283)

0.002		0.05	0.1	0.25	0.5	1	2	
Clay	Silt	VF	F	M	C	VC	Gravelly, Cobbly, or Stony	
		Sand						

U.S. DEPARTMENT OF AGRICULTURE (1951, Soil Survey Manual, p. 208)

Figure V-1 Comparisons of Particle Size Classification Systems (USGS Hydrologic Laboratory, Denver, Co., modified by Stream Systems Technology Center)



SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI

GRADATION CURVES

PROJECT

AREA

BORING NO.

DATE

ENG FORM 2087 REPLACES WES FORM NO. 1241, SEP 1967, WHICH IS OBSOLETE. (TRANSLUCENT)

U.S. GOVERNMENT PRINTING OFFICE

Figure V-2 Gradation Curve Graph Paper

B. Armoring

1. Non-moving, coarser particles accumulate in a surface layer.

2. Fine materials migrate to the surface through the coarse layer by hydraulic action until the coarse layer is thick enough to shield or "armor" the entire underlying bed surface.

3. May be disrupted during high flows and restored as flows diminish.

4. If armor layer is stable for the design event, reasonable to conclude no degradation will occur under design conditions.

5. Potential for armor layer development determined using incipient motion analysis and a representative bed material composition typical to the depth of expected degradation.

6. If no sediment of the computed size or larger is present in significant quantities in the bed, armoring will not occur.

7. D_{90} or D_{95} size of representative bed material is frequently found to be "paving the channel" when degradation is arrested.

8. Therefore, armoring is probable when computed incipient motion size is equal to or smaller than the D_{95} size of bed material.

9. **Depth of scour to armor (see Figure V-3):**

$$Y_s = Y_a\left(\frac{1}{P_c} - 1\right)$$

where:

Y_s = Depth of scour to the top of the armor layer (ft)

Y_a = Thickness of armor layer, usually 2 to 3 times, up to 4 times, D_c (ft)

P_c = Decimal fraction of original bed material coarser than the armor size, D_c

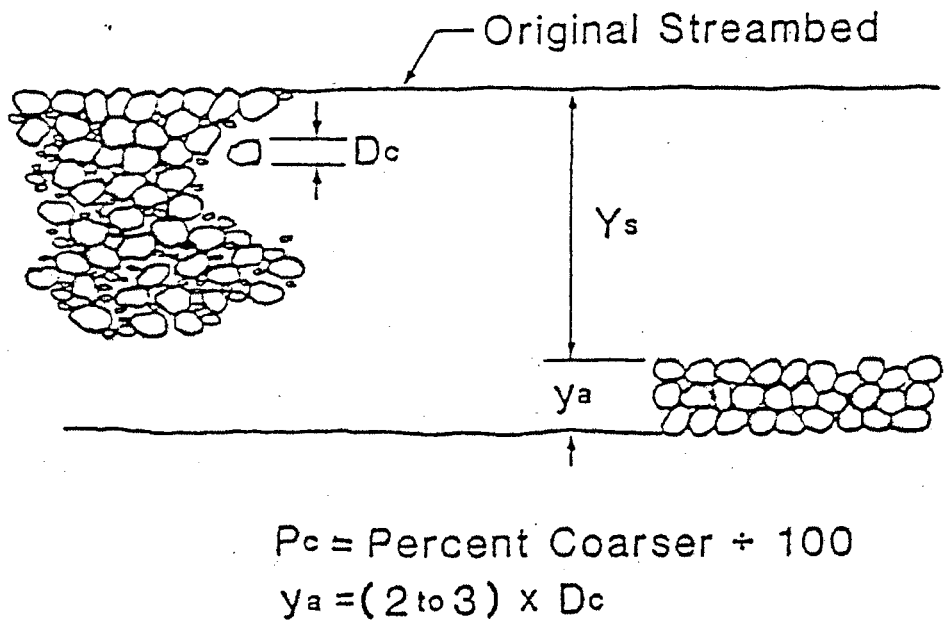
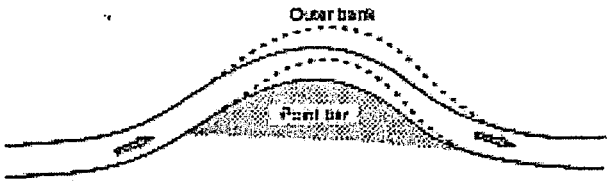


Figure V-3 Conceptual illustration of armor layer development (Mussetter et al., 1994, p. 3-28)

VI. Lateral Movement – Meandering Streams

A. Meandering streams move laterally and migrate downstream

1. **Difficult to predict when will occur**
2. **Direction and magnitude of movement not easily determined**
3. **Lateral movements up to 750 m/yr have been observed in large alluvial rivers**
4. **Meander belt often 15 to 20 times the channel width**
5. **Random factors involved in migration of meanders**
6. **Most rapid bank erosion is generally at outside, downstream from apex of bend**



Note: Dashed lines denote channel position after migration takes place.

Figure VI-1 Lateral Migration (Johnson and Stypula, 1993, p. 2-4)

B. Possible causes

1. **Sloughing of the banks**
2. **Nonuniform deposition of bed load**
3. **Debris such as trees**
4. **Coriolis force due to Earth's rotation**

C. Flow in channel bends

1. Non-uniform, non-symmetrical flow

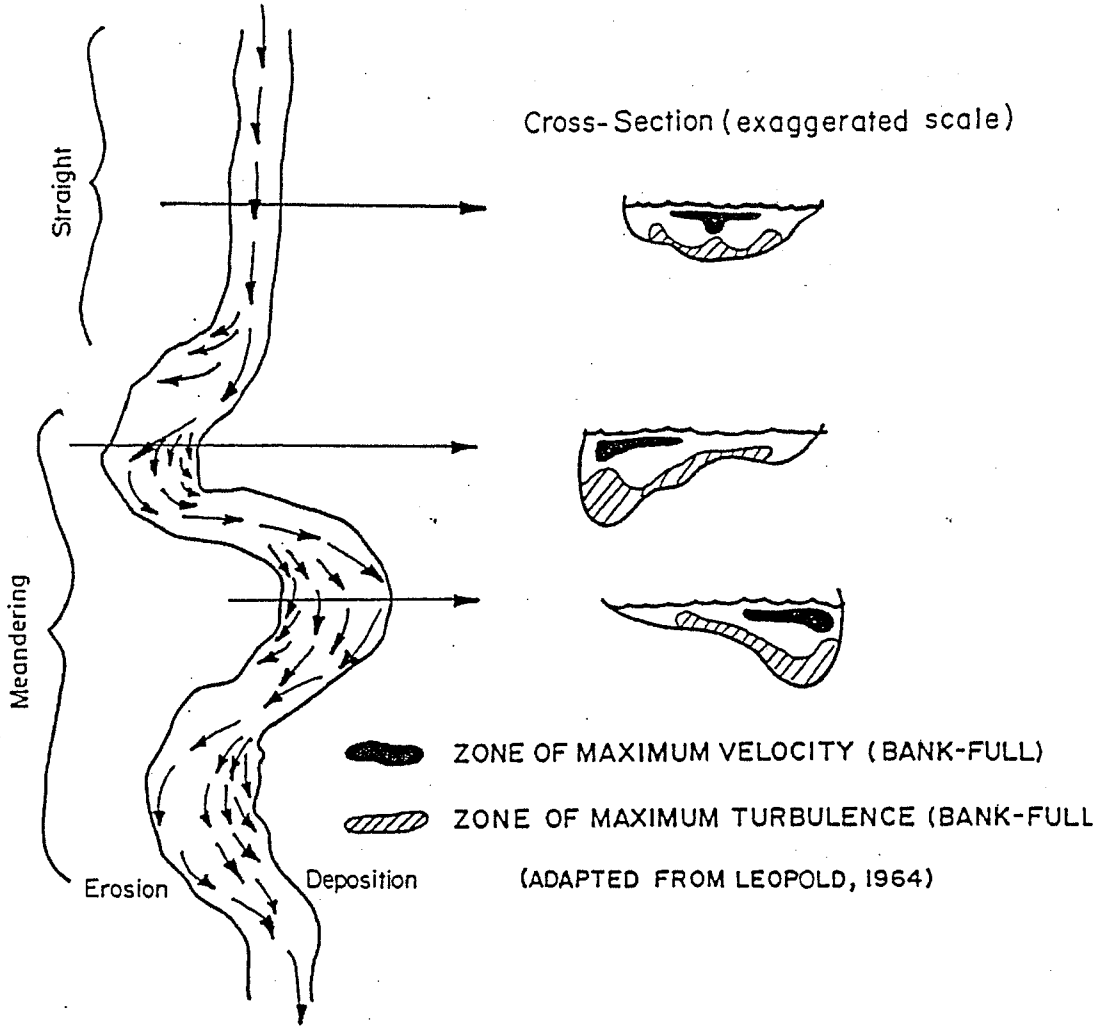


Figure VI-2 Primary downstream turbulent flow (forward) (Ethridge, 1983)

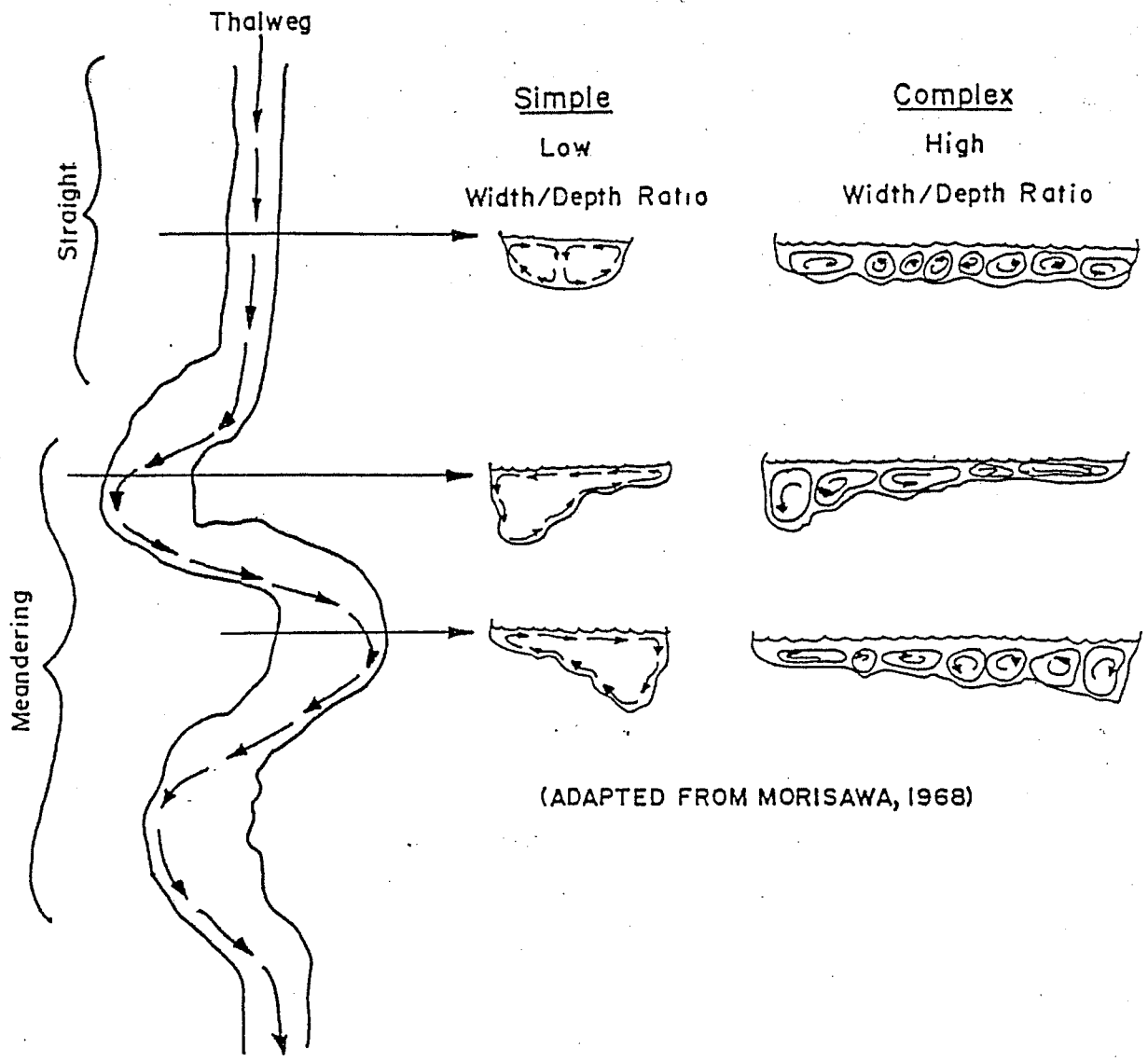


Figure VI-3 Secondary flow (helical type) (Ethridge, 1983)

2. **Centrifugal forces and secondary currents cause:**

   a) **Increased velocity and shear stress**

   b) **Superelevation of water surface elevation**

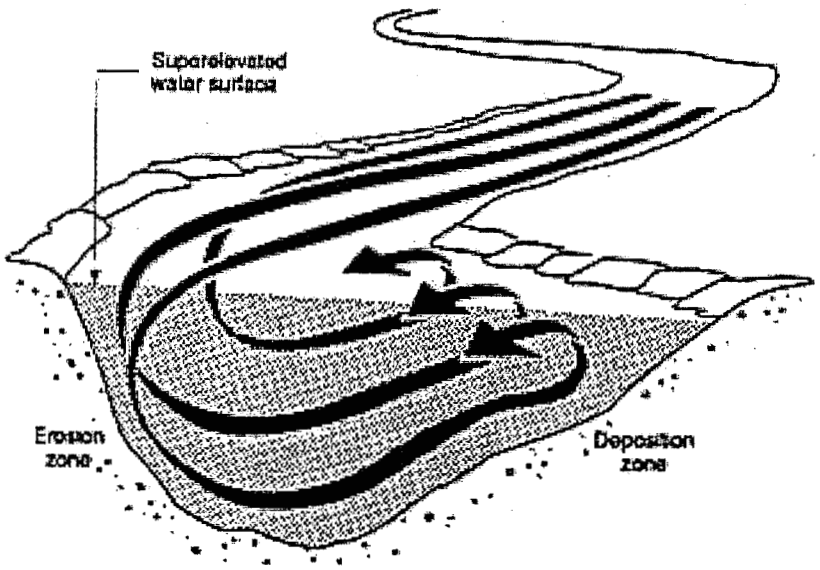


Figure VI-4 Spiral secondary flow (Johnson and Stypula, 1993, p. 3-4; adapted from Kunzig, 1989)

c) Magnitude of superelevation for subcritical flow:

$$Z = C\frac{V_a^2 T}{g R_0}$$

where:

