Using HECRAS TO Evaluate Scour At Bridges

County of Orange

Presented to the Flood Division

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by

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Approximately 575,000 bridges are built over waterways in the US. The most common cause of bridge failure is due to bridge scour of the foundation.

In 1993, the upper Mississippi flooding caused 23 bridge failures.

In 1994, flooding in Georgia (Alberto storm) 500 bridges were scour damaged. 31 experienced 15-20 feet of scour.

Definition of Scour

Scour is the removal of sediment (soil and rocks) from stream beds and stream banks caused by moving water

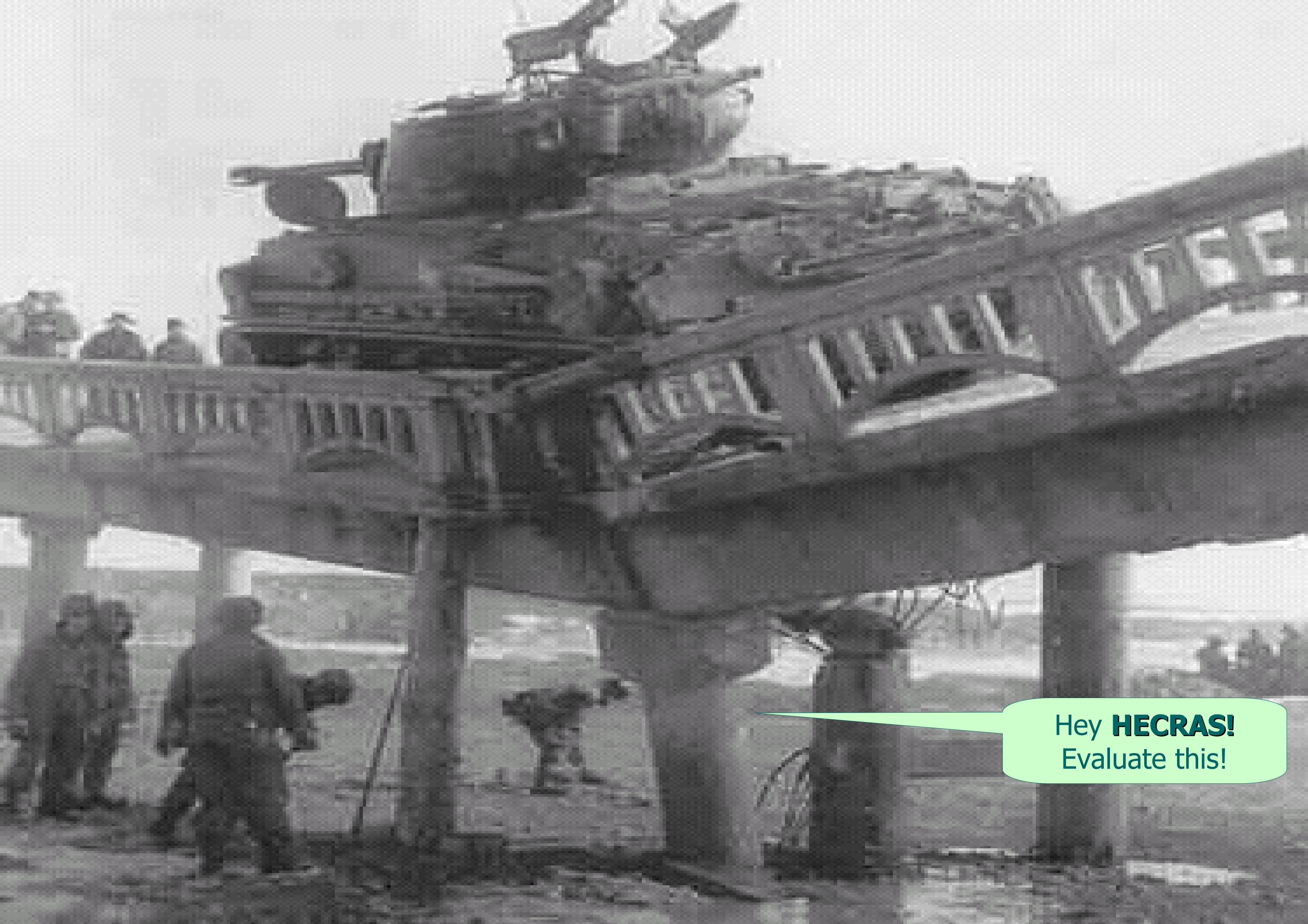
HEC18 - Evaluating Scour At Bridges

HEC18 was originally prepared by the FHWA in 1988. A fourth edition was completed in May 2001 and released to the public in July 2001

HECRAS - Version 3.0.1

The Hydrologic Engineering Center recently released River Analysis System (HECRAS) version 3.0.1 which includes significant new features, most notably the Unsteady Flow and Bridge Scour options. The bridge scour evaluation follows closely the HEC18 (4th Edition) methodology.

No reliable equations are available to predict all hydraulic flow conditions that may be reasonably expected to occur. Engineering judgement is required.


Hey HECRAS!
Evaluate this!

Rate of Scour

Scour will reach its maximum depth in:

- *sand and gravel bed materials in hours;*
- *cohesive bed materials in days;*
- *glacial tills, sand stones and shales in months;*
- *limestones in years and dense granites in centuries.*

Interstate 90 crossing of Schoharie Creek near Amsterdam, NY on April 5, 1987

Bridge Failure Due to Scour, Glasgow, Missouri

Components of Scour

I - Long Term Aggradation or Degradation

+

II - Contraction Scour

+

III - Local Scour (Piers and Abutments)

=

Total Scour

Long-Term Aggradation or Degradation

Long-term aggradation or degradation is due to natural or man-made induced causes which can affect the reach of river on which the bridge is located. The challenge for the engineer is to estimate long-term bed elevation changes that will occur during the life of the structure.

Contraction Scour

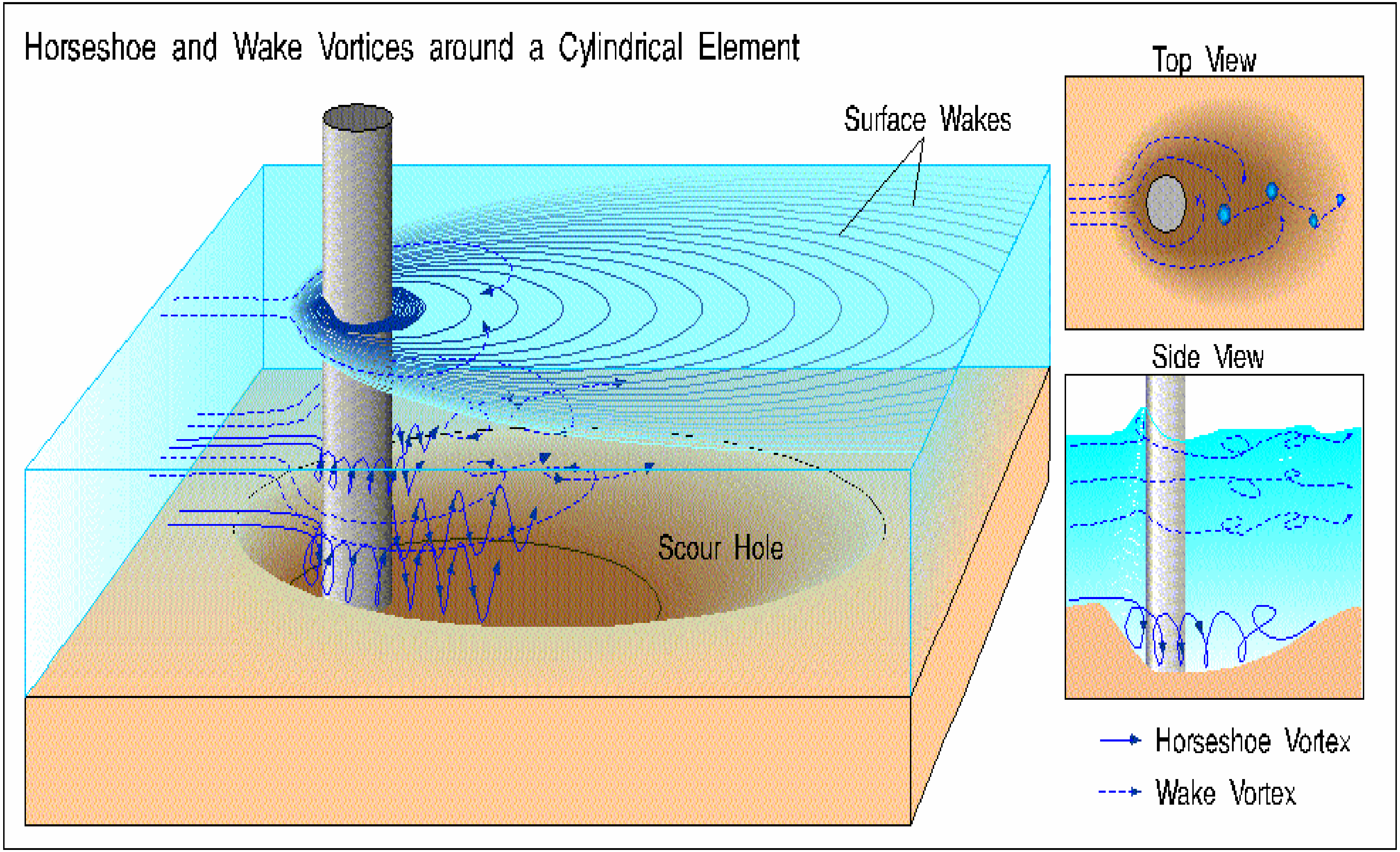
Involves removal of material from bed and banks across most of the channel width.

May be "***Live-bed***" Contraction Scour" or "***Clear-water***" Contraction Scour"

Local Scour

At Piers: Pier scour occurs due to the acceleration of flow around the pier and the formation of flow vortices. The “horseshoe vortices” remove material from the base of the pier and creates a scour hole.

