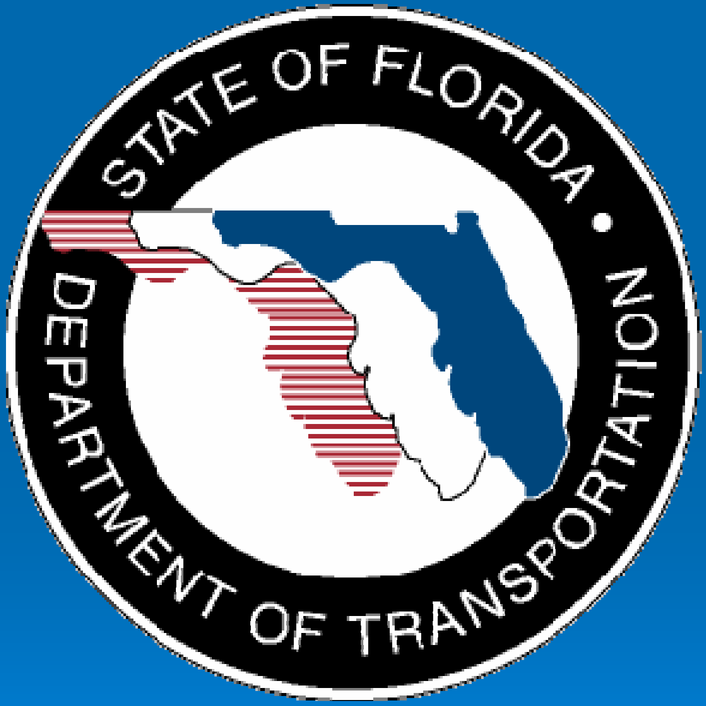
2005 Bridge Scour Short Course



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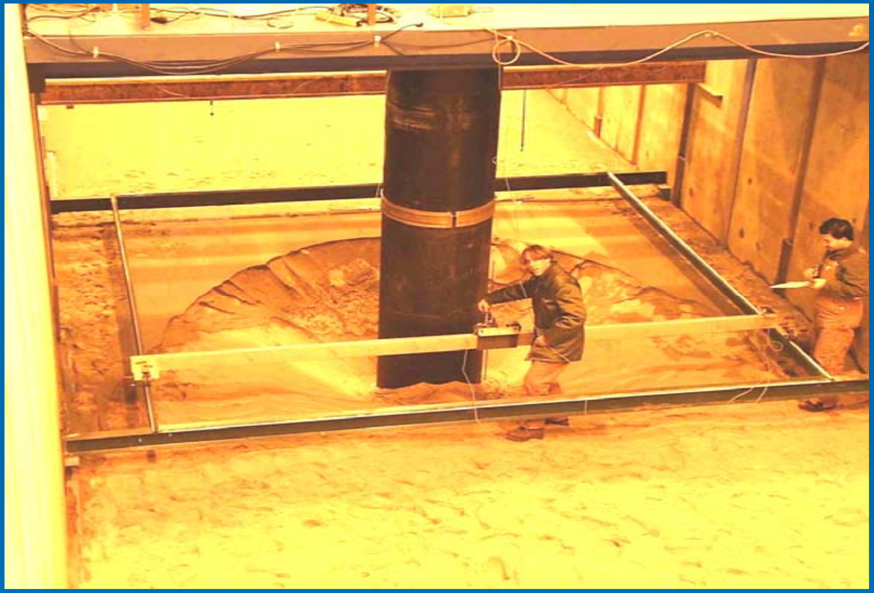

Two-Day Bridge Scour Short Course

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Speakers

Rick Renna	State Hydraulics Engineer Florida Department of Transportation
Max Sheppard	President OEA, Inc. Emeritus Professor University of Florida

Workshop Objectives

- Overview of Sediment Scour at Bridges
- Local Scour at Single, Simple Piers
- Local Scour at Complex Piers
- Other Bridge Scour Issues
    - Time rate of local scour
    - Piers in close proximity
    - Scour in cohesive sediments and erodible rock

Workshop Outline

- Day 1 - Morning Session
  - Introduction
    - Definitions/Classification
    - Sediment transport review
  - Bridge Scour
    - General
    - Aggradation/Degradation
    - Contraction
    - Local

Workshop Outline (Cont.)

- Day One - Afternoon Session
  - Local scour at single, simple pier
    - Clear-water scour
    - Live-Bed scour
    - Predictive equations
    - Example problem
  - Local scour at complex piers
    - Methodology
    - Pier classification

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Workshop Outline (cont.)

- Day 2 - Morning Session
  - Local scour at complex piers (cont.)
    - Case 1 pile cap above bed
      - Example problem
    - Case 2 partially buried pile cap
    - Case 3 buried pile cap
  - EXCEL program
    - Example problems

Workshop Outline (cont.)

- Day 2 - Afternoon Session
  - Local scour at complex piers (cont.)
    - Example problems (cont.)
  - Other scour issues
    - Time rate of scour
    - Effects of suspended fine sediment on scour
    - Piers in close proximity to other structures
    - Scour in cohesive sediments and erodible rock

Bridge Scour Review

- What is Bridge Scour?
- What Causes Bridge Scour?
- Scour Mechanisms and Classifications
  - General scour
  - Aggradation and degradation
  - Contraction
  - Local

What is Bridge Scour?

- Removal of Sediment from the vicinity of the bridge

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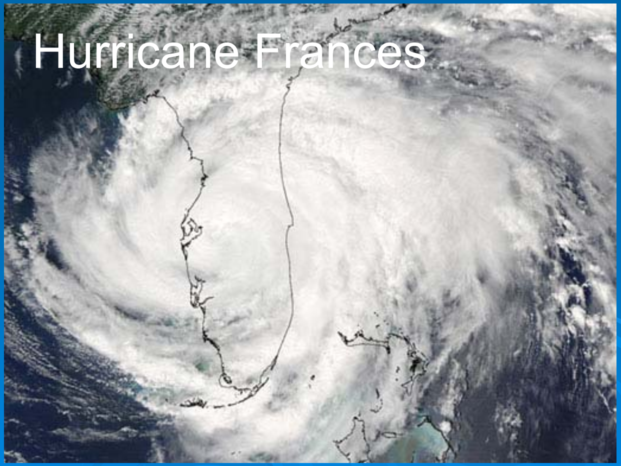
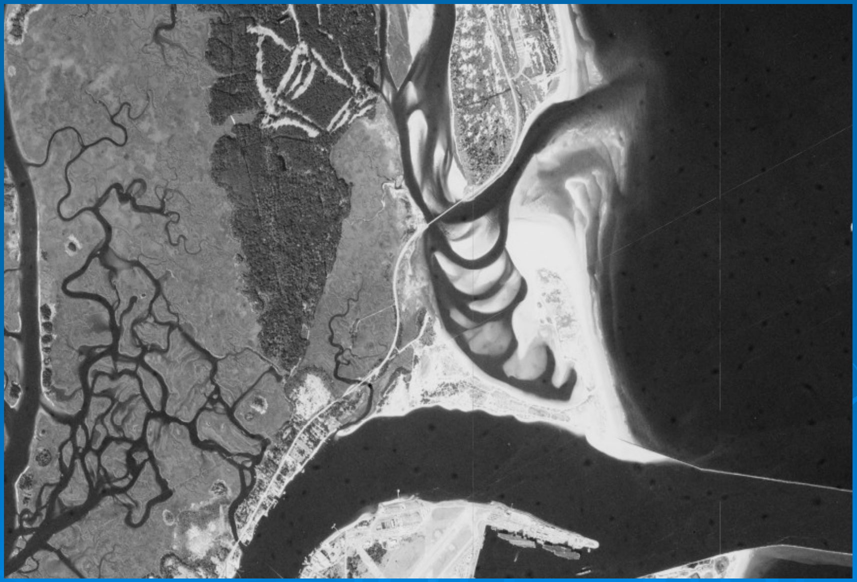
What Causes Bridge Scour?

- Long Term
  - Channel Migration
  - Aggradation, Degradation
- Short term
  - Increased flow velocities
    - Currents
    - Waves



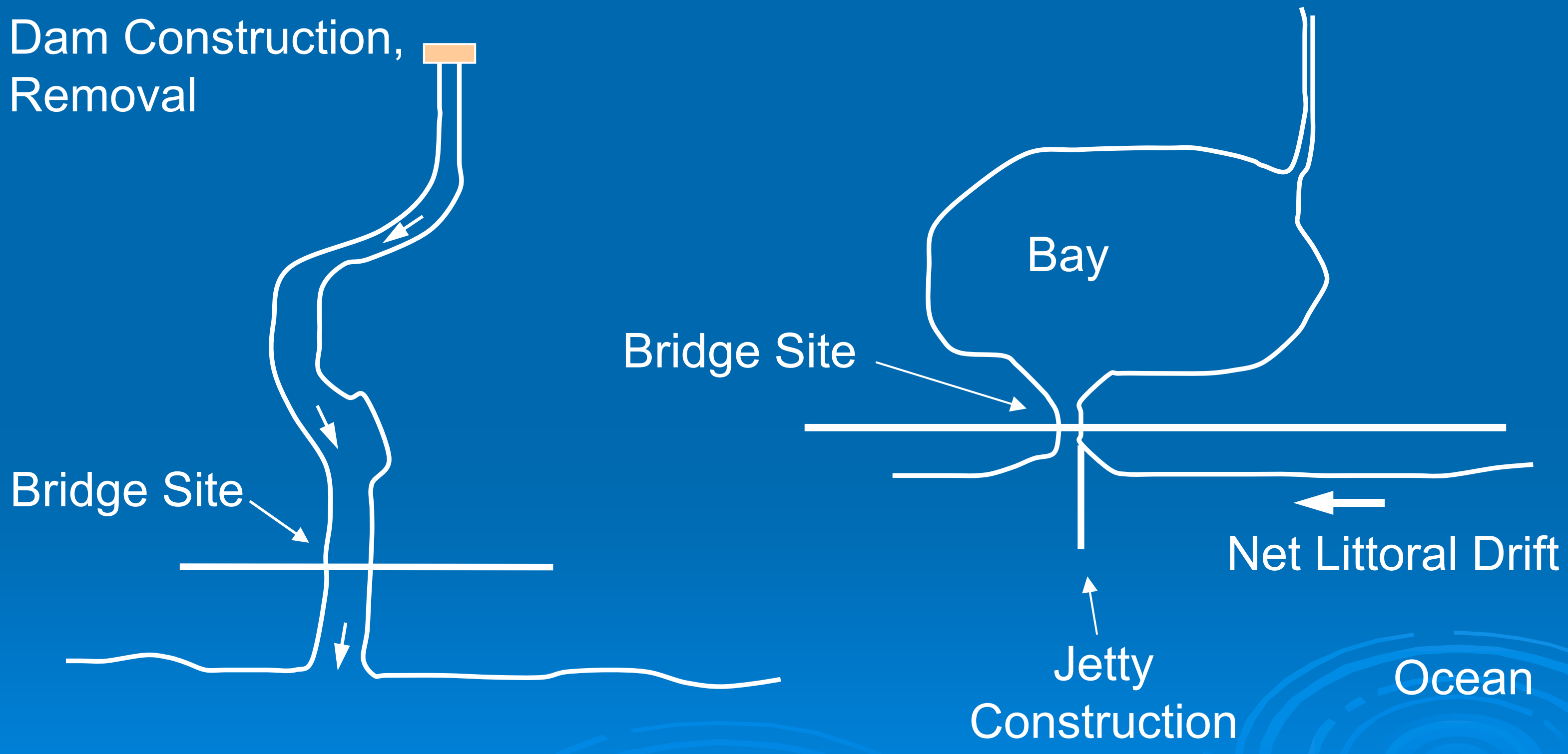
Scour Classification

- General Scour - Channel Migration



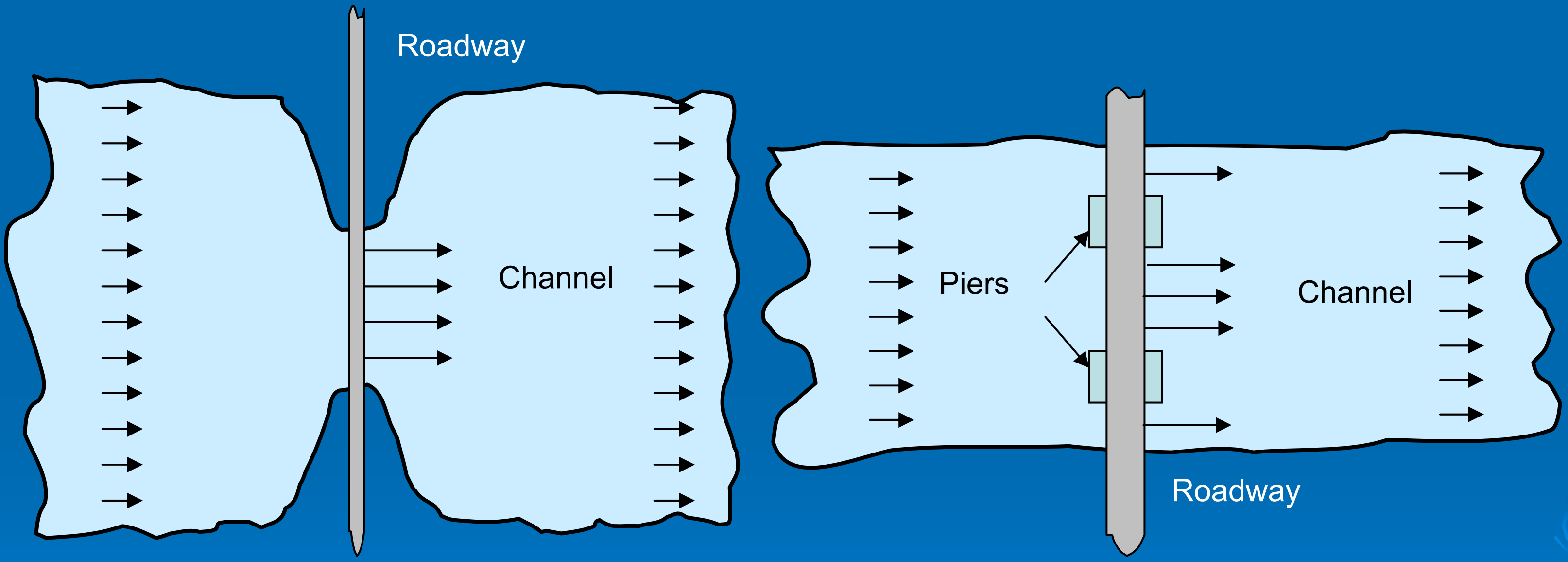
Scour Classification (cont.)

- Aggradation Degradation



Scour Classification (cont.)

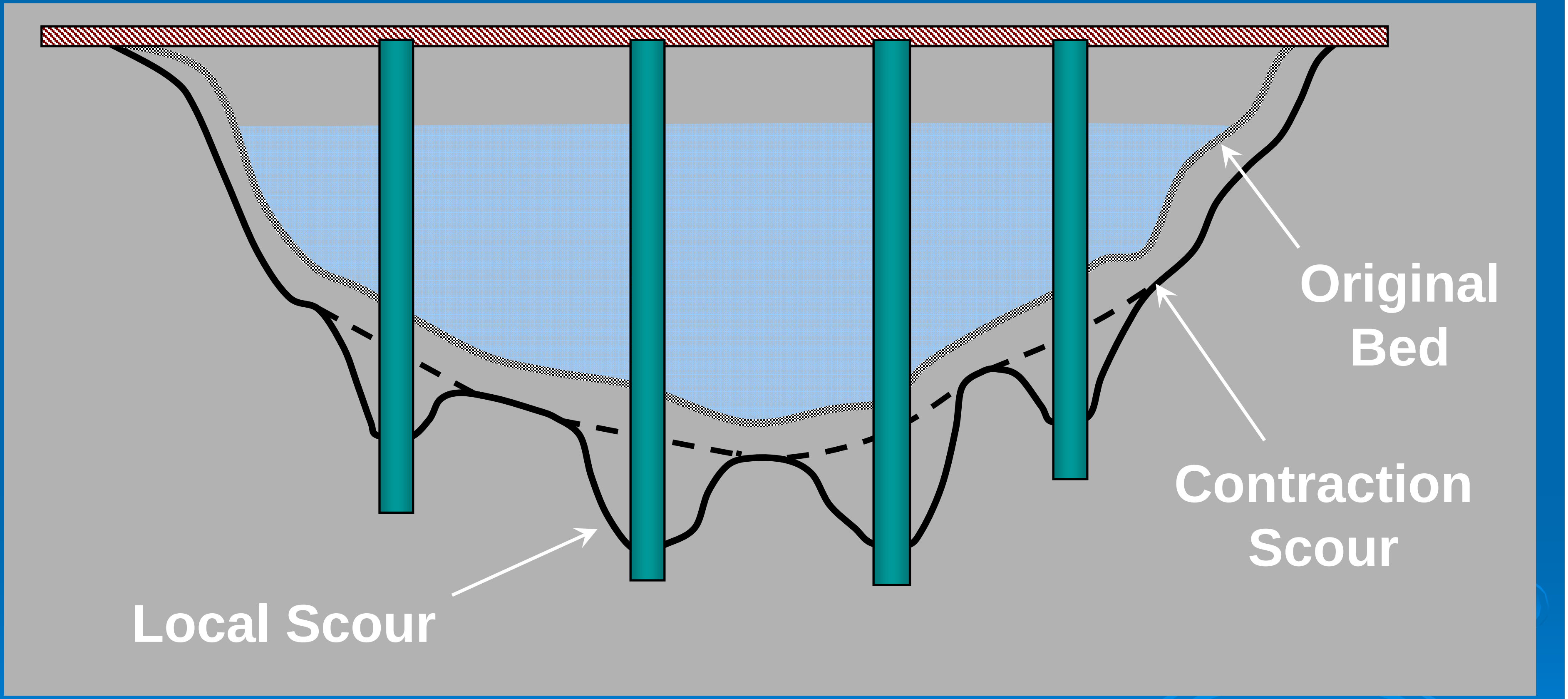
- Contraction



Scour Classification (cont.)

- Contraction Scour

Scour Classification (cont.)



Scour Classification (cont.)

