Bridge Inspection:
Scour Physics and Changes to HEC-18

Michigan Bridge Conference

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Case Studies of Bridge Failure Due to Scour

- Many cases of bridge failure.
- Causes discussed later.
- Causes large increase in bridge cost.
- Can cause loss of life.

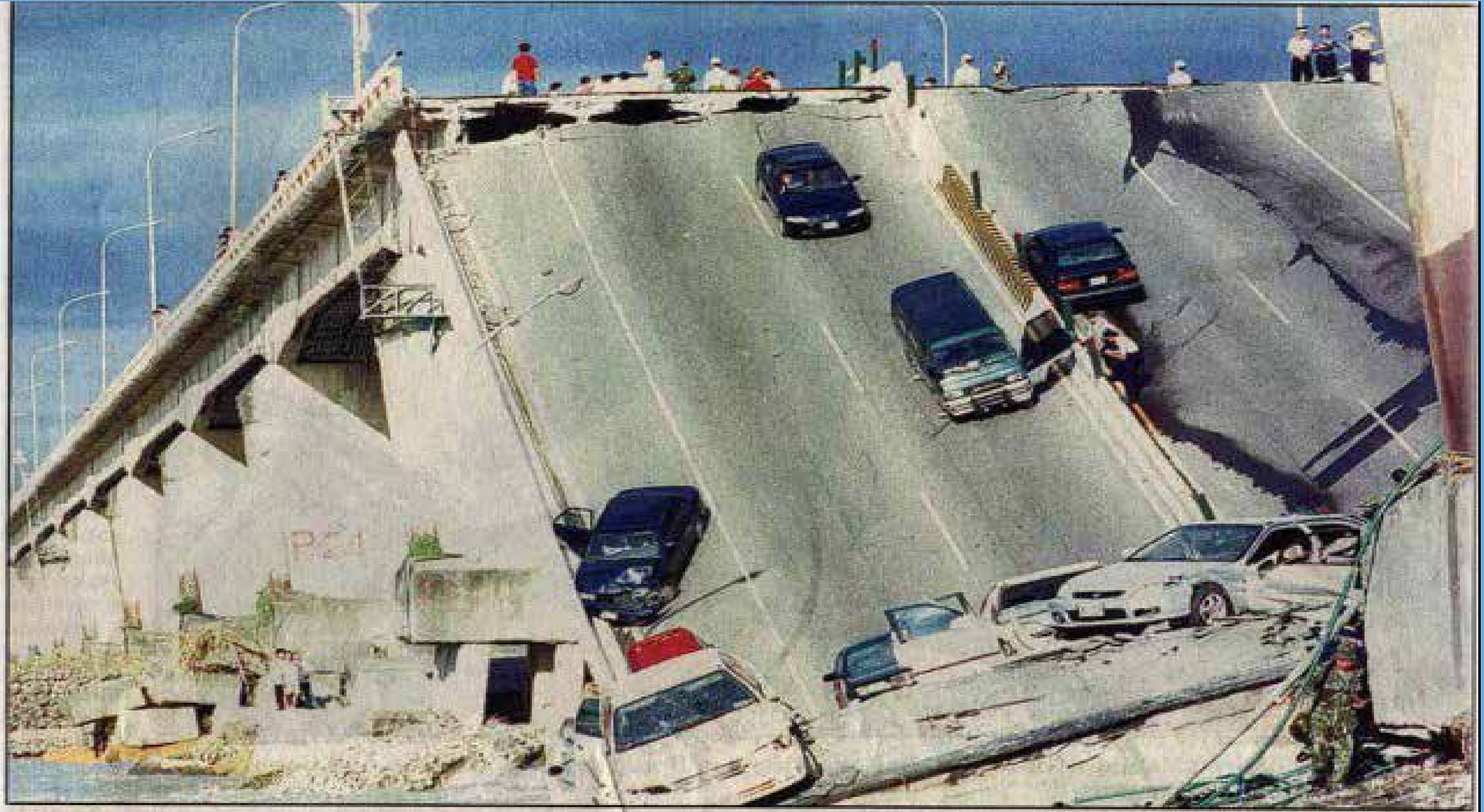
- From "Countermeasures for Hydraulic Problems at Bridges" by FHA, 1978

Abutment Failure, Arizona

Pier Failure, California

Abutment Failure in Iowa

Pier Collapse-Taiwan
Caused by Stone Quarrying



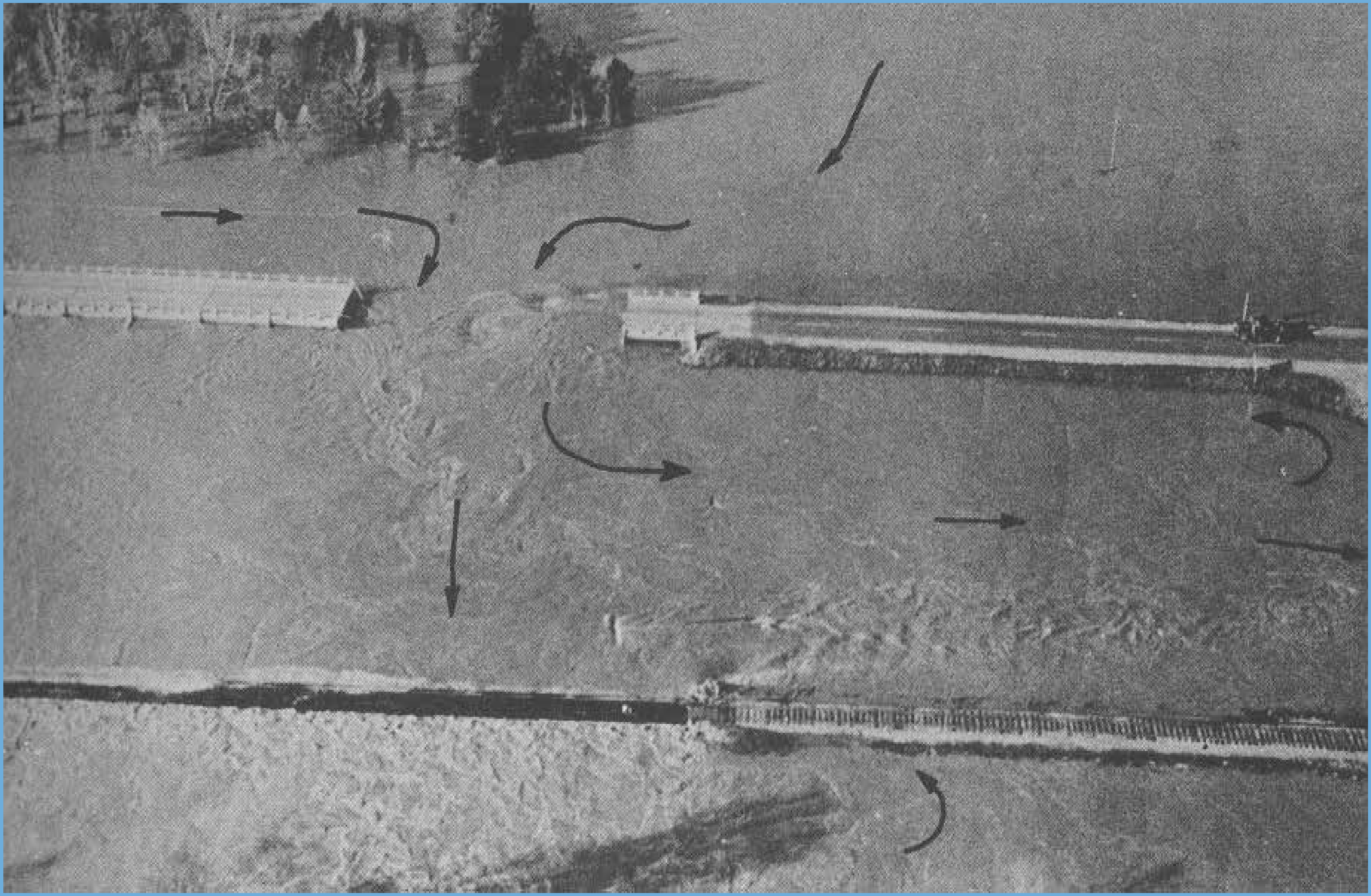
ON THE BRINK ... Cars lying on a collapsed bridge that links Taiwan's Kaohsiung and Pingtung counties yesterday. At least 16 cars came down with the bridge when it collapsed, injuring 22 people. Two beams of the Kaoping bridge snapped following the collapse of a pier. The collapse was suspected to have been triggered by illegal stone quarrying of the pier, which was weakened further by waters swollen by Typhoon Bilis last week. — AFP picture

Abutment Failure, Nebr.

Debris-Pier Failure, MS

Pier Failure, Montana

Pier Failure, MS



Pier Scour, Nev

Bridge Scour Hydraulics

- Reasons why bridges fail
- Scour caused by many flow patterns
- In general, water velocity high enough to move sediment.

Causes of Bridge Scour

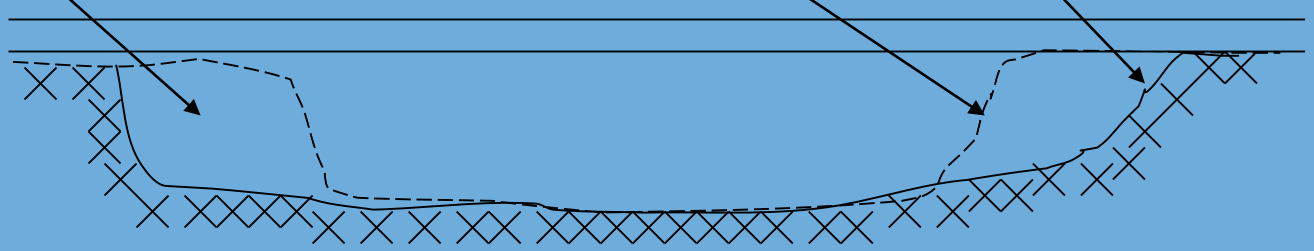
- Contraction scour
- Bed degradation
- Vortices
- Out-flanking
- River widening???
- Abutment scour causes pier failure!

Contraction Scour

- For some bridges the width of the river has been narrowed to reduce span length.
- This smaller flow cross-sectional area leads to higher velocity (V=Q/A)
- If increased velocity is high enough, then the sediment will start to erode.