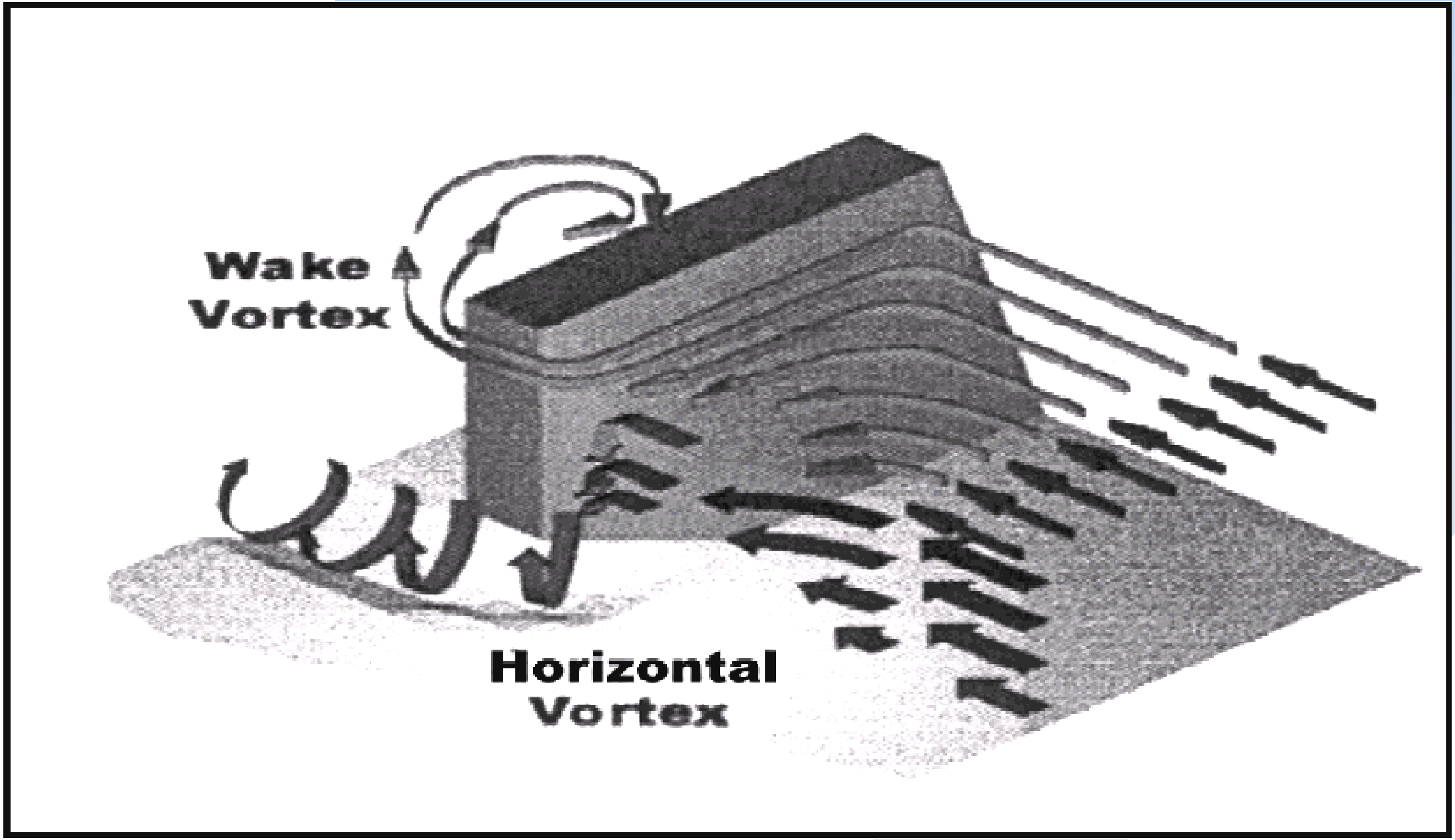
Scour at a cylindrical pier



Local Scour

At Abutments: The obstruction of the flow forms a horizontal vortex starting at the upstream end of the abutment and running along the toe of the abutment and forms a vertical wake vortex at the downstream end of the abutment

Abutment scour



Contraction scour (somewhere) in Missouri during May and June of 1995.

Walnut Street Bridge (Harrisburg, PA) collapse--January 1996


WHTM

This bridge (location unknown) failed due to scour at the base of the piers caused by a turbulent horseshoe vortex system.

Bridge on the Enoree river in South Carolina which failed due to scour at the base of the piers caused by a turbulent horseshoe vortex system.

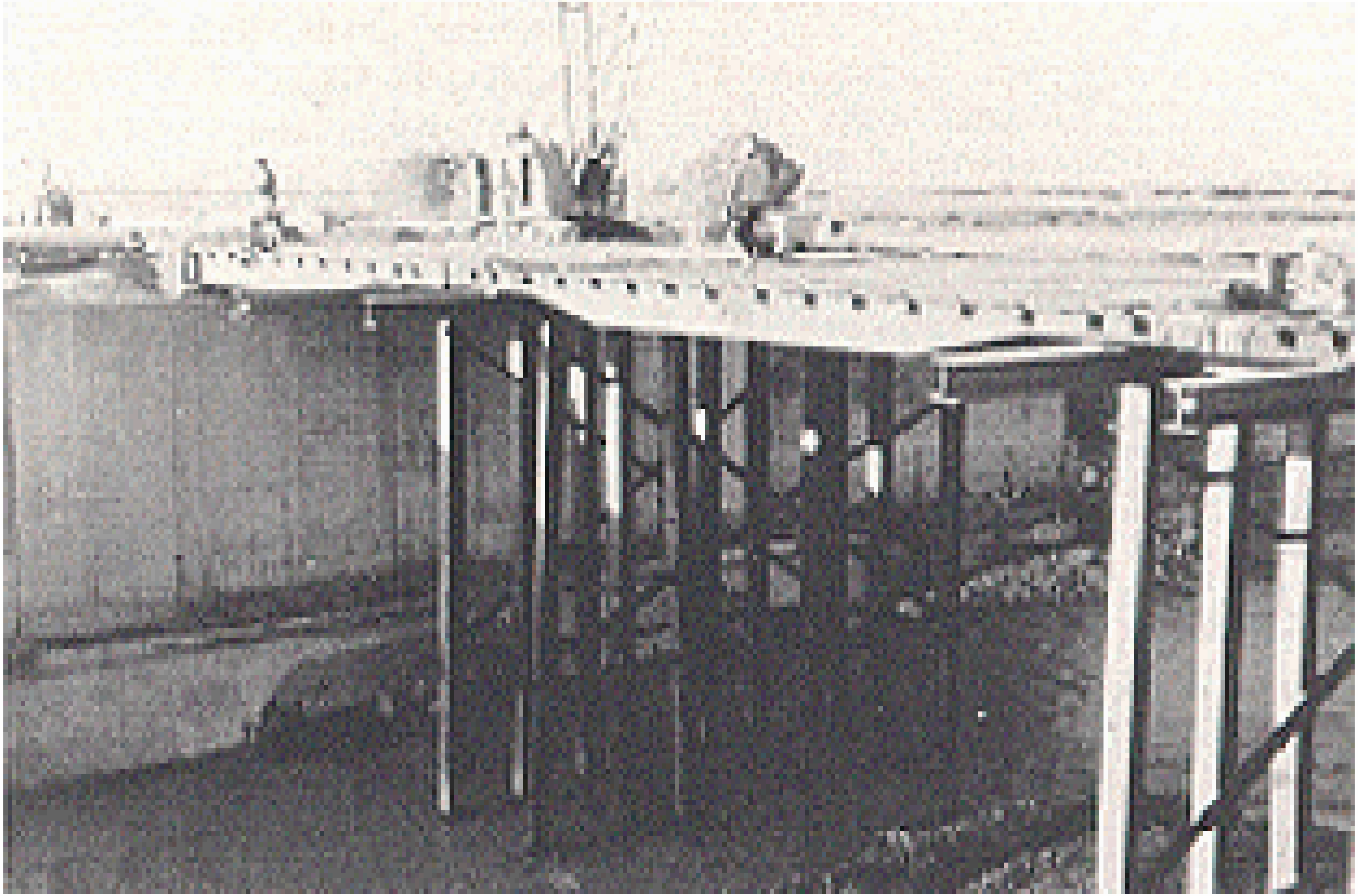


Photo: Robert Reynaga Caltrans

March 10, 1995 - Interstate 5 near Coalinga, over the Arroyo Pasajero

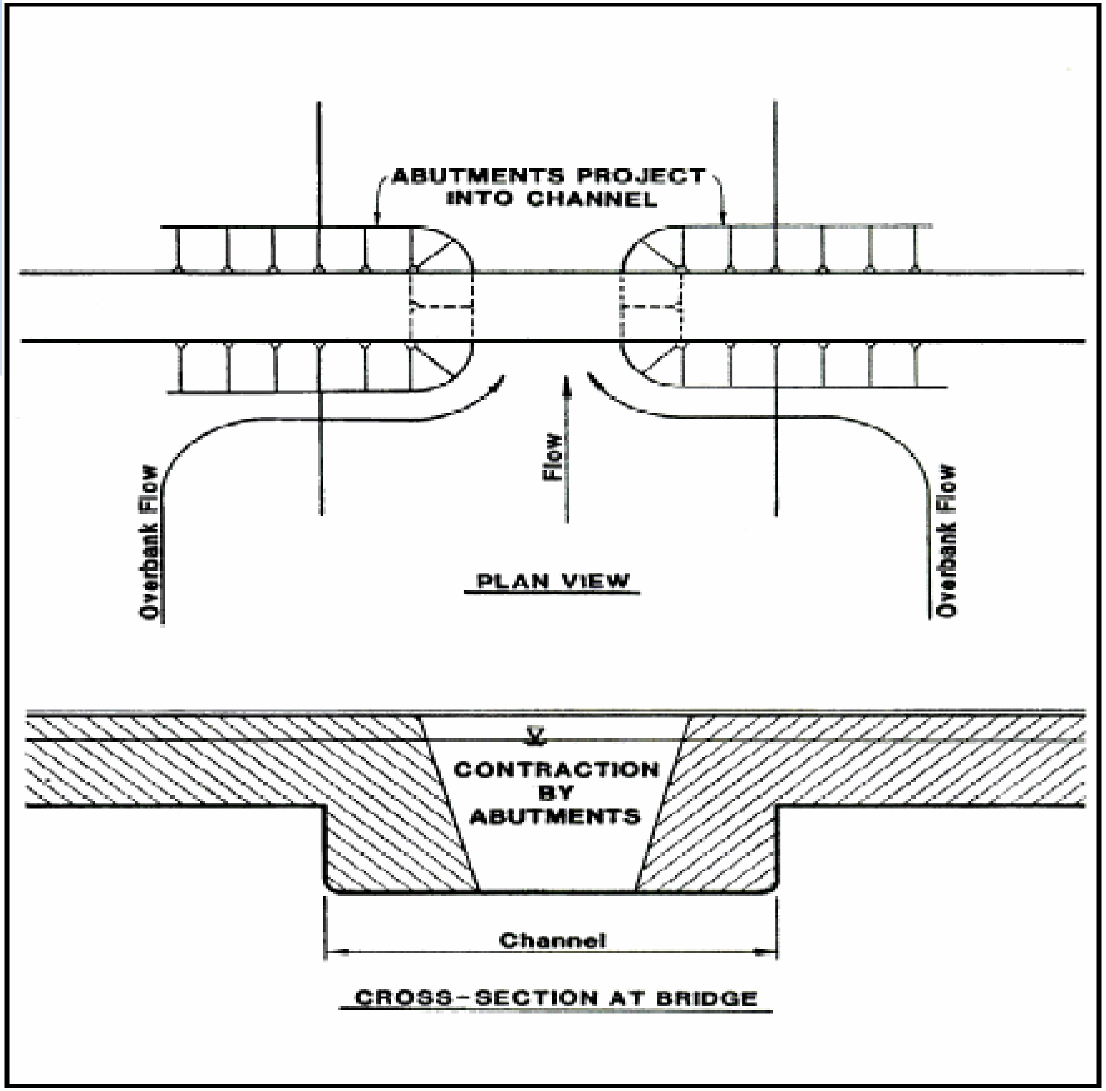
Long-Term
Aggradation or Degradation

Procedures for estimating long-term aggradation and degradation at bridges are presented in HEC20 (Stream Stability at Highway Structures) and are not a part of this presentation