Z = superelevation (rise in water surface between a theoretical level water surface at the center line and the outside water surface elevation (ft)

C = coefficient (ranges from 0.5 to 3.0; Corps uses 0.5 or 1.0 based on flow type, cross section shape, and type of curve, EM 1110-2-1601)

V_a = mean channel velocity (ft/s)

T = water-surface width at center line water surface elevation (ft)

g = gravitational acceleration (ft/s^2)

R_0 = mean radius of channel centerline at bend (ft)

D. Considerations in bend design

1. Channel design flow less than 50 cfs (HEC-15)

   a) Roadside channel - instability not tolerated

   b) Select design permissible tractive shear stress greater than flow induced stress

   c) Average tractive force or shear stress on channel:

$$\tau = \gamma R S$$

where:

τ = average shear stress on channel (lb/ft^2)

γ = unit weight of water (lb/ft^3)

R = hydraulic radius (area/wetted perimeter) (ft)

S = channel bed slope (ft/ft)

d) **Maximum shear stress for straight reach:**

$$\tau_d = \gamma d S$$

where:

τ_d = **maximum shear stress for straight reach (lb/ft^2)**

d = **maximum depth of flow (ft)**

S = **channel bed slope (ft/ft)**

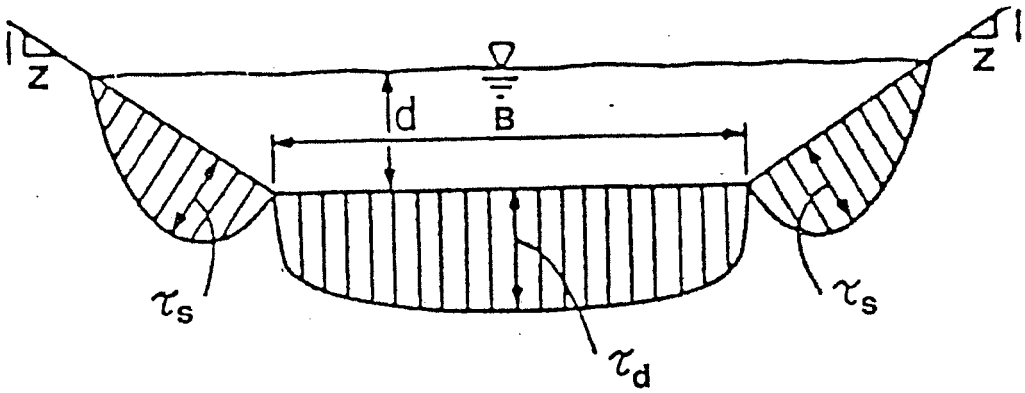


Figure VI-5 Typical distribution of shear stress (Chen and Cotton, 1988, p. 14)

e) **Maximum shear stress in bend is a function of the ratio of channel curvature to bottom width (R_c / B)**

where:

R_c = **radius of curvature of channel centerline (ft)**

B = **bottom width (ft)**

$$\tau_b = k_b \times \tau_d$$

where:

τ_b	=	**Maximum shear stress in the bend**
k_b	=	**coefficient, ranges from 1.05 to 2.0 for R_c / B ratio from 10 to 2.**
τ_d	=	**Maximum shear stress in a straight reach**

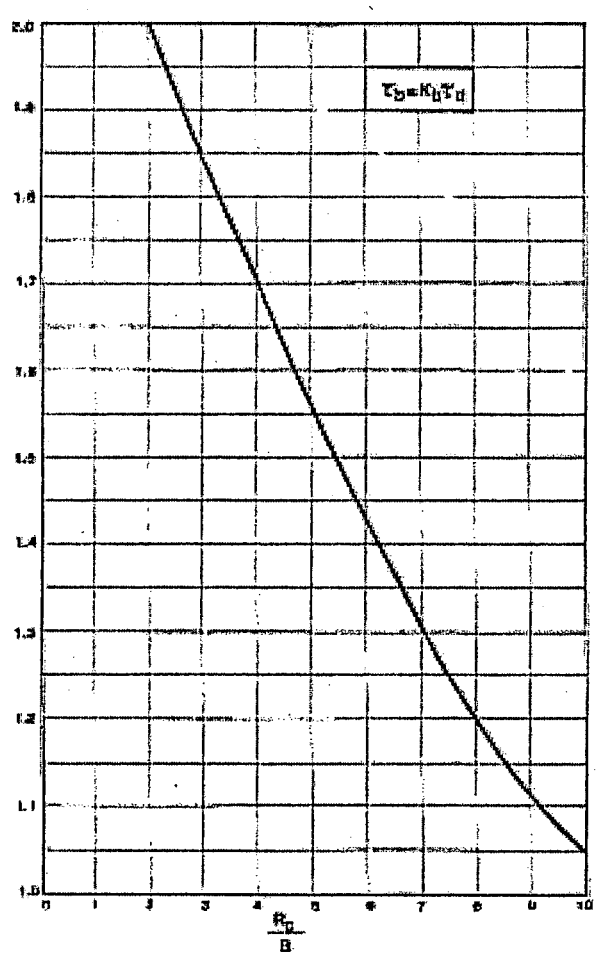


Figure VI-6 K_b factor for maximum shear stress on channel bends (Chart 10, Chen and Cotton, 1988, p. 47)

f) Flow around bend creates secondary current, imposing higher stress on channel bottom and banks - persists a distance L_p

L_p is a function of bed roughness and flow depth, in units of the hydraulic radius, R

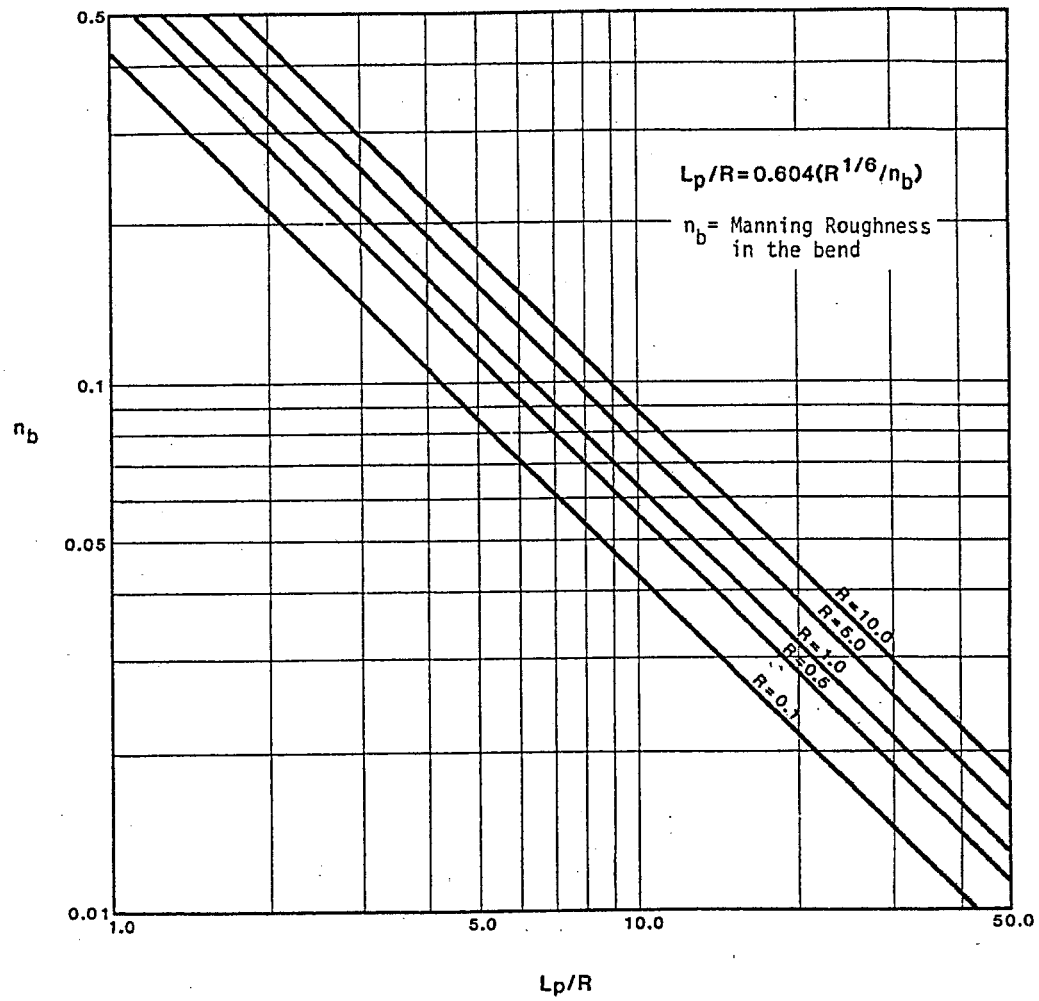


Figure VI-7 Protection Length, L_p, downstream of channel bend
(Chart 11, Chen and Cotton, 1988, p. 48)

2. Channel design flow greater than 50 cfs (HEC-11)

Typical D_{50} riprap design:

$$D_{50} = C \frac{0.001 V_a^3}{d_{avg}^{0.5} \, k_1^{1.5}}$$

where:

D_{50} = the median riprap particle size (ft)

V_a = average velocity in the main channel (ft/s)

d_{avg} = average flow depth in the main channel (ft)

K_1 = defined as:

$$K_1 = \left[1 - \left(\sin^2 \theta / \sin^2 \phi\right)\right]^{0.5}$$

θ = the bank angle with the horizontal

ϕ = the riprap material's angle of repose

C = correction factor, for specific gravity of riprap other than 2.65 and a stability factor other than 1.2:

$$C = C_{sg} \times C_{sf}$$

$$C_{sg} = \frac{2.12}{(S_s - 1)^{1.5}}$$

where:

S_s = specific gravity of the rock riprap

$$C_{sf} = \left(\frac{SF}{1.2}\right)^{1.5}$$

for: R = curve radius
W = channel width

R/W	Stability Factor
> 30	1.2
10 to 30	1.3-1.6
< 10	1.7

E. Typical countermeasures for lateral shifting and instability

1. Construction of river control works
2. Bank stabilization

F. Effect of control of meander

1. Downstream bank erosion not likely to increase
2. Bank erosion location likely to change

VII. Toe Scour Estimates

A. Components of total vertical scour

1. Long-term degradation

2. General scour (design flood, contraction scour)

3. Local scour

   a) Bend scour

   b) Low flow channel incisement (thalweg formation) on the order of one to two feet

   c) Bed form scour for sand bed channels (Figure VII-1)

      (1) Antidunes in transitional and upper regime flow (Kennedy, 1963)

$$h_a = 0.14\frac{2\pi V^2}{g} = 0.027V^2$$

For $h_a < y$

where:

h_a	=	antidune height from crest to trough (ft) [use ½ of h_a for scour depth below original bed]
V	=	max. cross section channel velocity (ft/s)
g	=	gravitational constant, 32.2 ft/sec^2
y	=	actual depth of flow

Assume that $h_a = y$ when calculated value of $h_a > y$ since the antidune height can never be greater than the depth of flow.

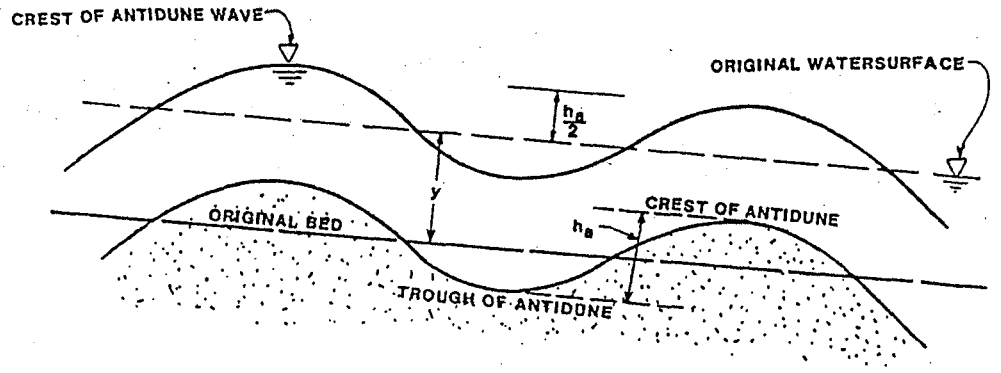


Figure VII-1 Definition sketch for antidune height (Simons, Li & Associates, 1985, p. 4.25)

(2) Dunes in lower regime flow (Simons and Richardson, 1960)

(a) Ratio of depth of flow to depth of dune height ranged from 1 to 5 (for Froude numbers 0.38 to 0.60) in studies.

(b) When ratio is one, dune troughs are depressed below the bed a distance of one-half the flow depth. When ratio is five, dune troughs are depressed below the bed a distance of one-tenth the flow depth. Therefore, the range is 10% to 50% of flow depth.

4. Safety factor

a) Dependent on acceptable risk

b) Should vary on level of confidence with methods applied and confidence in data

c) Ranges from 1.0 to 1.5

B. Blodgett's (1986) relationship (Brown and Clyde, 1989)

d_S = 12 ft for D_{50} < 0.005 ft (1.5 mm)

$d_S = 6.5D_{50}^{-0.11}$ for D_{50} > 0.005 ft (1.5 mm)

where:

d_S = estimated probable maximum depth of scour (ft)

D_{50} = median diameter of bed material (ft)

1. For natural scour and fill phenomenon in straight channels and in channels having mild bends
2. Measure d_s from lowest elevation in cross section
3. Assume low point in cross section may move adjacent to channel bank
4. General scour - calculated depth of scour must be added to predicted long term degradation and any local scour to obtain total required toe down depth
5. HEC-11 design example with Blodgett's relationship

   a) Data and scour calculations

   Given data:

D_{50}	=	0.5 ft (0.15m) channel bed material
θ	=	26.56° (2:1 slope) proposed bank protection
T	=	3 ft (riprap thickness)
		Maximum channel depth = 15.0 ft.

Scour Calculations:

$$d_S = 6.5D_{50}^{-0.11}$$

$$d_S = 6.5(0.5)^{-0.11} = 7.0 \text{ ft}$$

Potential maximum scour depth = 15.0 ft + 7.0 ft = 22.0 ft.