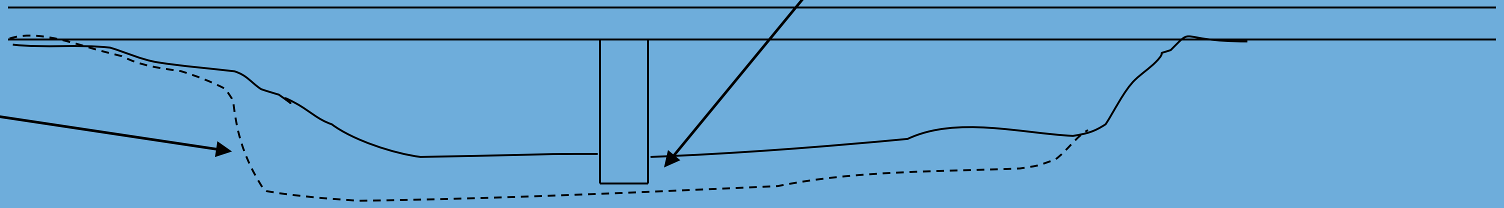
Contraction Scour Schematic

- Original riverbanks
- Reduced flow area
- Bridge Abutments

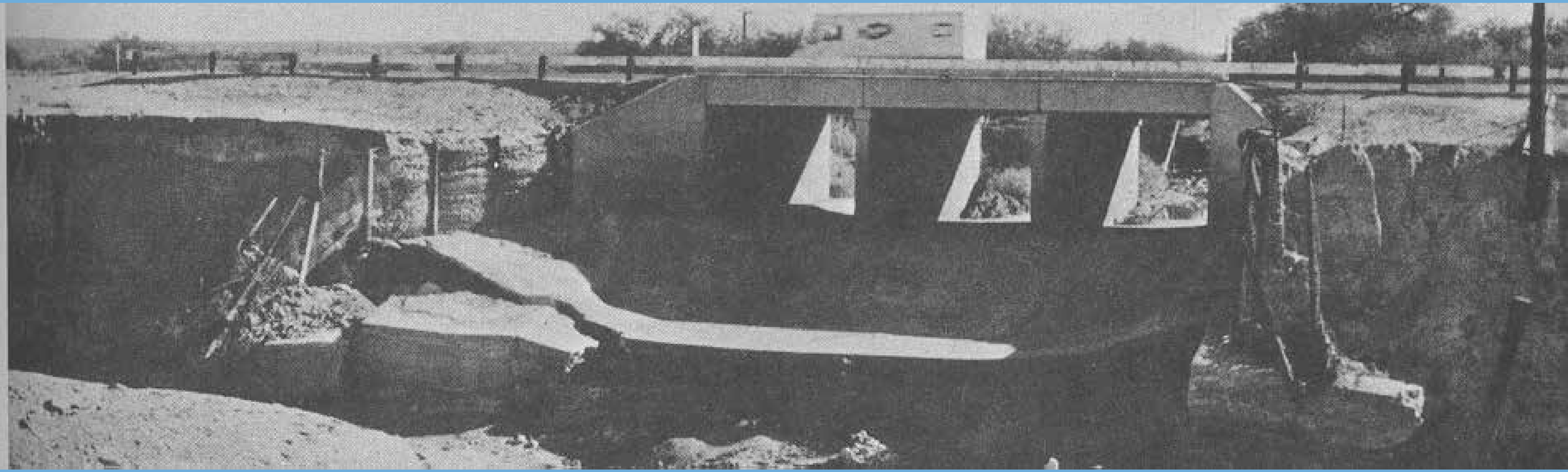


Riverbed Degradation

- Some rivers have beds that are naturally degrading due to conditions upstream or downstream.
- Any bridge piers or abutments built will need to have a deeper foundation.

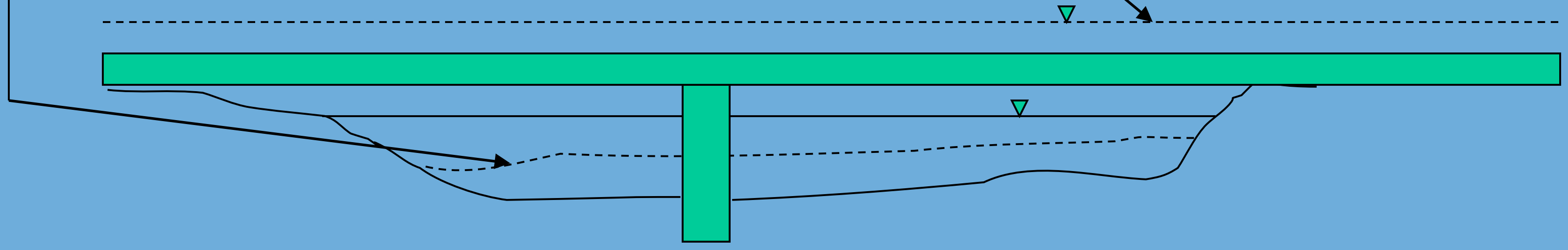


Degradation Failure,Ariz.

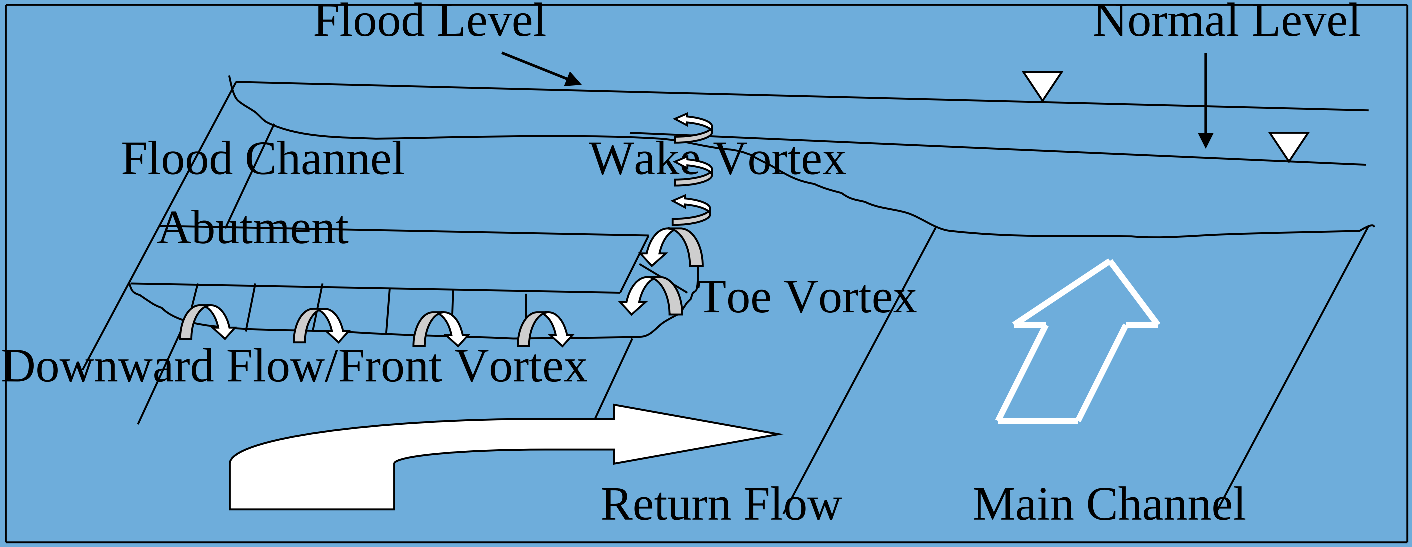


Riverbed Aggradation

- Some rivers have beds that are naturally aggrading due to conditions upstream or downstream.
- Higher riverbed leads to increased flow depth and bridge over-topping.



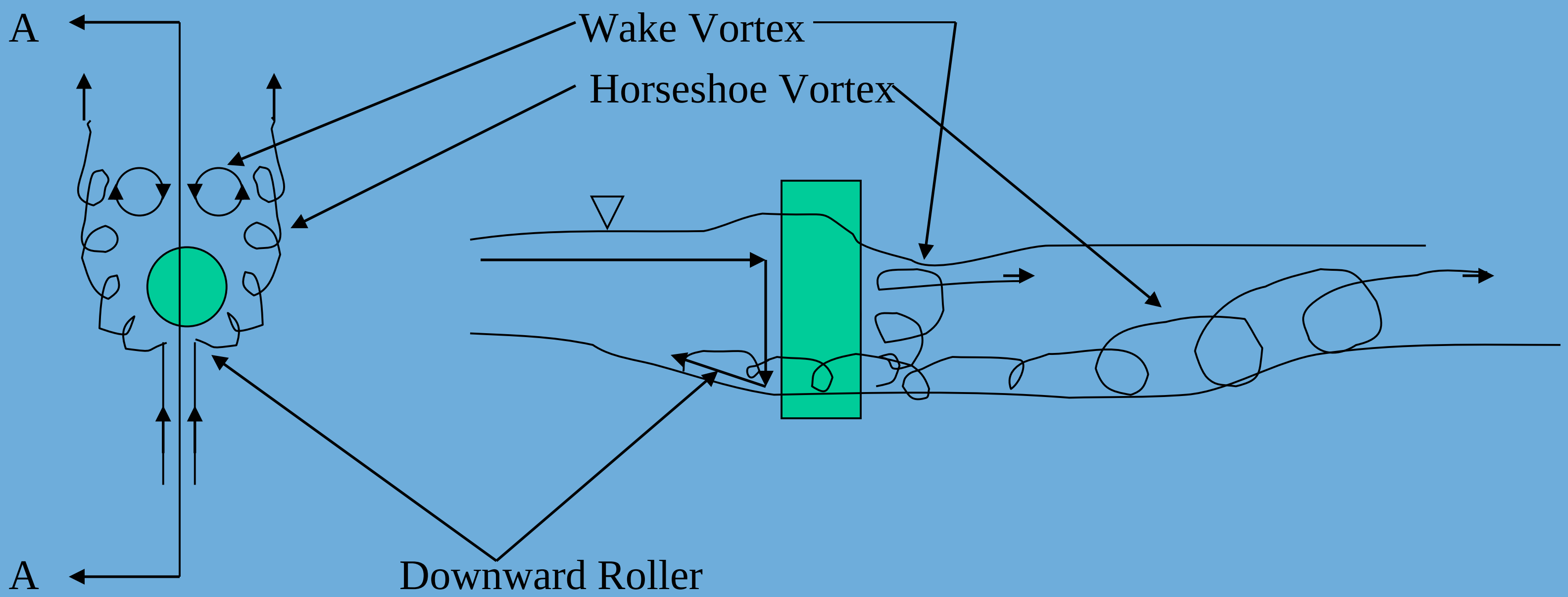
Vortices Around Abutments



Vortices Around Piers

- PLAN

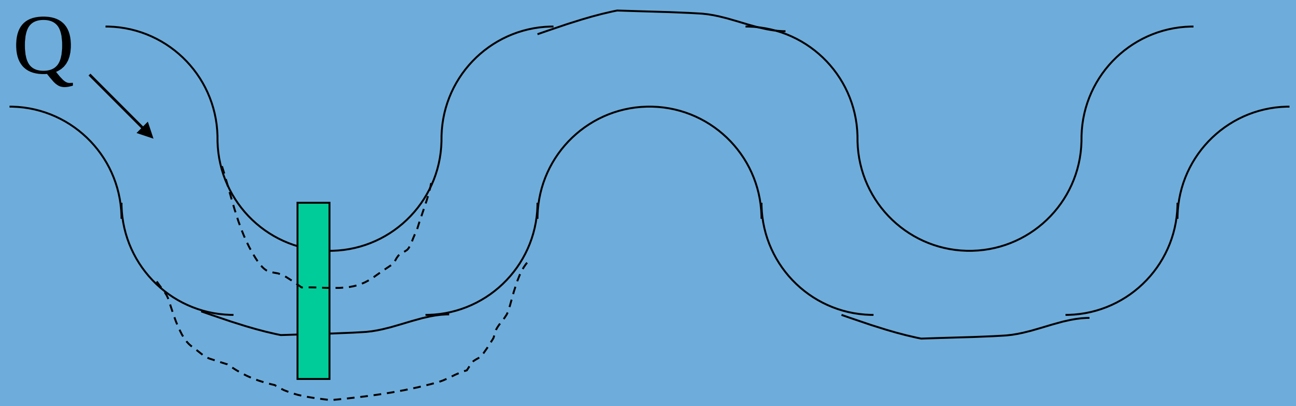
SECTION A-A



Some Videos

River Out-Flanking Bridge Opening

- Some rivers continue to meander and migrate in plan view.
- River may go around (out-flank) the bridge opening, or attack abutment.