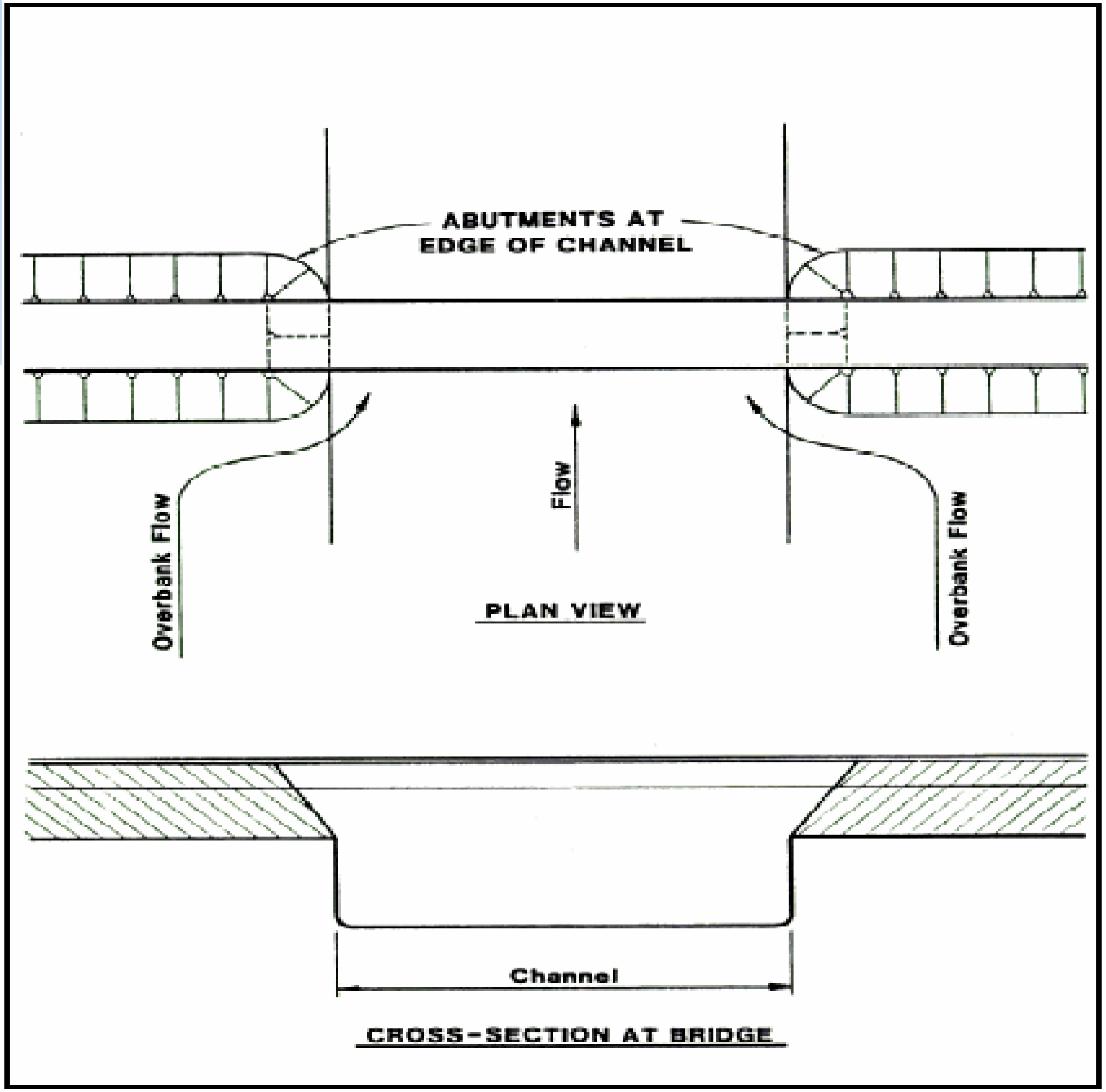
Contraction Scour Cases

- Case I - Overbank flow on a floodplain being forced back to the main channel by the approaches to the bridge
- Case II - Flow is confined to the main channel (no overbank flow). The normal river channel width becomes narrower due to the bridge itself or the bridge site is located at a narrowing reach of river
- Case III - A relief bridge in the overbank area with little or no bed material transport in the overbank area (clear water scour)
- Case IV - A relief bridge over a secondary stream in the overbank area with bed material transport (similar to case 1)

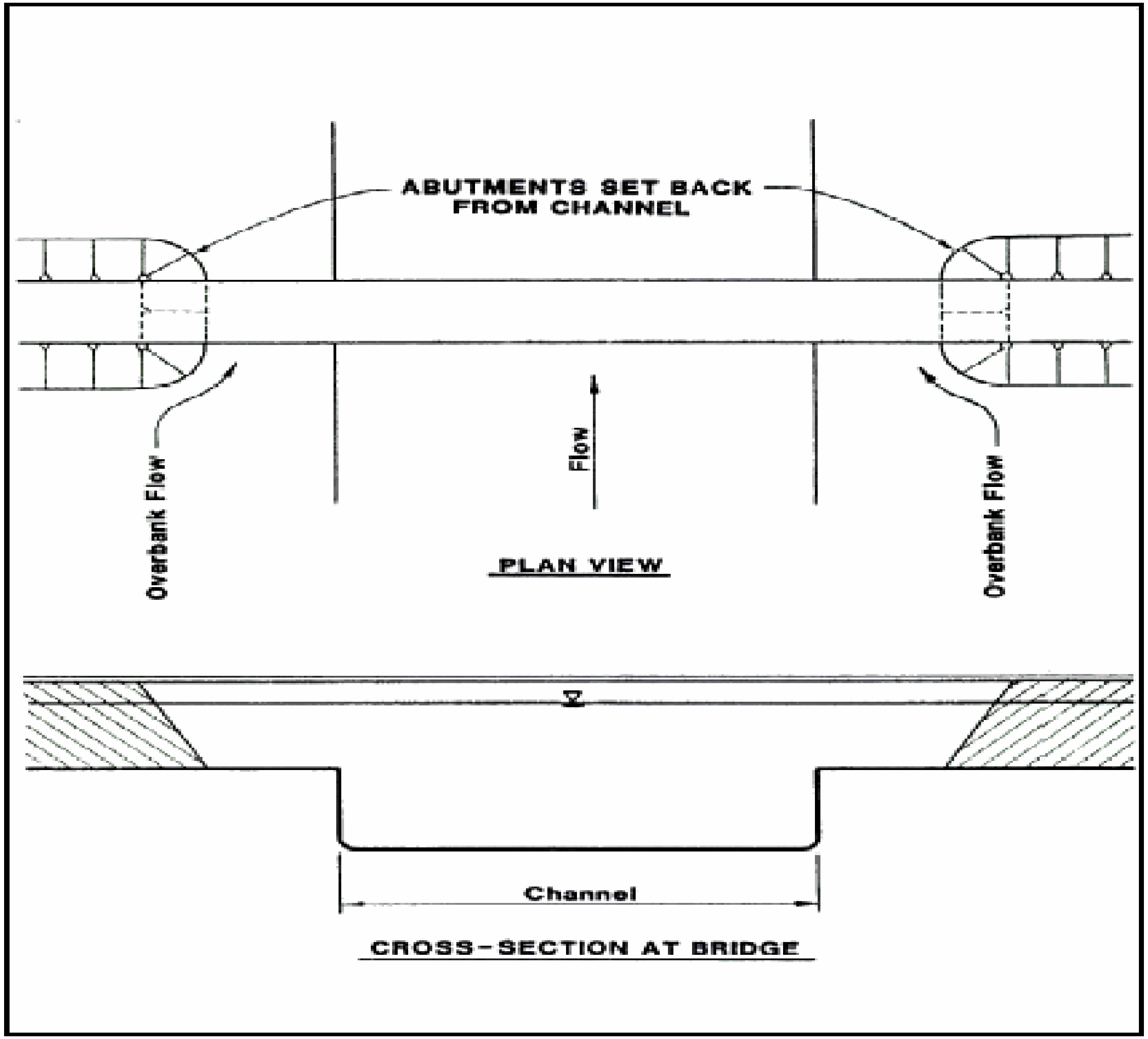
Case 1a - Abutments project into channel