- Local Scour

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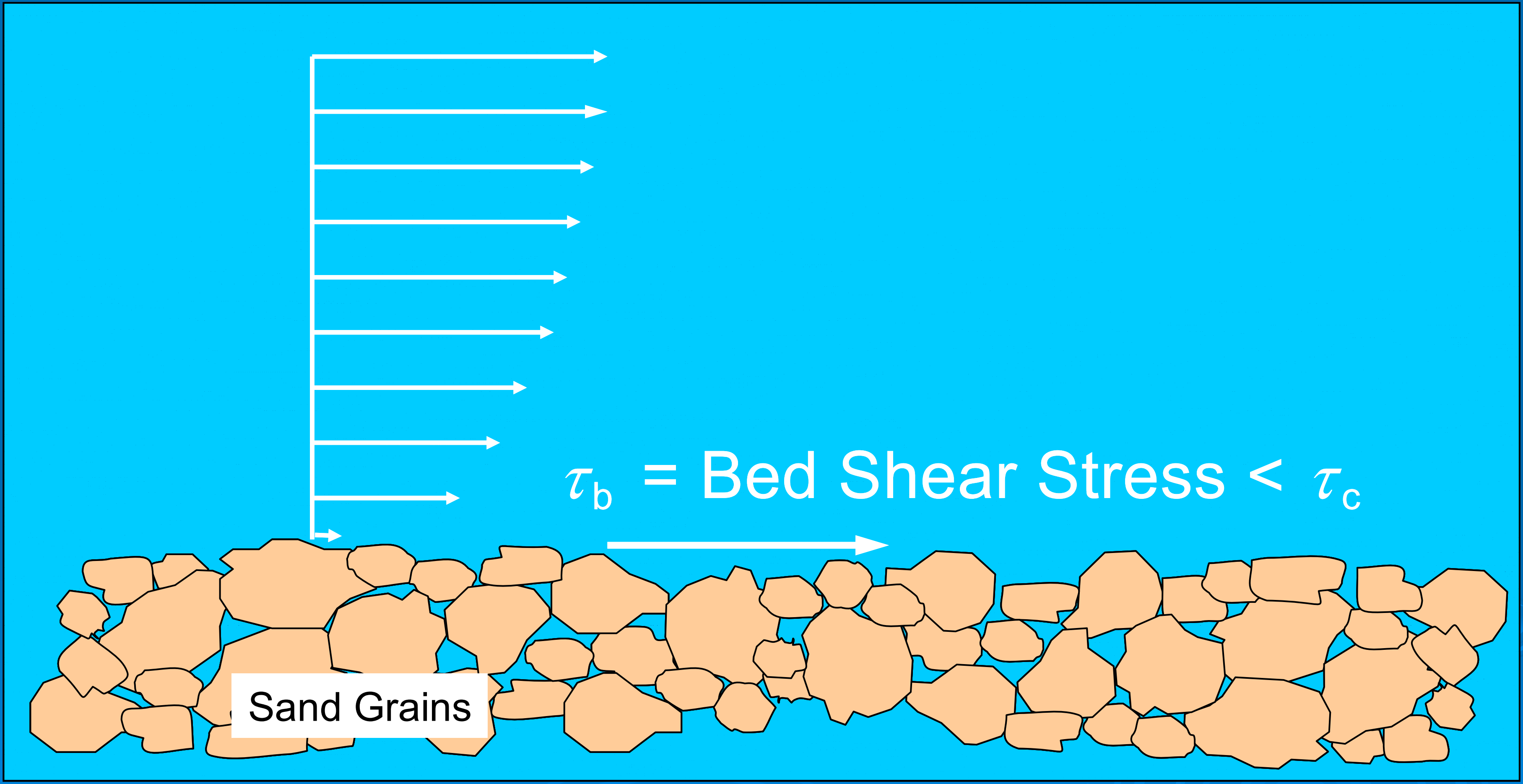
Sediment Transport

Sediment Transport



τ_b = Bed Shear Stress < τ_c

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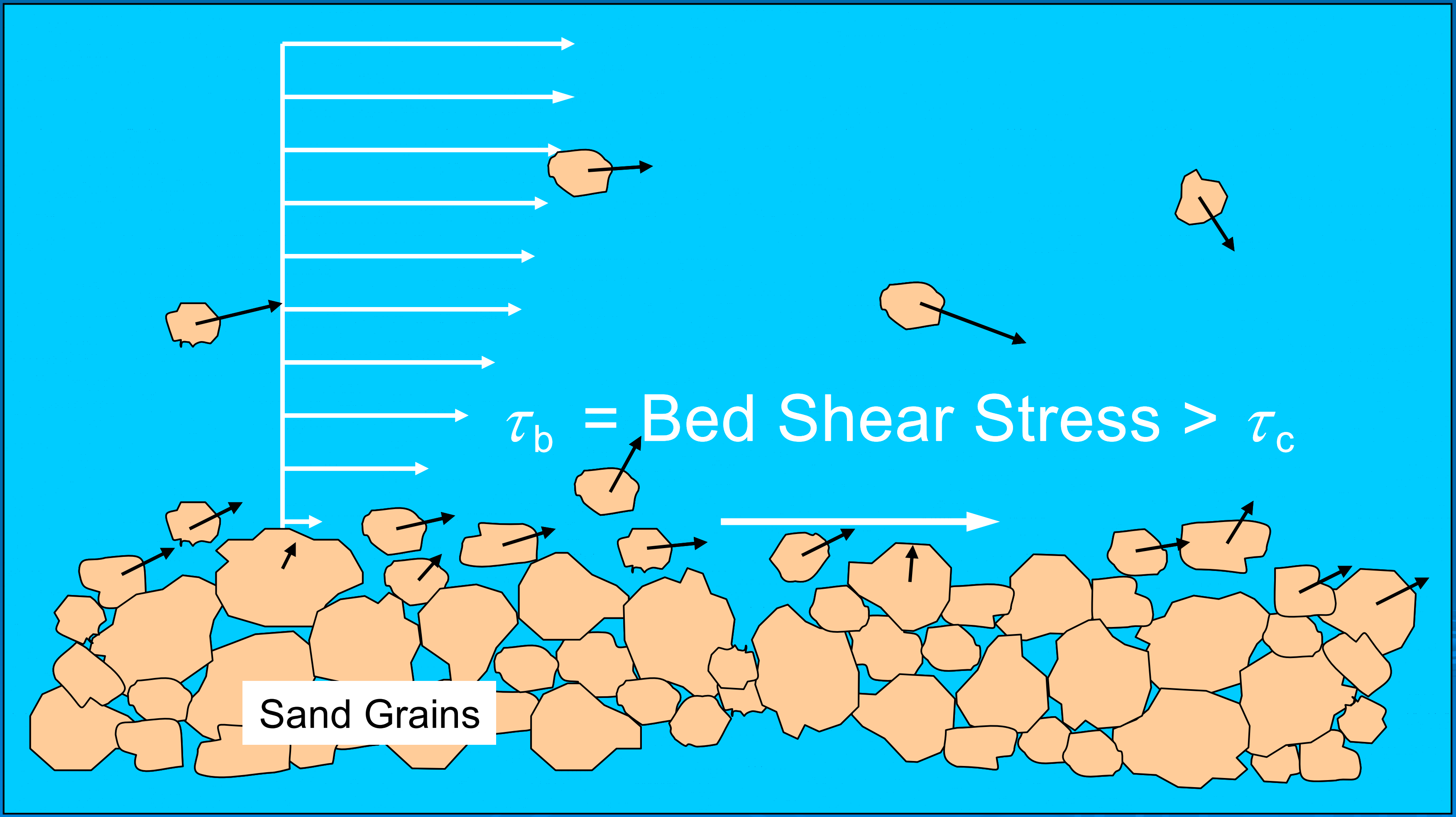
Sediment Transport (cont.)



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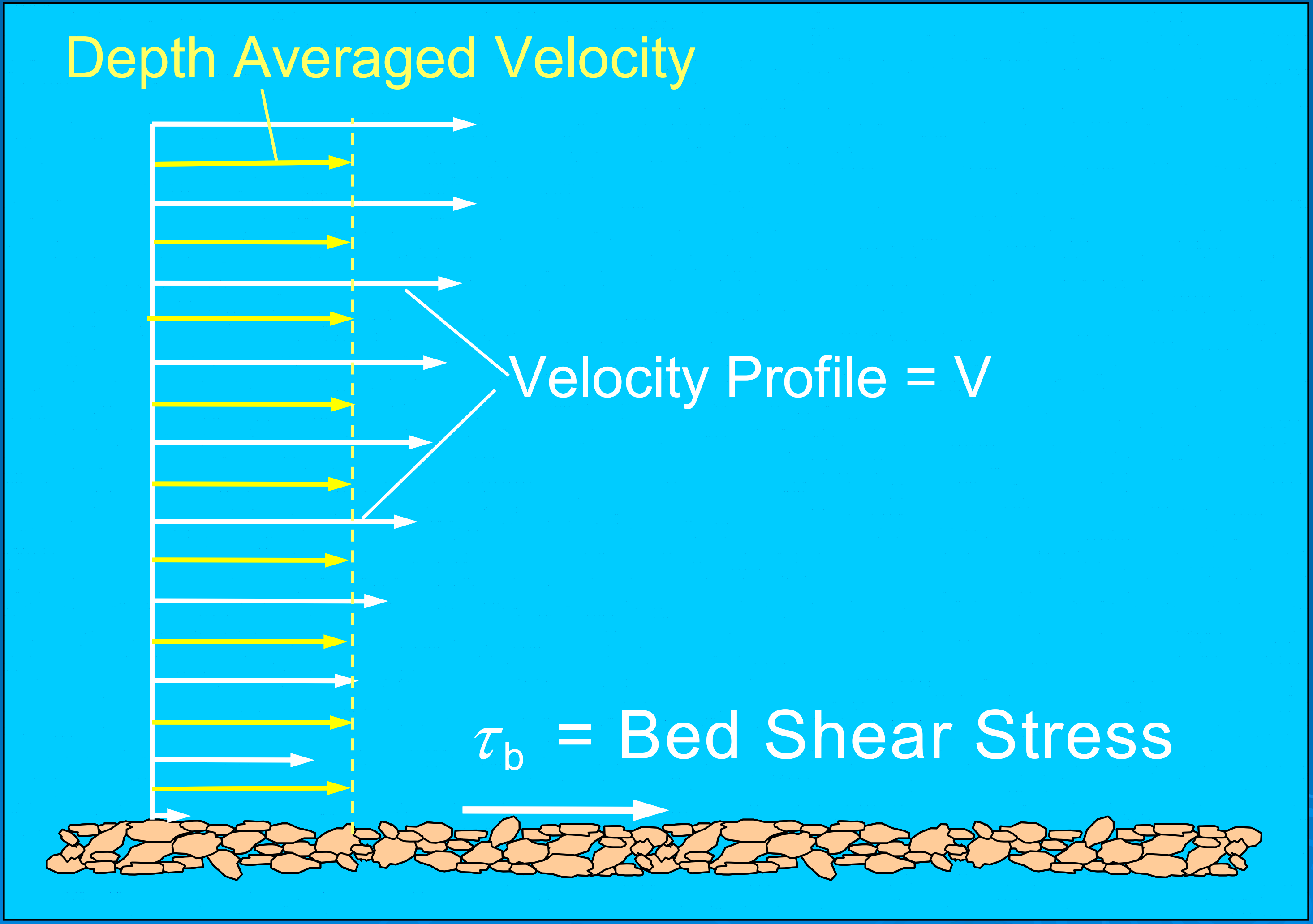
Sediment Transport (cont.)



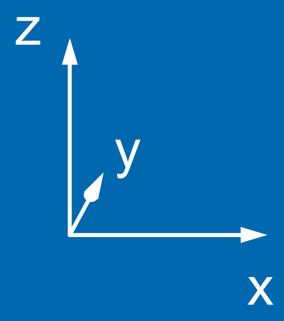
Depth Averaged Velocity

Velocity Profile = V

τ_b = Bed Shear Stress

Sediment Transport (cont.)

For fully developed velocity profiles and hydraulically rough bed



$$v = 2.5 \sqrt{\tau_b / \rho} \; ln\left(\frac{30\,z}{k_s}\right)$$

$\rho \equiv$ mass density

$k_s \equiv$ bed roughness length =

$$\begin{cases} 2.5D_{50} & \text{for} \qquad\qquad D_{50} \geq 0.8 \text{ mm} \\ 5D_{50} & \text{for} \;\; 0.0 < D_{50} < 0.8 \text{ mm} \end{cases}$$

Sediment Transport (cont.)

Integrating over the depth, y_0, the depth averaged velocity is obtained

$$V = 2.5\sqrt{\tau_b/\rho}\;ln\left(\frac{11.0\;y_0}{k_s}\right)$$

or

$$\tau_b = \rho\left[\frac{V}{2.5ln\left(\frac{11.0\;y_0}{k_s}\right)}\right]^2$$

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Sediment Transport (cont.)

For fine sand $D_{50} < 0.8$ mm

$$V = 2.5\sqrt{\tau_b/\rho}\; ln\left(\frac{4.4\,y_0}{D_{50}}\right)$$

and

$$\tau_b = \rho\left[\frac{V}{2.5\,ln\left(\frac{4.4\,y_0}{D_{50}}\right)}\right]^2$$

Sediment Transport (cont.)

For fine sand $D_{50} \geq 0.8$ mm

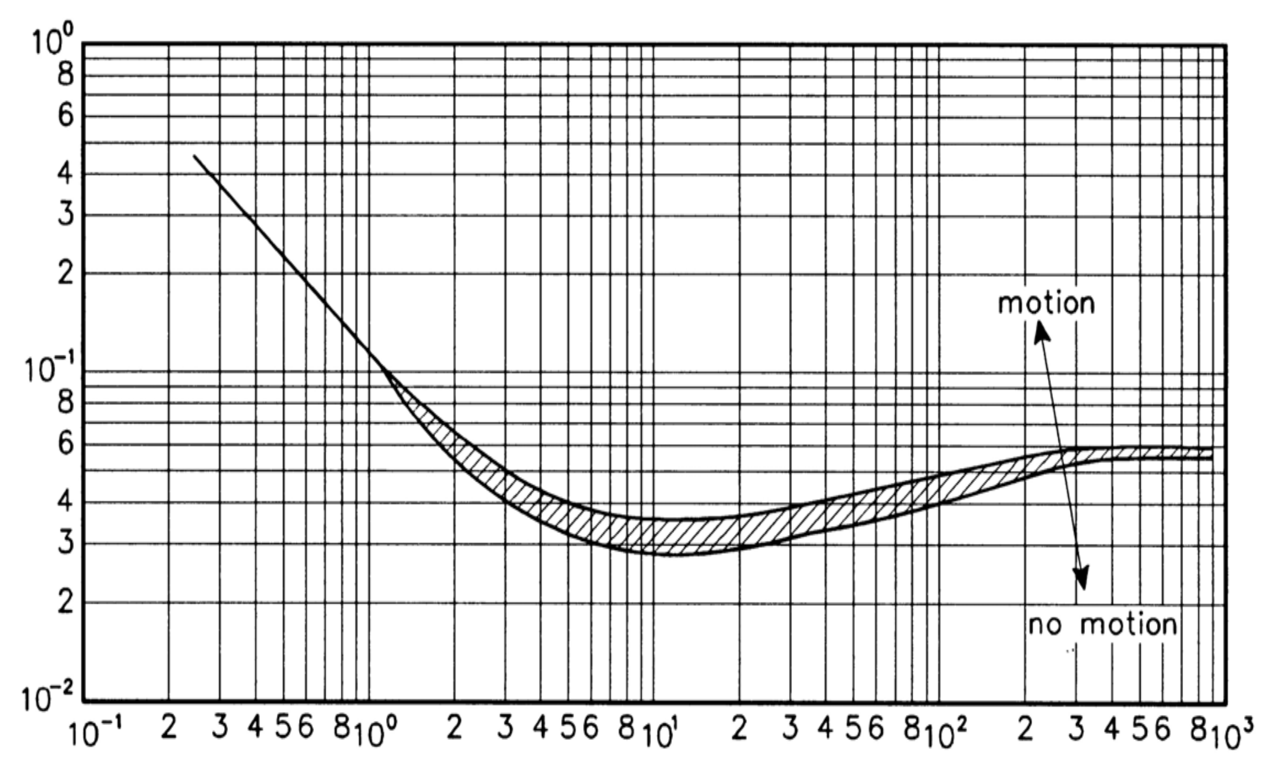
$$V = 2.5\sqrt{\tau_b/\rho}\; ln\left(\frac{2.2\, y_0}{D_{50}}\right)$$

and

$$\tau_b = \rho\left[\frac{V}{2.5\, ln\left(\frac{2.2\, y_0}{D_{50}}\right)}\right]^2$$

INITATION OF SEDIMENT MOTION (SHIELDS 1936)

$$\frac{\tau}{\left(\rho_s - \rho\right)\, g\, D_{50}}$$



$$\text{Reynolds Number Based on Friction Velocity} \equiv \frac{\sqrt{\frac{\tau}{\rho}}\; D_{50}}{\nu}$$

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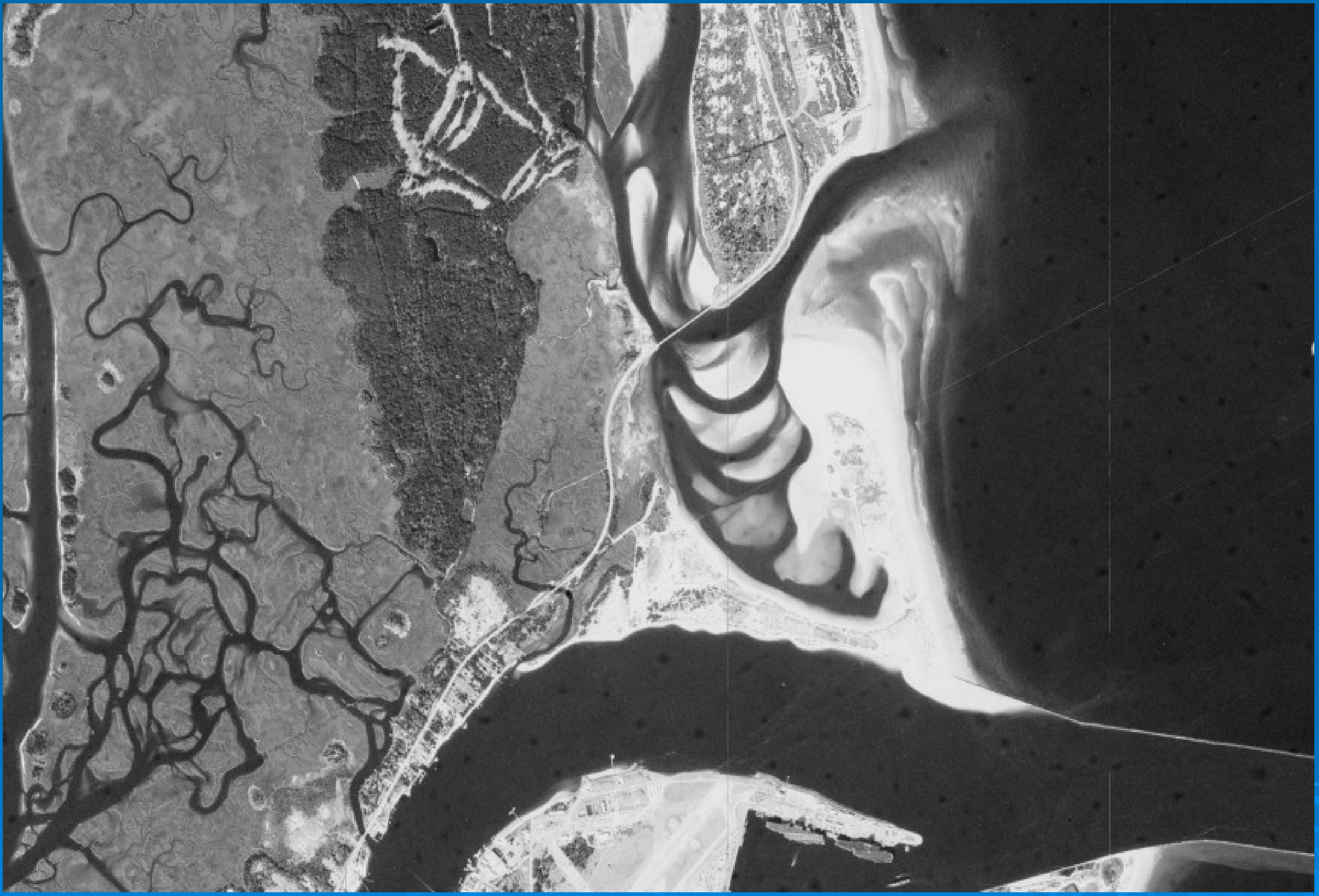
General Scour

General Scour
Channel Migration

General Scour
Inlet Instability



Contraction Scour

Contraction Scour

- Steady Uniform Flow (simple geometry)
  - Live-bed Contraction Scour

$$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1}\right)^{\frac{6}{7}} \left(\frac{W_1}{W_2}\right)^{K_1}$$

Contraction Scour

- Live-bed Contraction Scour (cont.)

$$y_s = y_2 - y_o = \text{average contraction scour}$$

where

y_1 = Average depth in the upstream channel, ft (m)

y_2 = Average depth in the contracted section after scour, ft (m)

y_0 = Average depth in the contracted section before scour, ft (m)

Q_1 = Discharge in the upstream channel transporting sediment, ft^3/s (m^3/s)

Q_2 = Discharge in the contracted channel, ft^3/s (m^3/s)

W_1= Bottom width of the main upstream channel that is transporting bed material, ft (m)

W_2= Bottom width of the main channel in the contracted section less pier widths, ft (m)

K_1= Exponent listed in the following table.

Contraction Scour (cont.)

- Live-bed Contraction Scour (cont.)

$\frac{u_*}{\omega}$	K_1	Mode of Bed Material Transport
< 0.50	0.59	Mostly contact bed material discharge
0.50 to 2.0	0.64	Some suspended bed material discharge
> 2.0	0.69	Mostly suspended bed material discharge

Contraction Scour (cont.)