Example of River Meander

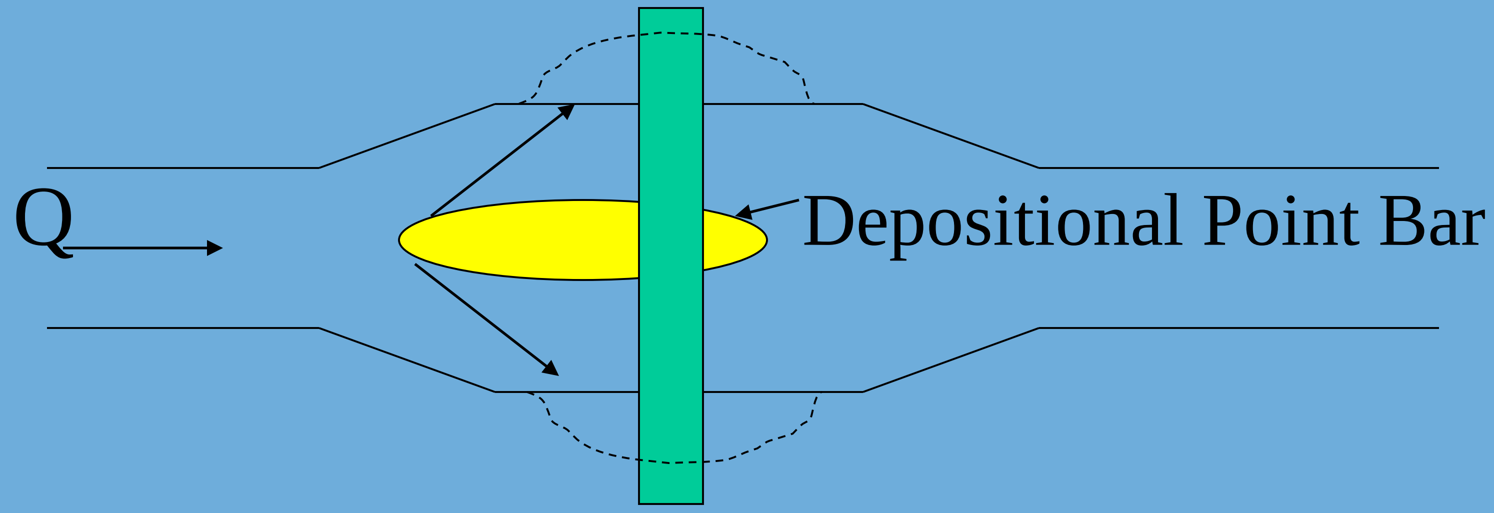
River Widening

- How can river widening lead to bridge failure????
- Widening river should *reduce* velocity!

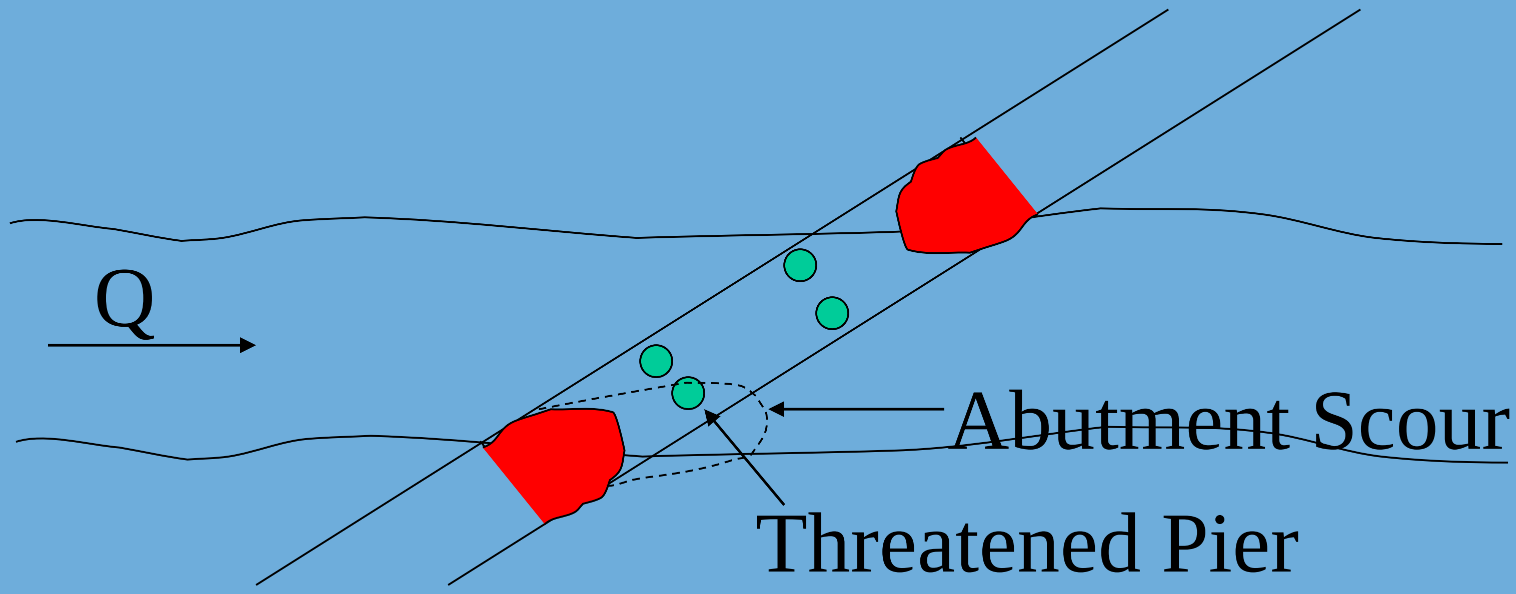
Widening → Out-Flanking

- Widening leads to decreased velocity.
- Decreased velocity can lead to sediment deposition (water not fast enough to transport sediment anymore.)
- Deposition can form point bars.
- Point bars divert flow towards bank.
- This causes bank erosion that threatens abutment.

Widening Leads to Flow Diverted at Abutment



Abutment Scour Affects Pier



Bridge Scour Prediction

- Summary of revised HEC 18, “Evaluating Scour at Bridges” Fifth Edition, FHA, Publ # FHWA-HIF-12-003.
- Should really follow HEC 18, but this summary will get you the main points.

Companion Documents

- HEC-20 “Stream Stability at Highway Structures”
- HEC-23 “Bridge Scour and Stream Instability Countermeasures”
- HEC-25 “Tidal Hydraulics”

7 Steps for Total Bridge Scour

- 1: Determine scour analysis variables
- 2: Determine Long-Term Bed Level Changes
- 3: Compute contraction scour magnitude
- 4: Compute local pier scour magnitude
- 5: Compute local abutment scour magnitude
- 6: Plot and evaluate total scour
- (removed previous Step 3: Evaluate scour analysis method)

Summary of Changes in Fifth Edition

- More on the policy and regulatory basis for the FHWA Scour program (not discussed here)
  - risk-based approaches,
  - developing Plans of Action for scour critical bridges
- Expanded discussion on
  - Countermeasures
  - Unknown Foundations

More Changes in Fifth Edition

- Contraction scour in cohesive soil
- Updated abutment scour estimation
- Alternative abutment design approaches
- Alternative procedures for pier scour
- Pier scour estimation with debris loading
  - in coarse soil
  - in cohesive material
  - in erodible rock

More Changes in Fifth Edition

- Revised pressure-flow scour guidance
- Scour prediction at bottomless culverts
- Discussion of scour at tidal bridges
- Added chapter on “Soils, Rock, and Geotechnical Considerations”

New Material: Unknown Foundations

- Refers to Plans of Action and FHWA documents:
  - NCHRP 21-5, 1995, "Determination of Unknown Subsurface bridge Foundations-Final Report," NCHRP Project 21-5
  - NCHRP 21-5, 1996, "Nondestructive Destructive of Unknown Subsurface Bridge Foundations " Research Results Digest No. 213

Steps to take for UF

- Prioritize UF bridges
- Collect historical, geologic, and Non-Destructive Testing info
- *www.fhwa.dot.gov/unknownfoundations*
- Assign Risk Categories
- Define Global Action Plan for all bridges