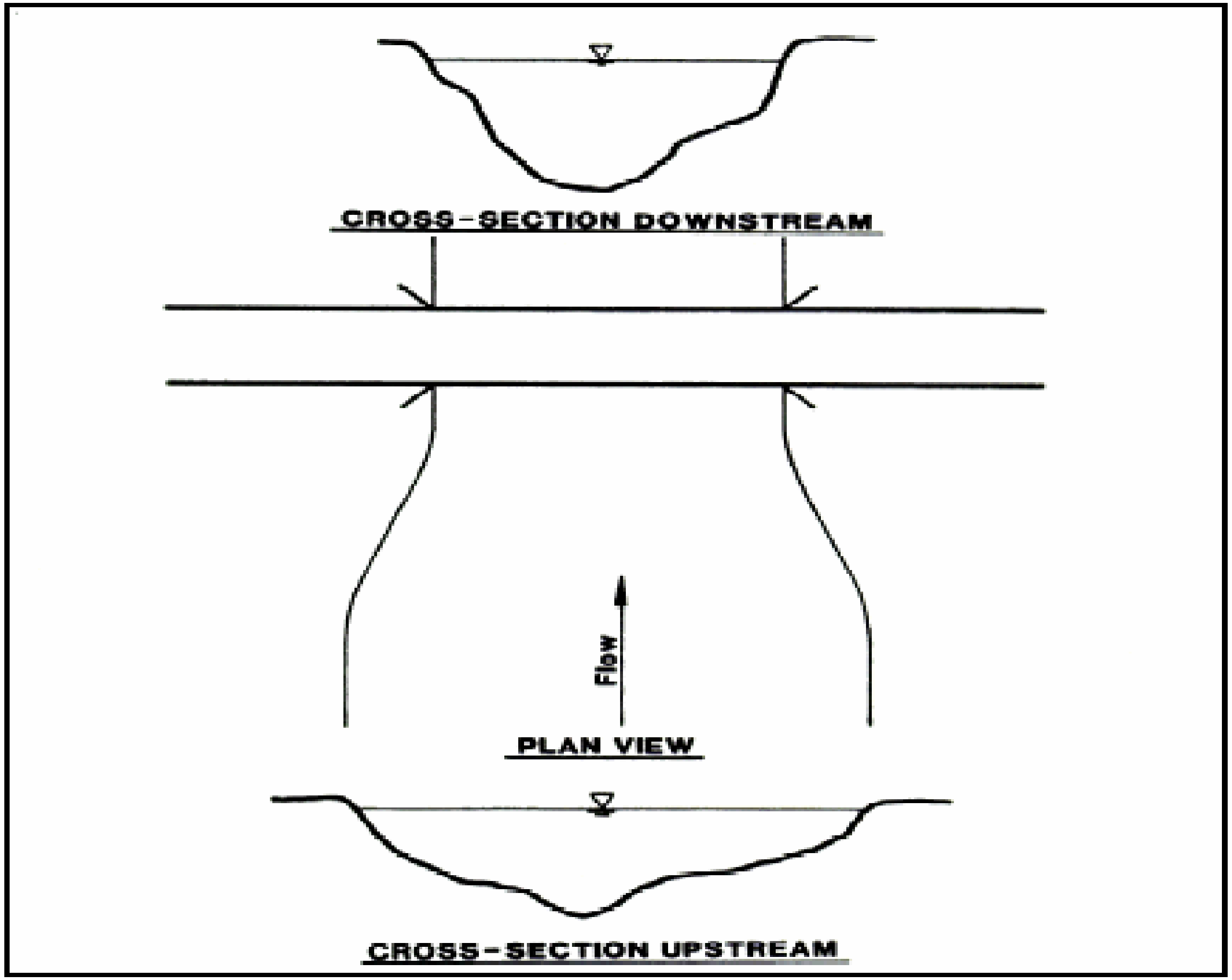
Case 1b - Abutments at edge of channel



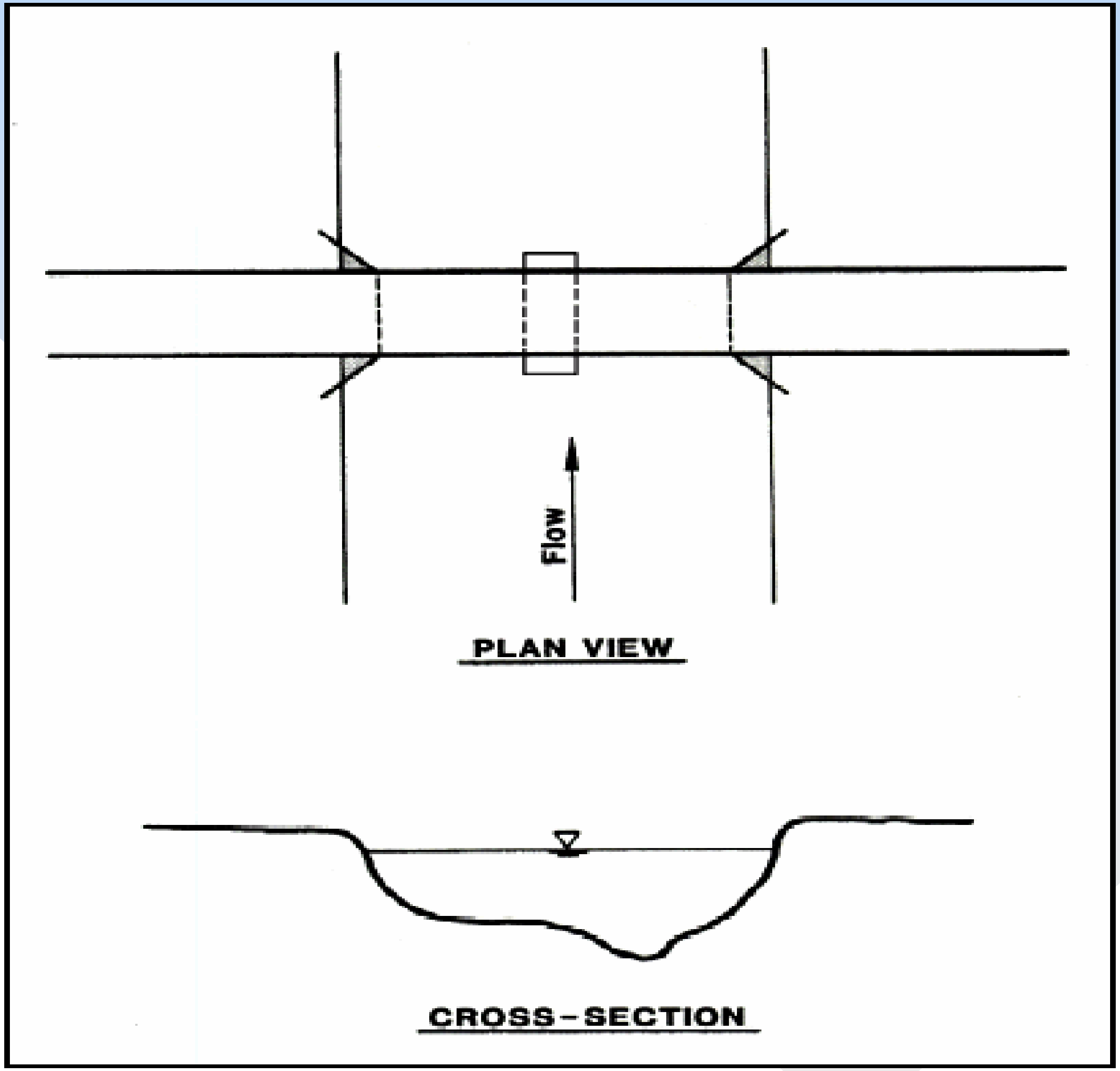
Case 1c - Abutments set back from channel