➢ Live-bed Contraction Scour (cont.)

where

$u_* = \sqrt{\tau_0 / \rho}$, shear velocity in the upstream section, ft/s (m/s)

ω = Fall velocity of bed material based on the D_{50}, ft/s (m/s)

g = Acceleration of gravity, 32.17 ft/s^2 (9.81 m/s^2)

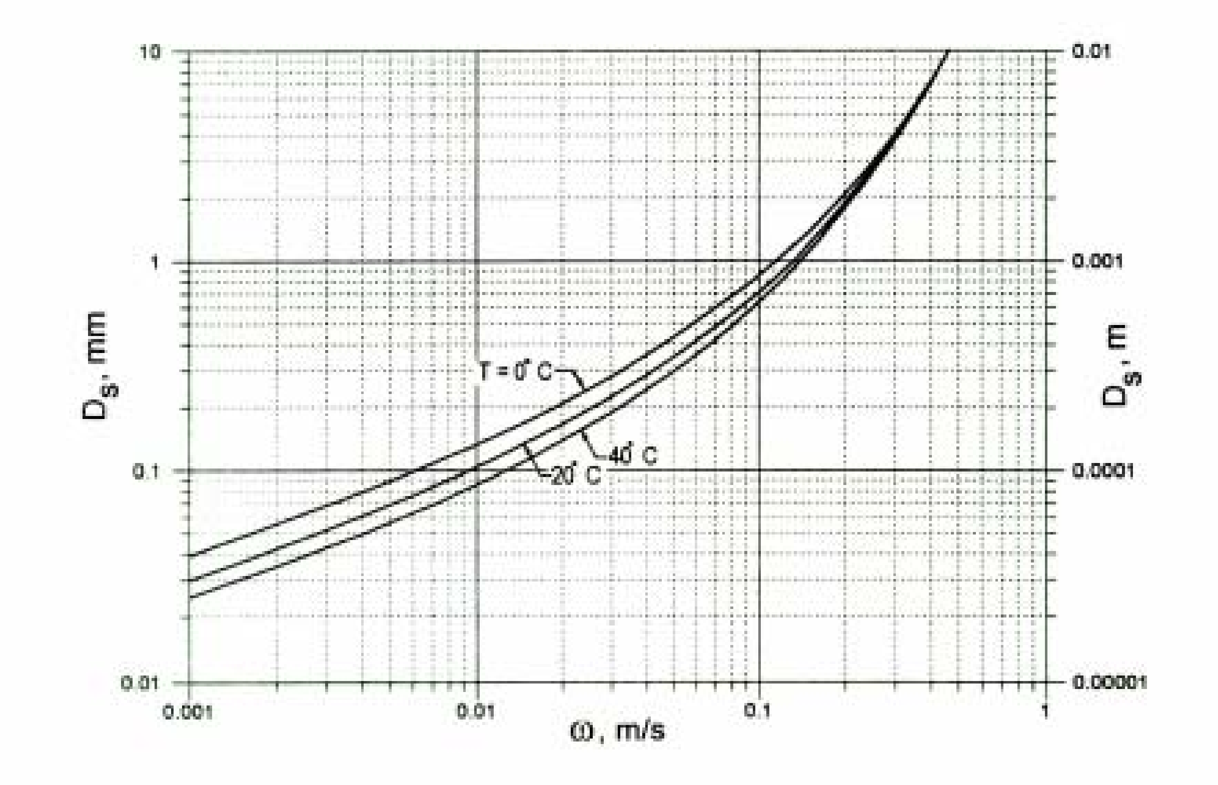
τ_o = Shear stress on the bed, lb_f /ft^2 (Pa)

ρ = Density of water, slugs/ft^3 (kg/m^3)

Contraction Scour (cont.)

- Live-bed Contraction Scour (cont.)

Fall Velocity



Contraction Scour (cont.)

- Clear-water Contraction Scour
- (simple geometry)

$$y_2 = \left(\frac{K_u Q^2}{D_m^{2/3} W^2} \right)^{3/7}$$

$y_s = y_2 - y_o$ = average contraction scour

Contraction Scour (cont.)

- Clear-water Contraction Scour (cont.)

where

y_2 = Average equilibrium depth in the contracted section after contraction scour, ft (m)

Q = Discharge through the bridge or on the set-back overbank area at the bridge associated with the width W, ft^3/s (m^3/s)

D_m = Diameter of the smallest non-transportable particle in the bed material (1.25 D_{50}) in the contracted section, ft (m)

D_{50} = Median diameter of bed material, ft (m)

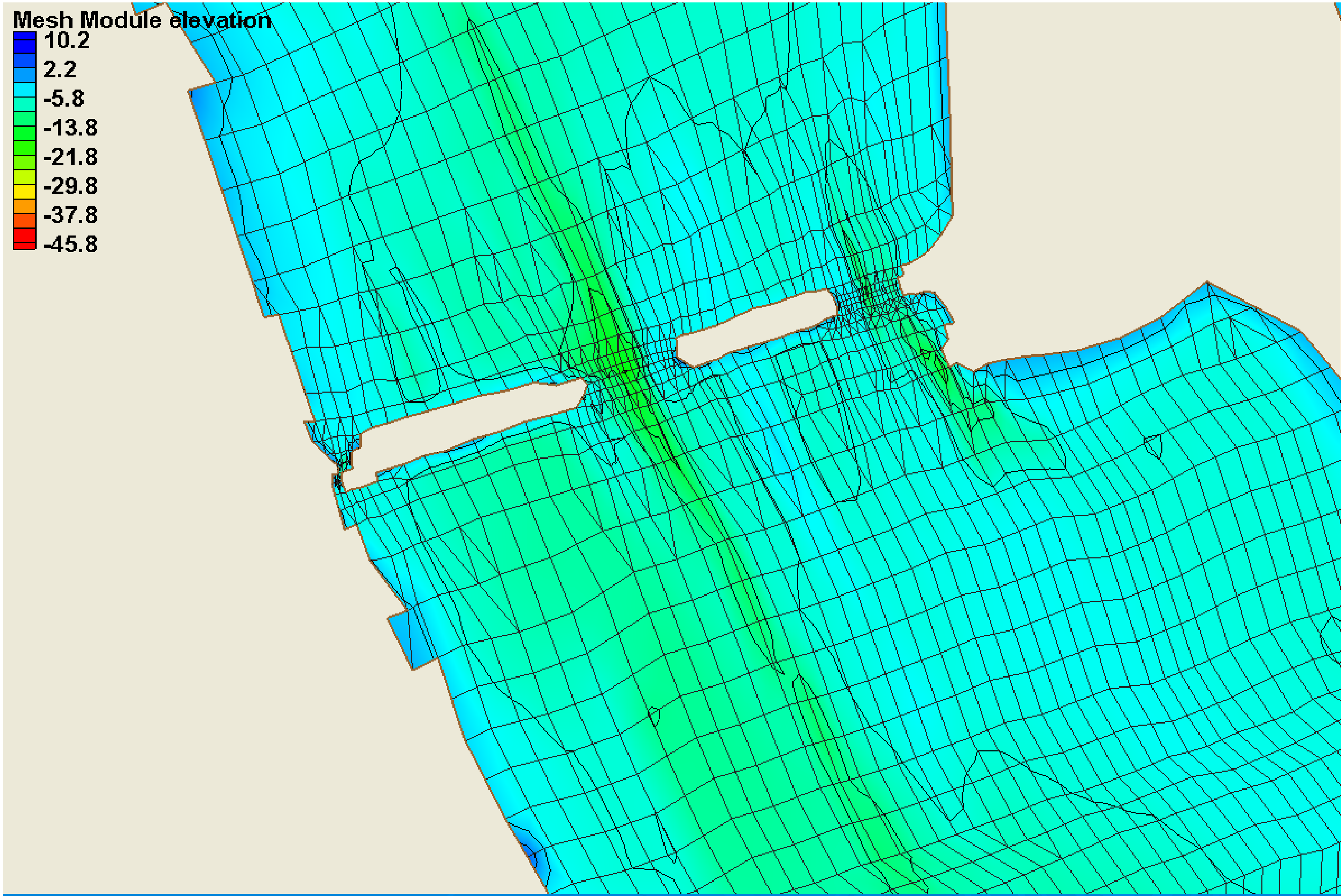
W = Bottom width of the contracted section less pier widths, ft (m)

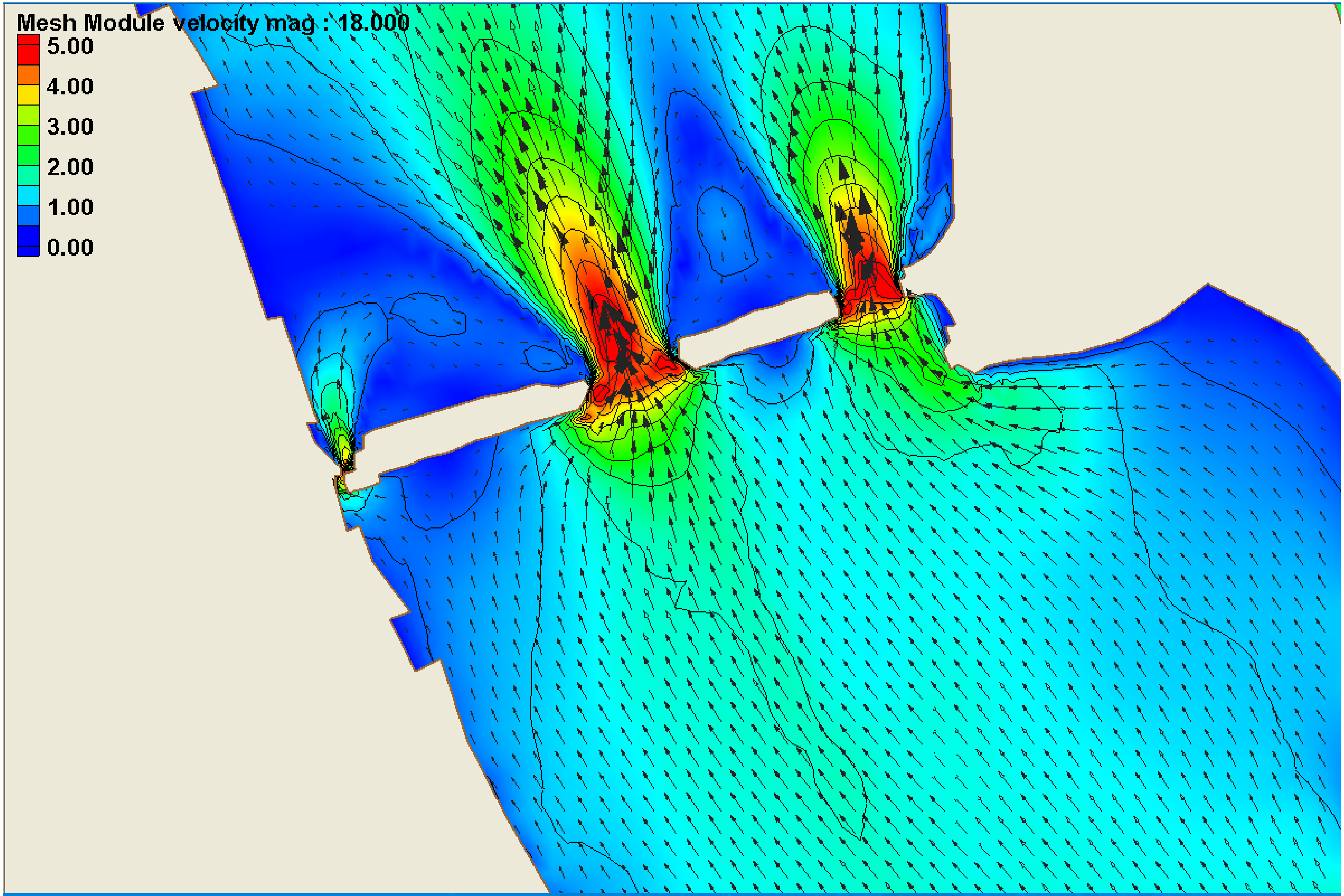
y_o = Average existing depth in the contracted section, ft (m)

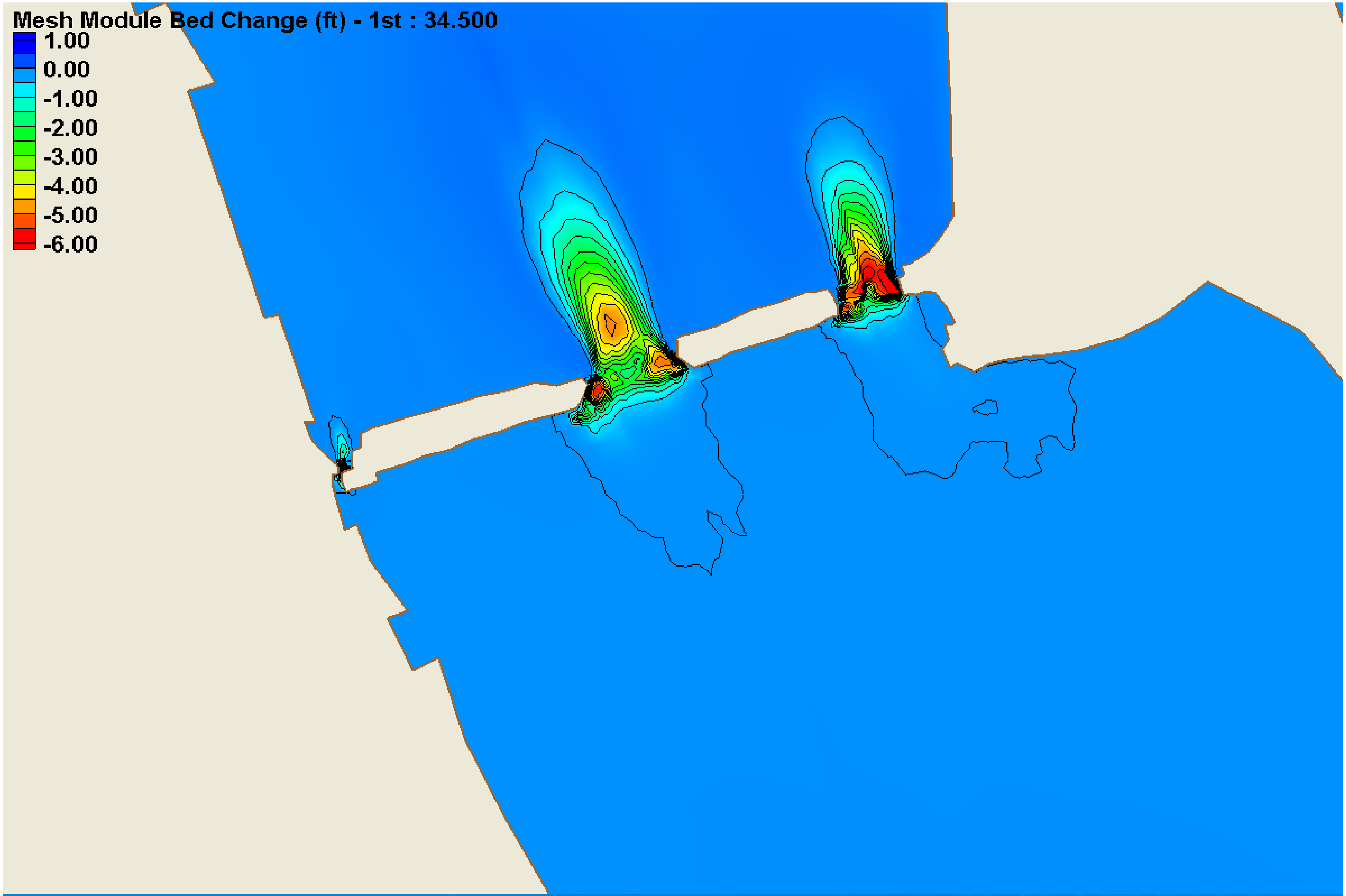
K_u = 0.0077 (when using English units)

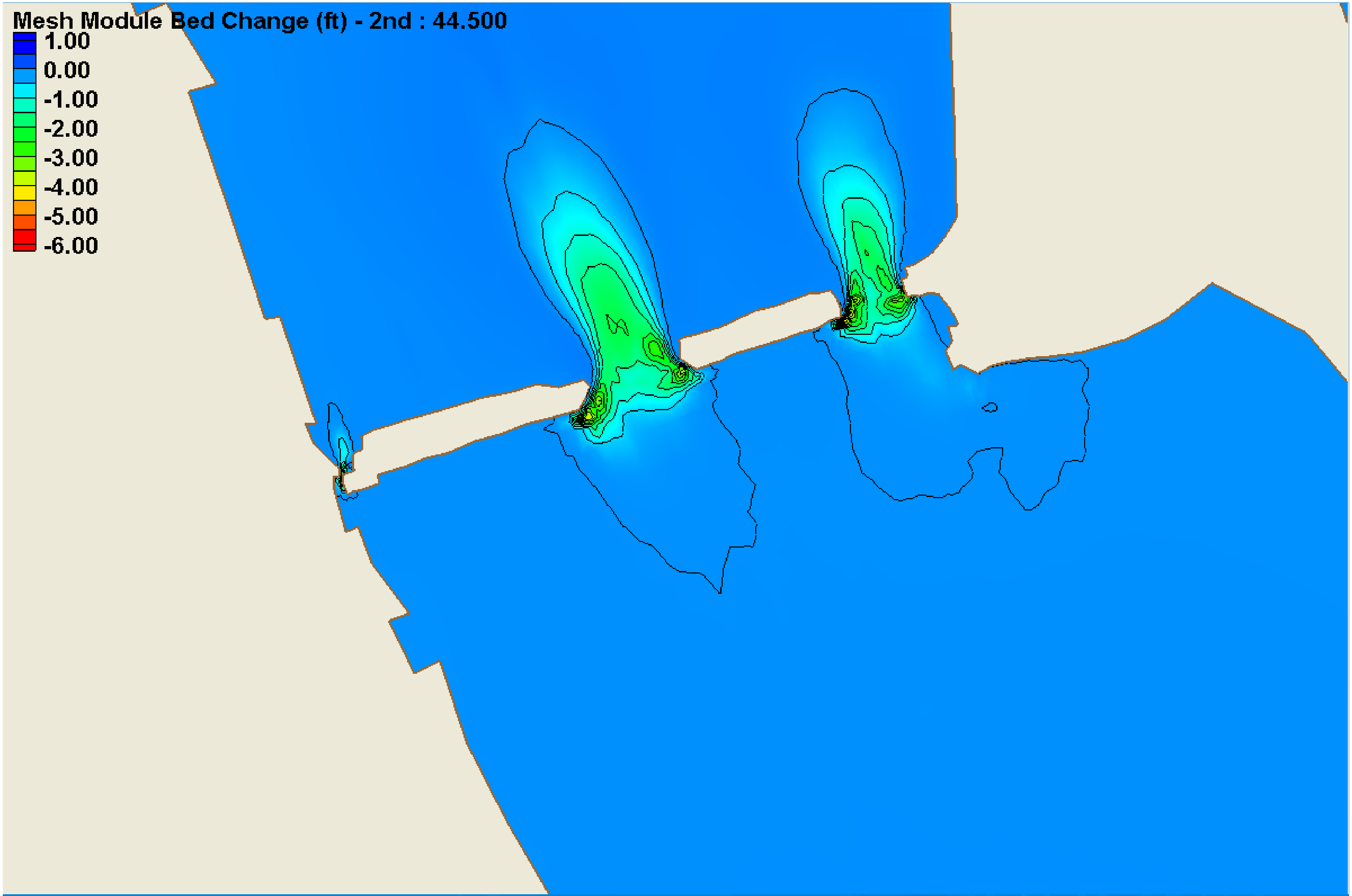
Contraction Scour (cont.)