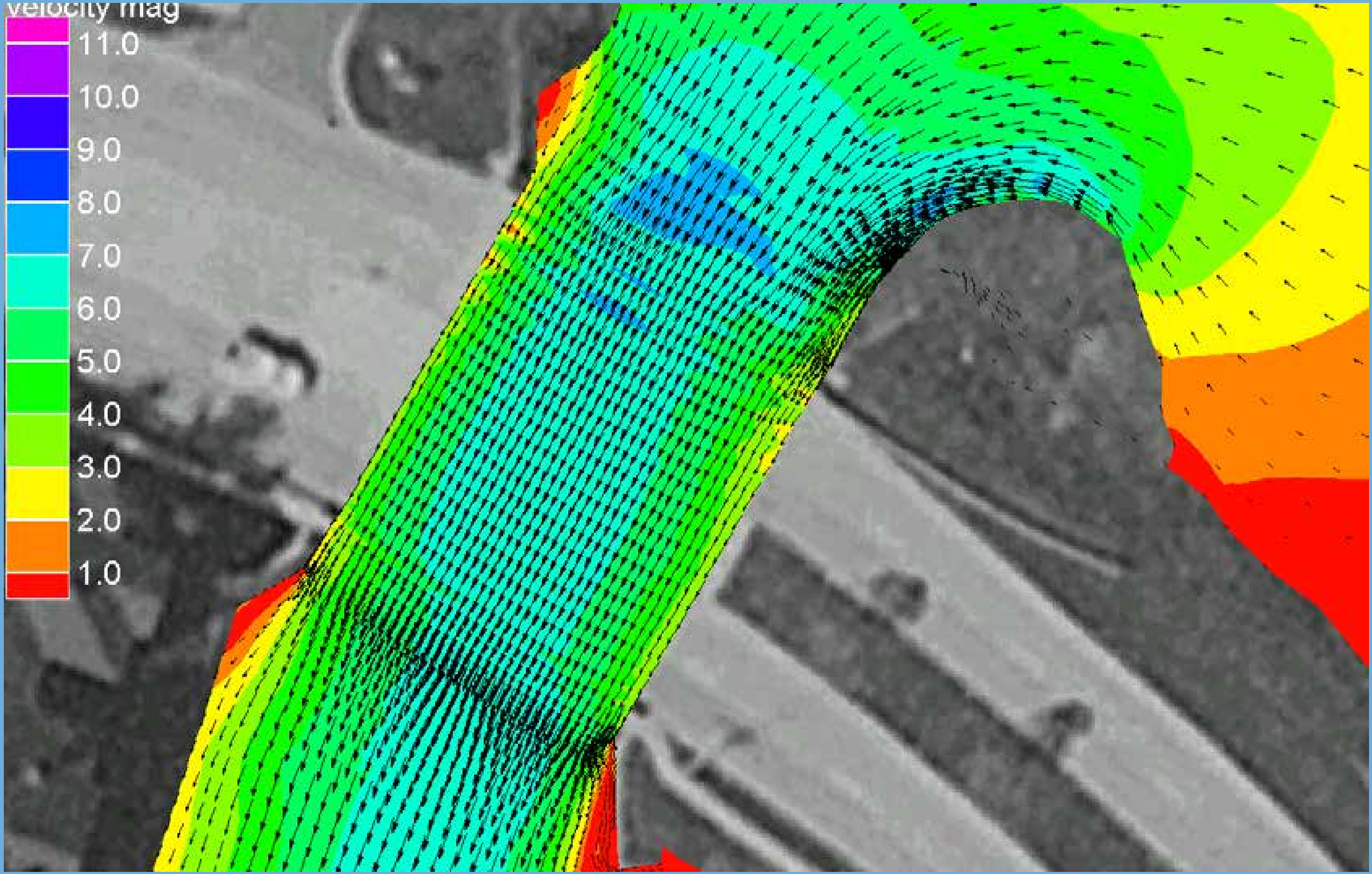
Non-Destructive Testing

- Sonic echo
- Bending wave
- Ultra-seismic
- SASW
- Dynamic foundation
- Borehole sonic or radar
- Induction field
- Core drilling
- Forensic engineering

Pier scour: Step 1: Determine Variables

- Find design Q (worst-case scenario) 500-yr Q or special angle, etc.
- Any future changes to river?
- Calculate water surface profiles (step method, HEC-2, WSPRO, etc.)
- Get geology, sediment size, cross-sections, planform, watershed data, similar bridge scour, energy gradeline slope, flooding history,location wrt other bridges or tributaries, meander history, erosion history, sand mining,etc.)

Step 1: 2-D Computer Modeling to Get Velocities



Step 2: Analyze Long-Term Bed Elevation Change

- Find trend of aggradation/degradation using either
  - past data,
  - Site evidence,
  - worst-case, or
  - software.

Step 3: Evaluate Scour Analysis Method

- Get fixed-bed hydraulic data
- Assess profile and planform changes
- Adjust fixed-bed hydraulics for profile and planform changes
- Compute contraction (discussed later)
- Compute local scour (discussed later)
- Get total scour by adding long-term degradation+contraction scour+local scour

Step 4: Compute Contraction Scour Magnitude

- Determine if clear water or live bed by incipient motion equation:
- $V_c = 6.19\ y^{1/6}\ D_{50}^{\ 1/3}$

V_c=min. vel. for size D_{50} sediment movement

y=flow depth (m)

D_{50}=sed. size of which 50% are smaller (m)

Step 4 Live-Bed Contraction Scour

$$\frac{y_2}{y_1} = \left[\frac{Q_2}{Q_1}\right]^{6/7} \left[\frac{W_1}{W_2}\right]^{k_1} ; y_s = y_2 - y_o$$

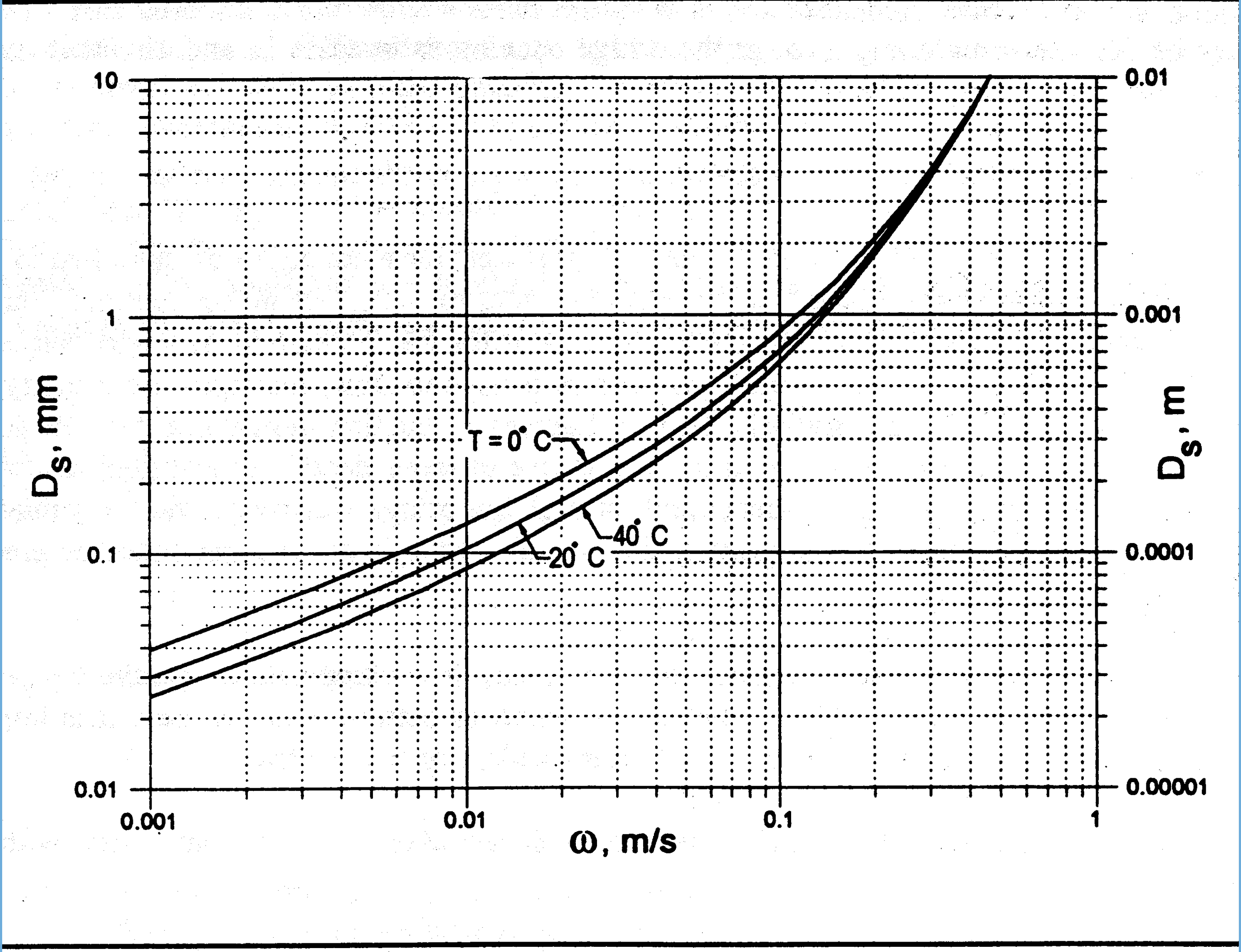
- y_2= contracted section flow depth (m)
- y_1=upstream main channel depth (m)
- y_o= contracted section flow depth (m) before scour
- y_s=scour depth (m)
- Q_1=flow in upstream channel transporting sediment (m^3/s)
- Q_2=contracted channel flow (m^3/s)
- W_1=upstream main channel bottom width (m)
- W_2=main channel contracted section bottom width without pier widths (m)
- k_1=exponent determined below

Step 4: k_1 Determination

V_*/w	k_1	Bed Transport Mode
<0.5	0.59	bed contact
0.5-2	0.64	some suspended load
>2	0.69	suspended load

- V^*=upstream shear velocity (m/s) $=(gy_1S_1)^{1/2}$
- $w=D_{50}$ fall velocity (following figure)
- S_1=main channel energy grade line slope
- g=acceleration of gravity (9.81 m/s^2)

Step 4: Fall Velocity, w



Step 4: Clear-Water Contraction Scour

$$y_2 = \left[\frac{n^2 Q^2}{K_s (S_s - 1) D_m W^2}\right]^{3/7}$$

- y_2=contracted section depth after contraction scour (m)
- Q=discharge through bridge (m^3/s)
- D_m=1.25D_{50} (m)=min. non-movable part.
- W=bottom width in contracted section wo pier widths

New Material: Contraction Scour in Cohesive Materials

- Can withstand more shear stress than sands
- $\tau = \gamma \left(\frac{V_2 n}{K_u}\right)^2 y_o^{-1/3}$ for initial shear stress
- $y_{s\_ult} \left(\frac{1.83V_2}{\sqrt{gy}} - \frac{K_u\sqrt{\frac{\tau_c}{\rho}}}{gny_1^{1/3}}\right)$ for ultimate scour depth

New Material: Time Rate of Scour

- $y_s = \dfrac{t}{\frac{1}{Z_i} + \frac{t}{y_{s\_ult}}}$
- Using $t = t_{event} + t_e$
- $t_e = \dfrac{y_{s\_ult}\, y_{s\_prior}}{Z_1 (y_{s\_ult} - y_{s\_prior})}$
- t_e is the equivalent time that that event would have required to reach the prior scour amount.

New Material:
Contraction Scour in Erodible Rock

- Can weather and have abrasion, wetting/drying, freeze-thaw, chemical reactions.
- Weakly-cemented sandstone may be as erodible as sand.