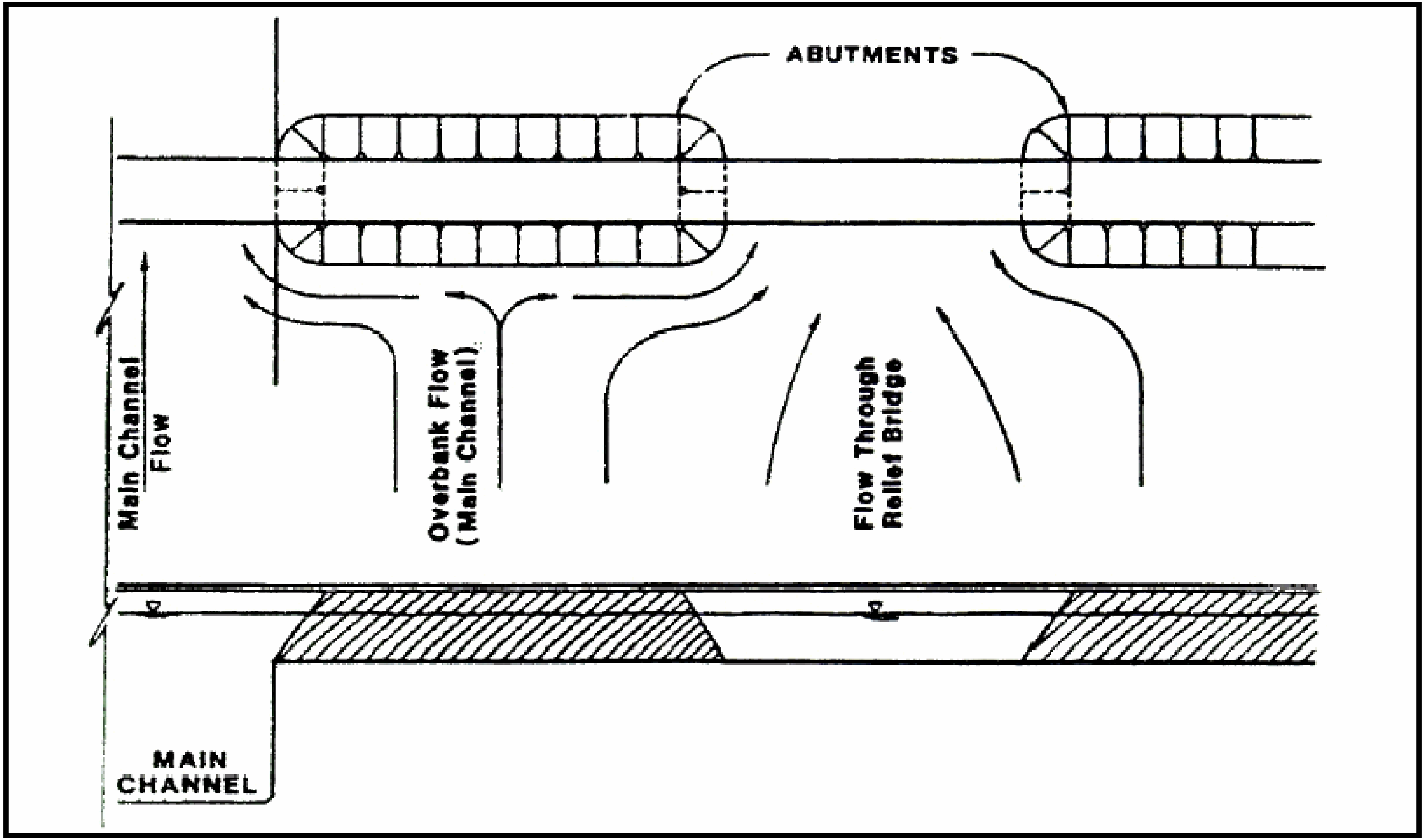
Case 2a - River narrows



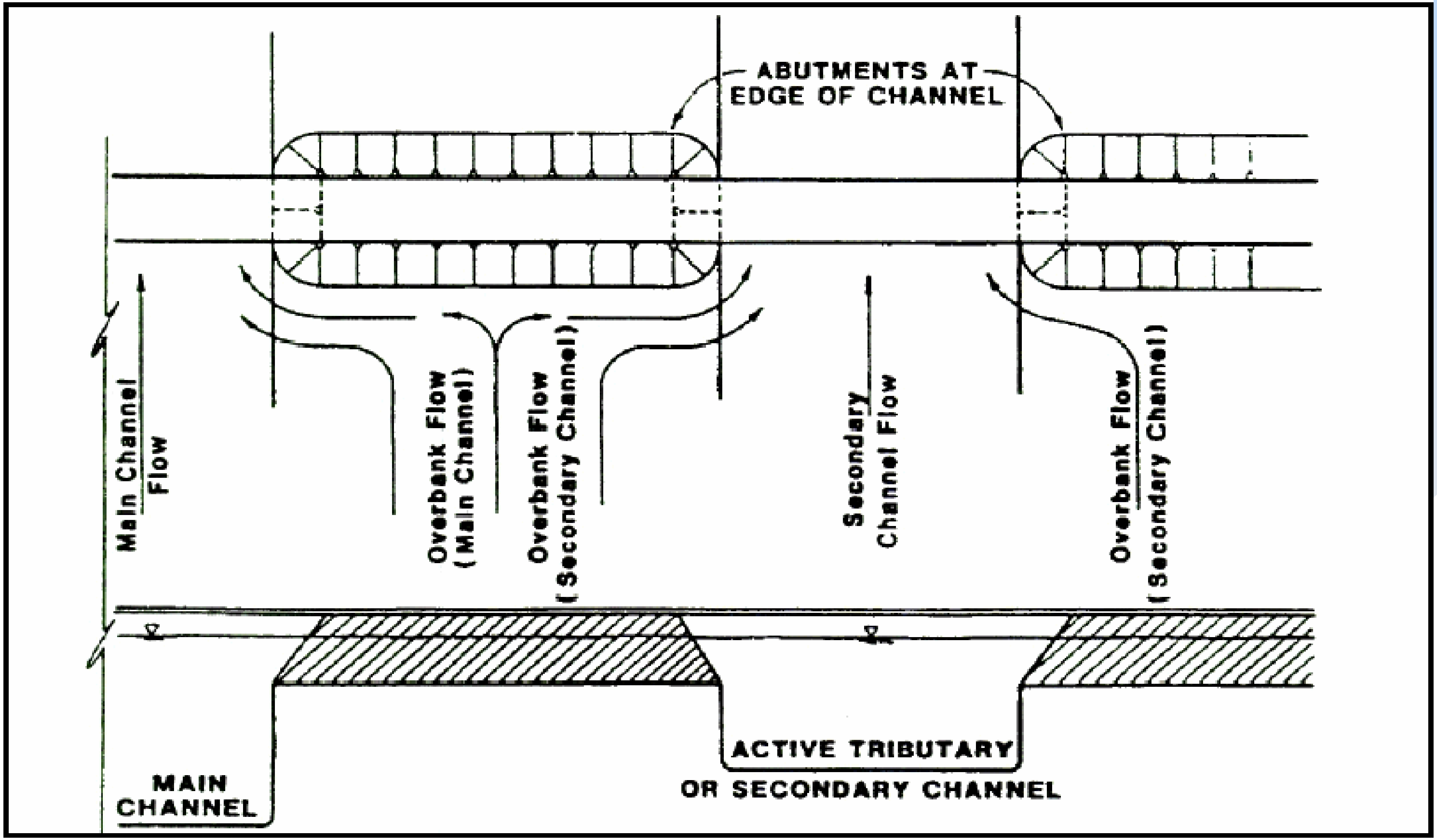
Case 2b - Bridge abutments and or piers constrict flow



Case 3 - Relief bridge over floodplain



Case 4 - Relief bridge over secondary stream



Contraction Scour Types

Live-bed Contraction Scour:

This occurs when bed material is already being transported into the contracted bridge section from upstream of the approach section (before the Contraction reach).

Contraction Scour Types

Clear-water Contraction Scour: This occurs when the bed material sediment transport in the uncontracted approach section is negligible or less than the carrying capacity of the flow.

Live-bed or Clear-water Determination

Clear-water: Vc > mean velocity

Live-bed: Vc < mean velocity

where Vc = critical velocity for beginning of motion

Live-bed or Clear-water Determination

Clear-water: Vc > mean velocity

Live-bed: Vc < mean velocity

$$V_c = 10.95 y_1^{1/6} D_{50}^{1/3}$$ (Laursen, 1963)

Where:

Y1 =depth of flow in the upstream of bridge

D_{50} = median diameter of bed material

Live-bed Contraction Scour Determination

$$\frac{y_2}{y_1} = \left[\frac{Q_2}{Q_1}\right]^{6/7} \left[\frac{W_1}{W_2}\right]^{K1} \left(\frac{n_2}{n_1}\right)^{k_2}$$

(Laursen, 1960)

And $$y_s = y_2 - y_0$$

Where:
Y_s = Average depth of scour
Y_0 = Average depth of flow in the contracted section before scour
Y_1 = depth of flow in the upstream of bridge
Y_2 = depth of flow in the contracted section
W_1 = bottom width upstream of bridge
W_2 = bottom width in the contracted section
Q_1 = flow in the upstream of bridge transporting sediment
Q_2 = flow in the contracted section
n_1 = Manning's "n" for the upstream of bridge
n_2 = Manning's "n" for the contracted section
K_1 and K_2 = Exponents depending upon the mode of bed material transport

V*/w	K_1	K_2	Mode of Bed Material Transport
<0.50	0.59	0.066	Mostly contact bed material
0.50 to 2.0	0.64	0.21	Some suspended bed material discharge
> 2.0	0.69	0.37	Mostly suspended bed material discharge

Live-bed Contraction Scour Determination

V*/w	K_1	K_2	Mode of Bed Material Transport
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0.50 to 2.0	0.64	0.21	Some suspended bed material discharge
> 2.0	0.69	0.37	Mostly suspended bed material discharge

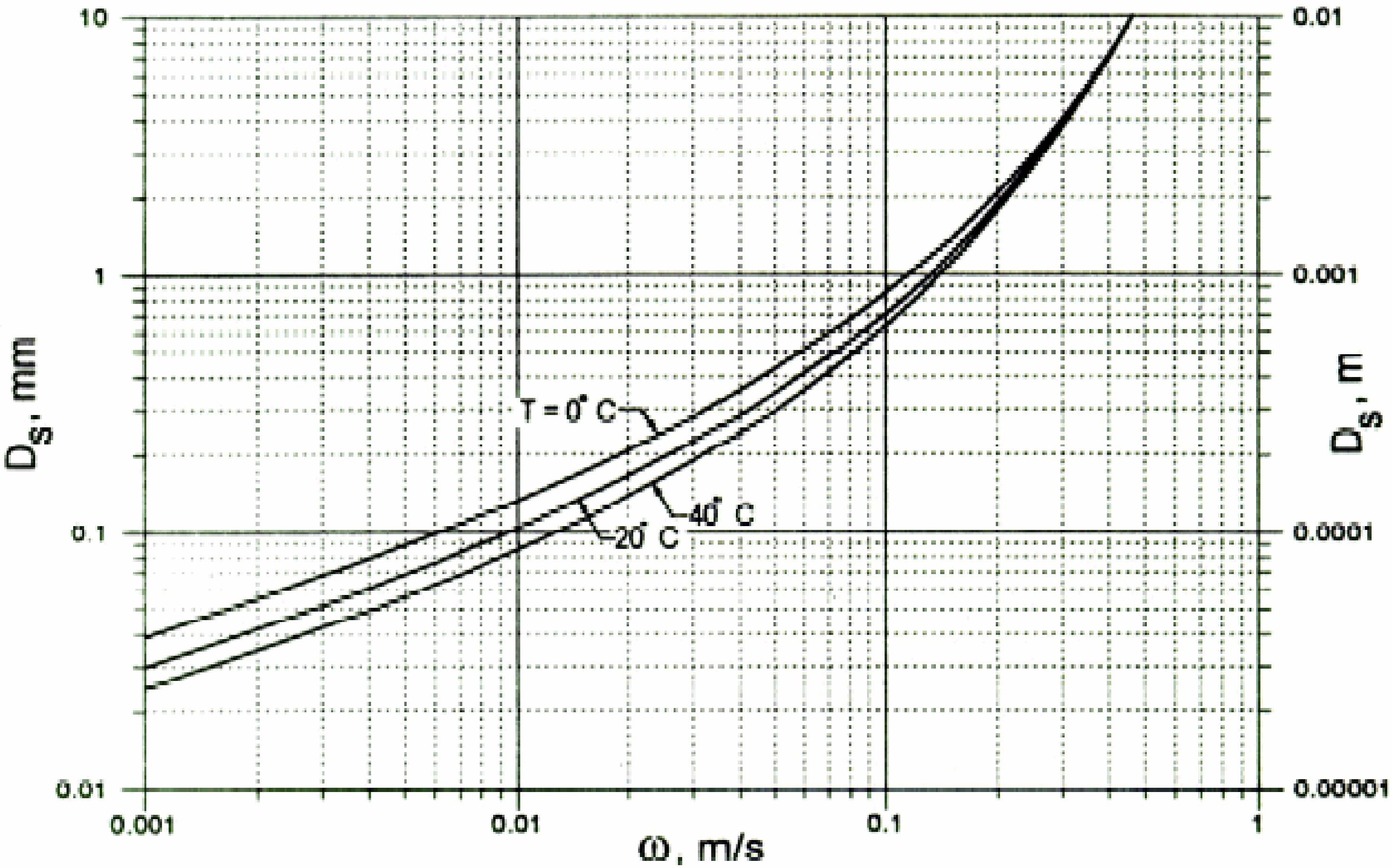
$$V_* = \left(\frac{\tau}{\rho}\right)^{\frac{1}{2}} = \left(g y_1 S_1\right)^{\frac{1}{2}}$$

Where:
V_* = Shear Velocity in the upstream section
w = Fall velocity of bed material
T = Shear stress on the bed
p = Density of water
g = Acceleration of gravity
S_1 = Slope of the energy grade line of main channel

I - Long Term Aggradation or Degradation

II - Contraction Scour (Live-bed)

III - Local Scour at Piers



Fall velocity of sand-sized particles with specific gravity of 2.65 in metric

Live-bed Contraction Scour Determination

$$\frac{y_2}{y_1} = \left[\frac{Q_2}{Q_1}\right]^{6/7} \left[\frac{W_1}{W_2}\right]^{K1}$$

Modified (Laursen, 1960)

And $$y_s = y_2 - y_0$$

Where:
Y_s = Average depth of scour
Y_0 = Average depth of flow in the contracted section before scour
Y_1 = depth of flow in the upstream of bridge
Y_2 = depth of flow in the contracted section
W_1 = bottom width upstream of bridge
W_2 = bottom width in the contracted section
Q_1 = flow in the upstream of bridge transporting sediment
Q_2 = flow in the contracted section
K_1 = Exponents depending upon the mode of bed material transport

V*/w	K_1	Mode of Bed Material Transport
<0.50	0.59	Mostly contact bed material
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Live-bed Contraction Scour Determination

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$$V_* = \left(\frac{\tau}{\rho}\right)^{\frac{1}{2}} = (g y_1 S_1)^{\frac{1}{2}}$$

Where:
V_* = Shear Velocity in the upstream section
w = Fall velocity of bed material
T = Shear stress on the bed
p = Density of water
g = Acceleration of gravity
S_1 = Slope of the energy grade line of main channel

Clear-water Contraction Scour Determination

$$\frac{y_s}{y_1} = 0.13\left[\frac{Q}{D_m^{\frac{1}{3}} y_1^{\frac{7}{6}} W}\right]^{\frac{6}{7}} - 1$$

(Laursen, 1963)

Where D_m is the effective mean diameter of the bed material (1.25 D_{50})

Local Scour
at Piers

Pier scour occurs due to the acceleration of flow around the pier and the formation of flow vortices. The “horseshoe vortices) remove material from the base of the pier and creates a scour hole.

This is erosion caused by the formation of a horseshoe vortex system at the base of a telephone pole. This occurred during the blizzard of '96 in the northeast.

This is erosion due to the formation of a horseshoe vortex around a van.