Set toe protection to this depth or sufficient volume placed at bank toe to protect to this depth.

d'_S **below existing channel bottom: 22.0 ft – 12.0 ft = 10.0 ft**

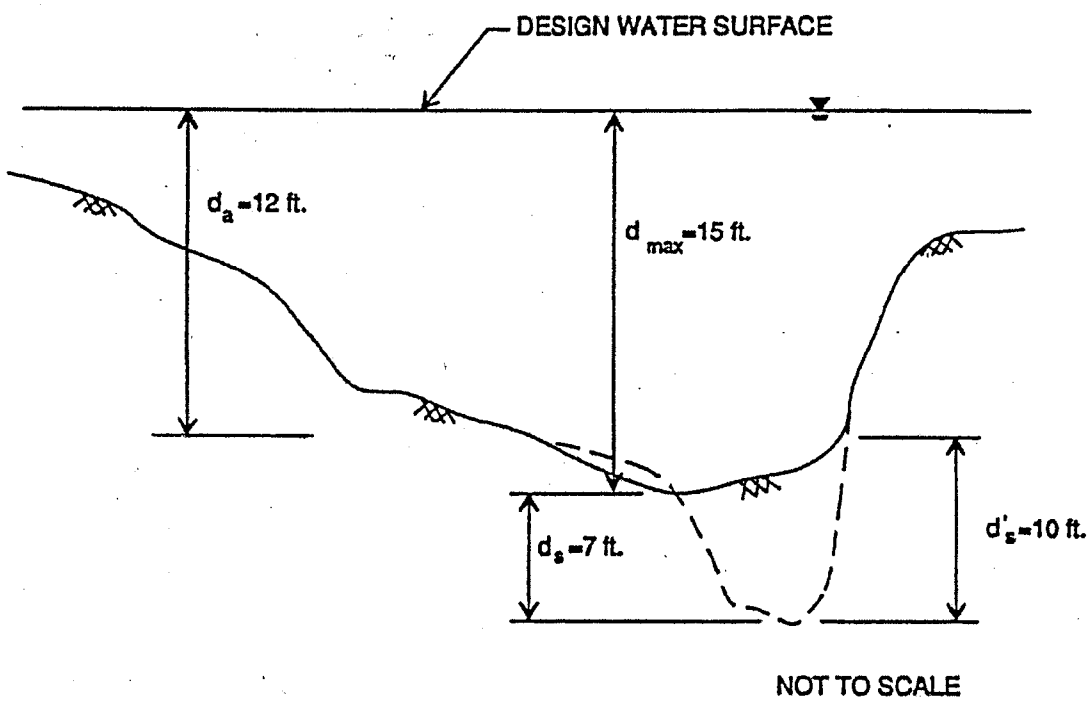


Figure VII-2 Channel cross section illustrating flow and potential scour depths (adapted from Brown and Clyde, 1989, p. 71)

b) **Rock quantity required below existing bed for weighted toe:**

$$R_q = \frac{d'_S(T)\,(1.5)}{\sin\theta}$$

R_q	=	**Required riprap quantity per ft of bank (ft^2)**
θ	=	**Bank angle with the horizontal (degrees)**
T	=	**Riprap layer thickness (ft)**

$$R_q = \frac{10(3)(1.5)}{\sin(26.56)} = 101\ ft^2$$

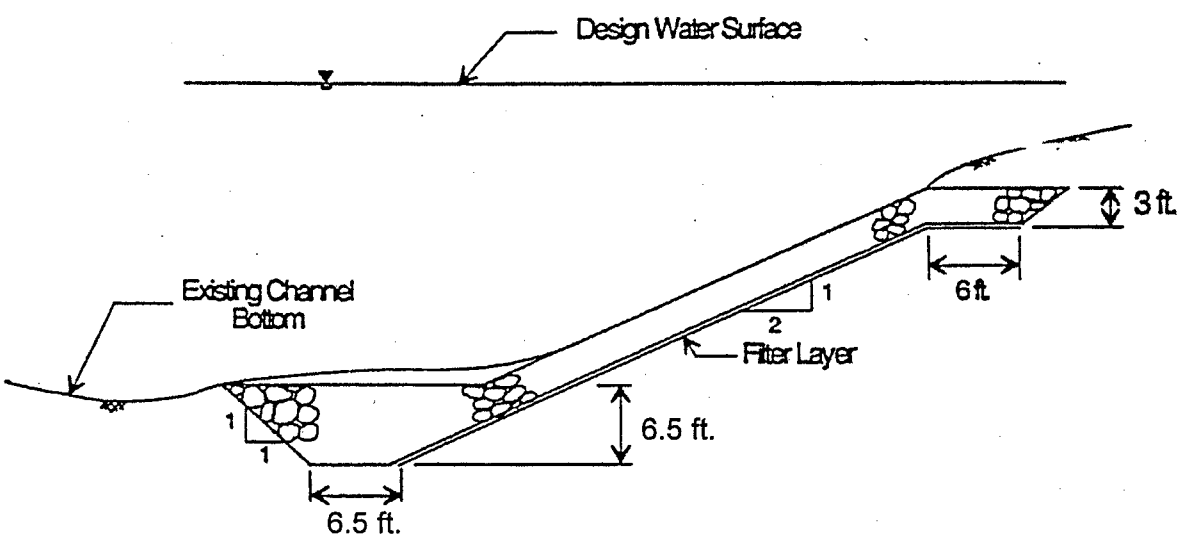


Figure VII-3 Toe and flank detail (adapted from Brown and Clyde, 1989, p. 72)

c) **Alternative weighted toe volume computations (Corps method):**

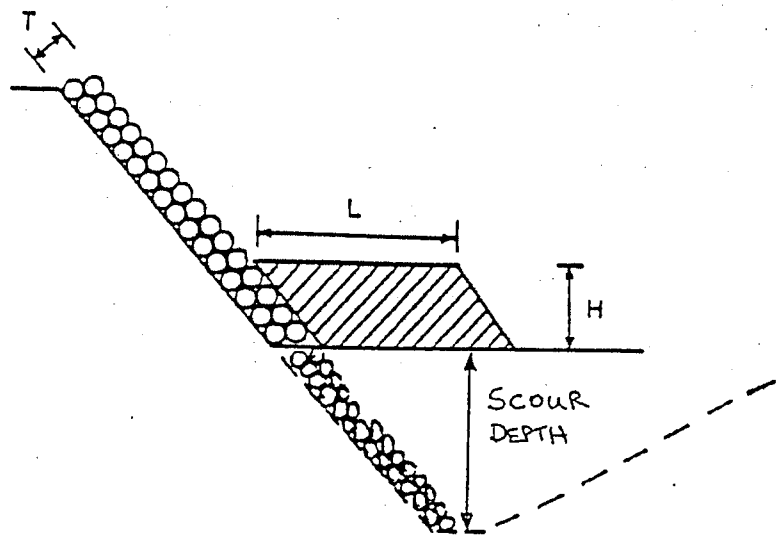


Figure VII-4 Toe Scour Protection (Maynord, 1990, and Corps, 1994)

1) **Launch Slope = 1*V*: 2*H***
2) **Scour Depth = Existing Elevation – Maximum Scour Elevation**
3) **Thickness After Launching = 1.5 * Bank Riprap Thickness (*T*)**
4) **For vertical launch distance < 15 ft, with 50% increase in rock volume for underwater placement:**

Volume = 1.5 * *T* * Launch Slope Length (ft^2 per lineal ft)
= 1.5 * *T* * Scour Depth * $\sqrt{5}$
= 3.35 * *T Scour Depth**

Weighted Toe Configuration:

Toe Height *H*= 2.5 to 4.0 times *T* for gradual scour in regular bendways

= 2.5 to 3.0 times *T* for rapid scour in impinged flow environment or gravel bed streams

Toe Length *L* Based on Required Toe Volume

May add safety factor – see EM 1110-2-1601 for other conditions

C. Levee design criterion (Los Angeles County Flood Control District, 1982)

- **For natural watercourses (assume for general and bend scour)**
- **Flexible or rigid lining**
- **Limited to 20 ft/sec (design to reduce velocity otherwise)**
- **Levee linings must extend below grade to cutoff depth or provide an apron that can adjust to scour conditions:**

	Cut off depths	
Velocity, ft/sec	Straight reach, ft	Curved reach, ft*
0-6	6	9
6-10	8	12
10-15	10	15
15-18	12.5	18
18-20	14	21

*** use greater of table values above or Fig. F-06 in manual (see Figure** VII-5**)**

- **Levee thickness:**

	Levee thickness – T			
	Concrete Levee		Gunite Levee	
Velocity ft/sec	Straight reach	Curved reach	Straight reach	Curved reach
0 – 10 fps	6-inch	8-inch	8-inch	10-inch
10 – 20 fps	8-inch	10-inch	not permitted	not permitted

- **Apron length for gabion levees:**

Gabion levees**	
Velocity, ft/s	Apron length, ft
0-7	12
8-10	18
11-15	21

**** Gabion levees not permitted for velocity > 15 ft/s**

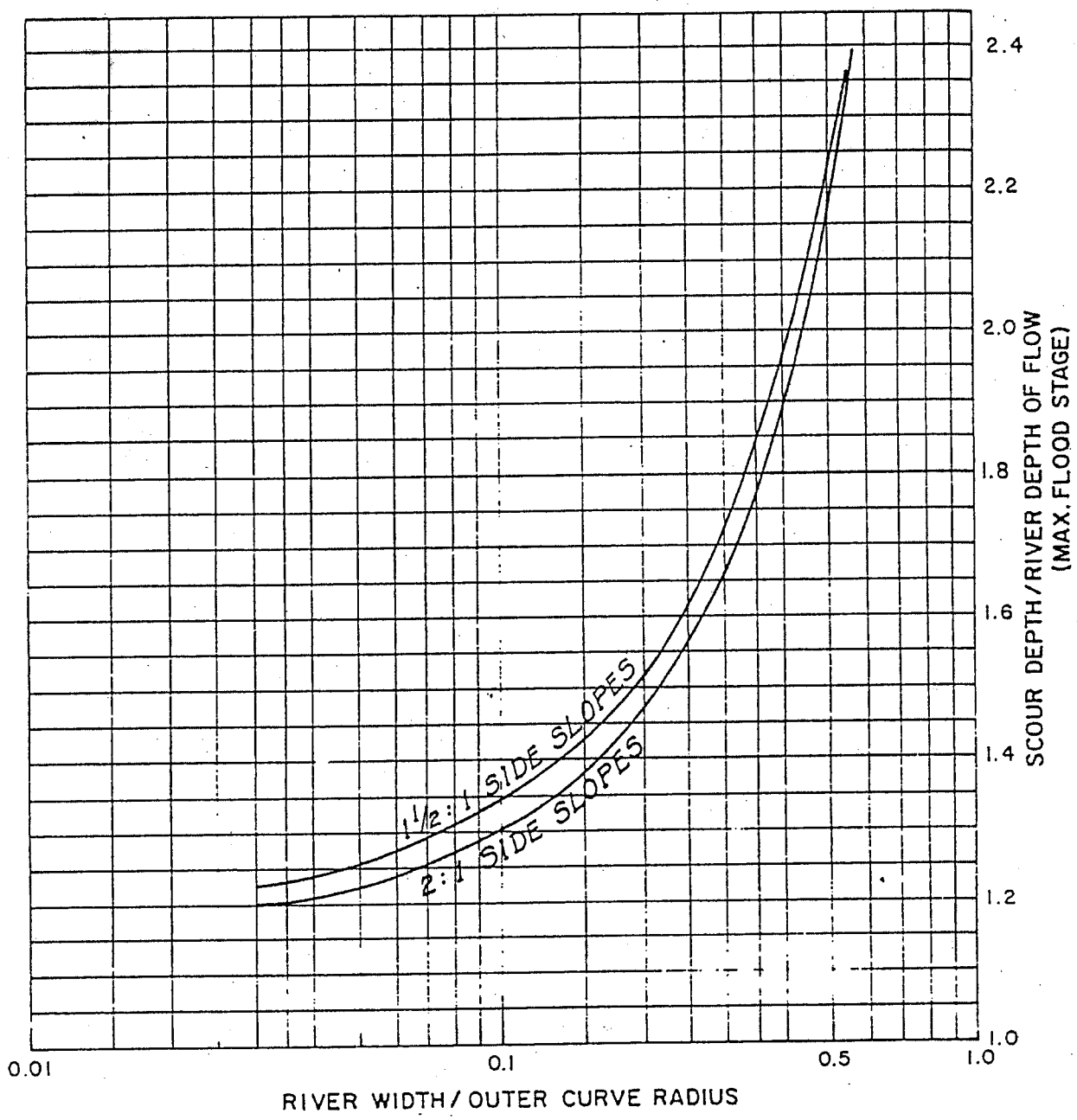


Figure VII-5 Scour depths on outer curves (L.A. Co. FCD, 1982, Fig. F-06, p. F-37)

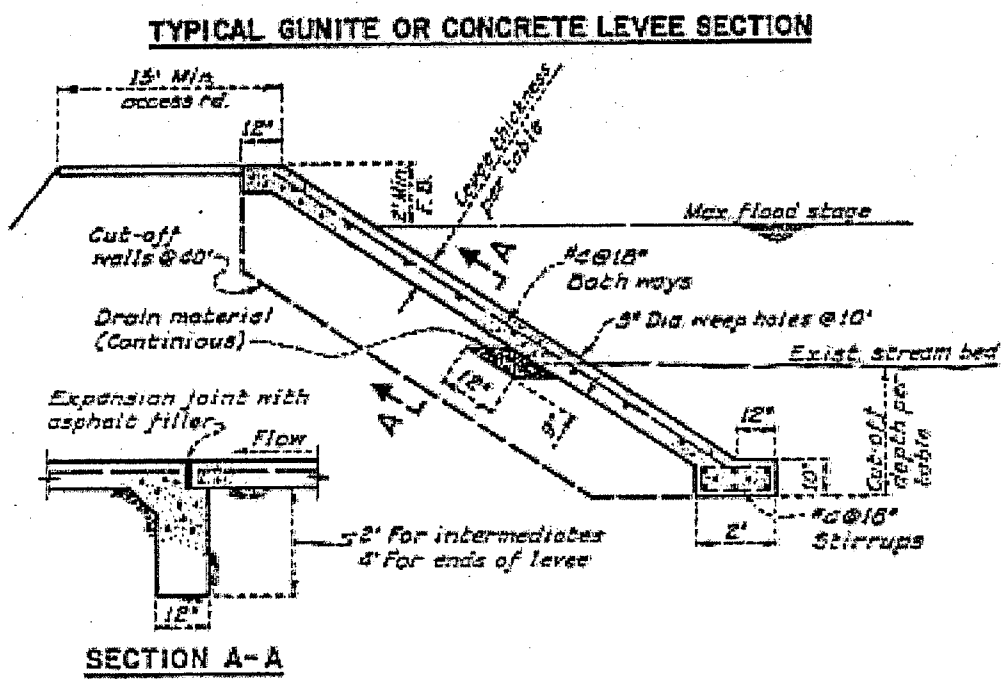


Figure VII-6 Typical gunite or concrete levee section (LA. Co. FCD, 1982, p. F-34)