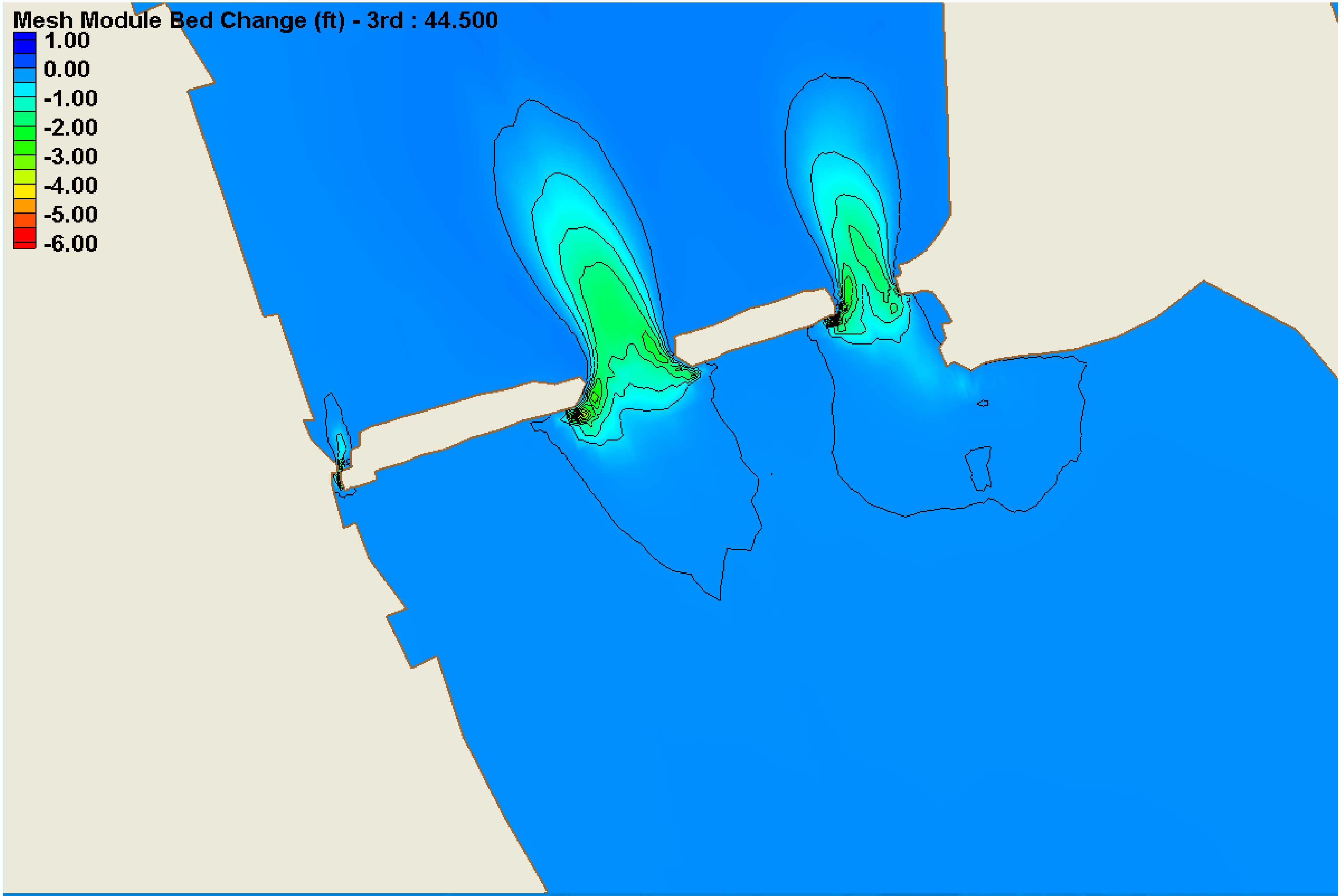
- Unsteady, Complex Boundary Flows
  - Need for 2D hydraulics model
    - RMA2
    - ADCIRC
  - Need for 2D sediment transport model
    - SED2D

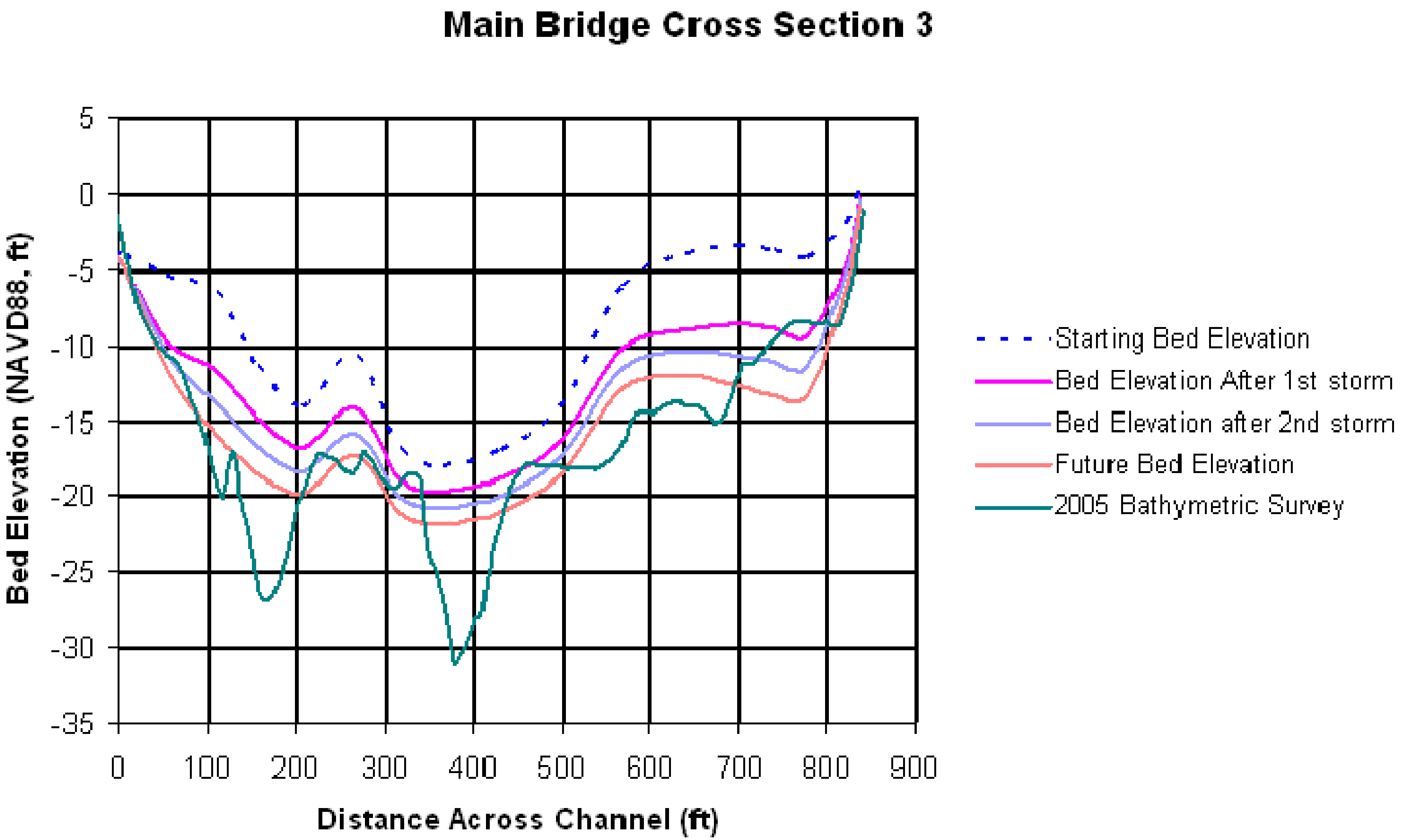

Mesh Module elevation
10.2
2.2
-5.8
-13.8
-21.8
-29.8
-37.8
-45.8


Mesh Module velocity mag : 18.000
5.00
4.00
3.00
2.00
1.00
0.00


Mesh Module Bed Change (ft) - 1st : 34.500
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00


Mesh Module Bed Change (ft) - 2nd : 44.500
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00


Mesh Module Bed Change (ft) - 3rd : 44.500
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00


Main Bridge Cross Section 3
Bed Elevation (NAVD88, ft)
5
0
-5
-10
-15
-20
-25
-30
-35
0
100
200
300
400
500
600
700
800
900
Distance Across Channel (ft)
Starting Bed Elevation
Bed Elevation After 1st storm
Bed Elevation after 2nd storm
Future Bed Elevation
2005 Bathymetric Survey

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Local Scour

Cohesionless Sediments

Equilibrium Scour Depths

Definitions

- Sediment Transport Critical velocity, V_C
  - Depth Averaged Velocity Required to Initiate Sediment Movement for a Flat Bed
  - Not to be confused with Flow Critical Velocity (Froude Number = 1)

Definitions (cont.)

- Clearwater Scour ($V/V_c < 1$)
  - Local scour that occurs when velocities upstream of the structure are below critical velocity
  - Transport of bed material at distance from the structure is negligible

- Live Bed Scour ($V/V_c \geq 1$)
  - Local scour that occurs when velocities upstream of the structure are above critical velocity
  - Transport of bed material at distance from the structure is not negligible

Local Scour

- Local Scour Mechanisms
  - Accelerated Flow
  - Secondary Flows
    - Horseshoe Vortex
    - Surface Vortex
    - Wake Vortices
    - Pressure Gradients

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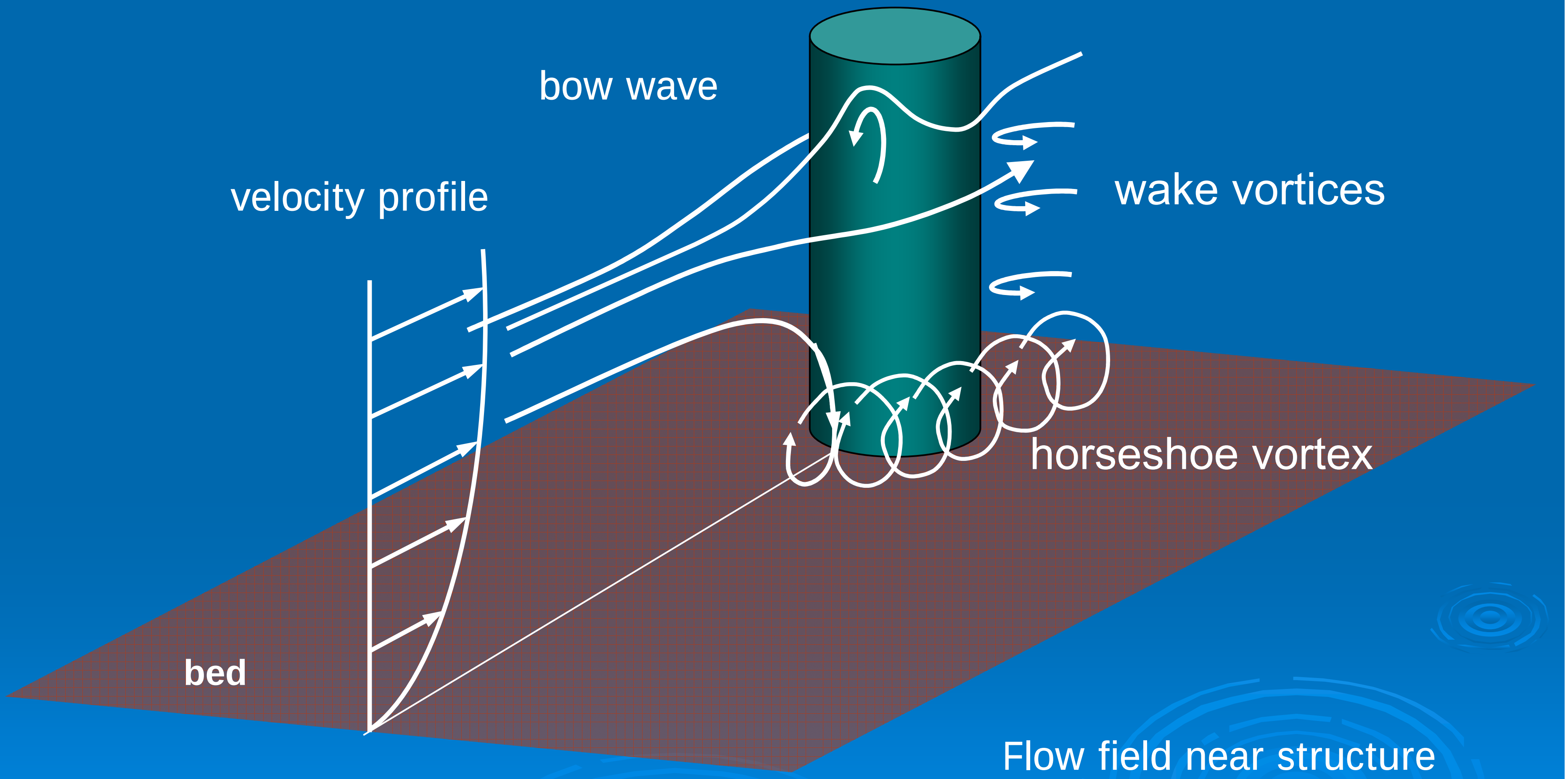
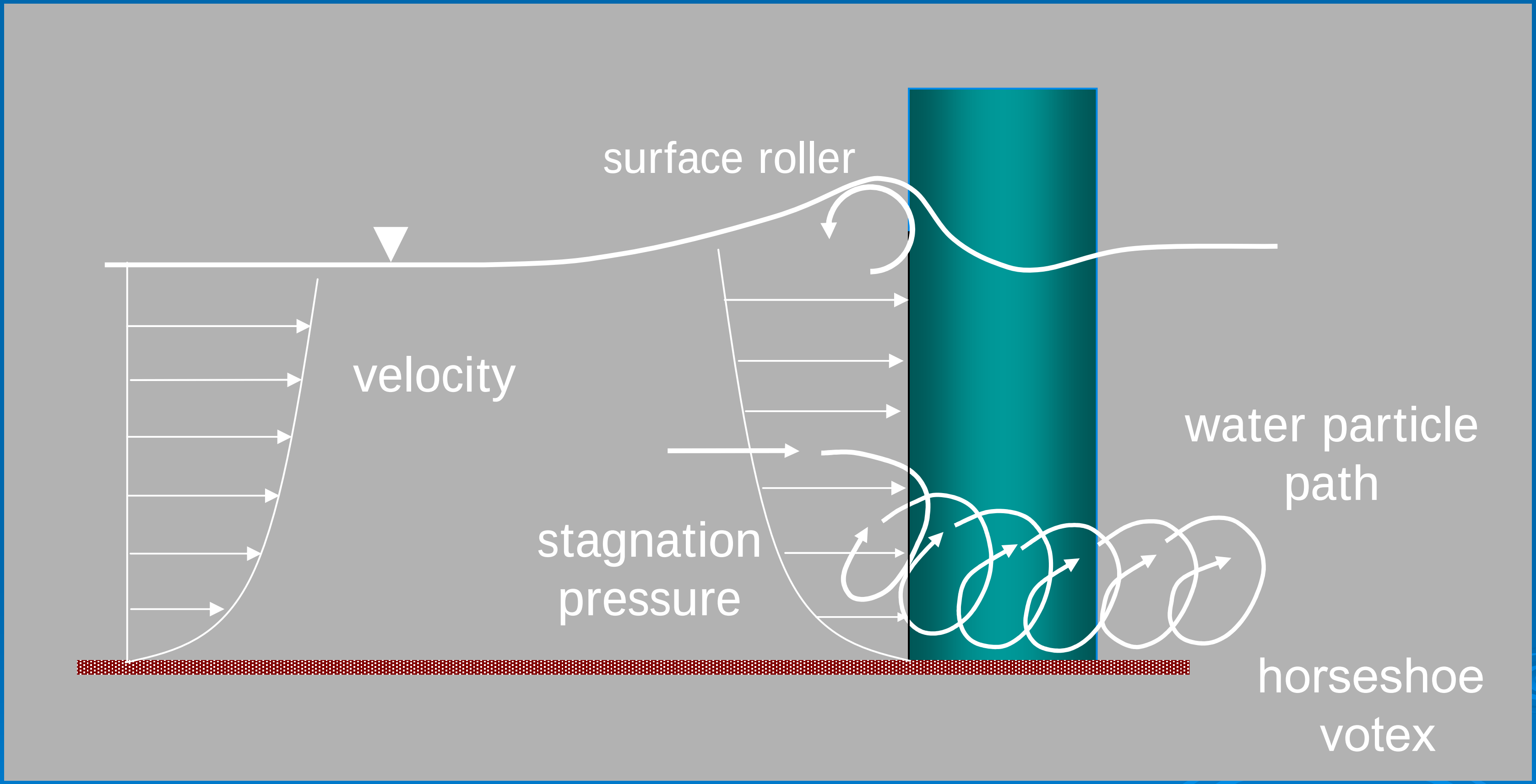
Local Scour Processes



Flow field near structure

Local Scour Processes



Local Scour Research

- Experimental
  - Laboratory Experiments
  - Field Measurements
- Analytical
- Computational (computer solution of governing equations)

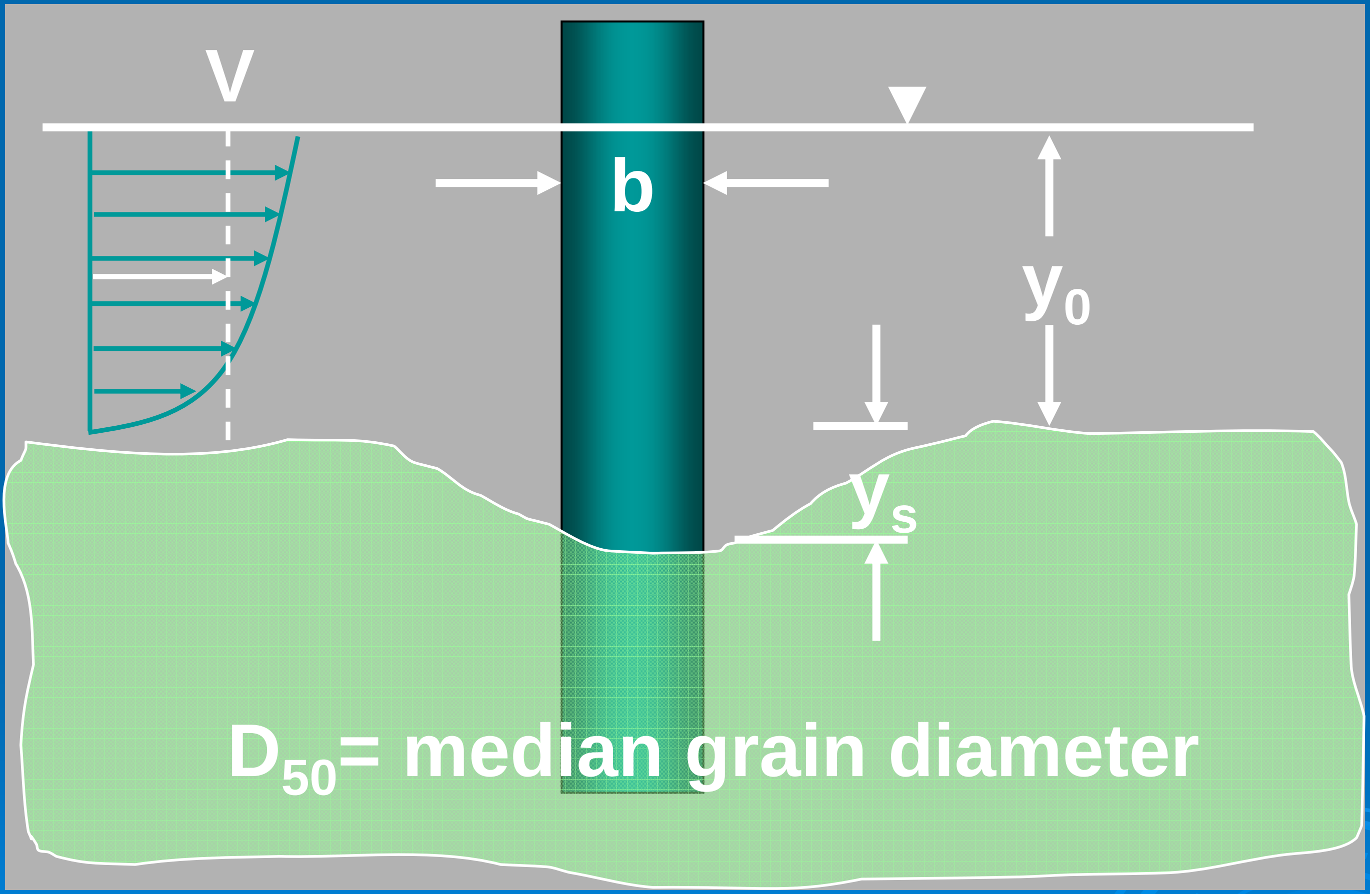
Experimental

- Most Successful Approach to Date (Due to Complexity of Problem)
- Provides Insight into Mechanisms
- Provides Data for Empirical Predictive Equations

Pier Scour Research

- Early Experimental Efforts
  - Chabert and Engeldinger (France)
  - Shen (Colorado State University)
  - Jain and Fischer (University of Iowa)
  - Raudkivi, Melville, Ettema, Chiew, (New Zealand)
  - Jones (FHWA)
- More Recent Work (Last 15 Years)
  - Sheppard (University of Florida)
  - Melville (Auckland University NZ)
  - Jones (FHWA)

Local Scour Definition Sketch



D_{50}= median grain diameter

Dimensional Analysis

$$y_s = f\,[\,\rho,\ \mu,\ g,\ D_{50},\ \sigma,\ \rho_s,\ y_0,\ V,\ b,\ h_{(pier)}\,]$$

$$\frac{y_s}{b} = f\left[\frac{y_o}{b}, \frac{V}{\sqrt{g y_o}}, \frac{\rho_s}{\rho}, \frac{Vb}{\nu}, \frac{V}{V_c}, \frac{b}{D_{50}},\ \sigma,\ h(pier)\right]$$

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Sheppard's Equations

$$\frac{y_s}{D^*} = f_1\left(\frac{y_0}{D^*}\right) f_2\left(\frac{V}{V_c}\right) f_3\left(\frac{D^*}{D_{50}}\right)$$

where

$D^* \equiv$ Effective diameter of the structure

Section Break

Local Scour at Single Structures with Simple Geometries

Equilibrium Local Scour Prediction Equations

- Number of equations in the literature
- FDOT requires the use of equations and methods developed by Sheppard et. al.
- These equations and how they were developed are presented in this section

Local Scour Equations

- Equations developed using dimensional analysis and the results of laboratory experiments
- Experiments were performed in 4 different laboratories and cover a wide range of conditions

Local Scour Equations (cont.)