New Material:
Scour at Open-Bottom Culverts

- No bottom, natural bed material.
- Put on spread footings on table soil
- May have scour at upstream corners
- Can have pressure flow if flowing full

New Material:
Scour at Open-Bottom Culverts

New Material:
Scour at Open-Bottom Culverts

- $y_{max} = KuQ_{Bl}{}^{0.28}\left(\frac{Q}{W_c D_{50}{}^{1/3}}\right)^{0.26}$

- For scour at corners

New Material: Pressure-Flow Scour

- Use existing equations for clear-water or live-bed scour
- Calc separation zone thickness, t:
- $\frac{t}{h_b} = 0.5\left(\frac{h_b h_t}{h_u{}^2}\right)^{0.2}\left(1 - \frac{h_w}{h_t}\right)^{-0.1}$
- h_b=vertical size of bridge opening
- h_t=distance between water surface and bottom of bridge girders

Step 5: Local Pier-Scour Magnitudes

$$\frac{y_s}{a} = 2K_1K_2K_3K_4\left(\frac{y_1}{a}\right)^{0.35} Fr_1^{0.43}\ ;\ Fr_1 = V_1/(gy_1)^{1/2}$$

- y_s=scour depth (m)
- y_1=flow depth directly upstream of pier(m)
- K_1=pier nose shape correction
- K_2=angle of attack correction
- K_3=bed condition correction
- K_4=armoring correction
- a=pier width(m)
- V_1=velocity upstream of pier(m/s)

Pier Nose Shape Correction, K_1

Pier Nose Shape	$\mathbf{K_1}$
Square nose	1.1
Round nose	1.0
Circular cylinder	1.0
Group of cylinders	1.0
Sharp nose	0.9

Angle of Attack Correction, K_2

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
L=pier length (m), a=pier width (m)			

Bed Correction Factor, K_3

Bed Condition	**Dune Height (m)**	**K_3**
Clear-Water Scour	N/A	1.1
Plane Bed and Antidune	N/A	1.1
Small Dunes	0.6<H<0.6	1.1
Medium Dunes	3<H<9	1.2
Large Dunes	9<H	1.3

Armoring Correction, K_4

- $K_4=[1-0.89(1-V_R)^2]^{0.5}$
- $V_R=(V_1-V_i)/(V_{c90}-V_i)$
- $V_i=0.645(D_{50}/a)^{0.053}\ V_{c50}$
- $V_c=6.19y^{\ 1/6}\ D_c^{\ 1/3}$
- Where
- V_1=approach velocity (m/s)
- V_{c90}=critical velocity to move D_{90}
- D_c=critical part. size (m) for critical vel.,V_c
- a=pier width (m)

Limiting Values of K_4

Factor	**Min. Bed Material Size**	**K_4 min.**	**V_R>1.0**
K_4	D_{50}>0.06 m	0.7	1.0

Special Cases

- Very wide piers
- Exposed footings and/or piles
- Pile caps in flow
- Multiple columns skewed to flow
- Pressure flow scour deck over-topping
- Debris

New Material: Florida DOT Pier Scour Methodology

- Consider this as an alternative
- Includes sediment size also
- Various equations for ranges of V/V_c of 0.4 to 1.0; 1.0 to V_{lp}/V_c; and $>T_{lp}/V_c$
- V_{lp}=velocity of the live-bed peak scour

Pier Scour at Wide Piers

- Used when:
- y/a<0.8
- a/D_{50}>50 and
- Subcritical flow
- $K_W = 2.58 \frac{y}{a}^{0.34} Fr^{0.65}$ for clear-water
- $K_W = 1.0 \left(\frac{y}{a}\right)^{0.13}$ for live-bed

New Material: Scour from Debris on Piers

$$a_d^* = \frac{K_1(HW) + (y - K_1H)a}{y}$$

a_d^*=effective pier width

a=pier width perp to flow

K1=0.79 (rect debris;

0.21 triangular debris)

H=debris height

New Material: Pier Scour in Coarse Bed Material

- $y_s = 1.1K_1K_2a^{0.62}{y_1}^{0.38}tanh\left(\frac{H^2}{1.97\sigma^{1.5}}\right)$
- $H = \frac{V_1}{\sqrt{g(S_g-1)D_{50}}}$
- $\sigma = D_{84}/D_{50}$
- Only for clear water, D_{50}>20mm; σ>1.5

New Material: Pier Scour in Cohesive Material

- $y_s = 2.2K_1K_2a^{0.65}\left(\frac{2.6V_1 - V_c}{\sqrt{g}}\right)^{0.7}$
- V_c from material testing
- Use shear stress and time equations from those in contraction scour presented above

New Material: Pier Scour in Erodible Rock

- Erosion processes:
- Quarrying and plucking: removal of rock blocks
- Abrasion: Bedload rubbing of rock

New Material:
Pier Scour in Erodible Rock:
Quarrying and Plucking

Erodibility Index, $K=M_s K_b K_d J_s$

(rock parameters given in tables)

Critical Stream Power $P_c=K^{0.75}$

Approaching Stream Power, $P_a=7.583\rho\left(\frac{\tau}{\rho}\right)^{3/2}$

Local Stream Power $\frac{P}{P_a} = 8.42e^{-0.712\left(\frac{y_s}{b}\right)}$

Find lowest y /b value where P>P

New Material: Pier Scour in Erodible Rock: Abrasion

- Time rock is exposed to flow is important:
- $y_s = (GSN)(\Omega)$
- GSN=Geotech Scour Number from slake durability test
- Ω=cumulative stream power over time

New Material: Pier Scour in Erodible Rock: Abrasion

- Step 1: Get flow vs time from USGS data
- Step 2: Develop long-term cumulative stream power $P = VK_s(\rho_s - \rho_w)\mathrm{g}\mathrm{d}_{50}$
- Step 3: Get GSN from slake test of the bedrock
- Step 4: Calc total work done by stream over time, $\Omega =$ (Cum Stream Power at time 2- that of time 1).
- Step 5: Estimate scour: $y_s = (GSN)(\Omega)$

Abutment Scour Prediction

- Many kinds exist:
  - Different setbacks (in main channel, back on floodplain)
  - Shape (spill-through, vertical face, wingwall)
  - Angle to flow

Abutment Scour Prediction

$$\frac{y_s}{y_a} = 2.27 K_1 K_2 \left(\frac{L'}{y_a} \right)^{0.43} F_r^{0.61} + 1; F_r = \frac{V_e}{\sqrt{g y_a}}; V_e = \frac{Q_e}{A_e}$$

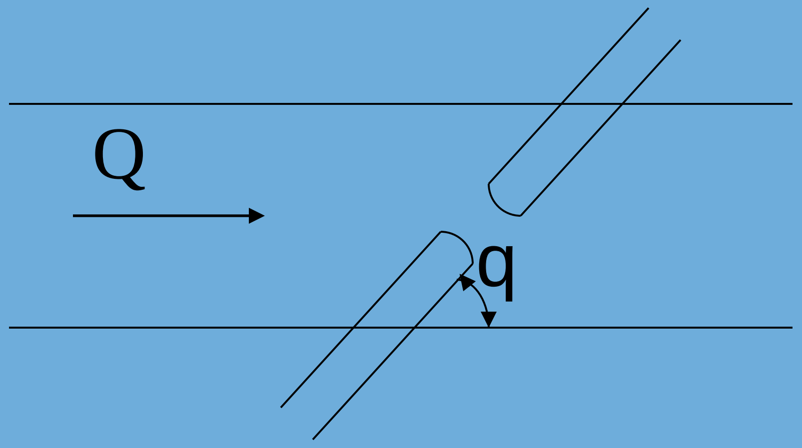
- K_1,K_2=correction coefficients
- L'=abutment length normal to flow (m)
- y_a=floodplain average depth (m)
- y_s=scour depth (m)
- Q_e=flow obstructed by abut. and embank. (m^3/s)
- A_e=cross-sect. flow obstr. by abut. and emb. (m^2)

Abutment Shape Correction, K_1

Description	$\mathbf{K_1}$
Vertical-wall	1.00
Vertical-wall/wing wall	0.82
Spill-through	0.55

Embankment Angle Correction, K_2

- $K_2=(q/90)^{0.13}$
- $q<90^o$ if embankment points downstream
- $q>90^o$ if embankment points upstream



Alternate Equation if $L'/y_1 < 25$

$$\frac{y_s}{y_1} = 4F_r^{0.33}\frac{K_1}{0.55}$$

- y_s=scour depth (m)
- y_1=flow depth at abutment (m)
- Fr=Froude Number at abutment
- K_1=abutment shape correction

New Material:
Alternative Approach-NCHRP 24-20

- Does not use effective embankment
- More physical equations
- Predicts total scour (don’t need to add contraction scour)
- Considers 3 scour conditions:
  - Abutment close to main channel,
  - Abutment set back from main channel, and
  - Embankment and abutment act as a pier.

New Material: Alternative Approach-NCHRP 24-20

- For first 2 scour conditions:
- $y_{max}=\alpha_A y_c$ or $y_{max}= \alpha_B y_c$
- $y_s=y_{max}-y_o$
- y_{max}=max flow depth from abut scour
- y_c=y with live-bed and clear-water scour
- α_A and α_B amplification factors for live-bed and clear-water, respectively (from charts)
- y_o=y prior to scour

New Material: Alternative Approach-NCHRP 24-20

- If $L > 0.75B_f$

$$y_c = y_1\left(\frac{q_{2c}}{q_1}\right)^{6/7}$$

- If $L < 0.75B_f$

$$y_c = \left(\frac{q_{2f}}{K_u D_{50}{}^{1/3}}\right)^{6/7}$$

May need 2D modeling to get velocity at the abutment

Step 7: Total Scour and Bridge Design

- Plot bed degradation elevation
- Subtract contraction scour and local scour (include local scour width as well=2depth)
- Is scour depth reasonable?
- Avoid overlapping scour holes
- Consider scour protection rather than a foundation deeper than the scour (can you count on it?)
- Evaluate cost, safety, environmental effects, ice, and debris.

Step 7:Re-Evaluation of Design

- Waterway width OK? (Leave as is?)
- Are scour holes overlapping?
- Relief bridges on floodplain needed?
- Abutments properly aligned?
- Can crossing location be changed?
- Can you train the flow at bridge?
- Is 2-D numerical model or physical model study needed?

New Material: Countermeasures

- Table 2.3. Hydraulic Design, Scour Design, and Scour Countermeasure Design Flood

Hydraulic Design Flood Frequency (QD)	**Scour Design Flood Frequency (QS)**	**Scour Countermeasure Design Flood Frequency (QCM)**
Q10	Q25	Q50
Q25	Q50	Q100
Q50	Q100	Q200
Q100	Q200	Q500

Scour Countermeasures

- Bank-hardening
  - Riprap
  - Toskanes
  - Cable-tied blocks
  - Geobags
- Flow-altering
  - Submerged vanes
  - Delta wings
- River-training
  - Groynes, spur dikes
  - Submerged vanes
  - Guidebanks
  - Grade-control structures

Bank-Hardening: Riprap

- Use round stones; flat ones can be lifted and washed away.
- Use well-graded stones so small ones fill void spaces. Largest size $=2D_{50}$; smallest size is gravel.
- Use geotextile filter fabric between bank material and riprap stones to prevent winnowing of fines. Place stones carefully. Seal sides of fabric to prevent undermining.
- Riprap blanket thickness should be at least 12 in. or $1.5D_{50}$.
- Difficult to place in flowing water. Can add additional thickness at toe to settle into place after initial settling.