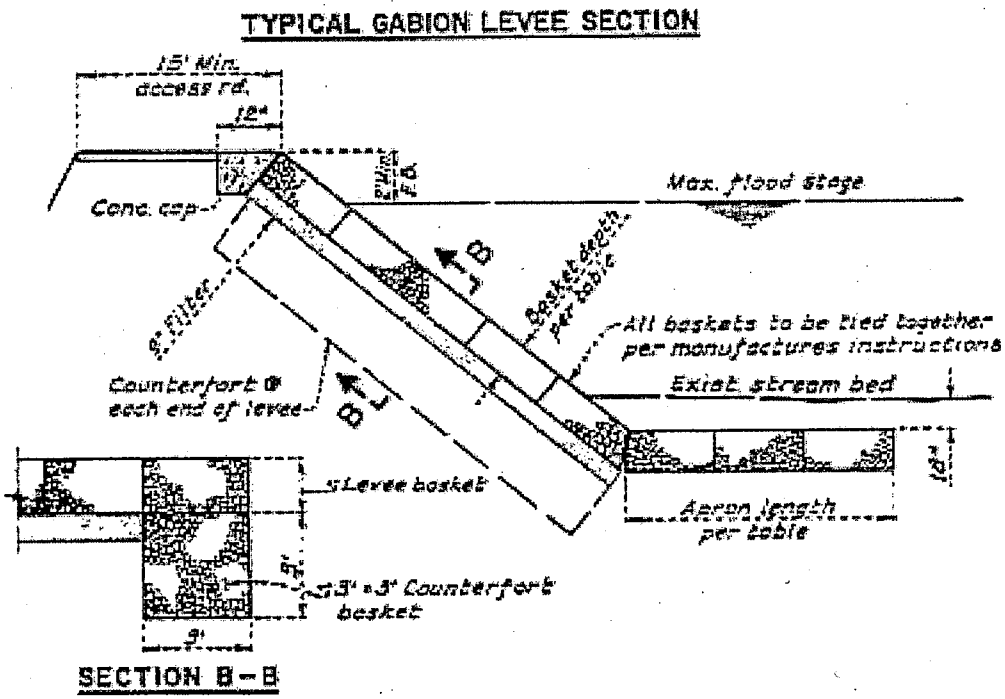


Figure VII-7 Typical gabion levee section (L.A. Co. FCD, 1982, p. F-34)

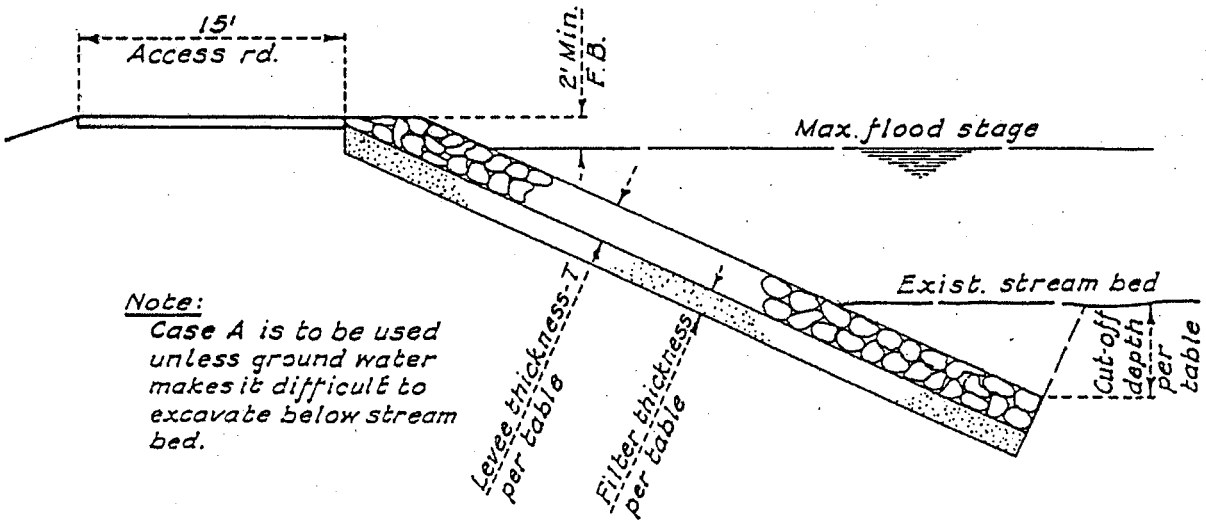


Figure VII-8 Typical rock rip-rap levee section, Case A (L.A. Co. FDC, 1982 p. F-35)

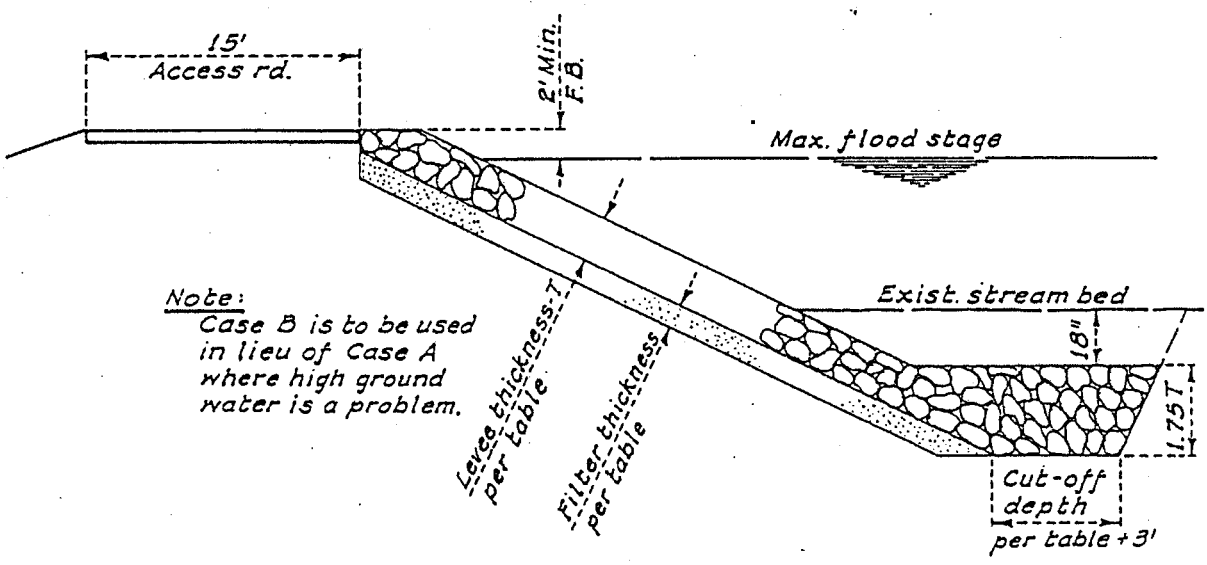


Figure VII-9 Typical rock rip-rap levee section, Case B (L.A. Co. FCD, 1982, p. F-35)

D. Corps of Engineers (EM 1110-2-1601)

1. Design curves for scour in bends are found in Plate B-42 of the Corps manual (see Fig. VII-10)

2. Based on the ratio of maximum water depth in the bend to the mean water depth in the approach channel

3. Note that the maximum depth in the bend ranges from about 1.5 to 3.5 times the mean depth in the approach channel

4. Plate B-42 represents upper limit for channels with irregular alignment - use 10% reduction from the bend scour design curve for relatively smooth alignment

5. Add this bend scour to expected long term degradation, general scour and other local scour components

As an alternative, see later discussion in Thorne, et al. (1995)

a) Applicable to high in-bank flows, i.e. water surface elevation of design flood in or only slightly above the top of revetment

b) For higher flows, authors suggest model floodplain water flow and sediment movement

c) Fitted equation (different than Plate B-42):

$$d_{max}/d_{bar} = 2.07 - 0.19 \log (R_c/w - 2)$$

where:

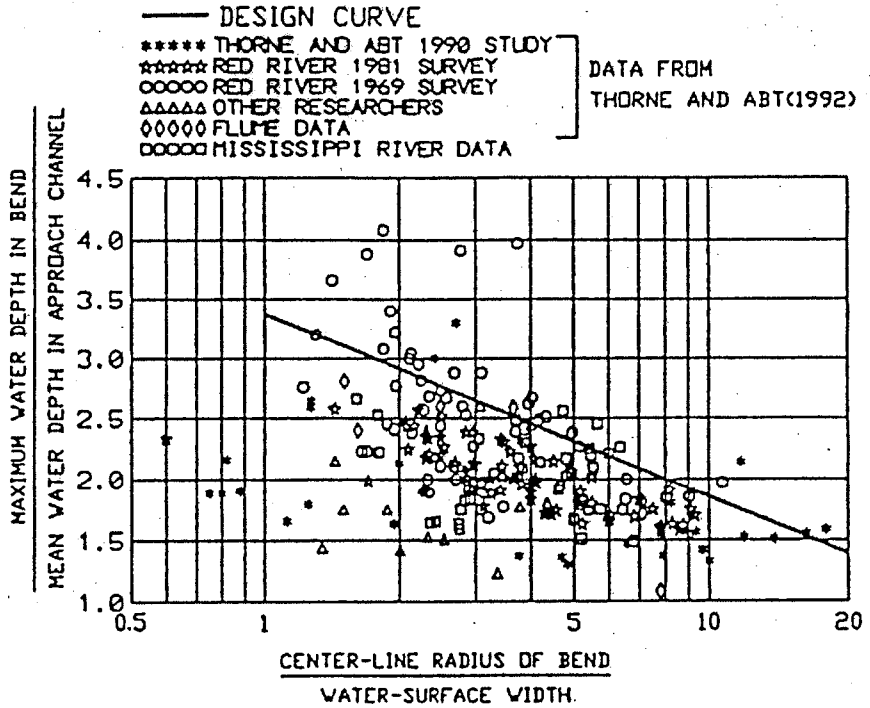
d_{max} = maximum depth in bend (ft)

d_{bar} = mean depth in approach channel (ft)

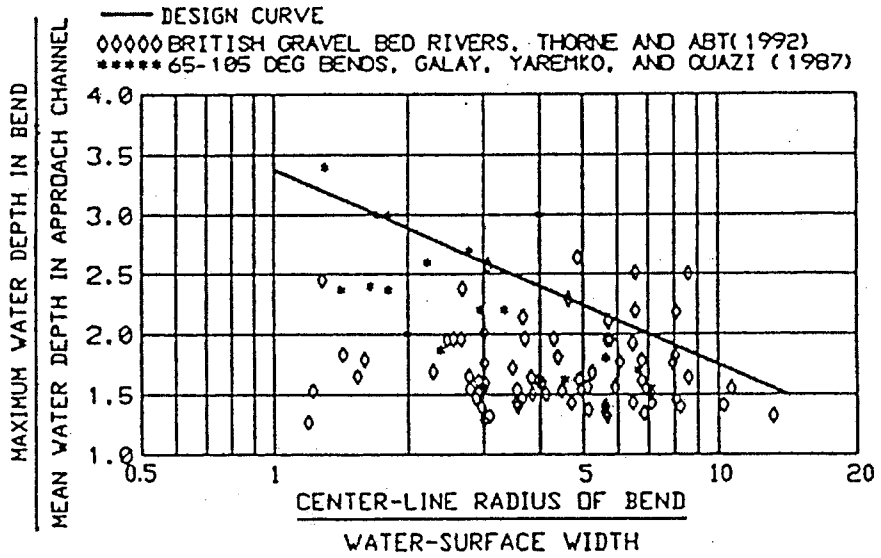
R_c = centerline radius of bend (ft)

W = water surface width (ft)

R_c/w = 2 is lower limit of applicability



SAND BED CHANNELS



GRAVEL BED CHANNELS

Figure VII-10 Scour depth in bends (EM 1110-2-1601 30 Jun 94, plate B-42)

E. Zeller's (1981) bend scour formula (Simons, Li & Associates, 1985)

$$\Delta Z_{bs} = \frac{0.0685 Y V^{0.8}}{Y_h^{0.4} S_e^{0.3}} \left[2.1 \left(\frac{\sin^2 \frac{\alpha}{2}}{\cos \alpha} \right)^{0.2} - 1 \right]$$

For sand bed channels, where α > *17.75 degrees (Rc/W <10)* *and*:

ΔZ_{bs} = bend scour component of total scour depth (ft)

V = mean velocity of upstream flow (ft/s)

Y = maximum depth of upstream flow (ft)

Y_h = hydraulic depth of upstream flow (ft)

S_e = approach energy slope or bed slope for uniform flow (ft/ft)

α = angle formed by projection of the channel centerline from the point of curvature to a point which meets a line tangent to the outer bank of the channel (degrees) For circular curves, R_c/W = Cos α/(4 Sin^2 (α/2))

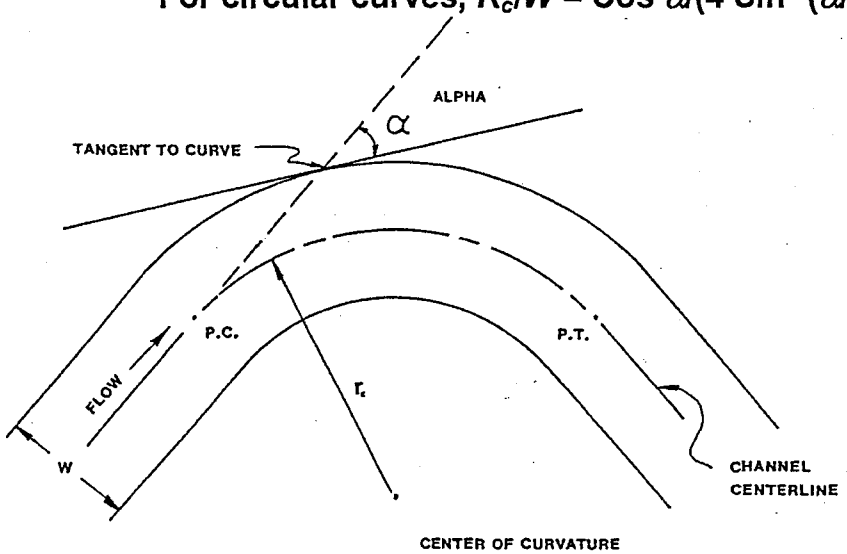


Figure VII-11 Illustration of terminology for bend scour calculations (Simons, Li & Associates, 1985, p. 5.107)

F. U.S. Bureau of Reclamation (Pemberton and Lara, 1984)

1. Introduction

   a) Channel scour during peak flood flows (general scour)

      (1) Type 1: Natural channel scour

      (2) Type 2: Scour induced by structures in or adjacent to the channel

   b) Equation types

      (1) Type A: Natural channel for constrictions and bends

         (a) Siphon crossing or any buried pipeline

         (b) Stability study of a natural bank

         (c) Waterway for one-span bridge

      (2) Type B: Bankline structures

         (a) Abutments to bridge or siphon crossing

         (b) Bank slope protection such as riprap, etc.