- Presentation of equations
- Brief description of the experiments
- Equations are separated into two flow conditions:
  - Clear-water scour
  - Live-bed scour

Local Scour Equations (cont.)

- Clear-water scour $0.47 \leq \dfrac{V}{V_c} \leq 1$

$$\frac{y_s}{D^*} = 2.5\, f_1\left(\frac{y_0}{D^*}\right) f_2\left(\frac{V}{V_c}\right) f_3\left(\frac{D^*}{D_{50}}\right)$$

where

$$f_1\left(\frac{y_o}{D^*}\right) = \tanh\left[\left(\frac{y_0}{D^*}\right)^{0.4}\right]$$

Local Scour Equations (cont.)

- Clear-water scour (cont.) $0.47 \leq \frac{V}{V_c} \leq 1$

$$f_2\left(\frac{V}{V_c}\right) = 1 - 1.75\left[ln\left(\frac{V}{V_c}\right)\right]^2$$

$$f_3\left(\frac{D^*}{D_{50}}\right) = \frac{D^*/D_{50}}{0.4\left(D^*/D_{50}\right)^{1.2} + 10.6\left(D^*/D_{50}\right)^{-0.13}}$$

Local Scour Equations (cont.)

- Live-bed scour $1 \le \frac{V}{V_c} \le \frac{V_{lp}}{V_c}$

$$\frac{y_s}{D^*} = f_1\left(\frac{y_0}{D^*}\right)\left[2.2\left(\frac{V - V_c}{V_{lp} - V_c}\right) + 2.5\, f_3\left(\frac{D^*}{D_{50}}\right)\left(\frac{V_{lp} - V}{V_{lp} - V_c}\right)\right]$$

Local Scour Equations (cont.)

- Live-bed scour $\frac{V}{V_c} \geq \frac{V_{lp}}{V_c}$

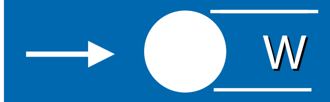
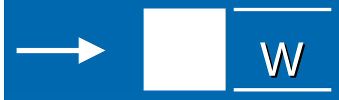
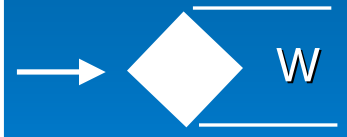
$$\frac{y_s}{D^*} = 2.2\,\tanh\left[\left(\frac{y_0}{D^*}\right)^{0.4}\right]$$

where

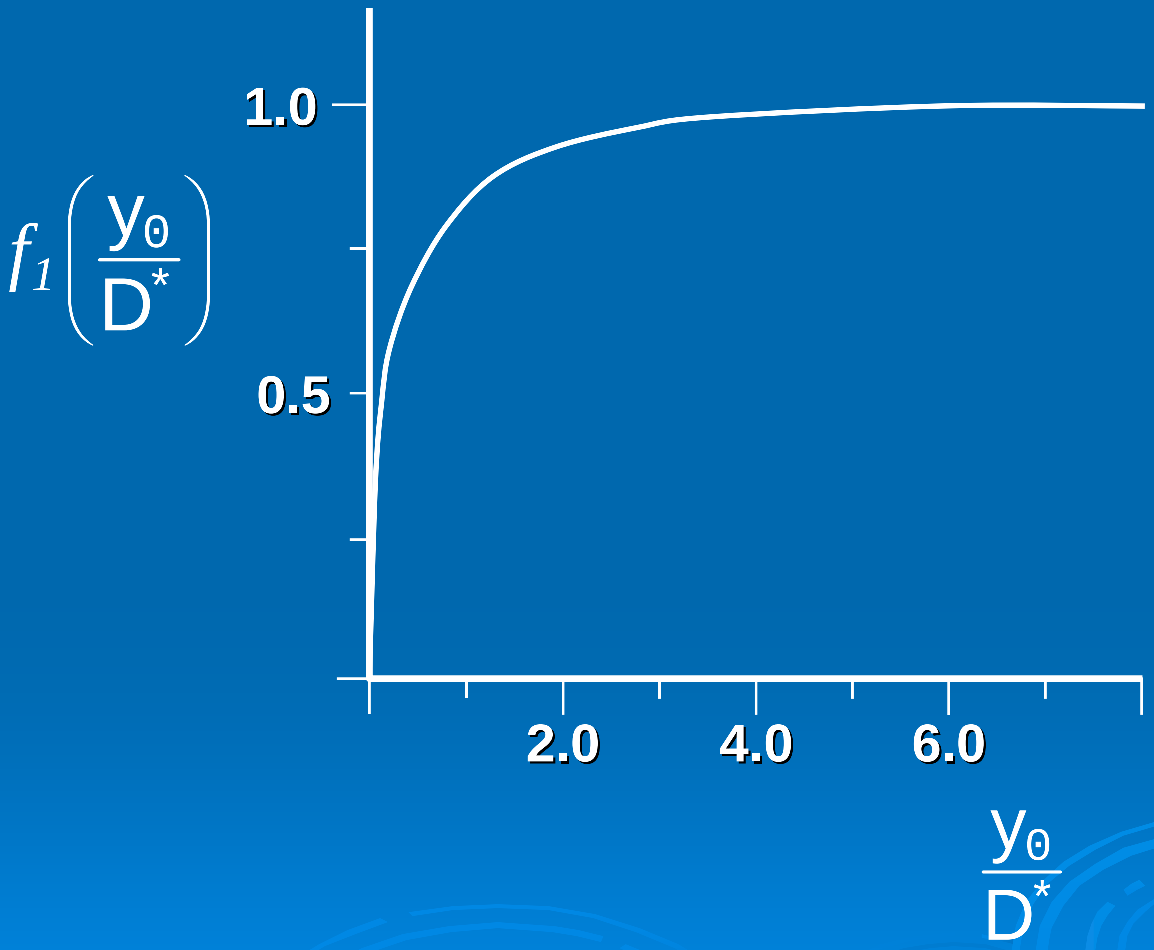
D^* is the “Effective Width” of the structure

No dependence on sediment size when $V >= V_{lp}$

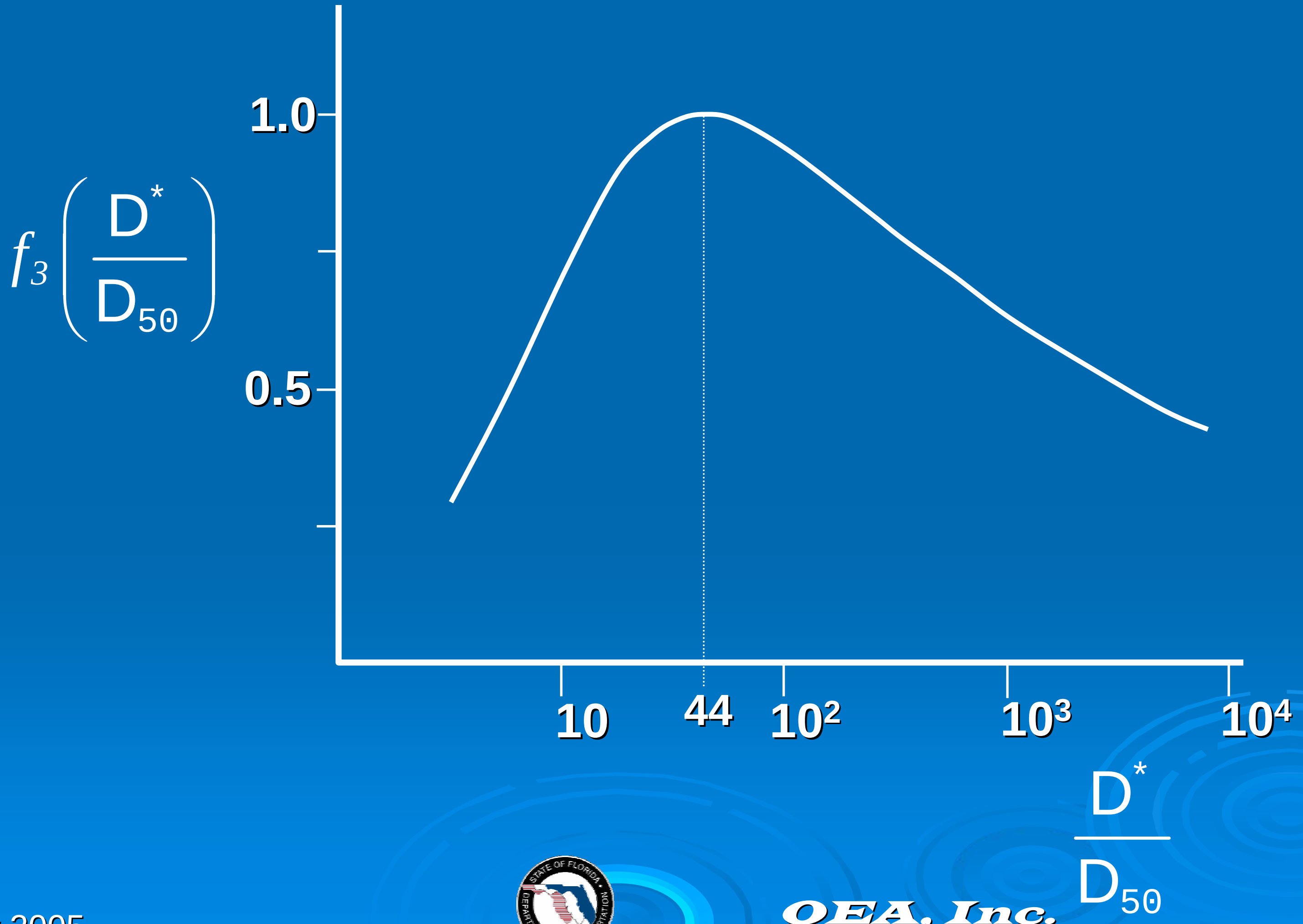
Local Scour Equations (cont.)

Structure Cross-Section	Projected Width	Effective Diameter D^*
	$W = D$	$D^* = D$
	$W = D$	$D^* = 1.23\ D$
	$W = 1.41\ D$	$D^* = 1.2\ D$

Graph of Function, f_1



Graph of Function, f_3



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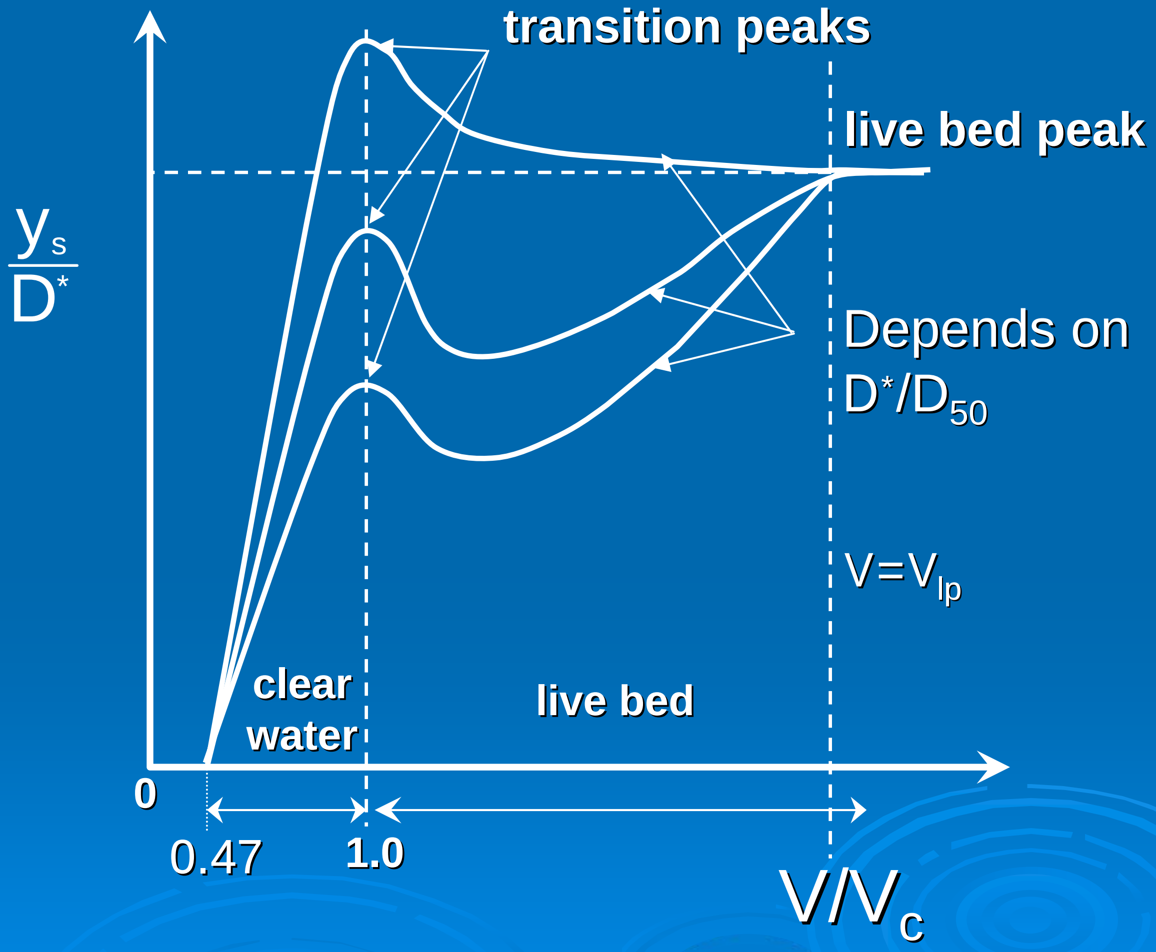
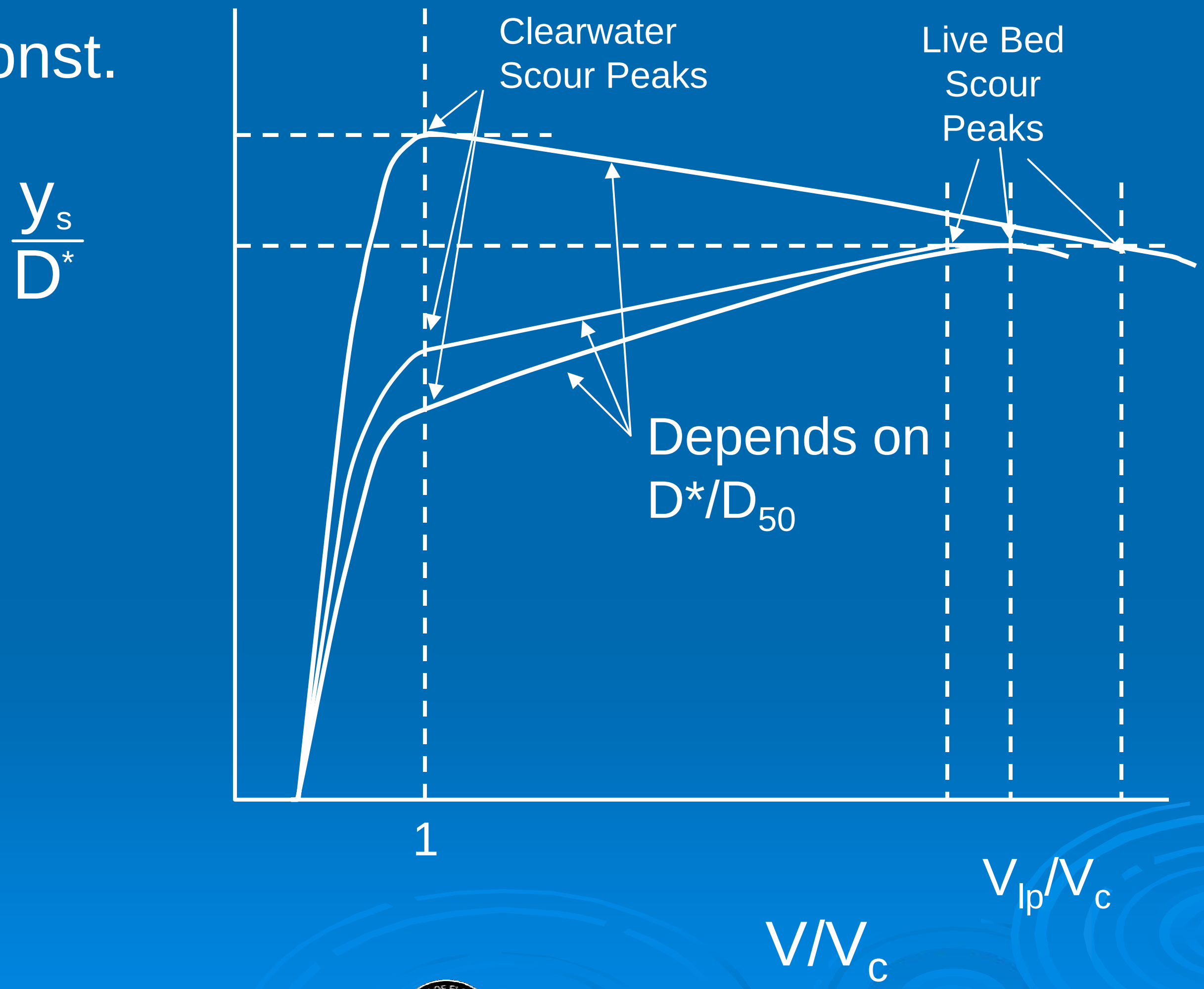
Actual Scour Dependence on Velocity

y_0/D^* constant



Predicted Scour Dependence on Velocity

$y_o/D^* = \text{const.}$



Local Scour Prediction

- Clearwater Scour
  - Maximum scour depth

$$y_s = 2.5\,D^*$$

- Live-Bed Scour
  - Maximum scour depth

$$y_s = 2.2\,D^*$$

Section Break

Basis For Sheppard's Single Pier Equations

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Basis For Sheppard's Single Pier Equations

- Research conducted in:
  - Hydraulics Laboratory,
    Civil and Coastal Engineering Dept., U.F.
  - Hydraulics Laboratory, CSU
  - USGS Laboratory, Turners Falls, MA
  - Hydraulics Laboratory,
    University of Auckland, Auckland, NZ