Sizing Riprap

$D_{50}=(t_c)_s/4$; d_{50} in ft, t_{cs} in psf

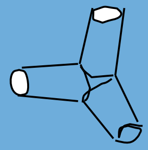
$$K=\frac{(t_c)_s}{(t_c)_b}=\sqrt{1-\frac{\sin^2 f}{\sin^2 q}}$$

$(t_c)_b=1.6gRS$

q=angle of repose;R=hydraulic radius;S=bed slope

Bank-Hardening: Toskanes

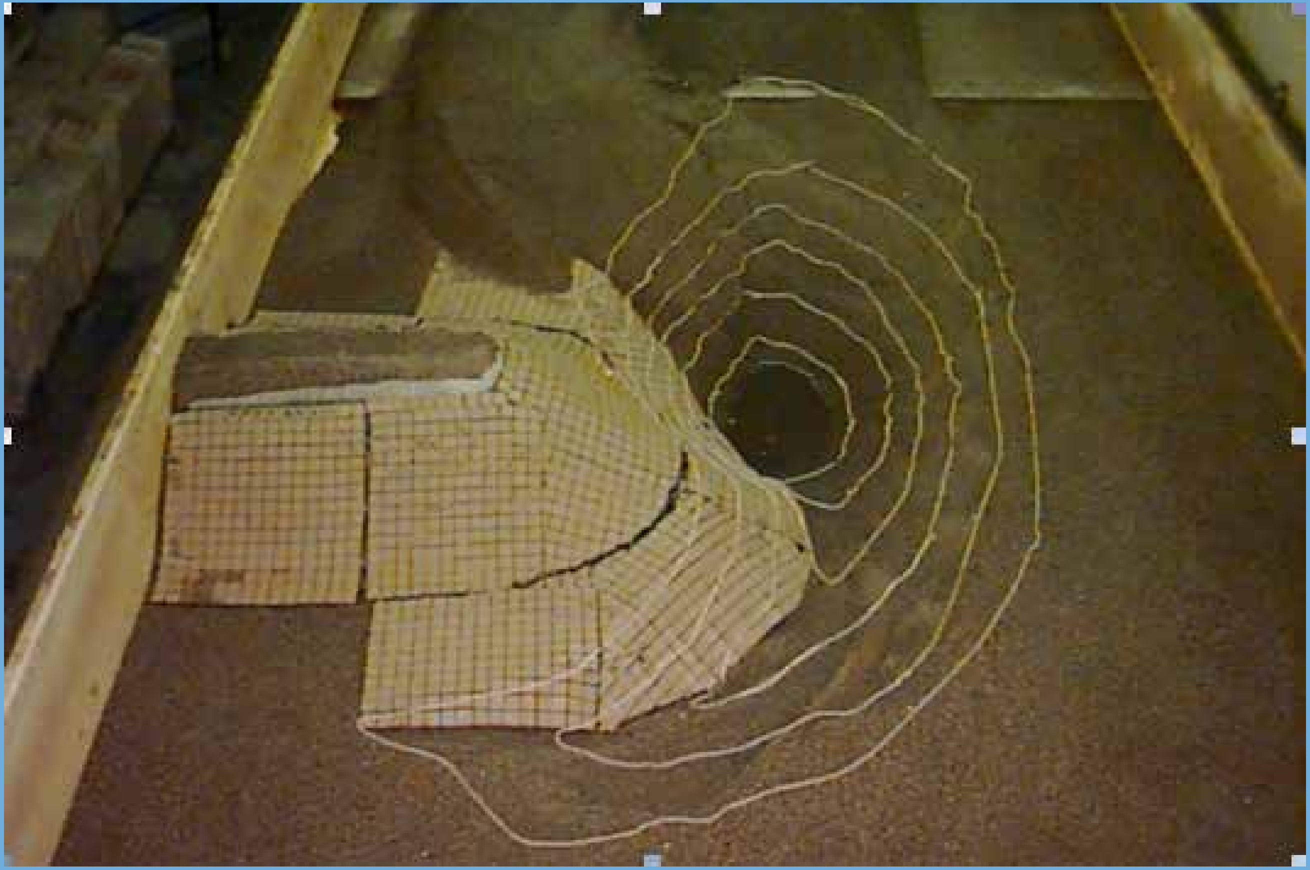
- Kind of jacks that interlock (Tetrapods)



- Won’t wash away as easily as riprap
- Placement similar to riprap

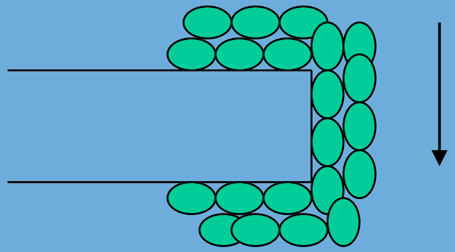
Bank Hardening: Cable-Tied Blocks

- Large concrete block tied together with cable. Acts as a mattress

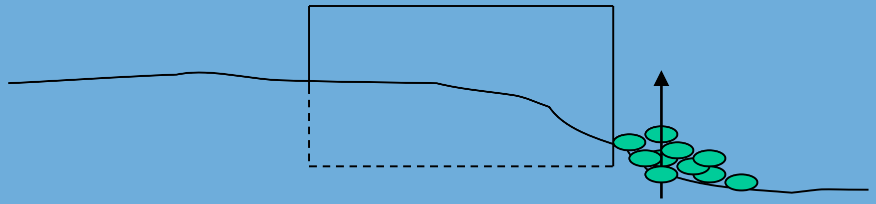


Bank-Hardening: Geobags-Pervious Bags Filled with Gravel

- PLAN

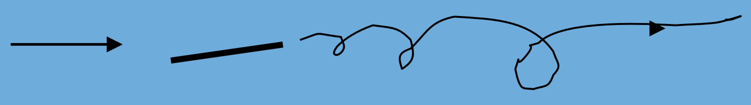


- SECTION
- Vertical water seepage
- No winnowing of fines

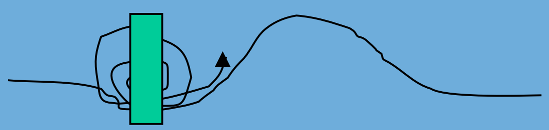


Flow Altering: Submerged Vanes

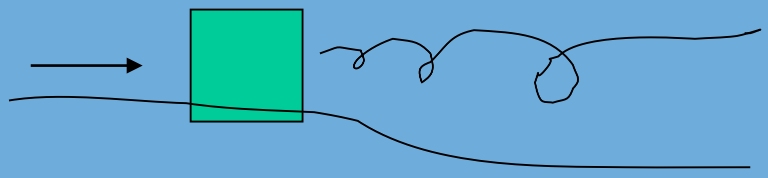
- Creates vortex to direct bed sediment
- Plan View