         (c) Spur dikes, groins, etc.

         (d) Pumping plants and canal headworks

      (3) Type C: Mid-channel structures

         (a) Piling for bridge

         (b) Piers for flume over river

         (c) Power line footings

         (d) River bed water intake structures

(4) Type D: Hydraulic structures across channel

(a) Dams and diversion dams

(b) Erosion controls

(c) Rock cascade drops, gabion controls, and concrete drops

c) Reclamation practice: compute scour by several methods, use judgment in averaging results or selecting appropriate method

2. Equation Types A and B

a) Based on constricted waterway reach

b) Four methods adapted from Neill (1973)

(1) Field measurements of scour (envelope curve)

(a) From ephemeral, relatively steep, wide sand bed streams in southwestern United States

(b) D_{50} from 0.5 to 0.7 mm (coarse sand)

(c) Slopes from 0.004 to 0.008 ft/ft

(d) See Figure VII-12 for general scour depth, d_s (ft)

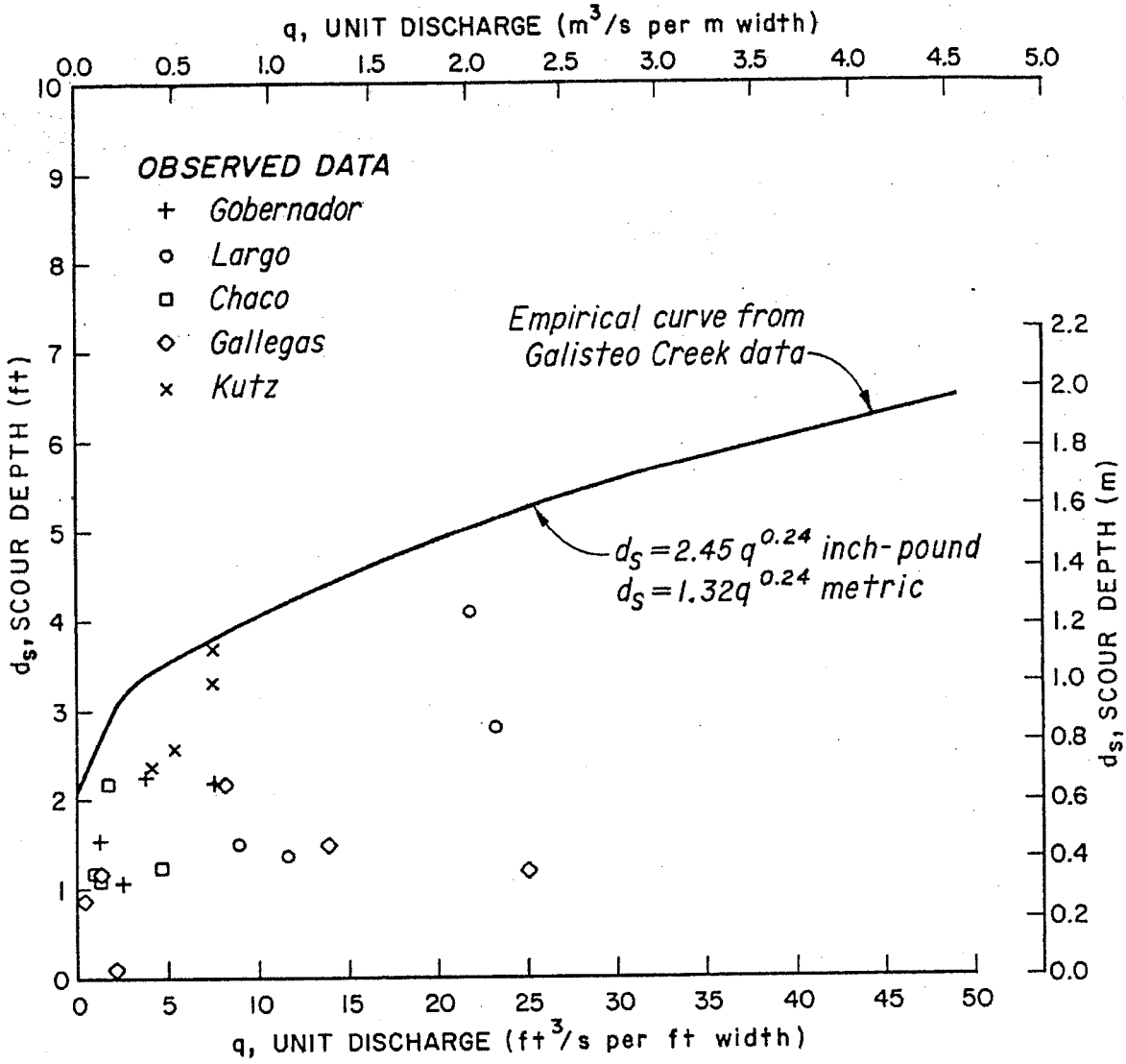


Figure VII-12 Navajo Indian Irrigation Project - scour versus unit discharge
(Pemberton and Lara, 1984, p. 33)

(2) Regime equations supported by field measurements

(a) Neill's (1973) approach

Based on field measurements in an incised reach:

$$d_f = d_i \left(\frac{q_f}{q_i} \right)^m$$

where:

d_f = scoured depth (general scour) below design floodwater level (ft)

d_i = average depth at bankfull discharge in incised reach (ft)

q_f = design flood discharge per unit width ($ft^3/s/ft$)

q_i = bankfull discharge in incised reach per unit width ($ft^3/s/ft$)

m = exponent varying from 0.67 for sand to 0.85 for coarse gravel

(b) Lacey's (1930) equation

$$d_m = 0.47\left(\frac{Q}{f}\right)^{1/3}$$

where:

d_m = mean water depth at design discharge (ft)

Q = design discharge (ft^3/s)

f = Lacey's silt factor = 1.76 $(D_m)^{1/2}$

and:

D_m = mean grain size of bed material (mm)

(c) Blench equation (1969)

$$d_{f0} = \frac{q_f^{2/3}}{F_{b0}^{1/3}}$$

where:

d_{f0} = water depth for zero bed sediment transport (ft)

q_f = design discharge per unit width ($ft^3/s/ft$)

F_{b0} = Blench's "zero bed factor" in ft/s^2 from Figure VII-13

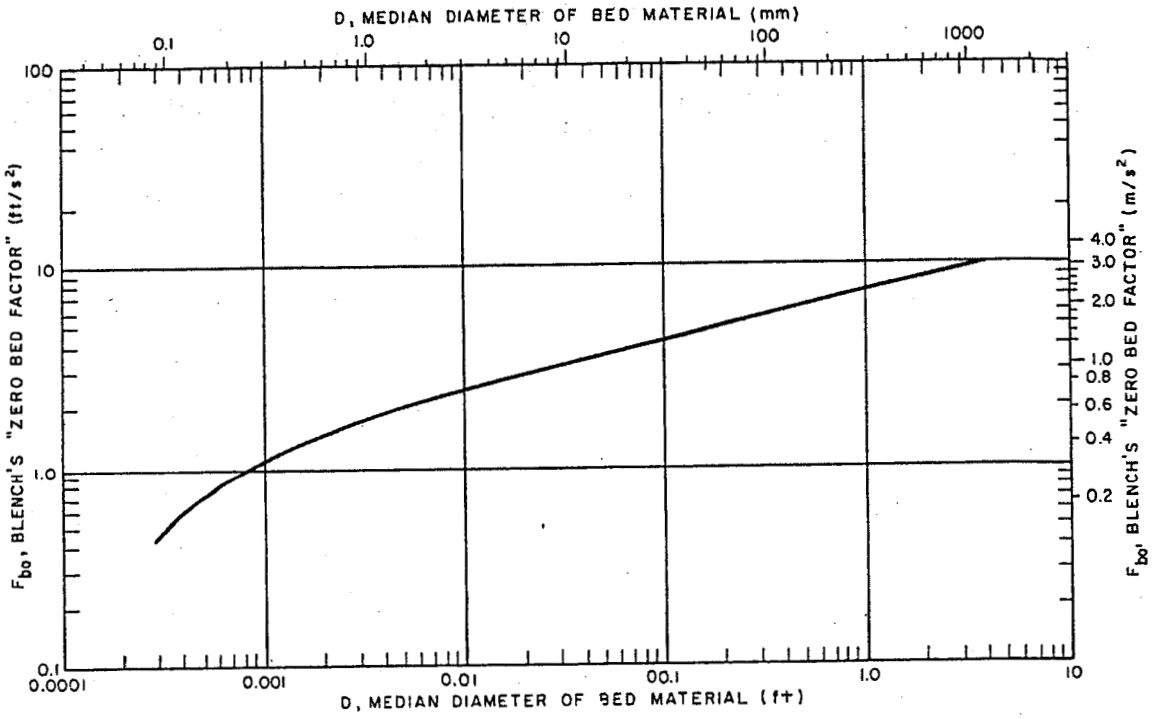


Figure VII-13 Chart for estimating F_{b0} (Pemberton and Lara, 1984, p. 35, after Blench, 1969)

(d) Calculating scour depth with the regime equations

(i) Accounts for probable concentration of flood flows in some portion of the natural channel

(ii) Depth of scour below streambed (Figure VII-14) [general scour plus bend scour and thalweg formation]:

$$d_s = Z\, d_f$$

$$d_s = Z\, d_m$$

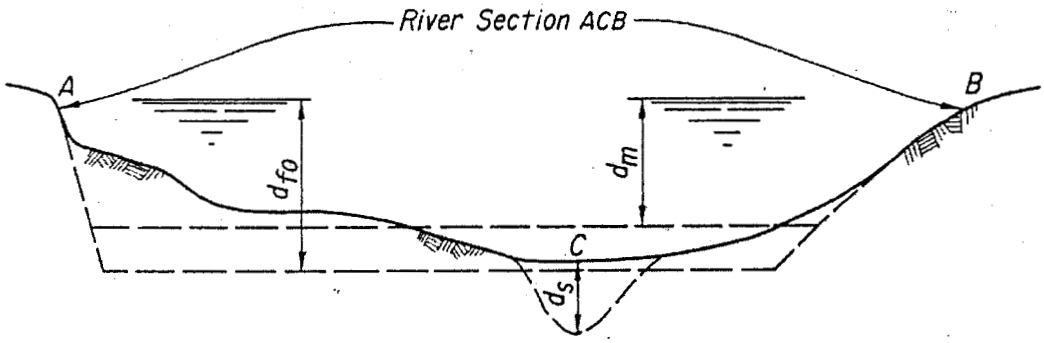
$$d_s = Z\, d_{f0}$$

where:

d_s = Depth of scour below low point in existing stream bed, in units of d_f, d_m, and d_{fo}

Z = Multiplying factor from Table VII-1

(iii) In an alluvial streambed, design should be based on channel shifting scour to any location



NOTE: $d_{fo} > d_f > d_m$. Point C is low point of natural section.

Figure VII-14 Sketch of natural channel scour by regime method (Pemberton and Lara, 1984, p. 36)

Table VII-1 Multiplying factors, *Z*, for use in scour depth by regime equations (Pemberton and Lara, 1984, p. 36)

Condition	Value of Z		
	Neill $d_s = Z\ d_f$	Lacey $d_s = Z\ d_m$	Blench $d_s = Z\ d_{fo}$
Equation Types A and B			
Straight reach	0.5	0.25	1/ 0.6
Moderate bend	0.6	0.5	1/ 0.6
Severe bend	0.7	0.75	1/ 0.6
Right angle bends		1.0	1.25
Vertical rock bank or wall		1.25	

1/ Z value selected by USBR for use on bends in river.

(3) Mean velocity from field measurements

(a) Obtain at least 4 surveyed cross sections

(b) Develop computer water surface profile model

(c) Obtain d_m from computer output

(d) $d_S = Z\, d_m$ using Lacey Z values (see Table VII-1) for general and bend scour

(4) Competent or limiting velocity control

(a) Assumes scour will occur until mean velocity is less than velocity for significant bed material movement (general scour)

(b) Competent mean velocities from Figure VII-15 and Table VII-2

$$d_S = d_m\left(\frac{V_m}{V_C} - 1\right)$$

where:

d_S = scour depth below streambed (ft)

d_m = mean depth (ft)

V_C = competent mean velocity (ft/s)

V_m = mean velocity (ft/s)

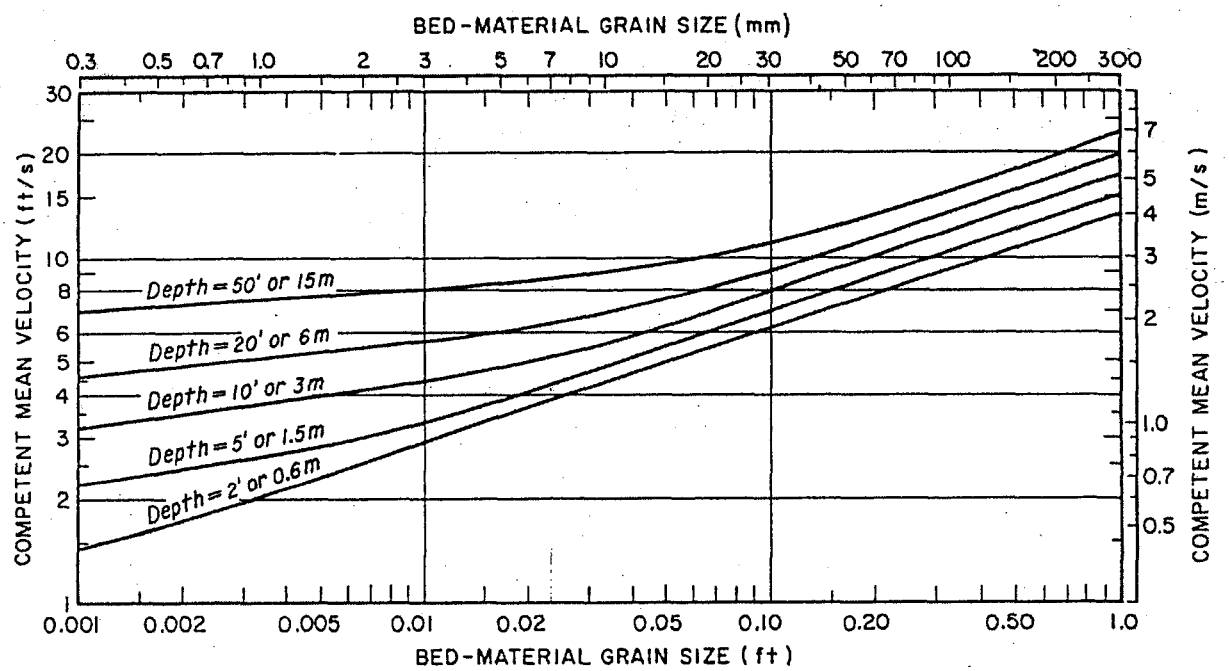


Figure VII-15 Suggested competent mean velocities for significant bed movement of cohesionless materials, in terms of grain size and depth of flow (Pemberton and Lara, 1984, p. 41, after Neill, 1973)

Table VII-2 Tentative guide to competent velocities for erosion of cohesive materials* (Pemberton and Lara, 1984, p. 38, after Neill, 1973)

Depth of flow		Competent mean velocity					
		Low values - easily erodible material		Average values		High values - resistant material	
ft	m	ft/s	m/s	ft/s	m/s	ft/s	m/s
5	1.5	1.9	0.6	3.4	1.0	5.9	1.8
10	3	2.1	0.65	3.9	1.2	6.6	2.0
20	6	2.3	0.7	4.3	1.3	7.4	2.3
50	15	2.7	0.8	5.0	1.5	8.6	2.6

* Notes: (1) This table is to be regarded as a rough guide only, in the absence of data based on local experience. Account must be taken of the expected condition of the material after exposure to weathering and saturation. (2) It is not considered advisable to relate the suggested low, average, and high values to soil shear strength or other conventional indices, because of the predominating effects of weathering and saturation on the erodibility of many cohesive soils.