Pier Scour Factors

- The greater the velocity upstream of the pier the deeper the scour
- An increase in flow depth can have a significant influence on the scour depth. It can be as much as twice.
- As the width of the pier increases, so does the scour depth
- If pier is skewed to the flow, the length can have an influence on the scour depth. When doubling the length, the scour depth increased by 30-60% depending upon angle of attack.
- Size and gradation of the bed material generally will not have an effect on the scour depth. What differs is the time it takes to achieve the maximum scour.
- Shape of the pier plays an important part in the scour depth.
- Formation of debris can increase the width of the pier, change its shape or change its projected length.

Live-bed and Clear-water Scour Determination
by CSU (Richardson 1990 eq.)

$$\frac{Y_s}{Y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{a}{Y_1}\right)^{0.65} Fr_1^{0.43}$$

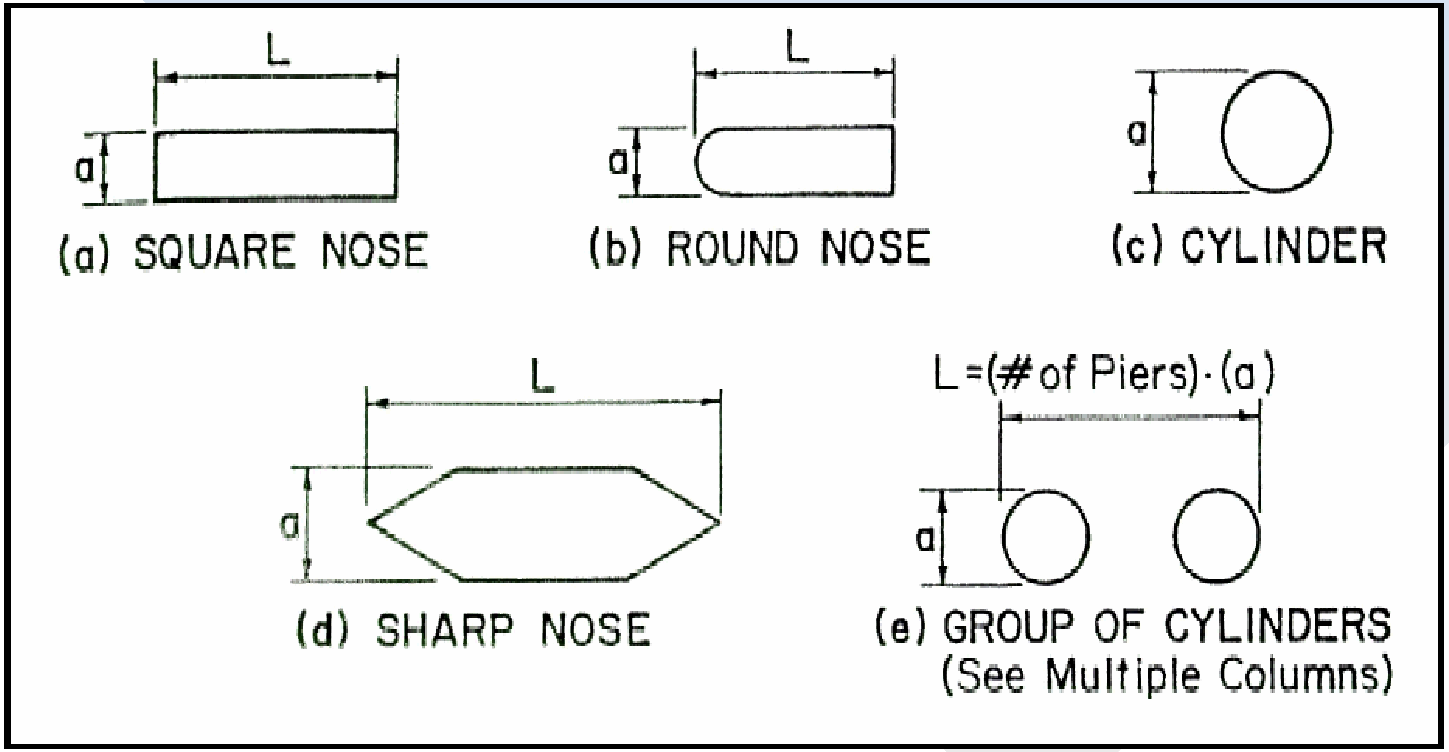
where:

Y_s = Scour depth
Y_1 = Flow depth directly upstream of the pier
K_1 = Correction factor for pier nose shape
K_2 = Correction factor for angle of attack of flow
K_3 = Correction factor for bed condition
K_4 = Correction factor for armoring by bed material size
a = Pier width
Fr_1 = Froude number directly upstream of pier

Common Pier Shapes

To be used for determining the K_1 (Pier Nose Shape correction factor) in equation:

$$\frac{Y_s}{Y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{a}{Y_1}\right)^{0.65} Fr_1^{\;0.43}$$



I - Long Term Aggradation or Degradation
II - Contraction Scour
III - Local Scour at Piers

K_1 is the Pier Nose Shape correction factor in equation:

$$\frac{Y_s}{Y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{a}{Y_1}\right)^{0.65} Fr_1^{0.43}$$

Table 6.1. Correction Factor, K_1, for Pier Nose Shape.

Shape of Pier Nose	K_1
(a) Square nose	1.1
(b) Round nose	1.0
(c) Circular cylinder	1.0
(d) Group of cylinders	1.0
(e) Sharp nose	0.9

For angle of attack < 5 deg. For greater angles, K_1=1.0 and K_2 dominates

I - Long Term Aggradation or Degradation
II - Contraction Scour
III - Local Scour at Piers

$$K_2 = \left(\cos\theta + (L/a)\sin\theta\right)^{0.65}$$

K_2 is the Angle of Attack correction factor in equation: $\frac{Y_s}{Y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{a}{Y_1}\right)^{0.65} Fr_1^{0.43}$

Table 6.2. Correction Factor, K_2, for Angle of Attack, θ, of the Flow.

Angle	L/a=4	L/a=8	L/a=12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

Angle = skew angle of flow
L = length of pier, m

Notes: *K_2 should only be applied when the entire length is subjected to the attack of flow*
K_2 max = 5.0

K_3 is the Bed Condition correction factor in equation:

$$\frac{Y_s}{Y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{a}{Y_1}\right)^{0.65} Fr_1^{0.43}$$

Table 6.3. Increase in Equilibrium Pier Scour Depths, K_3, for Bed Condition.

Bed Condition	Dune Height m	K_3
Clear-Water Scour	N/A	1.1
Plane bed and Antidune flow	N/A	1.1
Small Dunes	$3 > H \geq 0.6$	1.1
Medium Dunes	$9 > H \geq 3$	1.2 to 1.1
Large Dunes	$H \geq 9$	1.3

I - Long Term Aggradation or Degradation
II - Contraction Scour
III - Local Scour at Piers

$$\frac{Y_s}{Y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{a}{Y_1}\right)^{0.65} Fr_1^{0.43}$$

K_4 is the Correction Factor for armoring by bed-material size in equation:

K_4 min = 0.4

If D_{50} < 2mm or D_{95} < 20mm, then K_4 = 1.0

If D_{50} >= 2mm and D_{95} >= 20mm then

$$K_4 = (V_R)^{0.15}$$

where
$$VR = \left[\frac{V_1 - V_{icD_{50}}}{V_{cD_{50}} - V_{icD_{95}}}\right] > 0$$

$$V_{icDx} = 0.645\left(\frac{D_x}{a}\right)^{0.053} V_{cDx}$$

$$V_{cDx} = K_u Y_1^{\frac{1}{6}} D_x^{\frac{1}{3}}$$

V_{icDx} = Approach velocity required to initiate scour at the pier for grain size D_x
V_{cDx} = critical velocity for incipient motion for grain size D_x
y_1 = Depth of flow just upstream of the pier, excluding local scour, m (ft)
V_1 = Velocity of the approach flow just upstream of the pier, m/s (ft/s)
D_x = Grain size for which x percent of the bed material is finer, m (ft)
a = Pier width (ft)
K_u = 6.19 SI Units
K_u = 11.17 English Units

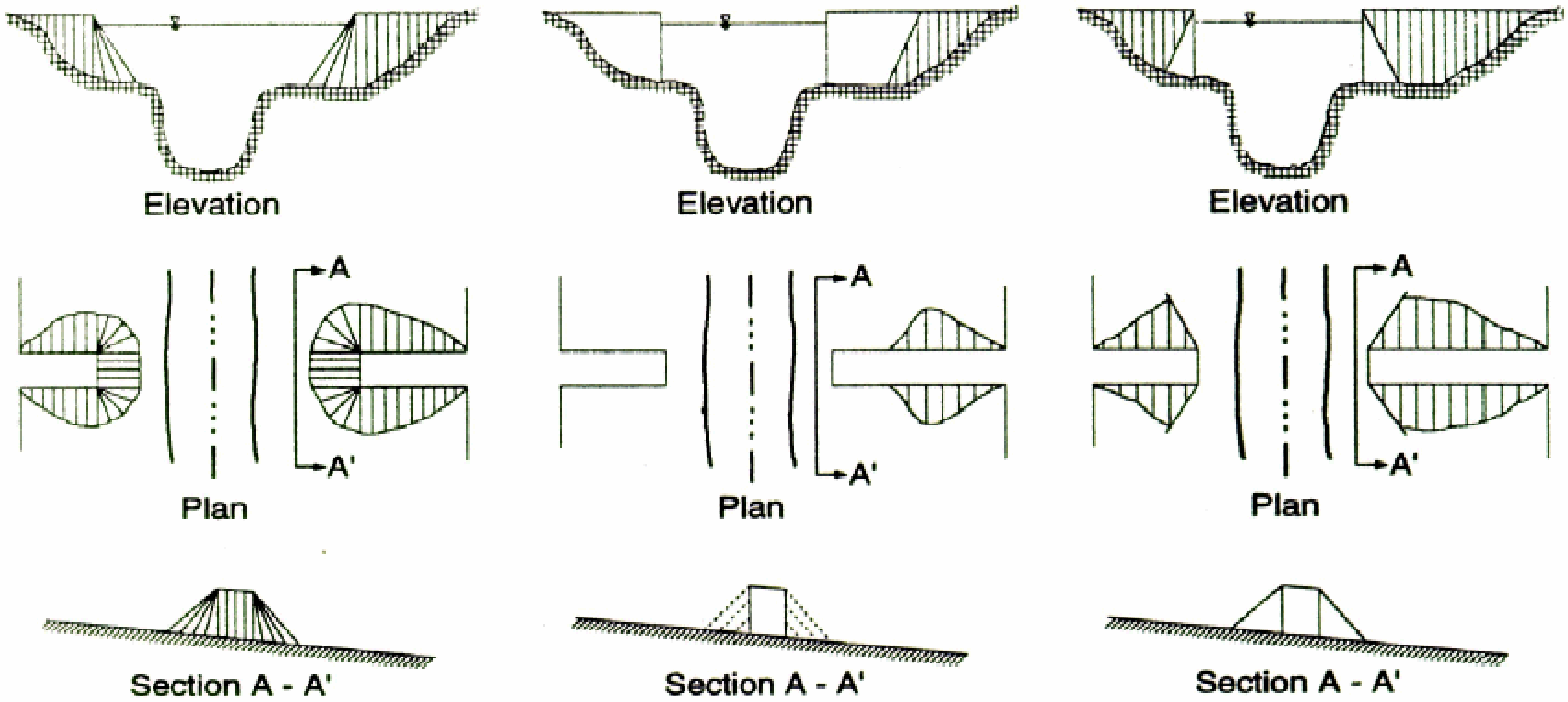
Local Scour at Abutments

Local scour occurs at abutments when the abutment and embankment obstruct the flow. The obstruction of the flow forms a horizontal vortex starting at the upstream end of the abutment and running along the toe of the abutment and forms a vertical wake vortex at the downstream end of the abutment

Abutment failure Causes

- Overtopping of abutments or approach embankments
- Lateral channel migration or stream widening processes
- Contraction scour
- Local scour at one or both abutments

Abutment Shapes



(a) Spill Through

(b) Vertical Wall

(c) Vertical Wall with Flared Wingwalls

Abutment Scour Factors

- Velocity of the flow just upstream of the abutment
- Depth of flow
- Length of the abutment if skewed to the flow.