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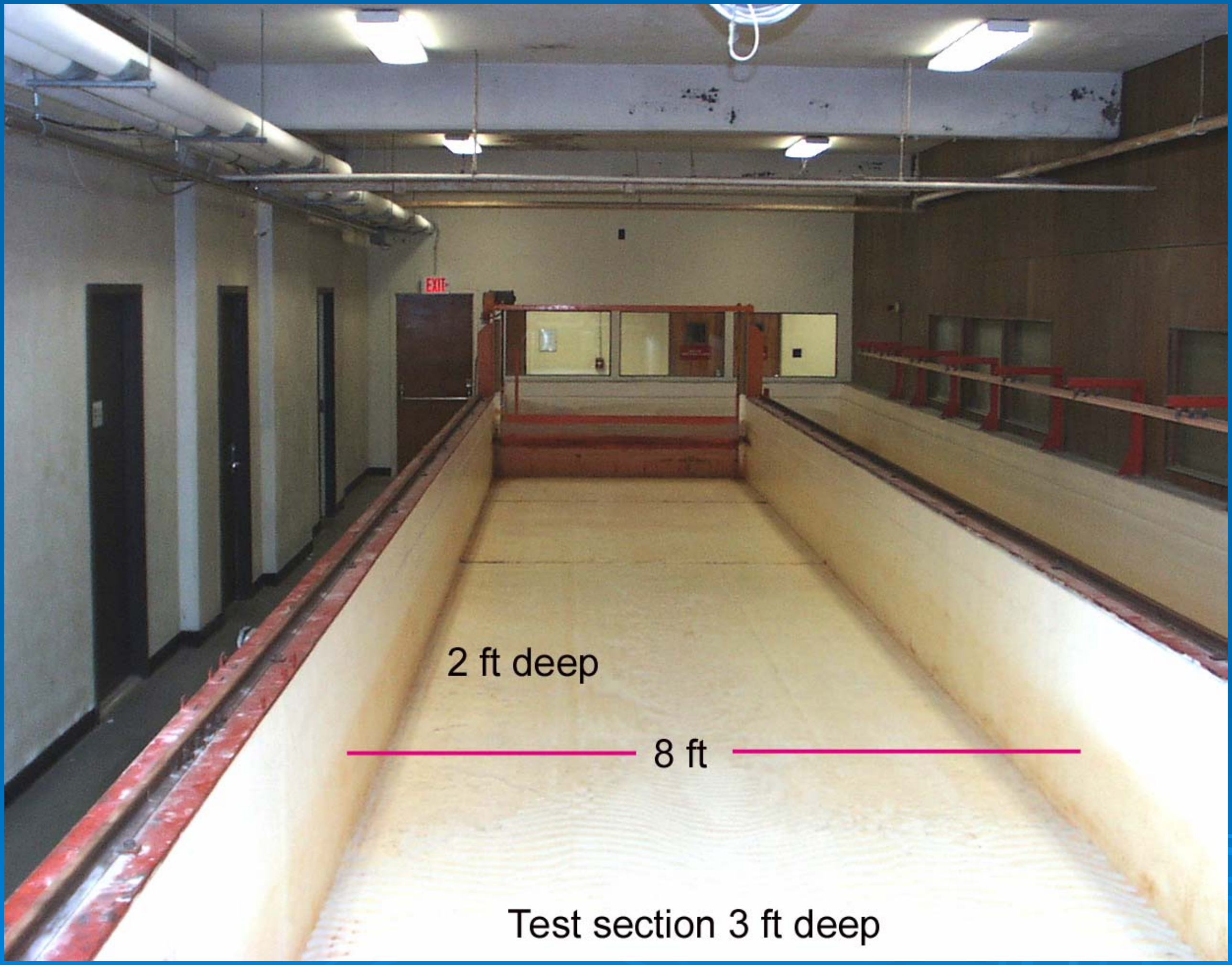
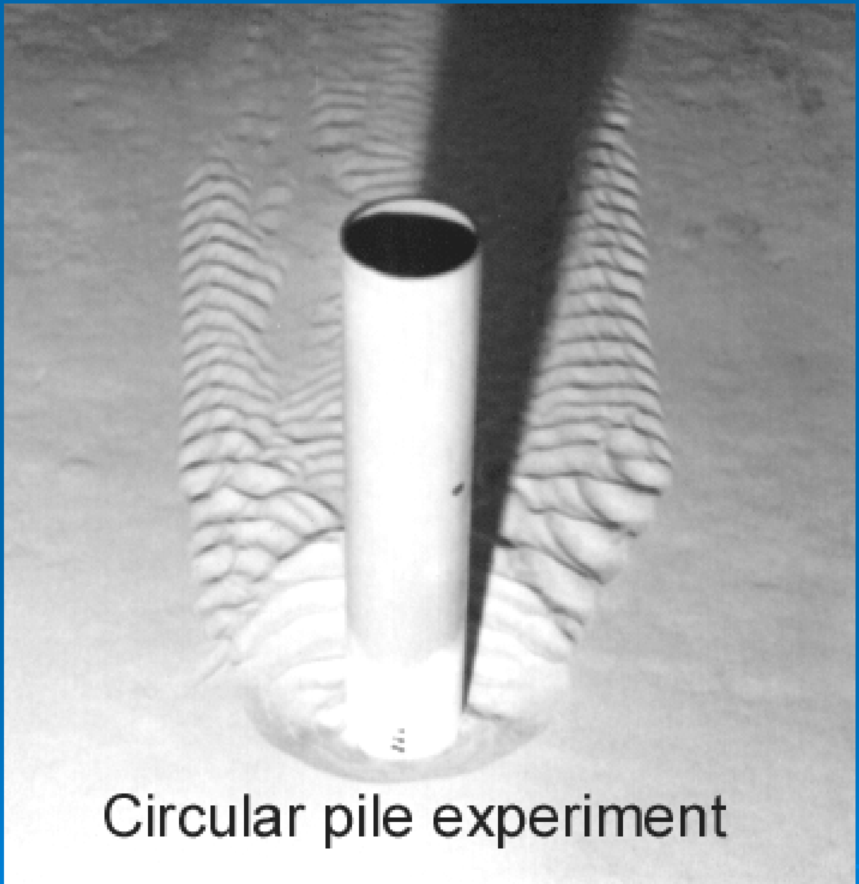
UF Experiments

- Long Duration
- Monitor Time Rate of Scour
- Uniform Sediment Grain Size
- Uniform Sediment Compaction
- Post Experiment Scour Hole Survey

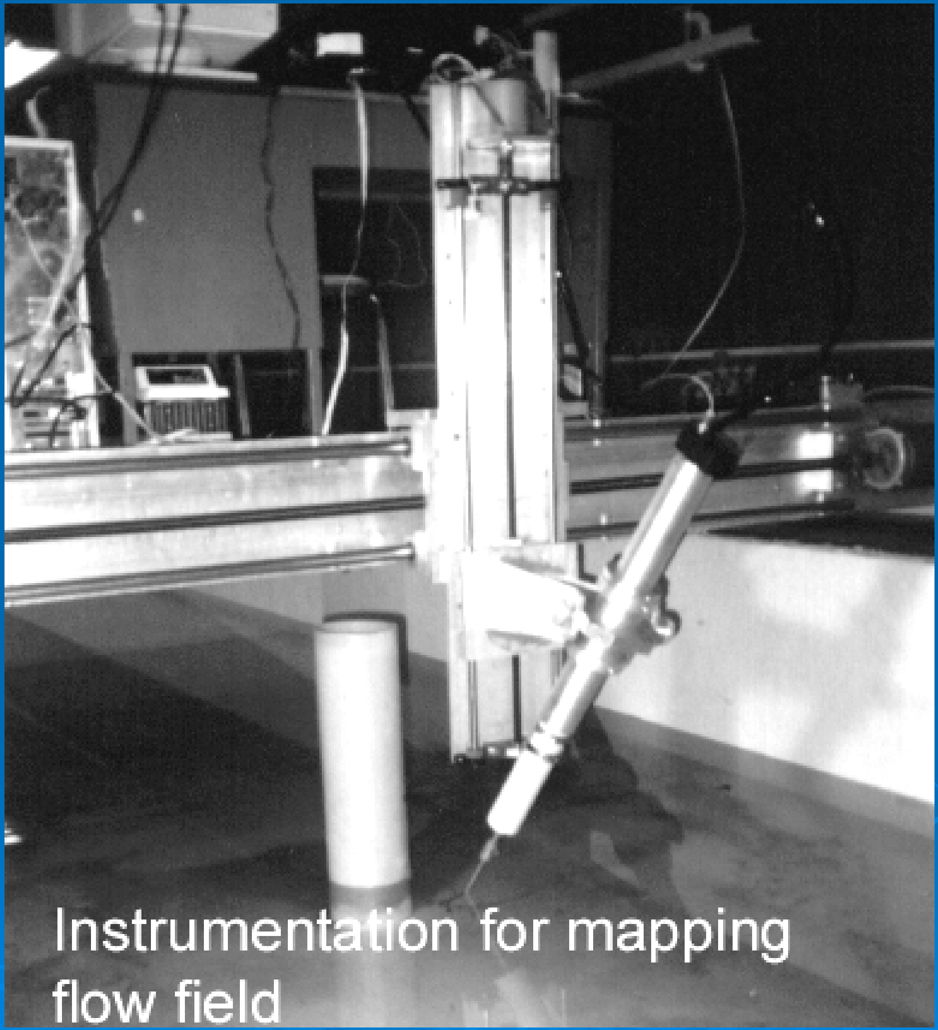
University of Florida Flume



U of F Flume (cont.)

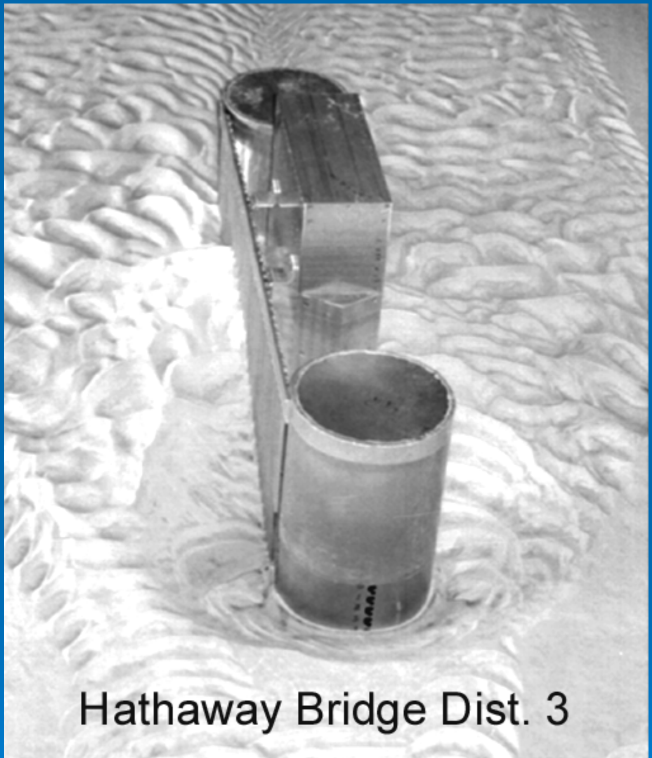


Circular pile experiment

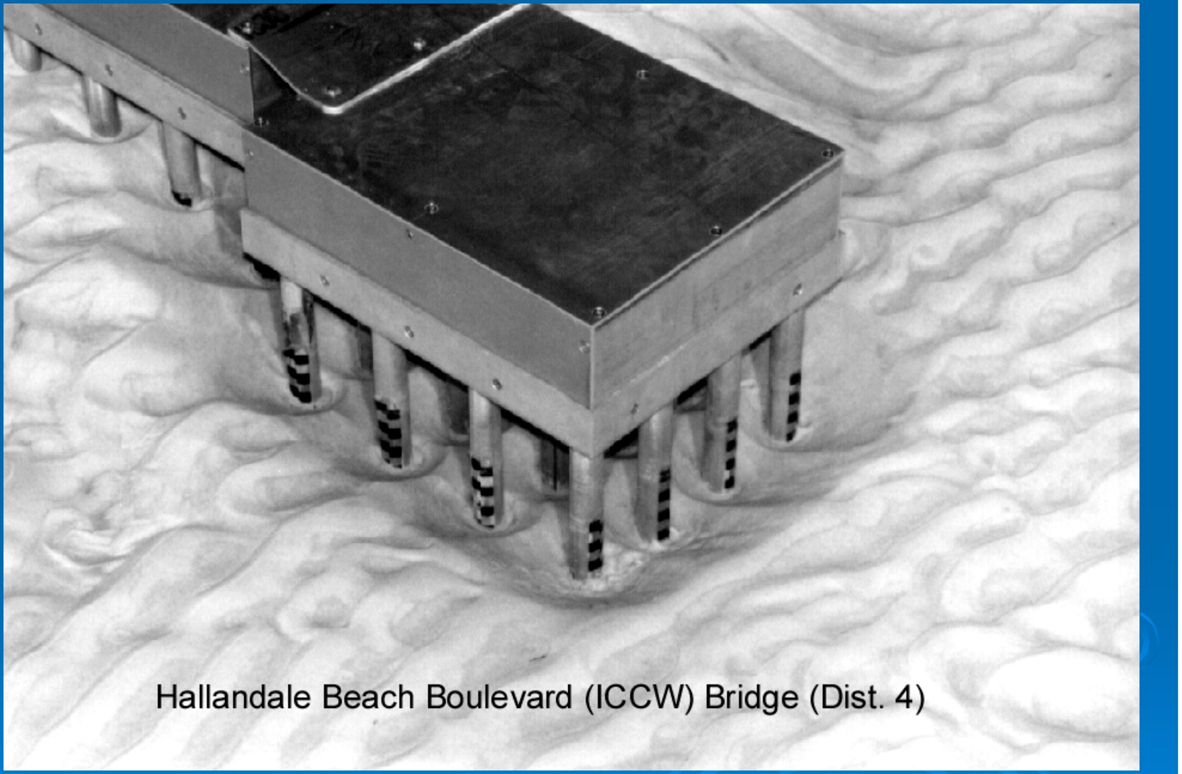


Instrumentation for mapping flow field

U of F Flume (cont.)

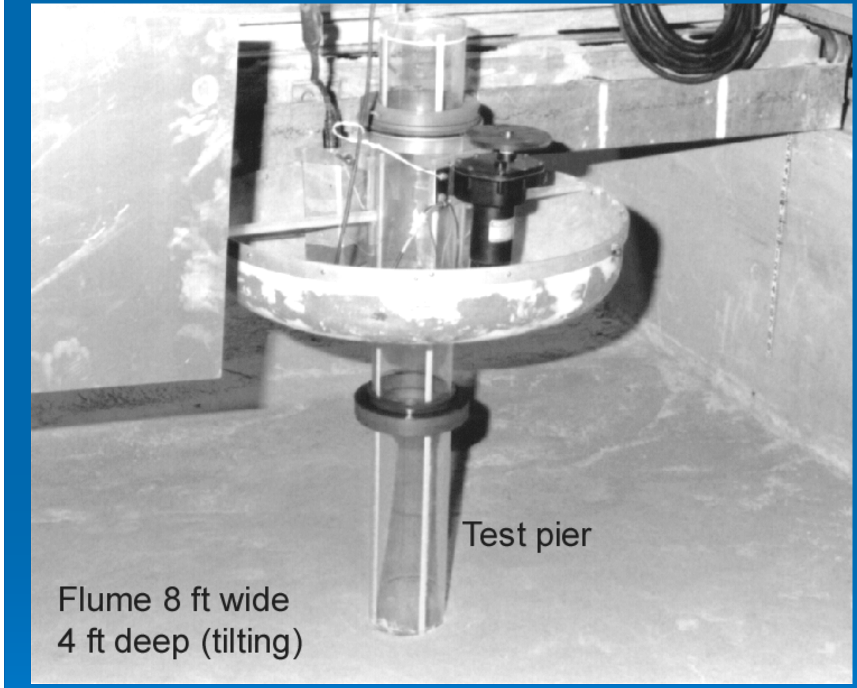


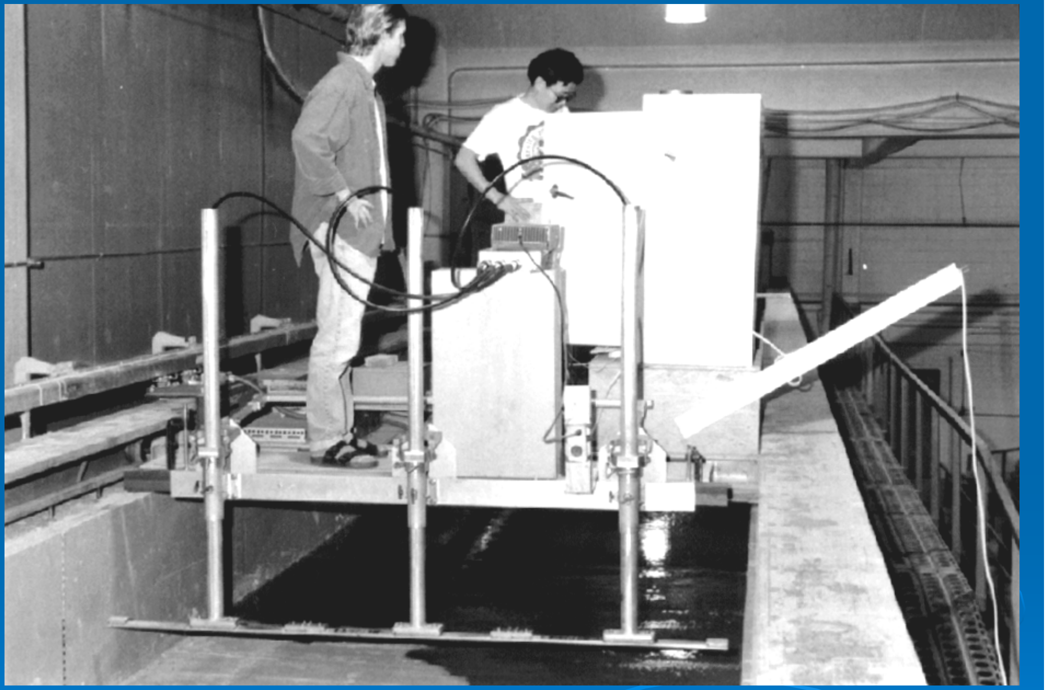
Hathaway Bridge Dist. 3



Hallandale Beach Boulevard (ICCW) Bridge (Dist. 4)

CSU
Experiments



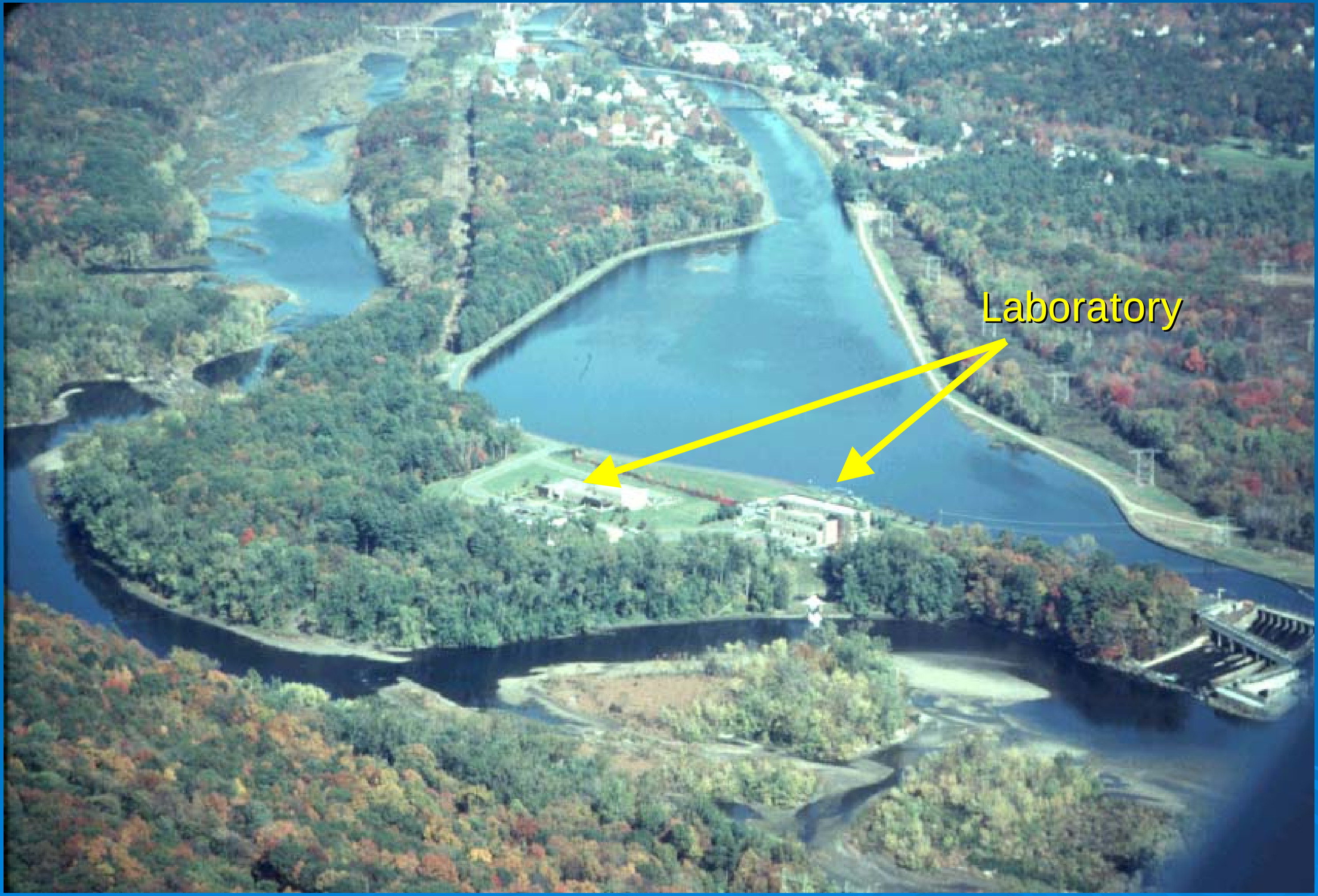


CSU Experiments (cont.)