VIII. Design Considerations for Toe Protection

A. General

1. Design Flow

   a) Usually examine a range of flows up to 100-year event

   b) Bankfull or overtopping event may generate greatest velocities and tractive forces

2. Design velocities

   a) Use local velocity, not average channel velocity (unless specified in equation)

   b) Local velocity along outside of bend may be 60% greater than the average velocity in the approach channel (Thorne, et al., 1995)

3. Longitudinal extent of protection

   a) Continue protection for a distance greater than the length that is subject to channel flow forces capable of dislodging/transporting bank material

   b) 1.0 main channel width upstream (scars on channel bank can be used to establish start - go 1.0 width upstream)

   c) 1.5 main channel width downstream

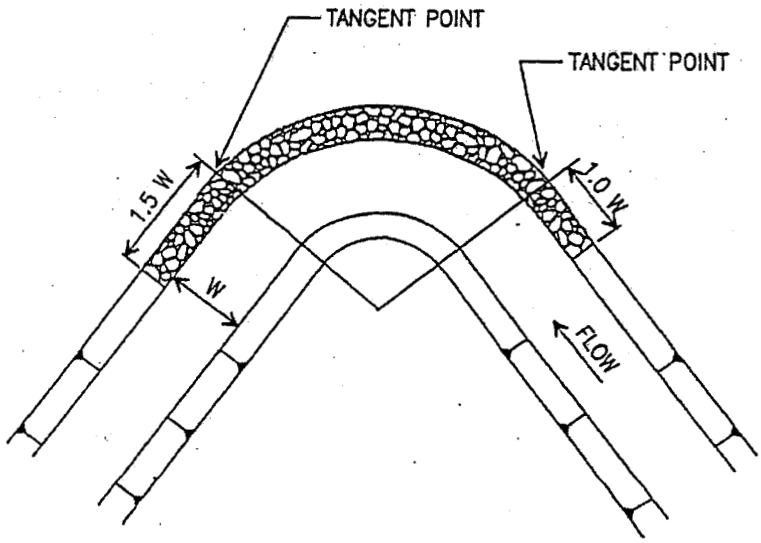


Figure VIII-1 Longitudinal extent of revetment protection (Brown and Clyde, 1989, p. 24)

d) **Minimum starting point – based on lab studies - needs to be site specific**

e) **Influenced by controls, bridge abutment, rock outcrop**

f) **If bridge has abutment adjacent to channel bank, will define downstream limit of channel movement:**

(1) No contraction or no flow expansion

Terminate bank protection 1.0 width downstream of control

(2) If significant contraction or expansion occurring

Terminate bank protection 4.0 times constricted channel width at the control

4. **Tie into stable bank area upstream and downstream to prevent flanking**

B. Rock toe keys (Johnson and Stypula, 1993)

1. Rock is keyed in – not end dumped
2. Placed to potential scour depth or a minimum of 5 feet below the original streambed elevation (Lagasse, et al., 1995)
3. Include long term degradation, local scour, general scour, thalweg formation, bed forms, etc. in total scour
4. Minimum rock dimension of 2 feet or minimum weight of 500 pounds for stability
5. Use quarried (angular) rock which tends to interlock
6. For high banks, consider construction bench and set back upper bank

C. Live cribwall

1. **Rectangular framework of logs or untreated timber, rock, and woody cuttings**
2. **Useful when space is limited and slopes cannot be cut back**
3. **May have finished streamside slopes as steep as 1H:10V**
4. **Useful for restoring lost banks**
5. **Construction details discussed in Gray and Leiser, 1982**
6. **May require rock toe key outside of structure**

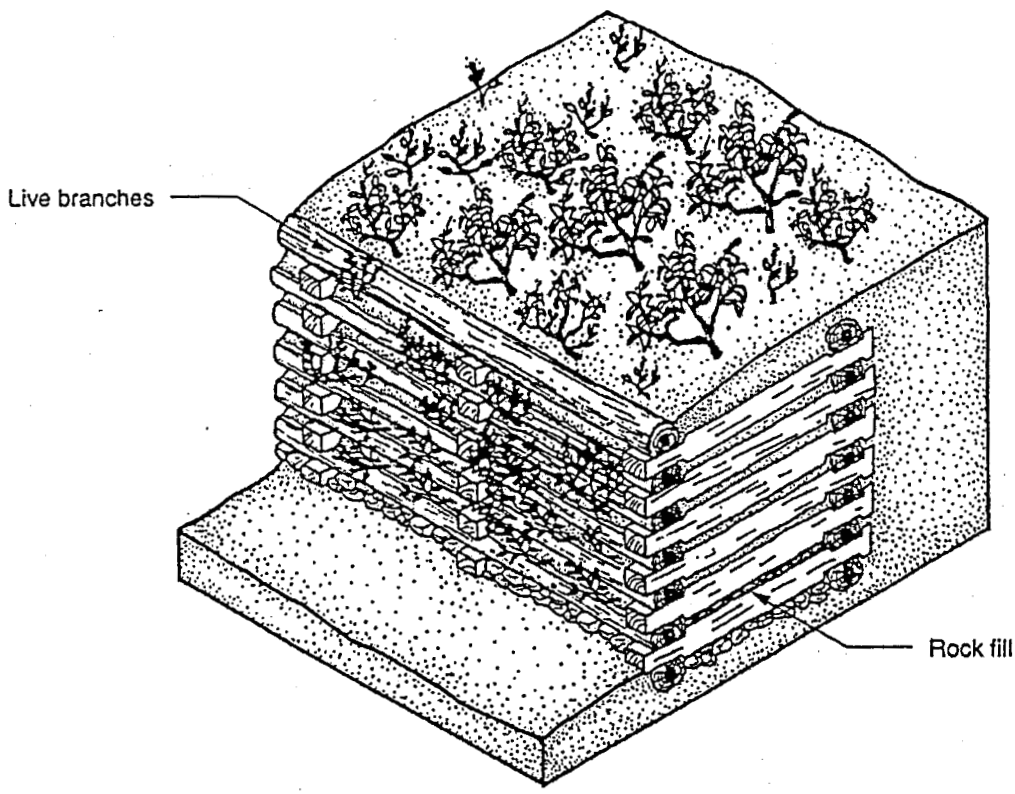
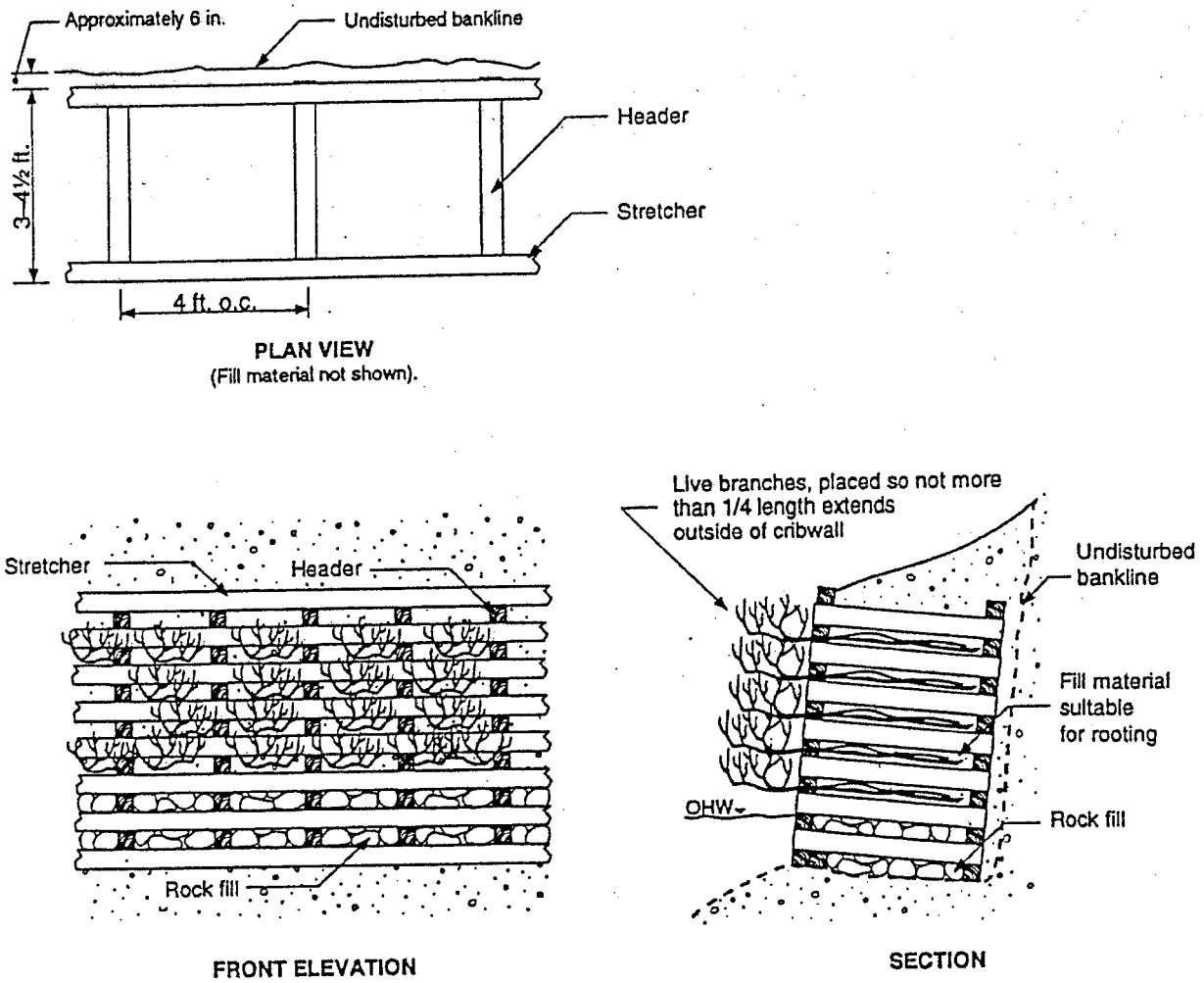


Figure VIII-2 Live Cribwall (Johnson and Stypula, 1993, p. 7-21)



NOTES:

The cribwall can be constructed with either round peeled timbers or square timbers.

Fill material should be suitable for rooting, but topsoil is not necessary. Ensure even filling of soil over branches, avoiding hollow spaces.

If possible, the basal cut end of branches should extend into the soil behind the wall.

Figure VIII-3 Installation of live cribwall (Johnson and Stypula, 1993, p. 8-24)

IX. Inspection and Maintenance (Johnson and Stypula, 1993)

A. Inspect toe protection during low water period

1. Areas of bare soil within the toe zone
2. Evidence of stone movement or displacement
3. Scour along the toe that leaves the upper bank unsupported
4. Evidence of bed degradation, headcuts, or scour holes that might undermine the toe
5. Settling, tilt, or horizontal displacement of cribwall structure

B. Monitor at least annually and after major floods

C. Maintain and repair as needed

1. Add rock to replace missing or displaced stones
2. Individual placement is recommended for better keying
3. Large rock, design size D_{100} or larger, should be used for replacement
4. Repair damaged filter layer before replacing rock
5. Depending on severity, fill scour holes formed at the toe with large rock

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XI. Acknowledgements

The presenters wish to acknowledge the many researchers and contributors to this field whose works are cited in the references and included in this presentation.

APPENDIX B

Predicting Bed Scour for Toe Protection Design in Bank Stabilization Projects

Summary Example Problem

Objective: Compute a reasonable bed scour depth for toe protection on the right side of the channel at cross section 12450 in Murrieta Creek for the 100-year flood. The design discharge is the 100-year discharge and the design life is 50 years.