Downstream View

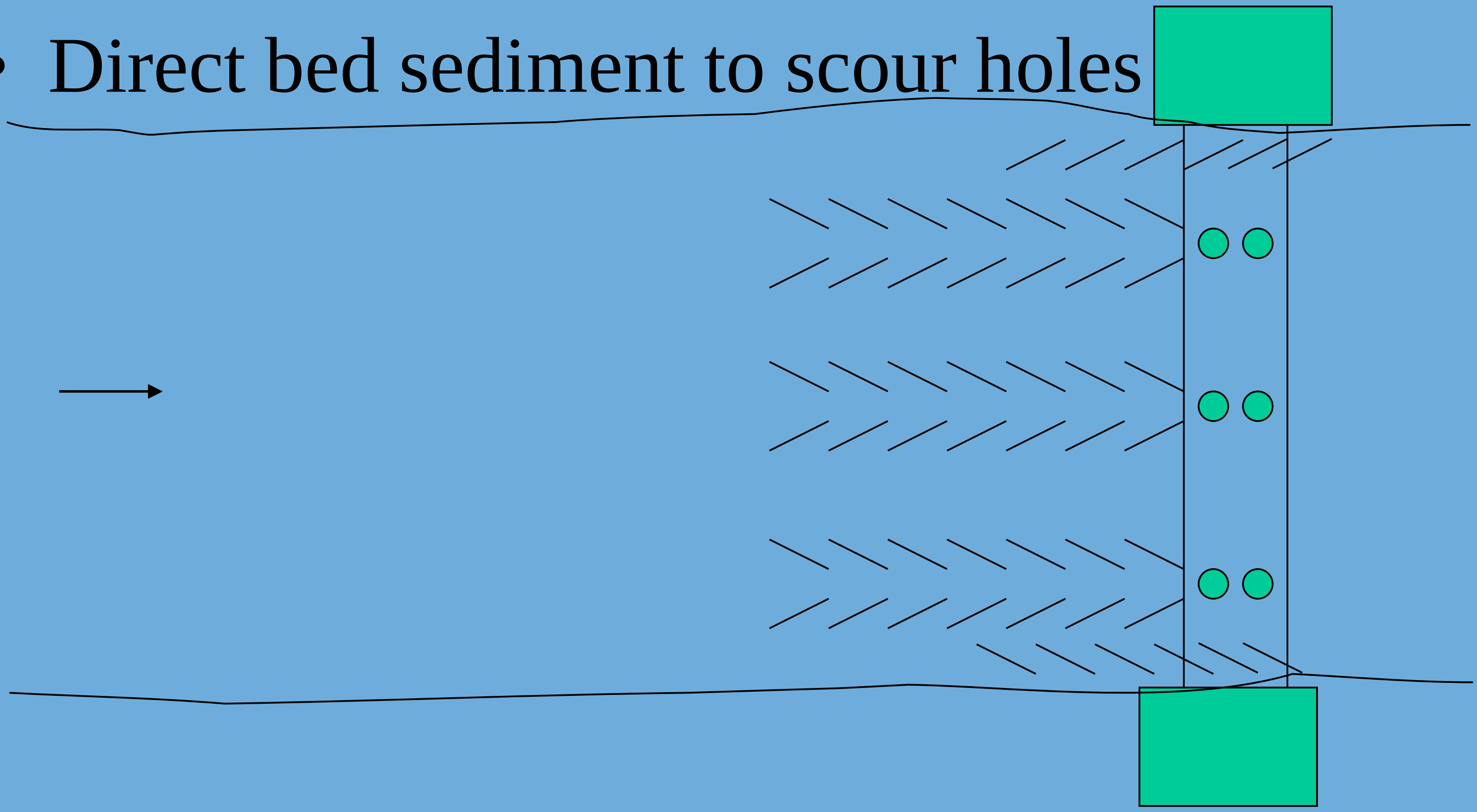


- Side View



Flow Altering: Submerged Vanes

- Direct bed sediment to scour holes

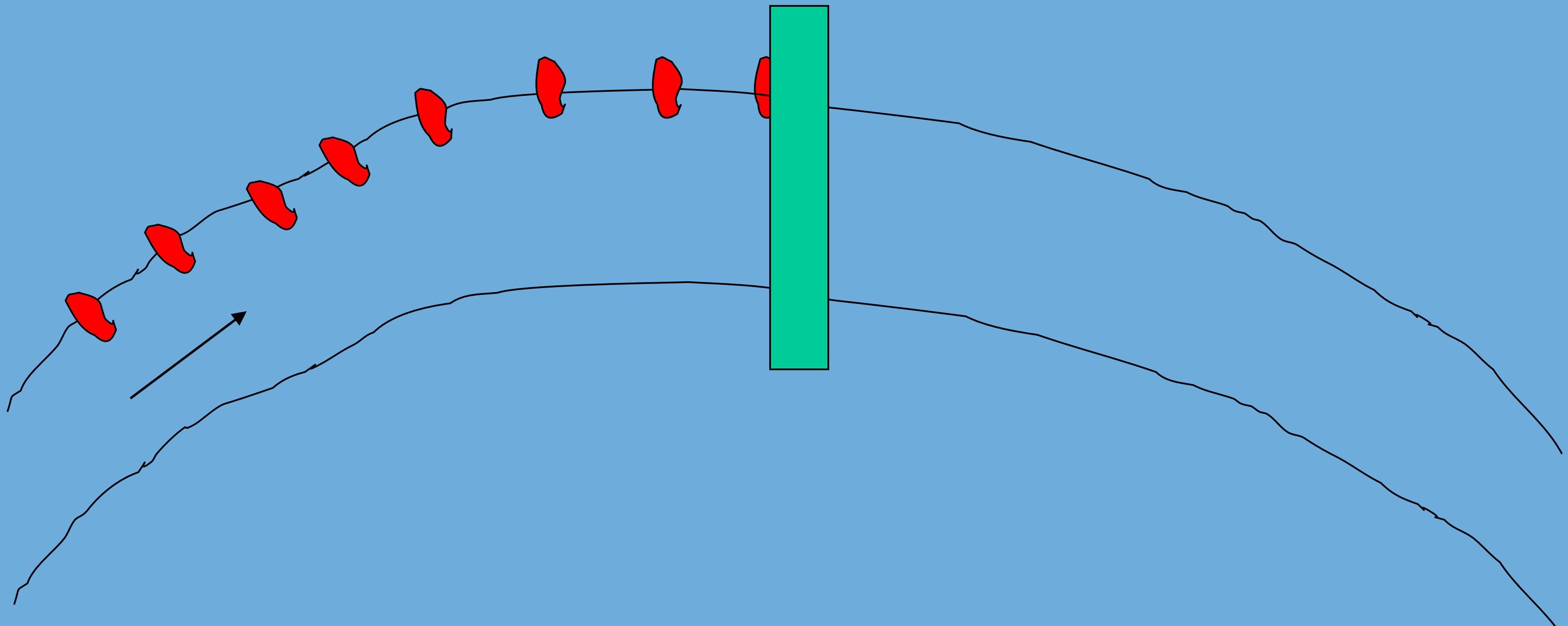


Flow Altering: Delta Wings

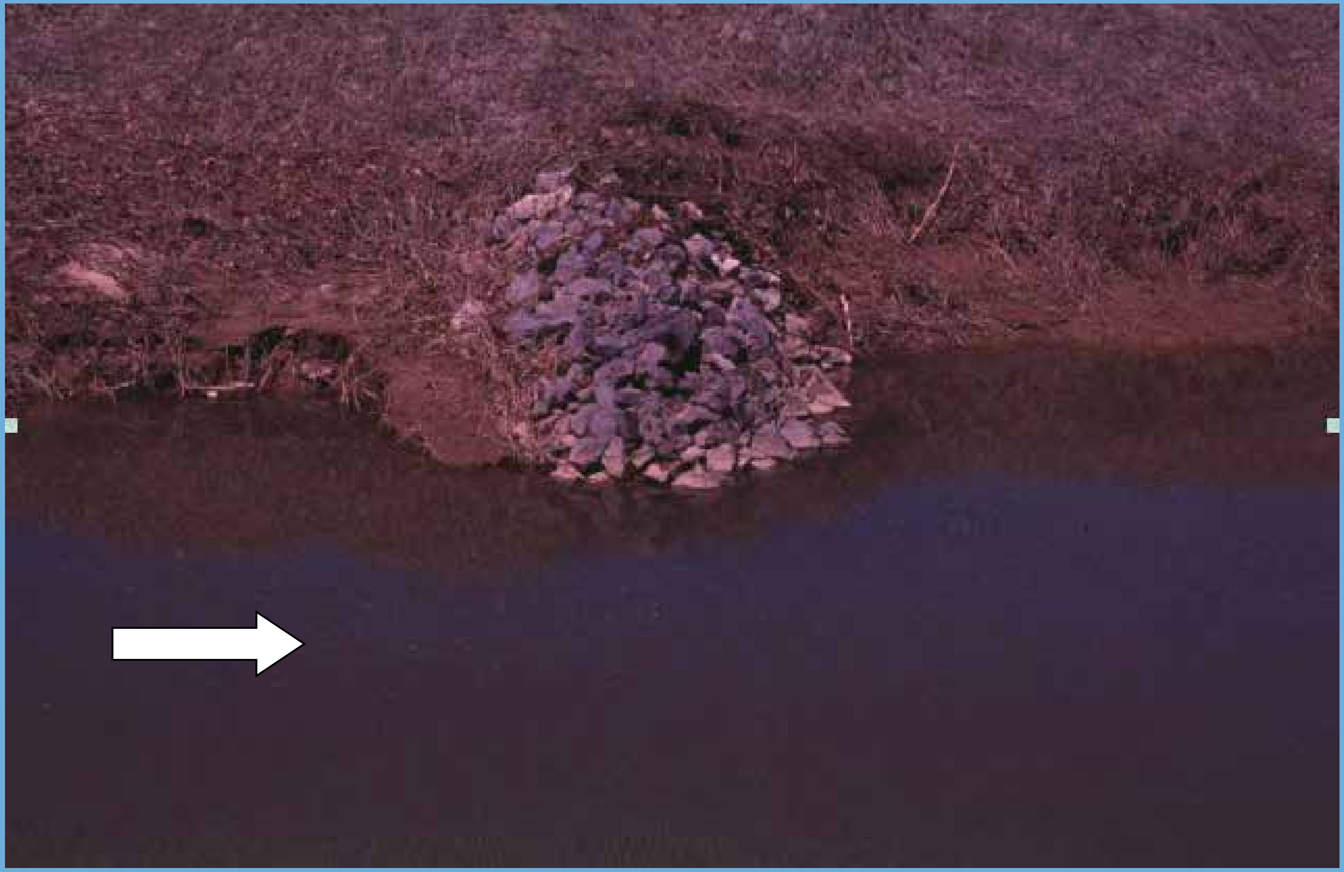
- Creates vortex to counter pier's horseshoe vortex