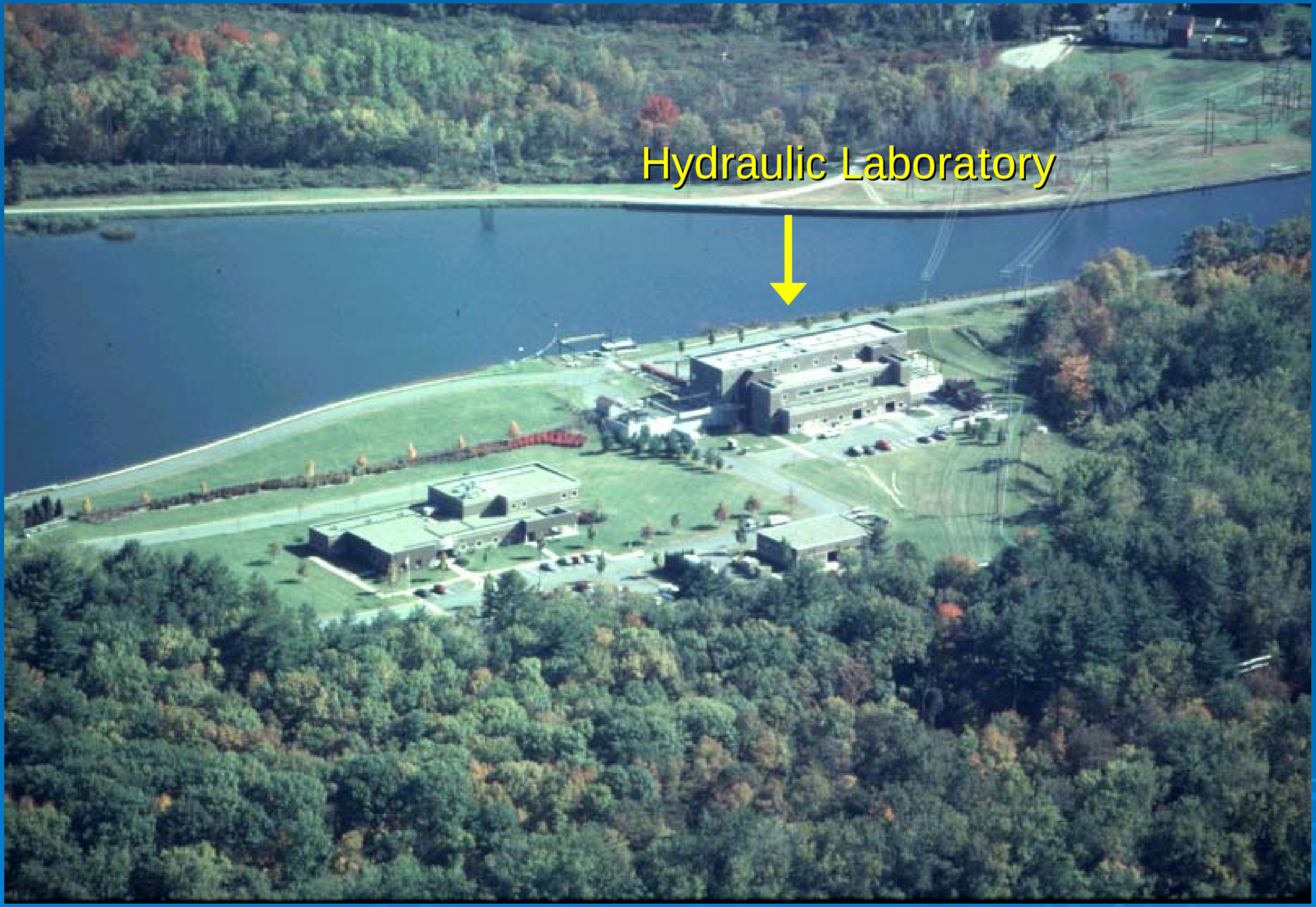
USGS Lab. Experiments

- Large Flume: 20 ft Wide, 21 ft Deep, 126 ft Long
- Clearwater Experiments
  - Tested Piles 4.5 in, 1 ft and 3 ft in Diameter
  - 3 Sediment Sizes Tested, 0.2 mm, 0.8 mm, 3.0 mm

USGS-BRD Laboratory



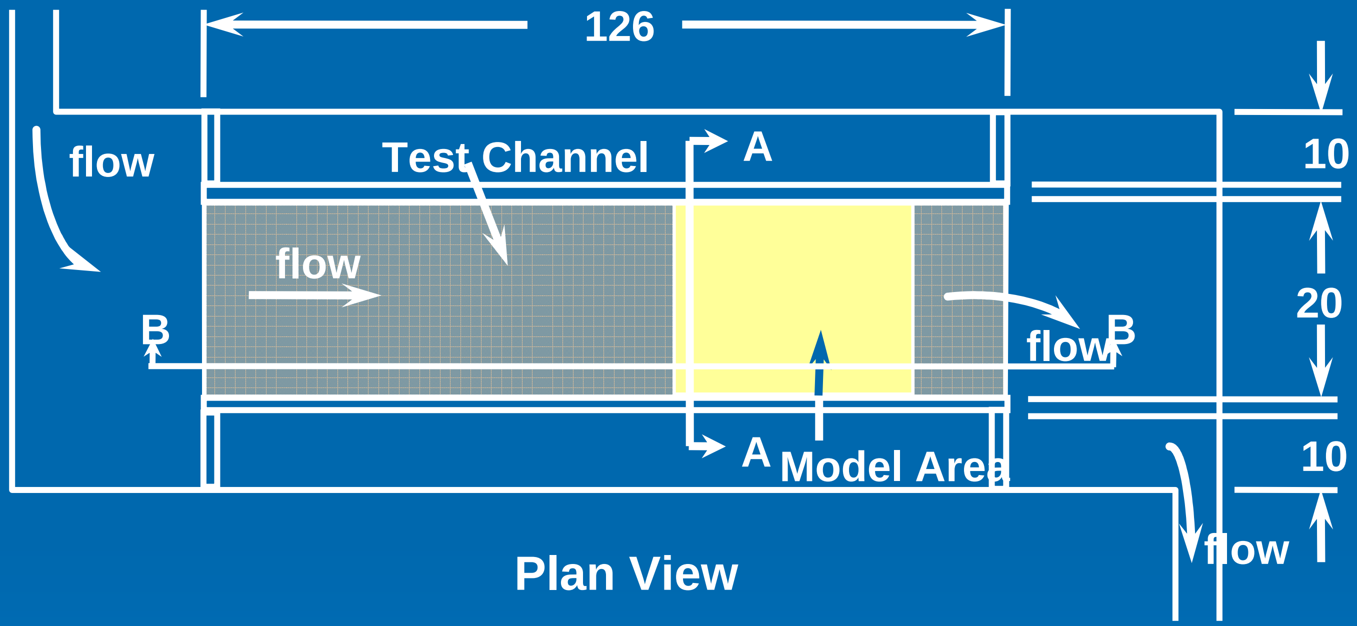
USGS-BRD Laboratory



USGS Lab. Experiments

USGS Lab. Experiments

Flow Intake from Reservoir



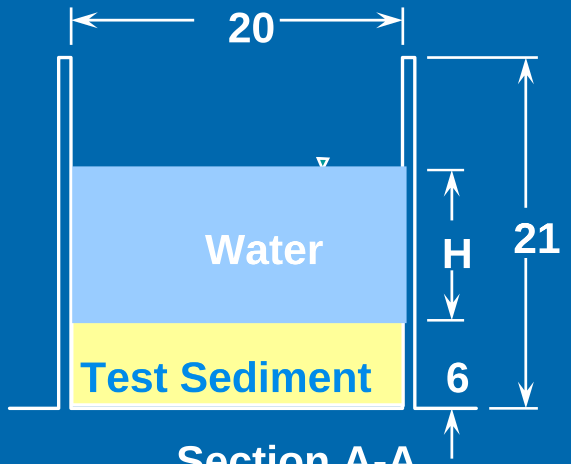
Plan View

<u>NOT TO SCALE</u>
All dimensions in feet

Flow Discharge
To Connecticut
River

Clearwater Scour Test Setup

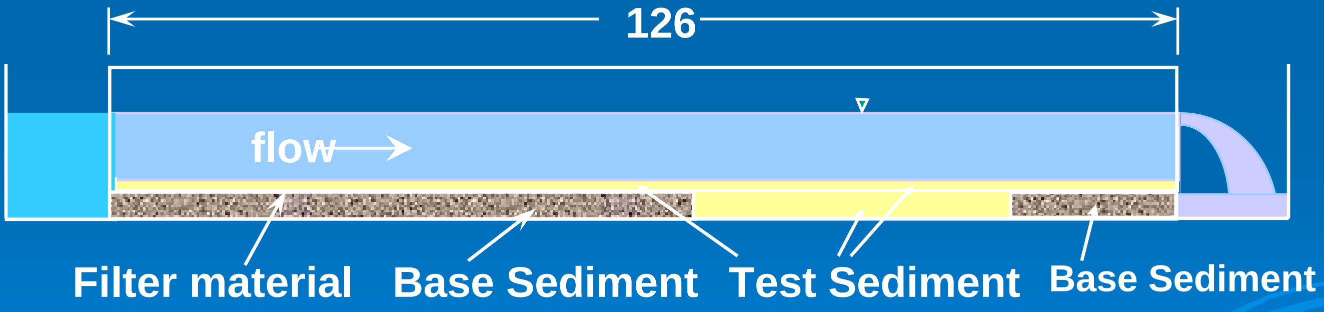
USGS Lab. Experiments



Section A-A

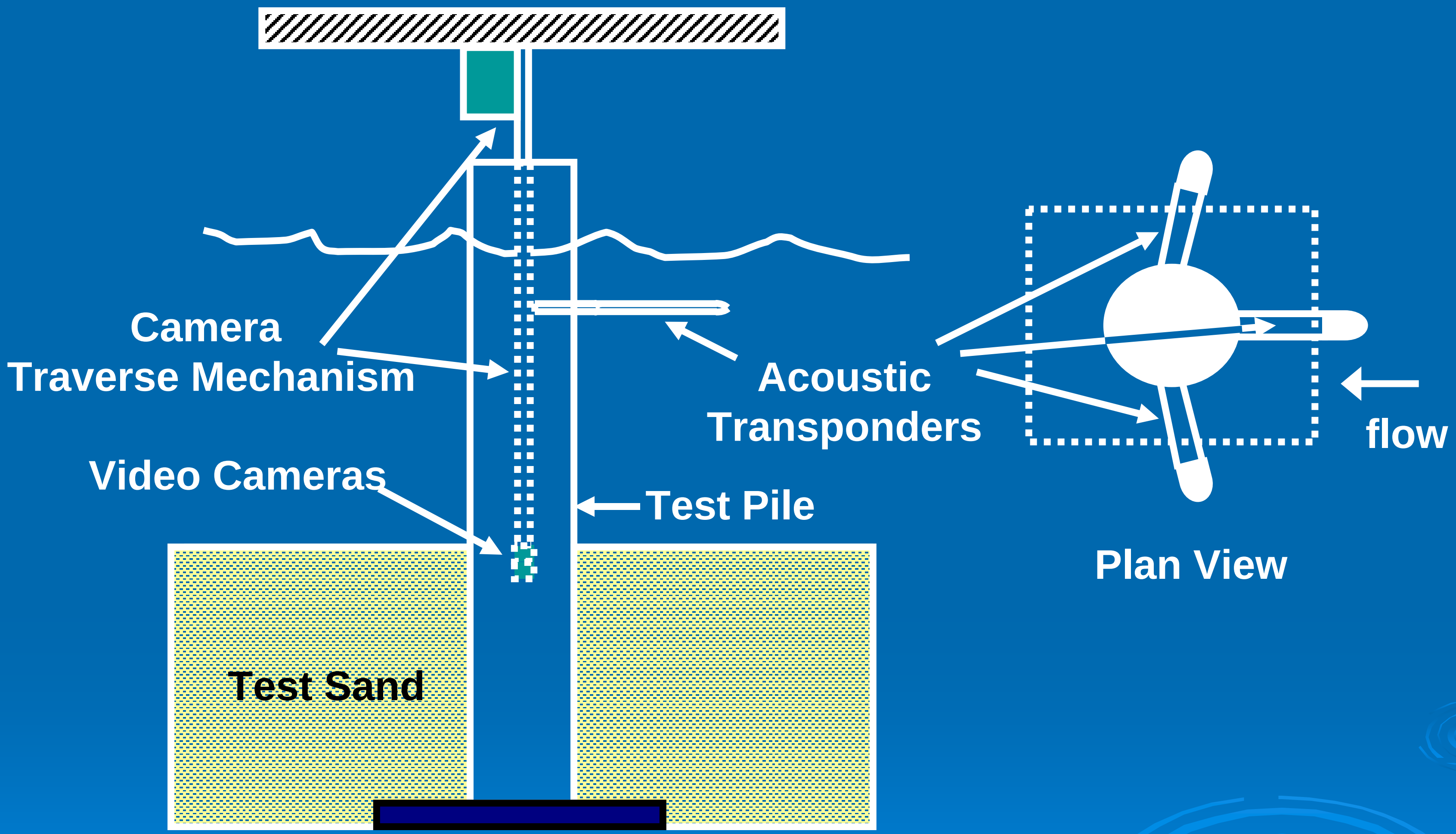
NOT TO SCALE
All dimensions in feet

H = 9’ for 3’ pile
H = 4’ for 4.5” and 1’ piles



Section B-B

Acoustic Scour Depth Meters



Test Piles with Scour Depth Instrumentation

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Instrumentation

- Acoustic Scour Depth Instruments
- Internal Video Cameras
- External Video Cameras
- Flow Velocity, Water Temperature

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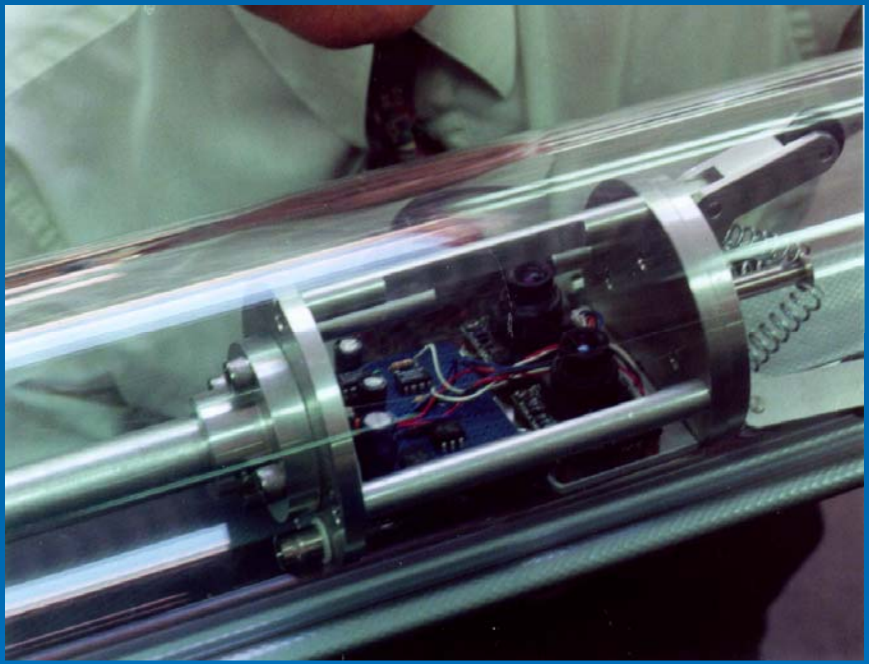
Acoustic Scour Depth Instrument