Given Data:

1.0 From Hydraulic Model of Murrieta Creek for 100-Year Discharge:

Cross section 12450 (see Figure 1 and Figure 2):
Q_{100} = 38,600 cfs
Q_{100} Channel = 34,454 cfs
Minimum Channel Elevation = 970.3 ft (msl)
Water Surface Elevation = 991.5 ft
Maximum Flow Depth = 21.2 ft
Mean (Hydraulic) Depth in Channel (A/T) = 15.3 ft
Channel Froude Number = 0.60
Energy Grade Slope = 0.006655 ft per foot
Average Channel Velocity = 13.3 ft/sec
Maximum Channel Velocity = 15.5 ft/sec
Channel Centerline Radius of Curvature (R_c) = 5,300 ft
Channel Top Width (W) = 170 ft
R_c/W = 31.2 (mild bend)
Channel Outside Radius = 5,385 ft
Right Channel Side Slope = 2H:1V
D_{50} = 1.8 mm (very coarse sand) = 0.00591 ft

Approach Channel (Upstream):
Mean (Hydraulic) Depth in Approach Channel (A/T) = 12.3 ft
Maximum Depth in Approach Channel = 17.6 ft
Approach Energy Slope = .004458 ft/ft
Mean Velocity of Approach Channel = 11.2 ft/s

2.0 From Hydraulic Model of Murrieta Creek for Bankfull Discharge:

Cross section 12450:

$Q_{Bankfull}$ = 18,000 cfs

Maximum Flow Depth at Bankfull = 14.0 ft

Mean (Hydraulic) Depth at Bankfull (*A/T*) = 8.9 ft

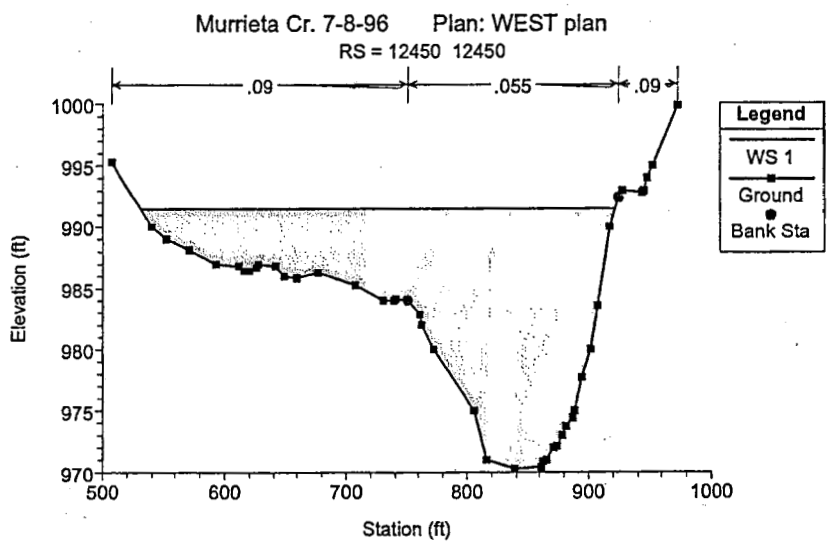


Figure 1 - Looking downstream at XSEC 12450 for 100-year discharge

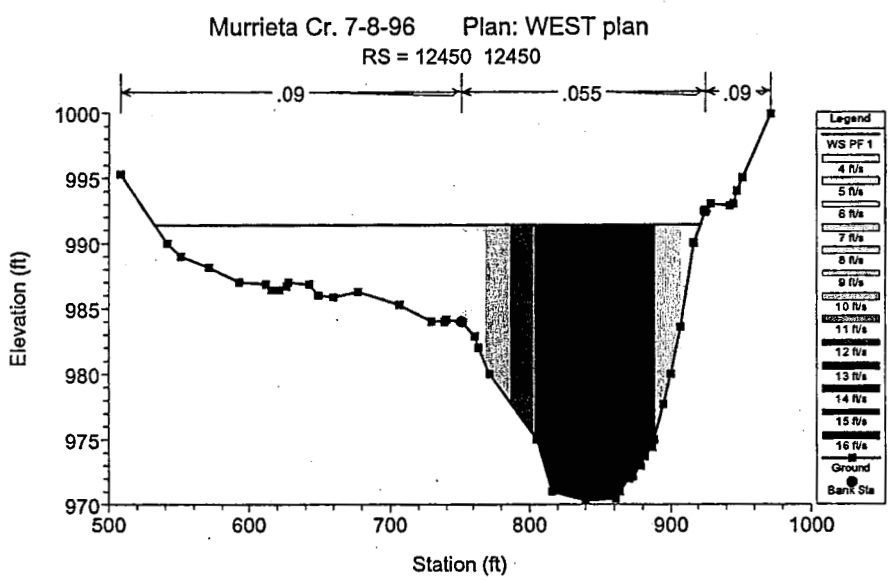


Figure 2 - Velocity distribution at XSEC 12450 for 100-year discharge

General:

The evaluation of total scour and application for toe protection will include:

1. Long term scour (long term bed elevation change) - from HEC-6 or other sediment routing model, extrapolating trend of historical bed elevations, equilibrium or stable slope analysis, or limitation by armoring if armored condition will be stable.

2. General scour for the 100-year design event - from HEC-6 or other sediment routing model, sediment continuity equations, contraction scour equations, or other empirical or analytical methods.

3. Local Scour
   a. Pier or abutment scour
   b. Bend scour
   c. Bed forms scour (for sand bed channels)
   d. Thalweg formation

4. Safety Factor – multiplier of the total scour, usually ranging from 1.0 to 1.5

5. Subtraction of the scour depth (often referred to as d_s) from the lowest elevation in the channel bed (see Figure VII-14, p. 59 of the course notes).

Note that this example evaluation is fictional, and is based upon the judgment, experience, and interpretation of the authors. Your interpretation may be different, but remember the key word in our objective is <u>reasonable</u>. In some cases, it is appropriate to be conservative, but being highly conservative for every assumption may not necessarily be reasonable.

Part 1 – Long Term Scour

Based on an extrapolation of historical bed elevations obtained from cross section surveys, we predict that the bed elevation at cross section 12450 will degrade 3.5 feet over the next 50 years, which is the design life timeframe.

Part 2 – General Scour

For this example, we will use various equations or methods presented in the course material to evaluate general scour and we will use our judgment to make a final selection. Note that some of the methods also may be presumed to include bend scour or other local scour components. We will account for this in the final addition to get the total scour.

2.1 Blodgett's (1986) Relationship (Brown and Clyde, 1989)

Blodgett's relationship is applicable for straight channels and channels with mild bends. HEC-11 defines bends as follows:

Mild	$R_c/W > 30$
Moderate	$10 < R_c/W < 30$
Sharp	$R_c/W < 10$

The example reach qualifies as a mild bend because $R_c/W = 31.2$.

Since this is a "general scour" estimate, we must add it to the long-term scour and local scour. Bend scour is essentially ignored since there is no adjustment for bend in the following equations:

1) $d_S = 12$ ft for $D_{50} < 0.005$ ft (1.5 mm)

2) $d_S = 6.5 D_{50}^{-0.11}$ for $D_{50} > 0.005$ ft (1.5 mm)

where:

d_S = estimated probable maximum depth of scour (ft)

D_{50} = median diameter of bed material = 0.00591 (ft) (for D_{50} = 1.8 mm)

Since D_{50} is greater than 1.5 mm, use equation *2*):

$$d_S = 6.5 D_{50}^{-0.11}$$

$$\boxed{d_S = 6.5\,(.00591)^{-0.11} = 11.43 \text{ ft, say } 11.4 \text{ ft}}$$

2.2 *Levee Design Criterion (Los Angeles County Flood Control District, 1982)*

	Cut off depths	
Velocity, ft/sec	Straight reach, ft	Curved reach, ft*
0-6	6	9
6-10	8	12
10-15	10	15
15-18	12.5	18
18-20	14	21

* Use greater of table values above or Fig. F-06 in manual (see Figure 3 next page)

Given data:

Maximum velocity = 15.5 ft/sec
Flow depth = 21.2 ft
River width / Outer curve radius = 170 ft / 5,385 ft = 0.032
Side slope = 2:1

a) From Figure 3 (next page):

Scour depth / River depth of flow = 1.2
Scour depth = (1.2)*(21.2 ft)
Scour depth = 25.44 ft

b) From table above with 15-18 ft/sec and curved reach
Scour depth (cut off depth) = 18 ft

Use the larger value, or 25.44 ft, say 25.4 ft

It is assumed that this method includes general scour and bend scour because specific cut off depths are provided for curved reaches.

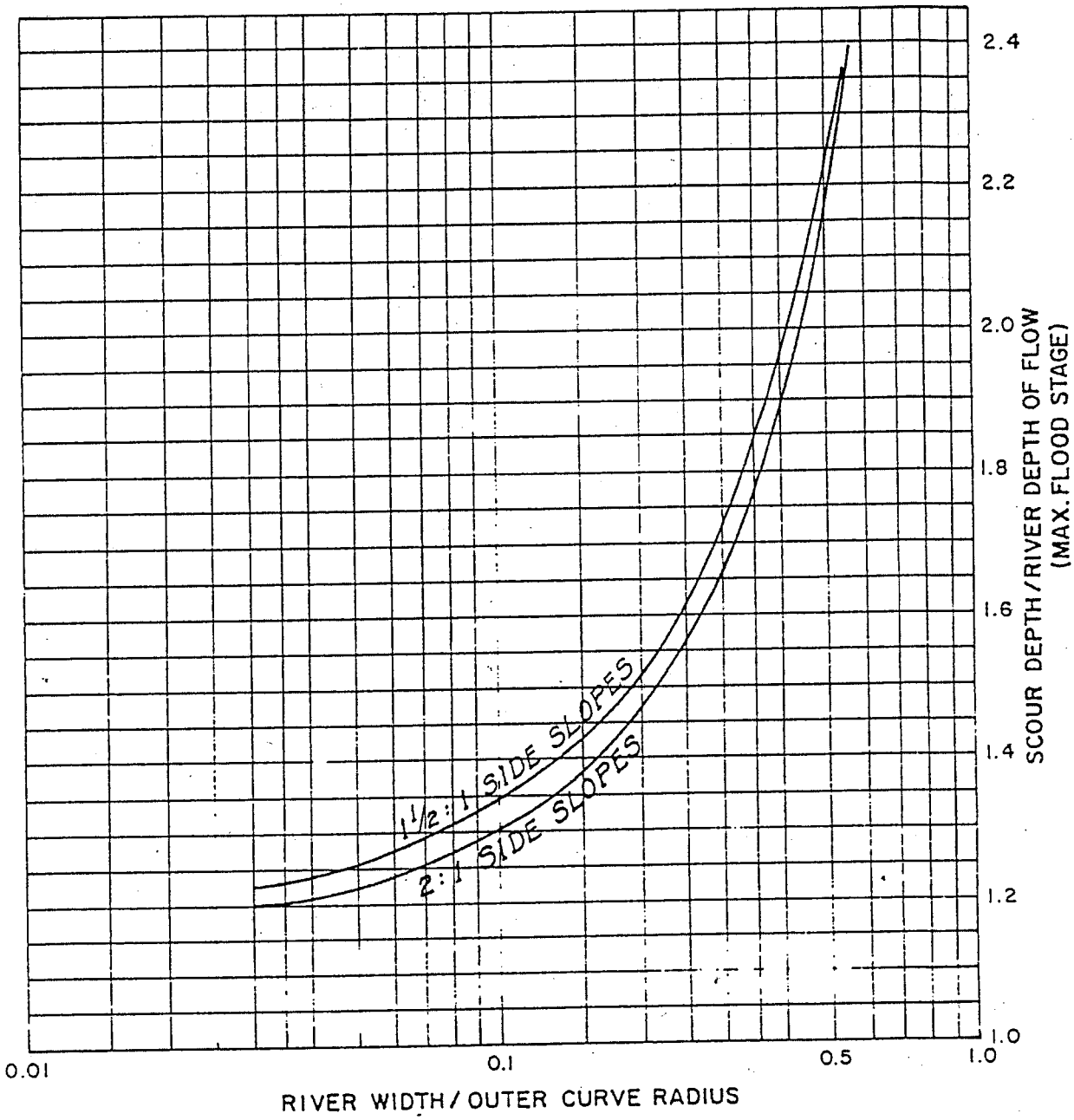


Figure 3 - Scour Depths on Outer Curves

2.3 Neill's (1973) Approach

Based on field measurements in an incised reach:

$$d_f = d_i \left(\frac{q_f}{q_i} \right)^m$$

where:

d_f	=	scoured depth below design floodwater level (ft)
d_i	=	average depth at bankfull discharge in incised reach = 8.9 (ft)
q_f	=	design flood channel discharge per unit width = 34,454 / 170 = 202.7 ($ft^3/s/ft$)
q_i	=	bankfull discharge in incised reach per unit width = 18,000 / 170 = 105.9 ($ft^3/s/ft$)
m	=	exponent varying from 0.67 for sand to 0.85 for coarse gravel (since D_{50} is sand, use 0.67)

$$d_f = 8.9 \left(\frac{202.7}{105.9} \right)^{0.67} = 13.75 \text{ ft}$$

$$\boxed{d_s = Z\, d_f = 0.5\,(13.75) = 6.88 \text{ ft, say } 6.9 \text{ ft}}$$

Where Z = 0.5 for straight (or mild bend) reach.

It is assumed that this method includes general scour, bend scour, and thalweg formation based on the method description.

2.4 Lacey's (1930) equation

$$d_m = 0.47\left(\frac{Q_{ch}}{f}\right)^{1/3}$$

where:

d_m = mean water depth at design discharge

Q_{ch} = design discharge in channel = 34,454 (ft^3/s)

f = Lacey's silt factor = 1.76 $(D_m)^{1/2}$ = 1.76 $(1.8)^{1/2}$ = 2.36

and:

D_m = mean grain size of bed material = 1.8 (mm)

$$d_m = 0.47\left(\frac{34{,}454}{2.36}\right)^{1/3} = 11.49 \text{ ft}$$

$$\boxed{d_s = Z\, d_m = 0.25\,(11.49) = 2.87 \text{ ft, say } 2.9 \text{ ft}}$$

Where Z = 0.25 for straight (or mild bend) reach

It is assumed that this method includes general scour, bend scour, and thalweg formation based on the method description.

2.5 Blench Equation (1969)

$$d_{f0} = \frac{q_f^{2/3}}{F_{b0}^{1/3}}$$

where:

d_{f0} = water depth for zero bed sediment transport (ft)
q_f = design discharge per unit width = 202.7 $ft^3/s/ft$
F_{b0} = Blench's zero bed factor in ft/s^2 from Figure 5

$$d_{f0} = \frac{202.7^{2/3}}{2.0^{1/3}} = 27.39 \text{ ft}$$

$$\boxed{d_s = Z\, d_{f0} = 0.6\,(27.39) = 16.43 \text{ ft, say } 16.4 \text{ ft}}$$

where: Z = 0.6 for both straight reaches and moderate to severe bends. The scour depth is assumed to include general scour, bend scour, and thalweg formation.