Live-bed and Clear-water
Scour Determination

I - Froelich's Live-bed Abutment Scour Equation
(when the ratio of the length of the abutment (normal to flow) to flow depth <= 25)

II - Hire Live-bed Abutment Scour Equation
(when the ratio of the length of the abutment (normal to flow) to flow depth > 25)

I - Froelich's (1989) Live-bed Abutment Scour Equation

(ratio of the length of the abutment (normal to flow) to flow depth <= 25)

$$\frac{Y_s}{Y_a} = 2.27\, K_1 K_2 (L')^{0.43}\, y_a^{0.57}\, Fr_1^{0.61} + 1$$

Where
K1 = Coefficient for abutment shape
K2 = Coefficient for angle of embankment to flow
K2 = $(\theta / 90)^{0.13}$
$\theta < 90$ if embankment points downstream
$\theta > 90$ if embankment points upstream
L' = Length of active flow obstructed by the embankment
Ae = Flow area of the approach cross section obstructed by the embankment
Fr = Froude Number of approach flow upstream of the abutment
= $V_e/(g y_a)^{1/2}$
$V_e = Q_e / A_e$
Q_e = Flow obstructed by the abutment and approach embankment
Y_a = Average depth of flow on the floodplain (A_e /L)
L = Length of embankment projected normal to the flow
Y_s = Scour depth

Abutment Coefficients

K_1

Description	K_1
Vertical-wall abutment	1.00
Vertical-wall abutment with wing walls	0.82
Spill-through abutment	0.55

K_2

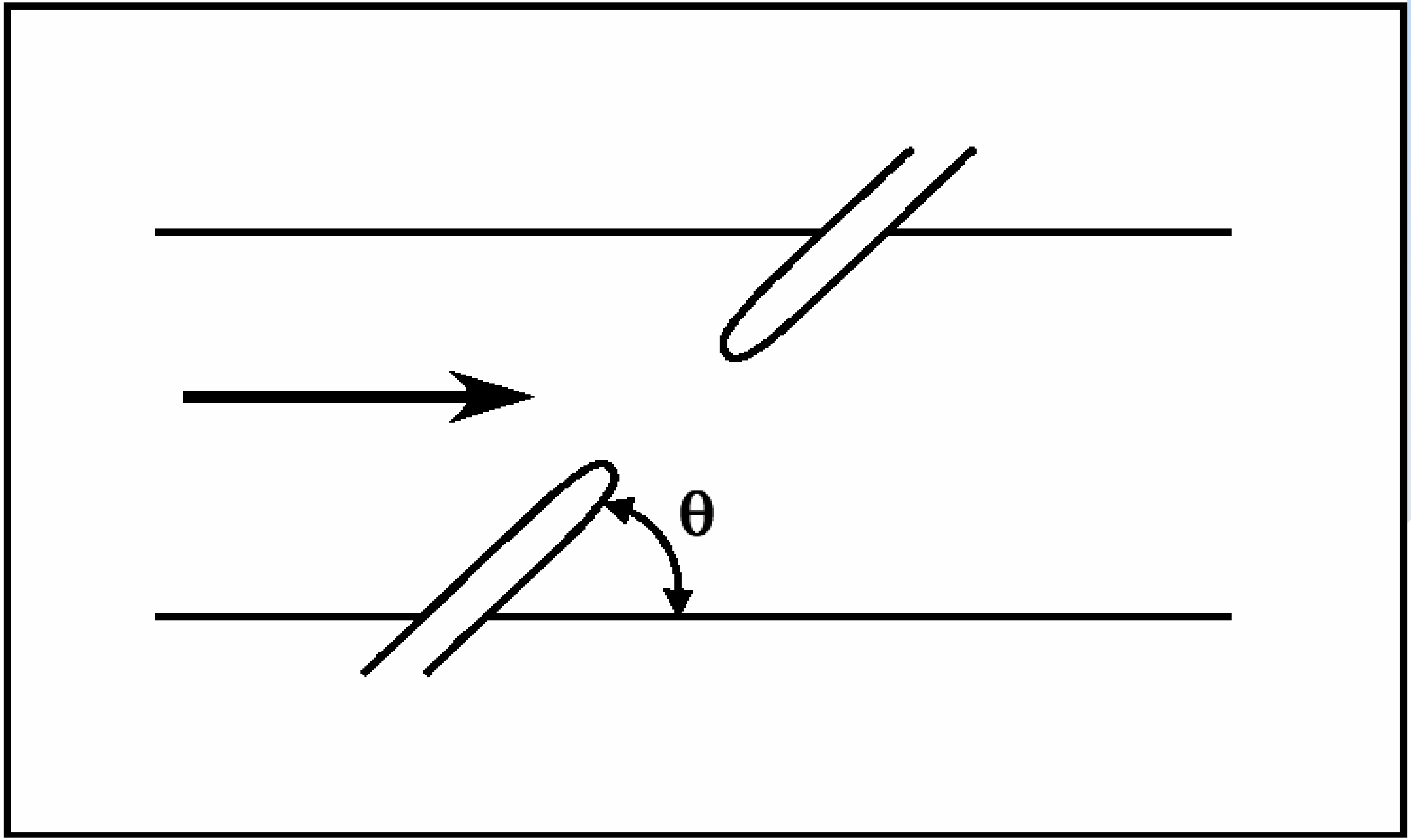
K2 = Coefficient for angle of embankment to flow

$$K2 = (\theta / 90)^{0.13}$$

$\theta < 90$ if embankment points downstream

$\theta > 90$ if embankment points upstream

Abutment Skew



For abutments angles upstream, the depth of scour increases

II - HIRE (Richardson 1990) Live-bed Abutment Scour Equation

(Recommended when the ratio of the length of the abutment (normal to flow) to flow depth > 25)

$$\frac{Y_s}{Y_1} = 4\left[\frac{K_1}{0.55}\right] K_2 Fr^{10.33}$$

K_1 = Coefficient for abutment shape

K_2 = Coefficient for angle of embankment to flow as calculated for Froelich's equation

Fr = Froude Number based upon the velocity and depth adjacent to and upstream of the abutment

Y_1 = Depth of flow at the abutment on the overbank or in the main channel.

Y_s = Scour depth

Suggested design approach

- No reliable equations are available to predict all hydraulic flow conditions that may be reasonably expected to occur. Engineering judgement is required.
- Place piers & abutment on scour resistant foundation such as rock or deep foundation.
- Pilings should be driven below the elevation of long-term degradation and contraction scour.
- Need to consider the potential for lateral channel instability.
- Spread footings should be placed below the elevation of total scour.

General Design Procedure

1. Select flood event
2. Develop water surface profiles
3. Estimate total scour
4. Plot total scour depth
5. Evaluate answers to above
6. Evaluate the bridge type, size and location
7. Perform bridge foundation analysis
8. Repeat the above procedure and calculate the scour for a super flood (500-year recommended). If hydrology for this flood is unavailable, use 1.7xQ100.

HECRAS EXAMPLE

D.1 ASSUMPTIONS

1. Debris aligns with the flow direction and attaches to the upstream nose of a pier. The width of the accumulation, W, on each side of the pier is normal to the flow direction.

2. The trailing end of a long slender pier does not add significantly to pier scour for that portion of the length beyond 12 pier widths. This is consistent with the current guideline in HEC-18 to cut K_2 at L/a = 12.

3. The effect of the debris in increasing scour depths is taken into account by adding a width, W, to the sides and front of the pier. Engineering judgment and experience is used to determine the width, W.

D.2 SUGGESTED PROCEDURE

1. Use K_1 and K_2 = 1.0

2. Project the debris pile and up to twelve pier widths of the pier length normal to the flow direction as follows:

L' = L or 12(a) (whichever is less)

$a_{proj} = 2W + a\cos\theta$ or $W + a\cos\theta + L'\sin\theta$ (whichever is greater)

3. Use K_1, K_2, K_3, K_4, and a_{proj} in the HEC-18 pier scour equation as follows:

$$\frac{y_s}{y_1} = 2.0\,(1.0)\,(1.0)\,K_3\,K_4\left(\frac{a_{proj}}{y_1}\right)^{0.65} Fr_1^{0.43}$$

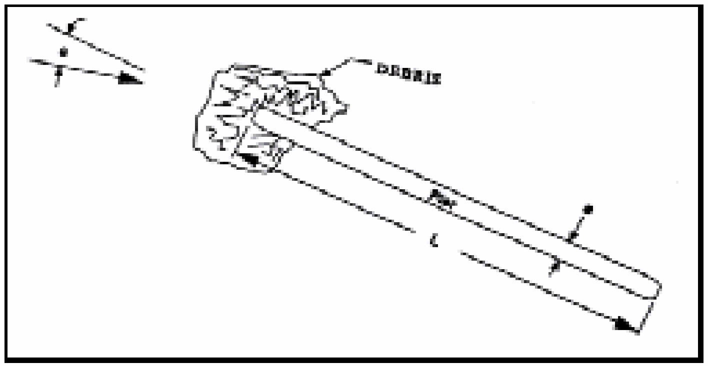


Figure D.1. Schematic for debris procedure.