River-Training: Groynes/Spur Dikes

- Rock structures tied into bank
- Directs flow away from bank



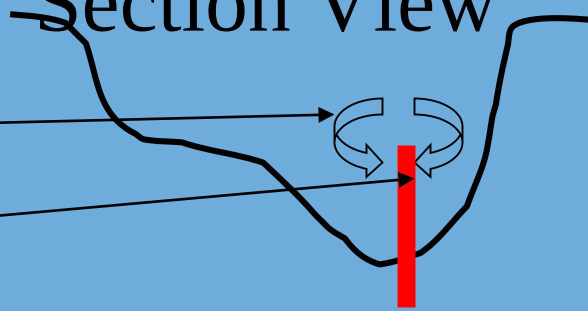
River-Training: Groynes/Spur Dikes

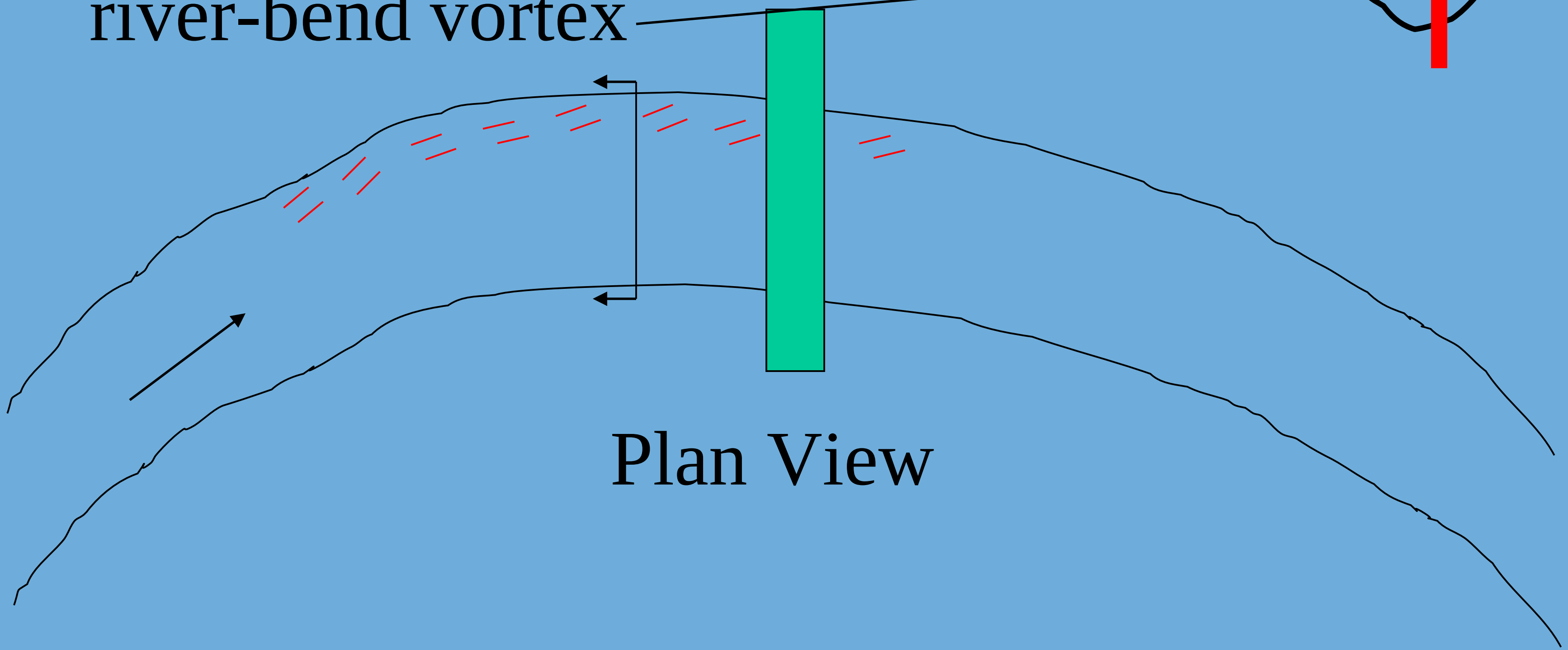


River-Training: Submerged Vanes

- Can stop bank erosion also.
- Vane vortex cancels

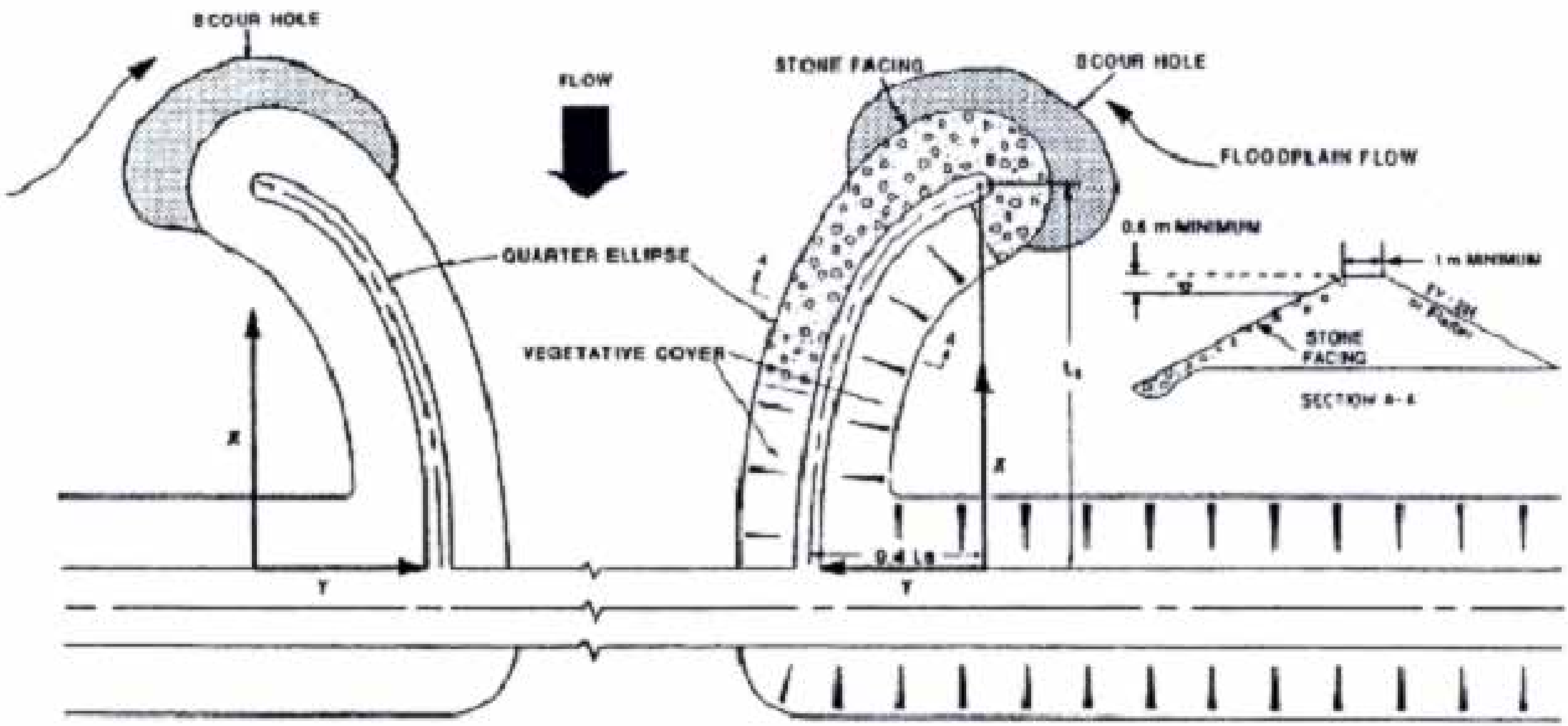
river-bend vortex





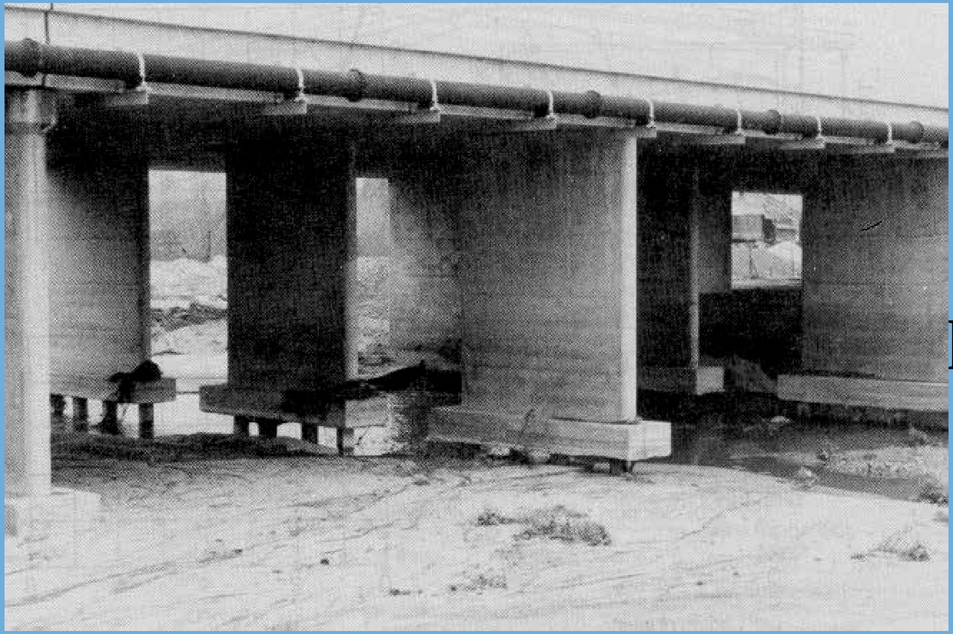
River-Training: Guidebanks

Guide flow through opening



Guidebank

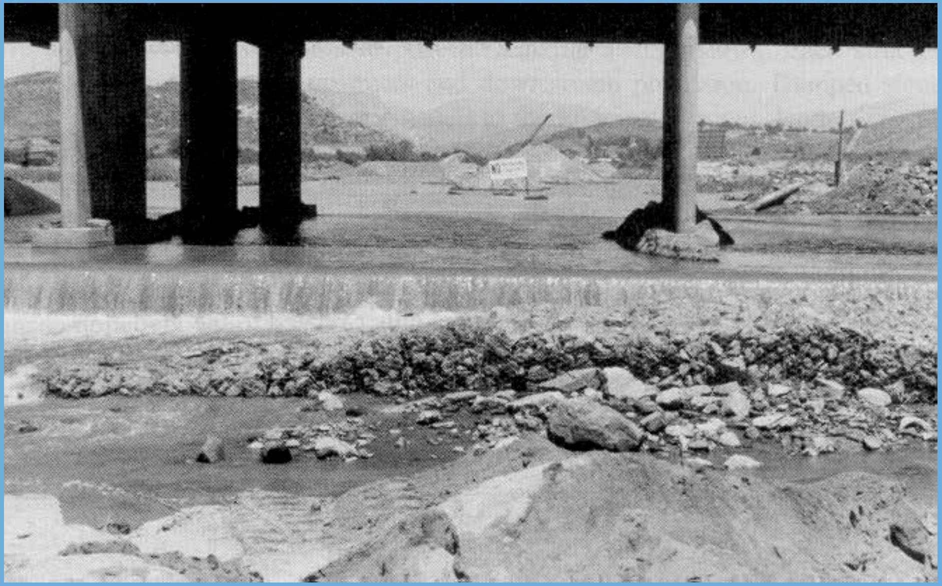
Grade-Control Structure



Small dam to fix bed elevation

Before

After



New Material: Inspecting Riprap

1. Riprap should be **angular and interlocking**
2. **Granular or geotextile filter** between the rock and the subgrade
3. Riprap should be **well graded**

4. problems:

-**Displaced** downstream

-**Slumped** down the slope

-Angular riprap material **replaced**

-Physically **deteriorated**

-Filter has been exposed or breached

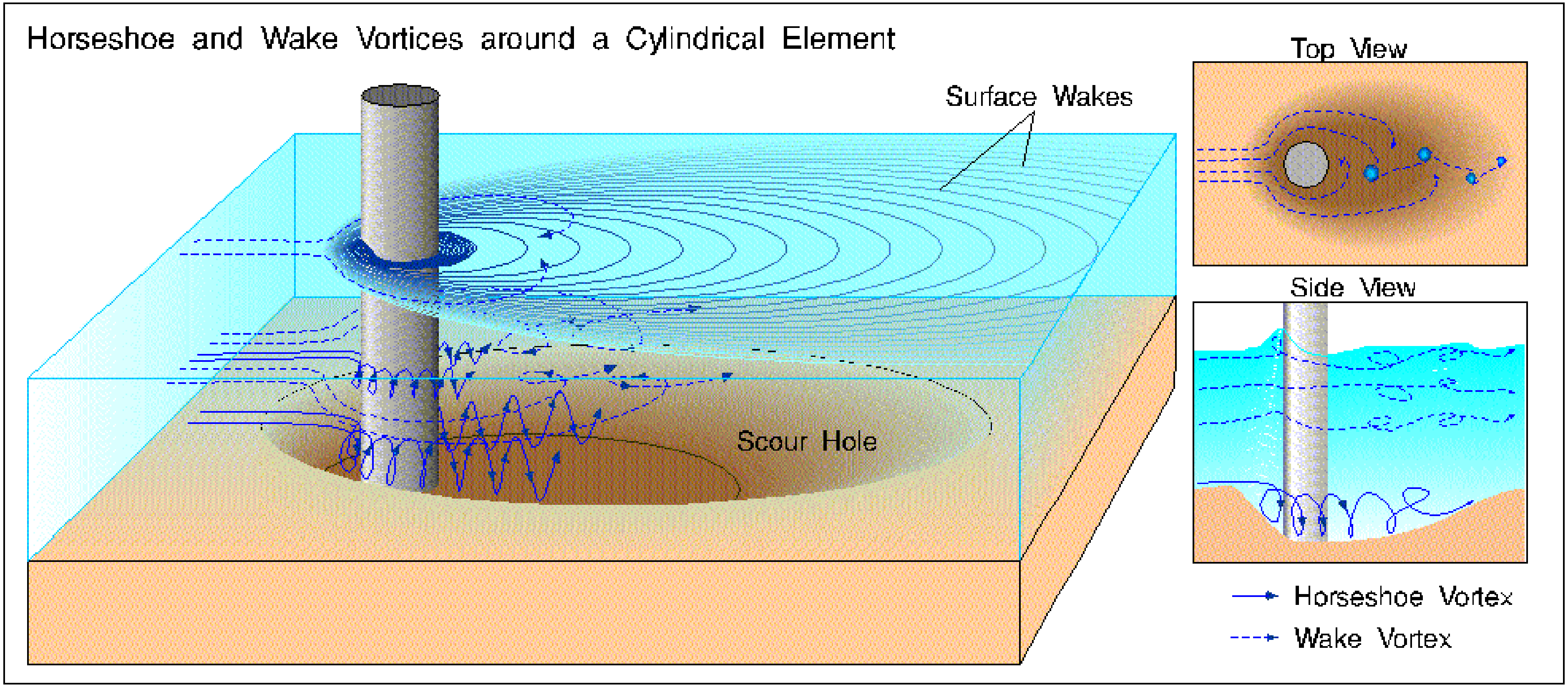
New Material: Inspecting Riprap

- More problems:

-Toe down should be deeper than the expected long-term degradation and contraction scour.

-Riprap should generally extend up to the bed elevation so that the top of the riprap is visible to the inspector during and after floods.

Thanks for Your Attention!!!



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