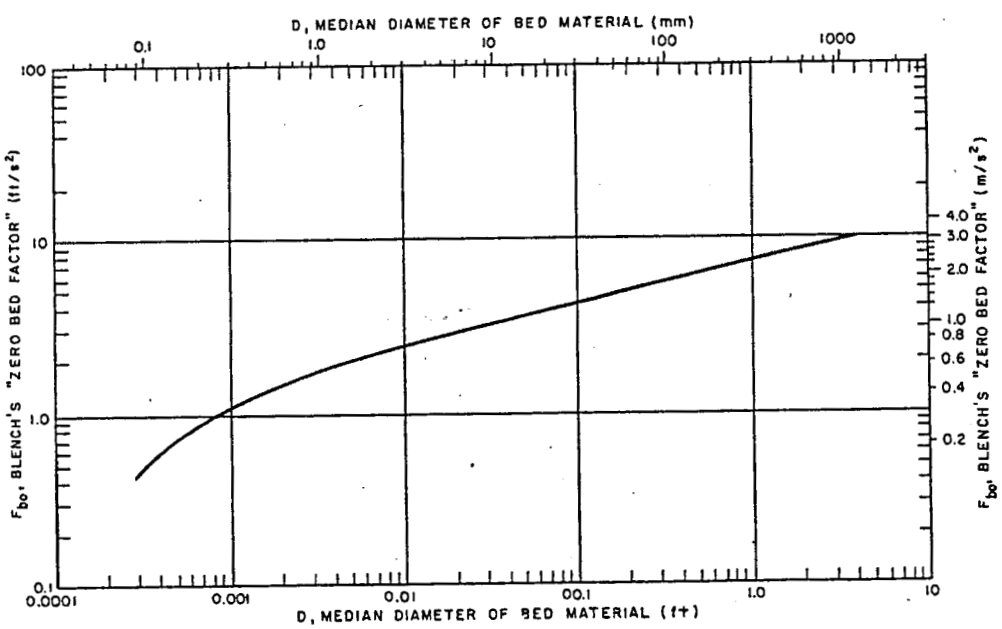


Figure 5 - Chart for estimating Zero Bed Factor

2.6 Competent or Limiting Velocity Control

$$d_S = d_m\left(\frac{V_m}{V_C} - 1\right)$$

where:

d_S = scour depth below streambed (general scour) (ft)

d_m = mean depth = 15.3 (ft)

V_C = competent mean velocity from Figure 6 below = 4.8 (ft/s)

V_m = mean velocity = 13.3 (ft/s)

$$d_S = 15.3\left(\frac{13.3}{4.8} - 1\right) = \boxed{27.09 \text{ ft, say } 27.1 \text{ ft}}$$

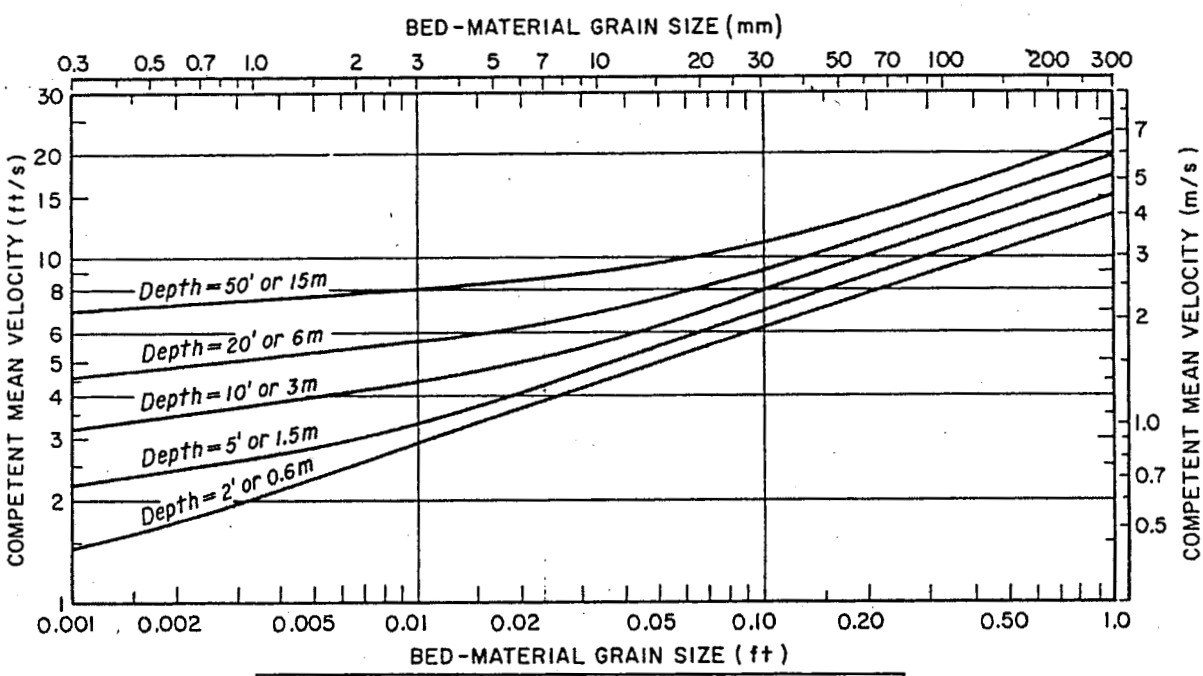


Figure 6 - Suggested Competent Mean Velocities

Part 3 – Local Scour

3.1 Pier and Abutment Scour

None in this example

3.2 Bend Scour

3.2.1 Zeller's (1981) Formula (Simons, Li & Associates, 1985)

$$\Delta Z_{bs} = \frac{0.0685\, Y V^{0.8}}{Y_h^{0.4}\, S_e^{0.3}} \left[2.1 \left(\frac{\sin^2 \frac{\alpha}{2}}{\cos \alpha} \right)^{0.2} - 1 \right]$$

where:

ΔZ_{bs} = bend scour component of total scour depth (ft)

V = mean velocity of upstream flow (ft/s)

Y = maximum depth of upstream flow (ft)

Y_h = hydraulic depth of upstream flow (ft)

S_e = approach energy slope or bed slope (ft/ft)

α = angle formed by the projection of the channel centerline from the point of curvature to a point which meets a line tangent to the outer bank of the channel (degrees)

From inspection, this method appears to be limited to sharp curves only with $R_c/W < 10$ or $\alpha > 18$ degrees. For a circular curve, these two values are related by:

$R_c/W = \text{Cos}\ \alpha/(4\ \text{Sin}^2\ (\alpha/2))$

In this example, $R_c/W = 31.2$, and assuming a circular curve, $\alpha = 10.2$ degrees using the above formula. Therefore, it does not fit within the apparent applicability of the Zeller equation.

3.2.2 Corps of Engineers (EM 1110-2-1601)

Use Plate B-42 for Sand Bed Channel (see Figure 4 next page):

Center-line radius of bend/water surface width = 5,300/170 = 31.2
Mean water depth in approach channel = 12.3 ft

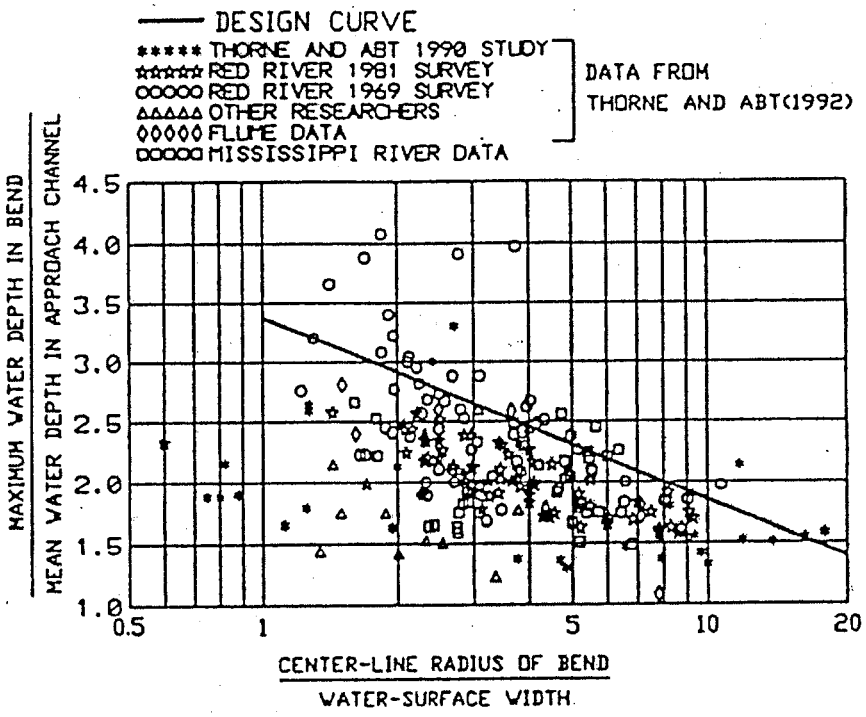
From extrapolation of the curve for sand bed channels, the estimated maximum water depth in bend/mean water depth in approach channel = 1.2

Maximum depth in bend = 1.2 (12.3) = 14.76 ft

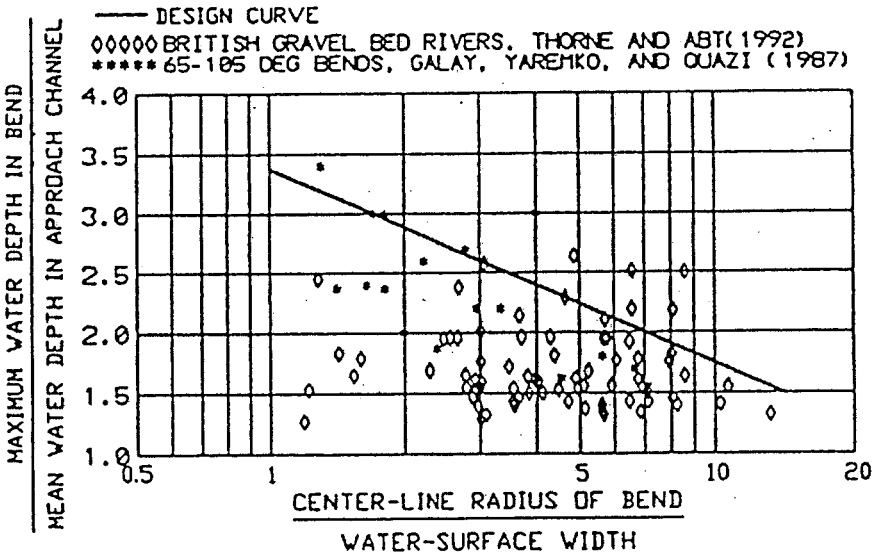
Scour depth = 14.76 – 12.3 = 2.46 ft, say 2.5 ft

Note that this is bend scour only and it must be added to long-term scour, general scour, and other local scour.

However, since this particular value was obtained by extrapolating a curve beyond the published limits, let's try a different method to determine bend scour for this example.



SAND BED CHANNELS



GRAVEL BED CHANNELS

Figure 4 - Plate B-42 EM 1110-2-1601

3.2.3 Thorne, et al. fitted equation to data

$$d_{max}/d_{bar} = 2.07 - 0.19 \log (R_c/w - 2)$$

where:

d_{max} = maximum depth in bend (ft)

d_{bar} = mean depth in approach channel = 12.3 ft

R_c = centerline radius of bend = 5,300 (ft)

w = water surface width = 170 (ft)

R_c/w = minimum value must be greater than 2.0 for this equation

therefore:

$$d_{max}/d_{bar} = 2.07 - 0.19 \log (5{,}300/170 - 2)$$

$$= 1.79$$

$$d_{max} = 1.79\, d_{bar}$$

$$d_{max} = 1.79\ (12.3)$$

$$d_{max} = 22.02 \text{ ft}$$

Scour Depth = 22.02 ft – 12.3 ft = 9.72 ft, say 9.7 ft

Assume that this value is applicable unless bend scour is already included in the scour method that we are examining. Note that this is bend scour only and it must be added to long-term scour, general scour, and other local scour.

3.3 Bed Forms Scour

1. Transitional or upper regime flow (Kennedy 1963)

$$h_a = 0.14\frac{2\pi V^2}{g} = 0.027V^2$$

For $h_a < y$

where:

h_a	=	antidune height from crest to trough (ft) [use ½ of h_a for scour depth below original bed]
V	=	maximum channel velocity
g	=	gravitational constant, 32.2 ft/sec^2
y	=	actual depth of flow

2. Lower regime flow (Simons and Richardson 1960)

Based on flume data, dunes were observed at Froude numbers between 0.38 to 0.60. Scour depths ranged from 10% to 50% of the flow depth. Since the channel Froude number in this example is 0.60, we can assume dune formation.

For illustration only, let's use 10% of the flow depth: (0.10)*(21.1) = 2.11 ft, say 2.1 ft

Note that the value for this scour component ranges from 2.1 to 10.6 feet for this example, using 10% to 50% of the flow depth.

3.4 Thalweg Formation

Usually taken to be on the order of 1 to 2 feet, depending on the size of the watercourse.

Assume equal to 2 feet for this regional watercourse, unless already accounted for in the scour method that we are examining.

Part 4 – Safety Factor

The safety factor usually ranges from 1.0 to 1.5 depending on the methods used, level of risk (consequence of failure), degree of variability in the channel conditions, and the uncertainty of the data.

The safety factor should be applied only where we think it is appropriate and in a manner that avoids overlapping largely conservative assumptions. The application of a safety factor may be highly individualistic, or in some cases, established by client direction or agency guidelines. It can be argued that different scour calculation methods deserve different safety factors, or that various land uses or other project considerations could be addressed with different safety factors.

For illustration only, safety factors of 1.0 and 1.1 are used in this example.

Part 5 – Application to Low Point in Channel

After calculating total scour by different approaches, select a reasonable total scour value that is consistent with your experience and judgment and apply this value to the low point elevation in the channel. This will assume that the low point or thalweg could migrate to the area of bank protection. Note that in a longer reach, the total scour may vary in the longitudinal direction and would need to be evaluated at different locations.

Depending on your objective, the selected value for total scour could be more towards the high end or closer to the average of the values calculated. All of the information at your disposal can be considered in this process, including any available scour measurements from past storms, calculations or evidence of scour in a nearby reach with similar characteristics, etc.

In this example, the channel has a minimum elevation of 970.3 ft (msl). The elevation for toe protection could range from elevation 960.9 ft (msl) [970.3 ft – 9.4 ft] to elevation 925.9 ft (msl) [970.3 ft – 44.4 ft) depending on the scour value selected.

A scour calculation summary is shown in Table 1.

Predicting Bed Scour for Toe Protection Design in Bank Stabilization Projects

Summary Example Problem

TABLE 1 - Scour Calculation Summary

Scour Component		Method	Blodgett	Competent Velocity	LA County Levee	Neil	Lacey	Blench
			Results (ft)					
Long term		Extrapolation of historical trend	3.5	3.5	3.5	3.5	3.5	3.5
General		Blodgett's (1986)	11.4					
General		Competent or Limiting Velocity (1973)		27.1				
General and bend		Los Angeles County Levee Criterion (1982)			25.4			
General and bend		Neil approach (1973)				6.9		
General and bend		Lacey equation (1930)					2.9	
General and bend		Blench equation (1969)						16.4
Local	pier	n/a	0	0	0	0	0	0
Local	abutment	n/a	0	0	0	0	0	0
Local	bend	Zeller's Formula (1981)	n/a	n/a	n/a	n/a	n/a	n/a
Local	bend	Corps of Engineers Plate B-42 (1994)	n/a	n/a	n/a	n/a	n/a	n/a
Local	bend	Thorne et al. equation (1995)	9.7	9.7	incl.	incl.	incl.	incl.
Local	bed forms	Simons and Richardson (1960)	2.1	2.1	2.1	2.1	2.1	2.1
Local	thalweg		2.0	2.0	2.0	incl.	incl.	incl.
		Subtotal Total Scour	28.7	44.4	33.0	12.5	8.5	22.0
		Safety Factor	1.0	1.0	1.0	1.1	1.1	1.1
		Total Scour	28.7	44.4	33.0	13.8	9.4	24.2
Max.	**44.4**	**ft**				**Min.**	**9.4**	**ft**
				Avg.	**25.6**	**ft**		