6.8 TOPWIDTH OF SCOUR HOLES

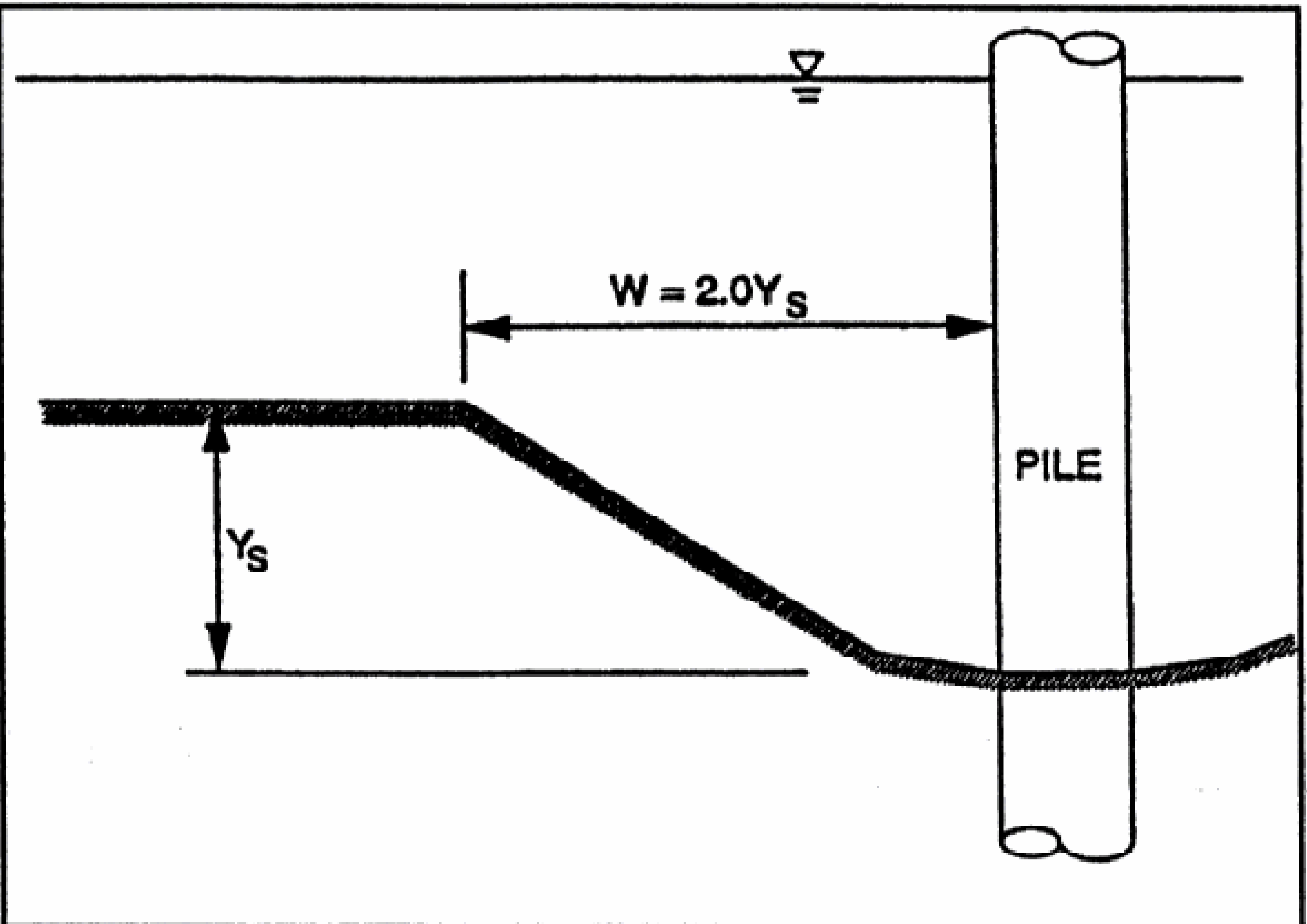
The topwidth of a scour hole in cohesionless bed material from one side of a pier or footing can be estimated from the following equation:[68]

$$W = y_s \ (K + \text{Cot}\ \theta) \tag{6.22}$$

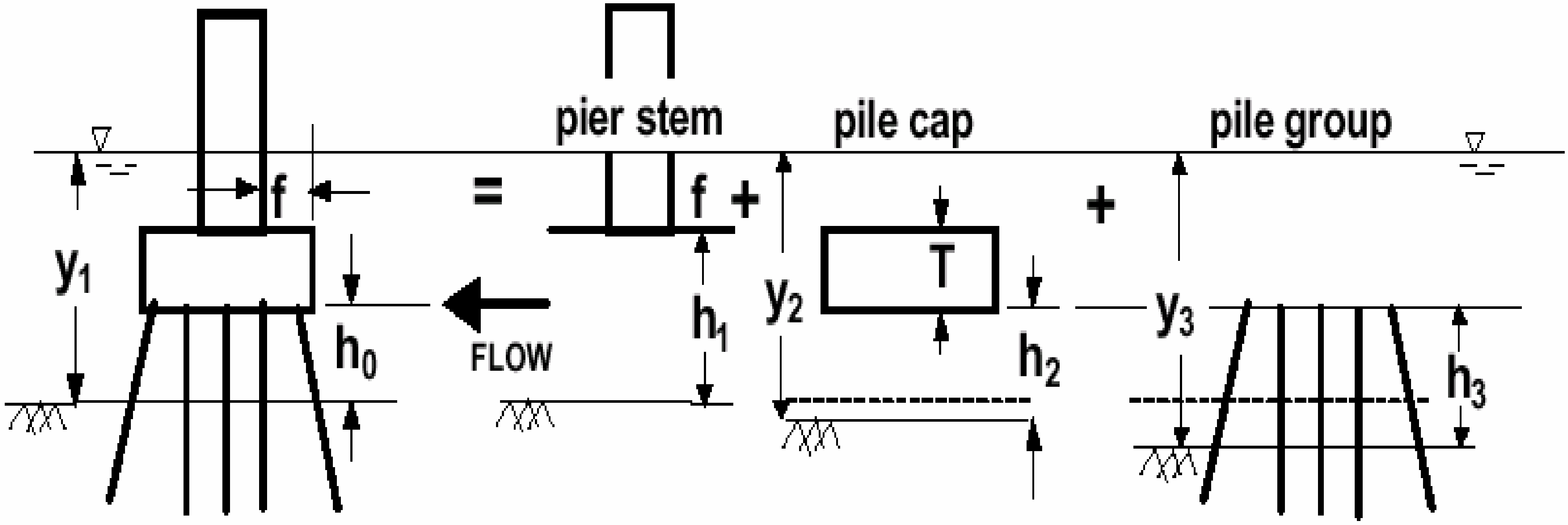
where:

W	=	Topwidth of the scour hole from each side of the pier or footing, m
y_s	=	Scour depth, m (ft)
K	=	Bottom width of the scour hole related to the of scour depth
θ	=	Angle of repose of the bed material ranging from about 30° to 44°

The angle of response of cohesiveness material in air ranges from about 30° to 44°. Therefore, if the bottom width of the scour hole is equal to the depth of scour y_s (K = 1), the topwidth in cohesionless sand would vary from 2.07 to 2.80 y_s. At the other extreme, if K = 0, the topwidth would vary from 1.07 to 1.8 y_s. Thus, the topwidth could range from 1.0 to 2.8 y_s and depends on the bottom width of the scour hole and composition of the bed material. In general, the deeper the scour hole, the smaller the bottom width. In water, the angle of repose of cohesionless material is less than the values given for air; therefore, a topwidth of 2.0 y_s is suggested for practical applications (Figure 6.15).

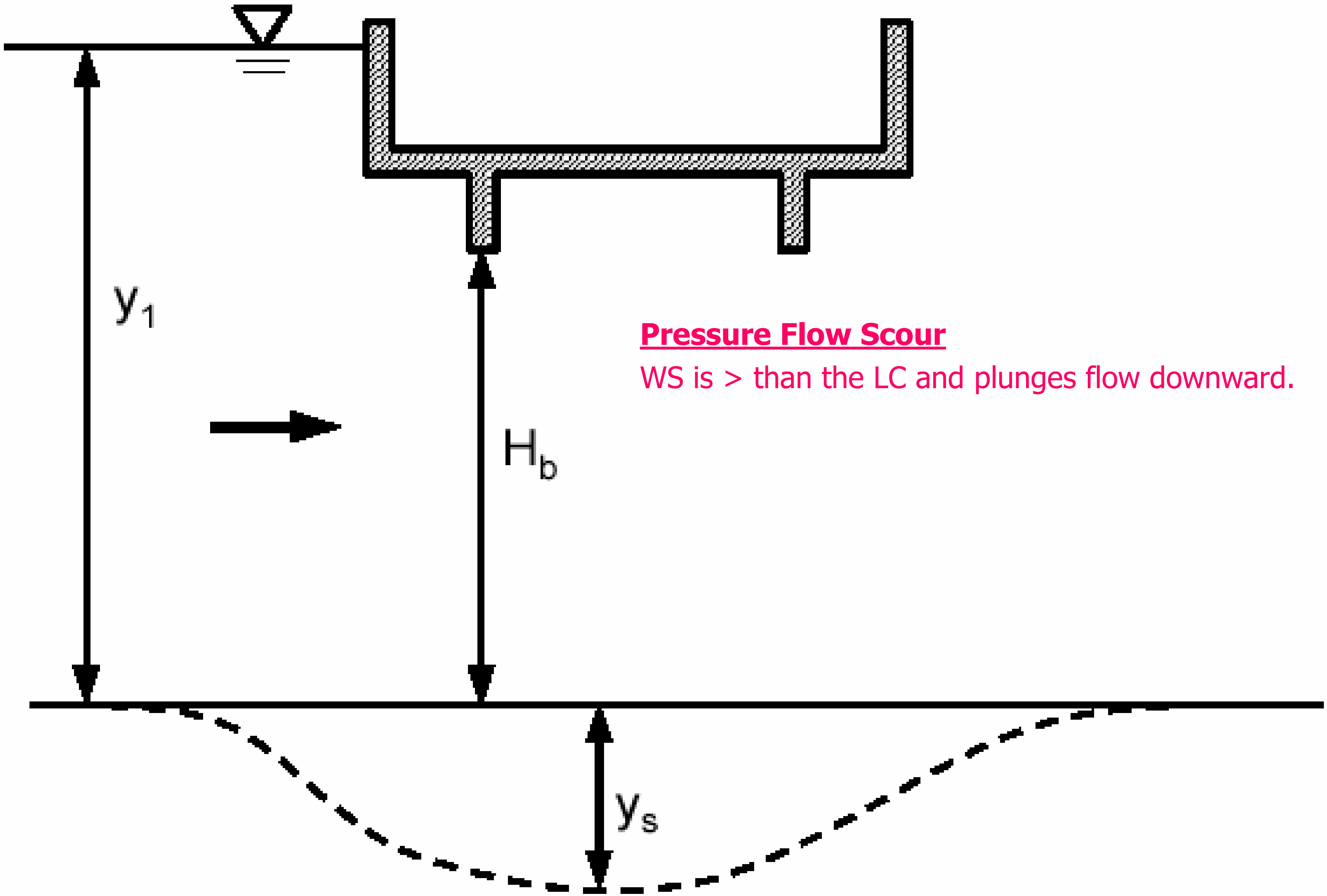

W = 2.0Y$_S$
PILE
Y$_S$

Mohammad Salim and Sterling Jones published "Scour Around Exposed Pile Foundations" in 1996 which more accurately estimates this case. However, more studies are needed for verification.



$$y_s = y_{s\,pier} + y_{s\,pc} + y_{s\,pg}$$

Figure 6.4. Definition sketch for scour components for a complex pier.[59]



Pressure Flow Scour

WS is > than the LC and plunges flow downward.