Video Cameras



Internal

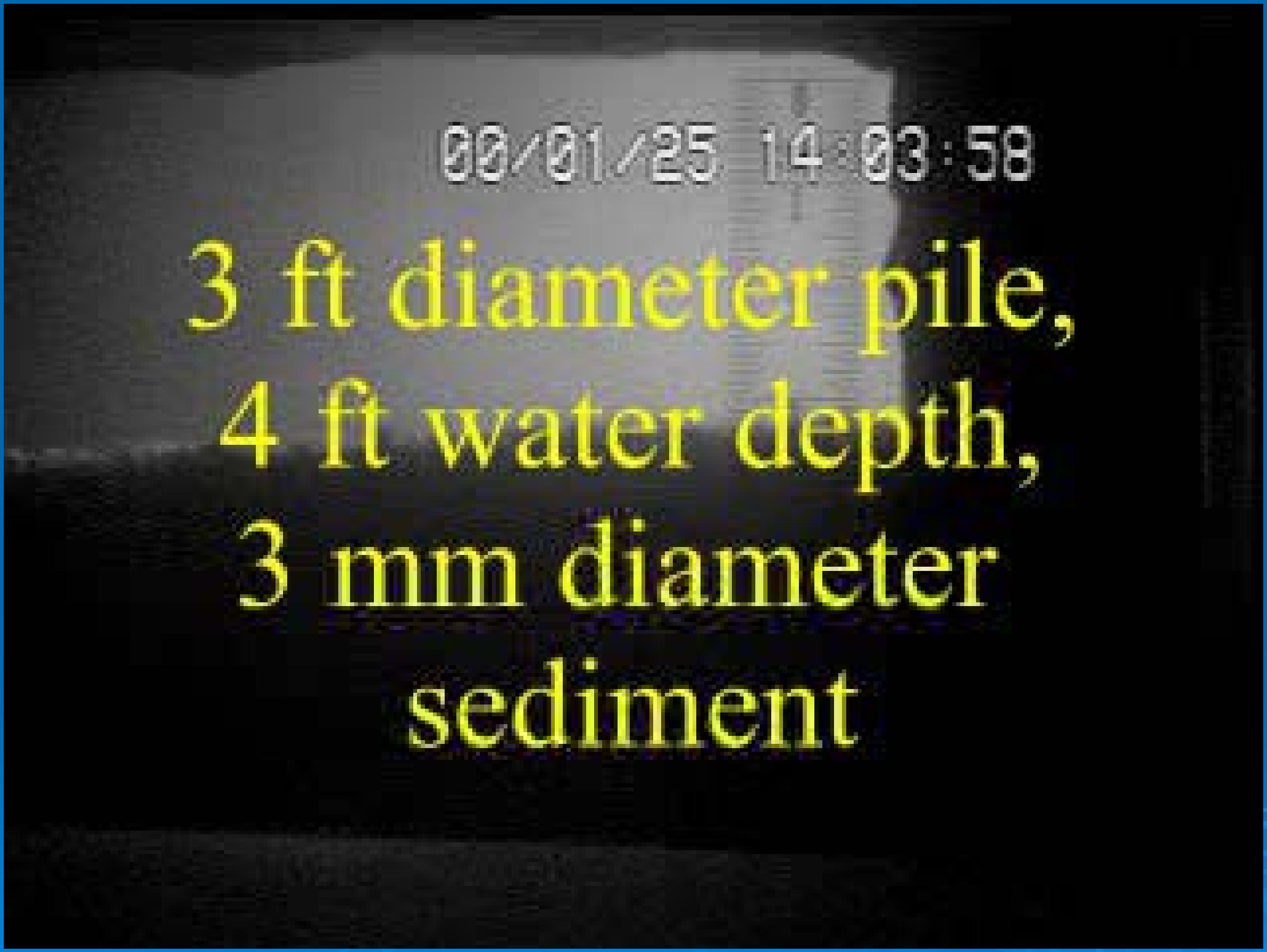
External

Velocity Instruments

Clearwater Scour Experiments

Clearwater Scour Experiments

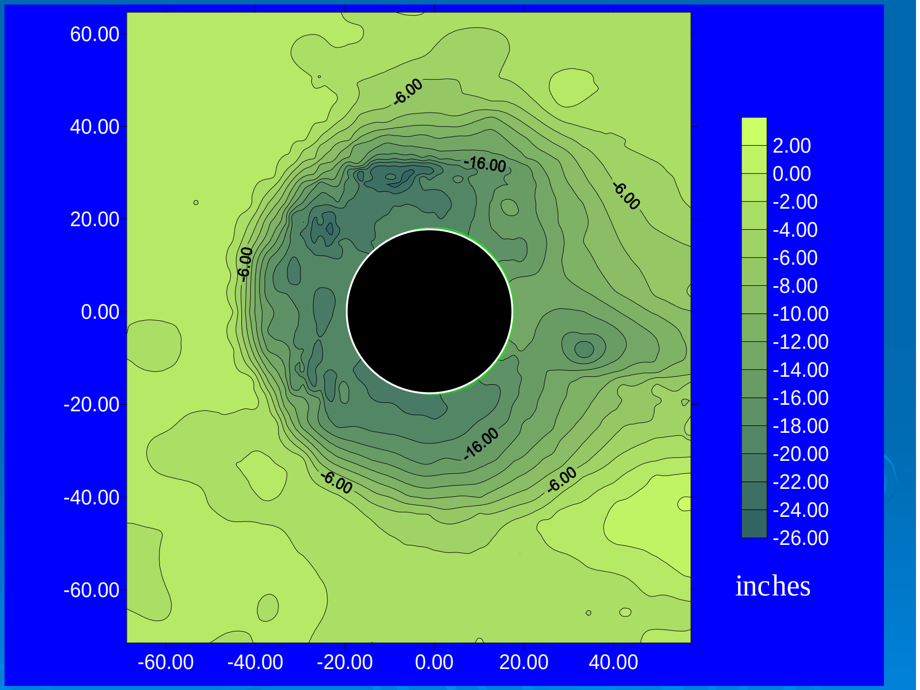
Clear-Water Scour Test



3 ft diameter pile,
4 ft water depth,
3 mm diameter
sediment

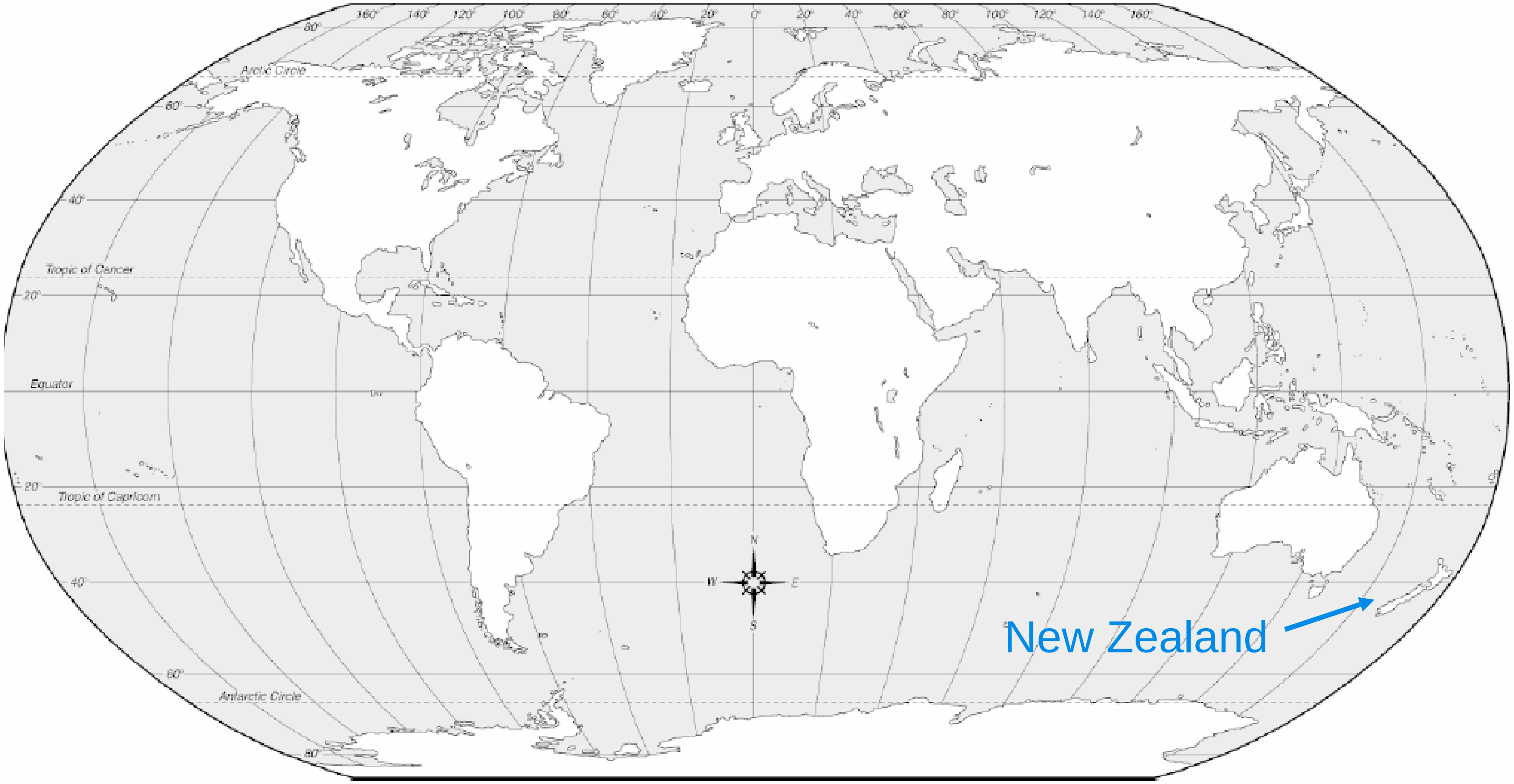
Clearwater Scour Experiments

3 ft diameter pile



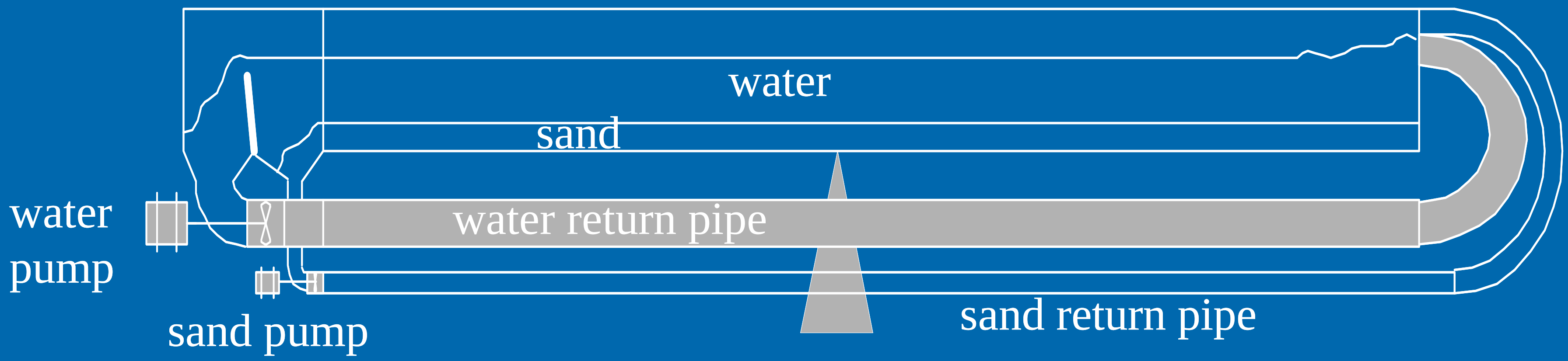
Univ. of Auckland Lab Exp.

(Live Bed Scour)



Univ. of Auckland Lab Exp.

Auckland Flume



Auckland Flume

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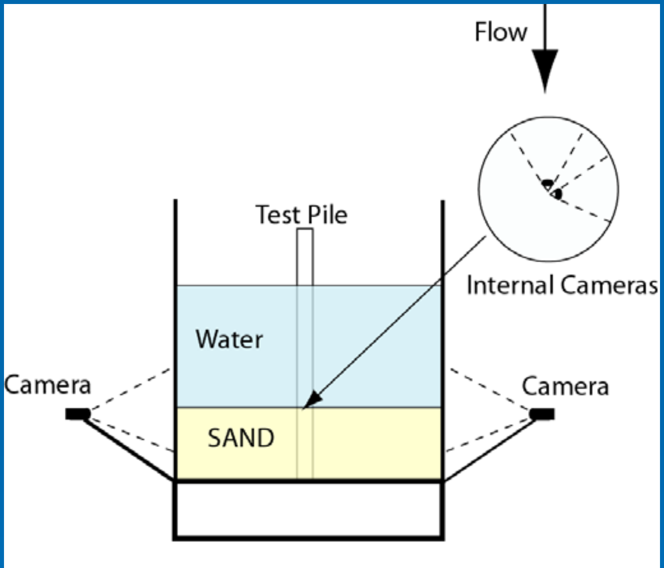
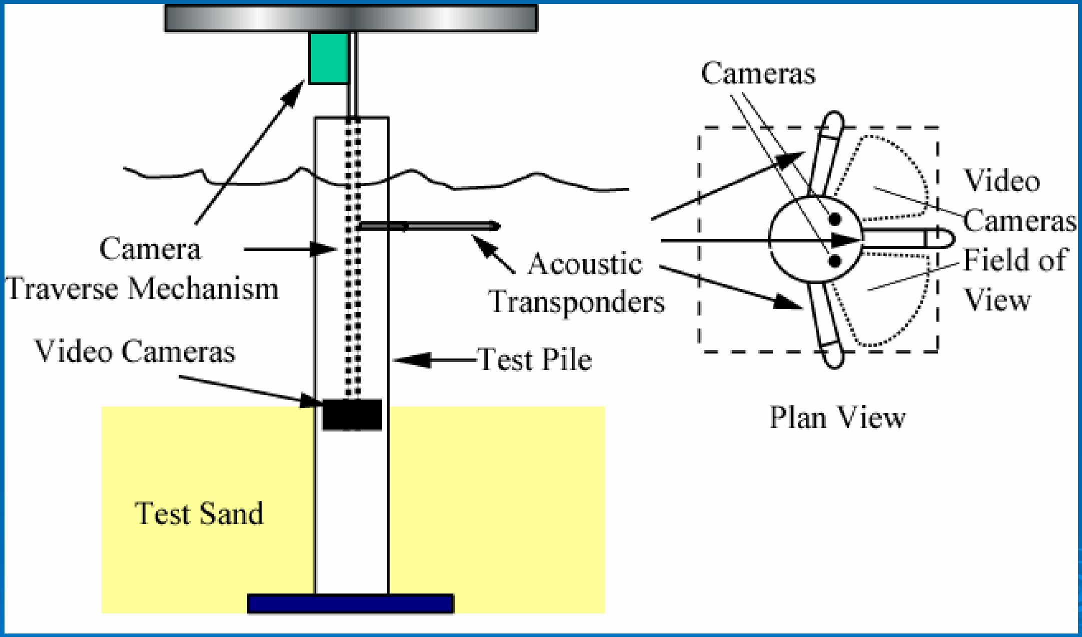
Auckland Flume

Instrumentation



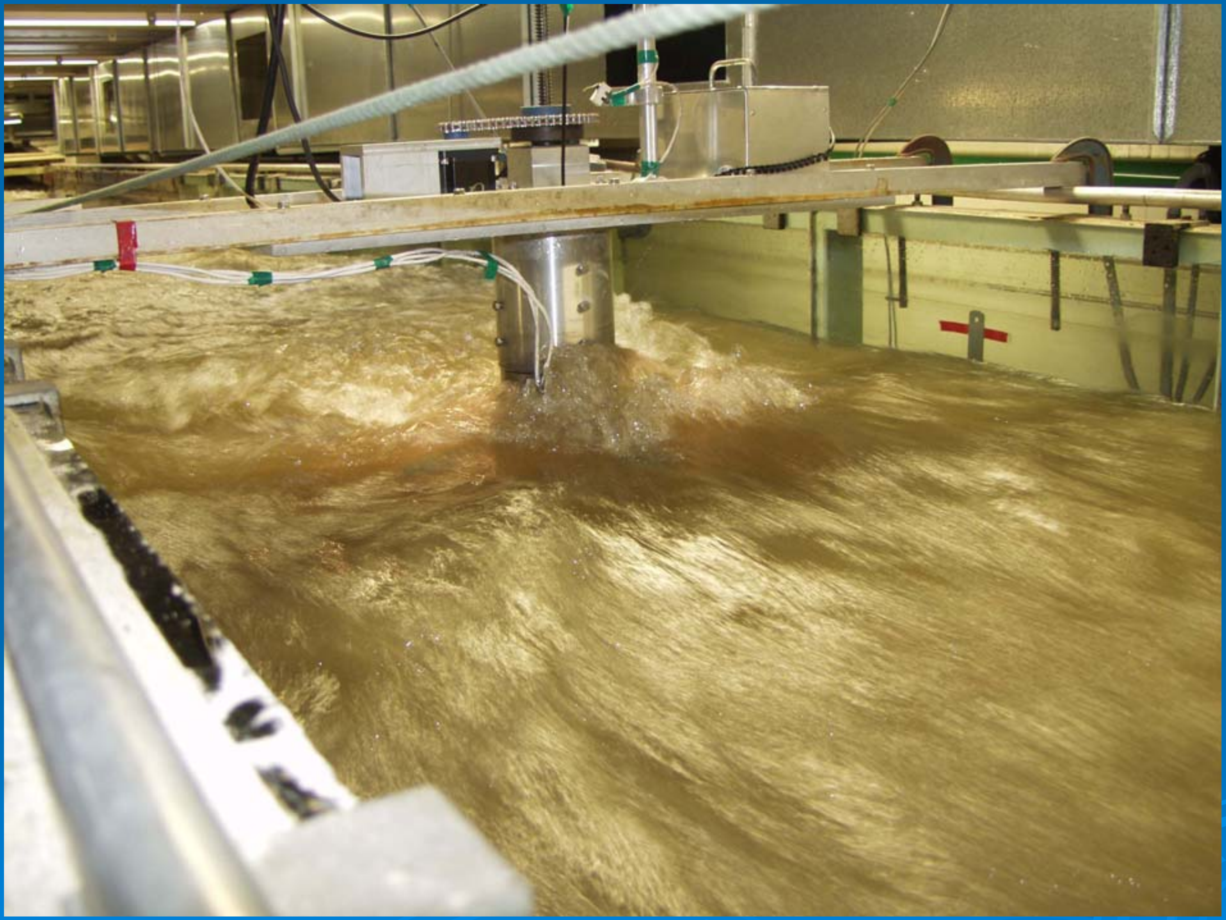
Flume Cross-Section



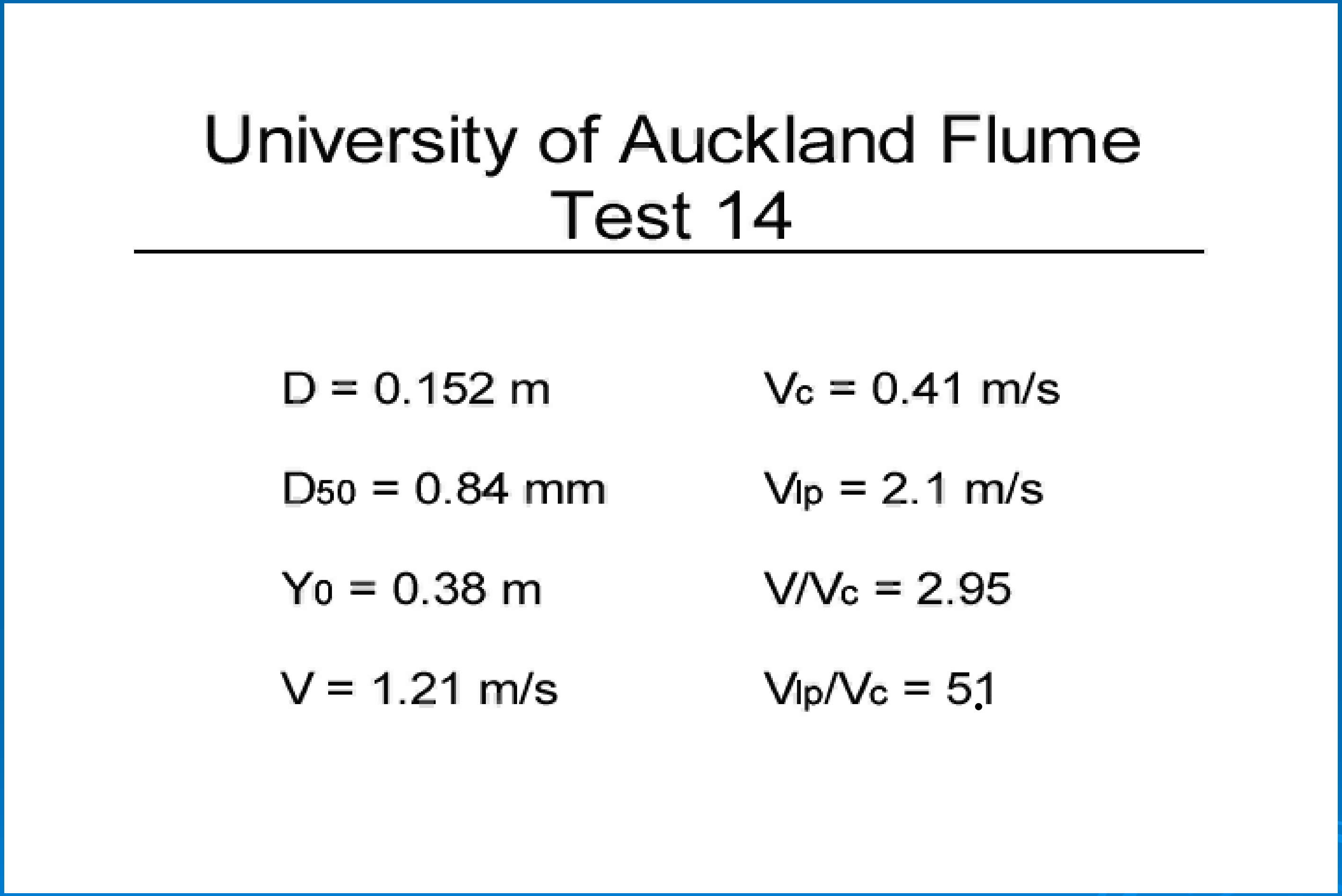
Live Bed Scour Test

Live Bed Scour Test

Live Bed Scour Test



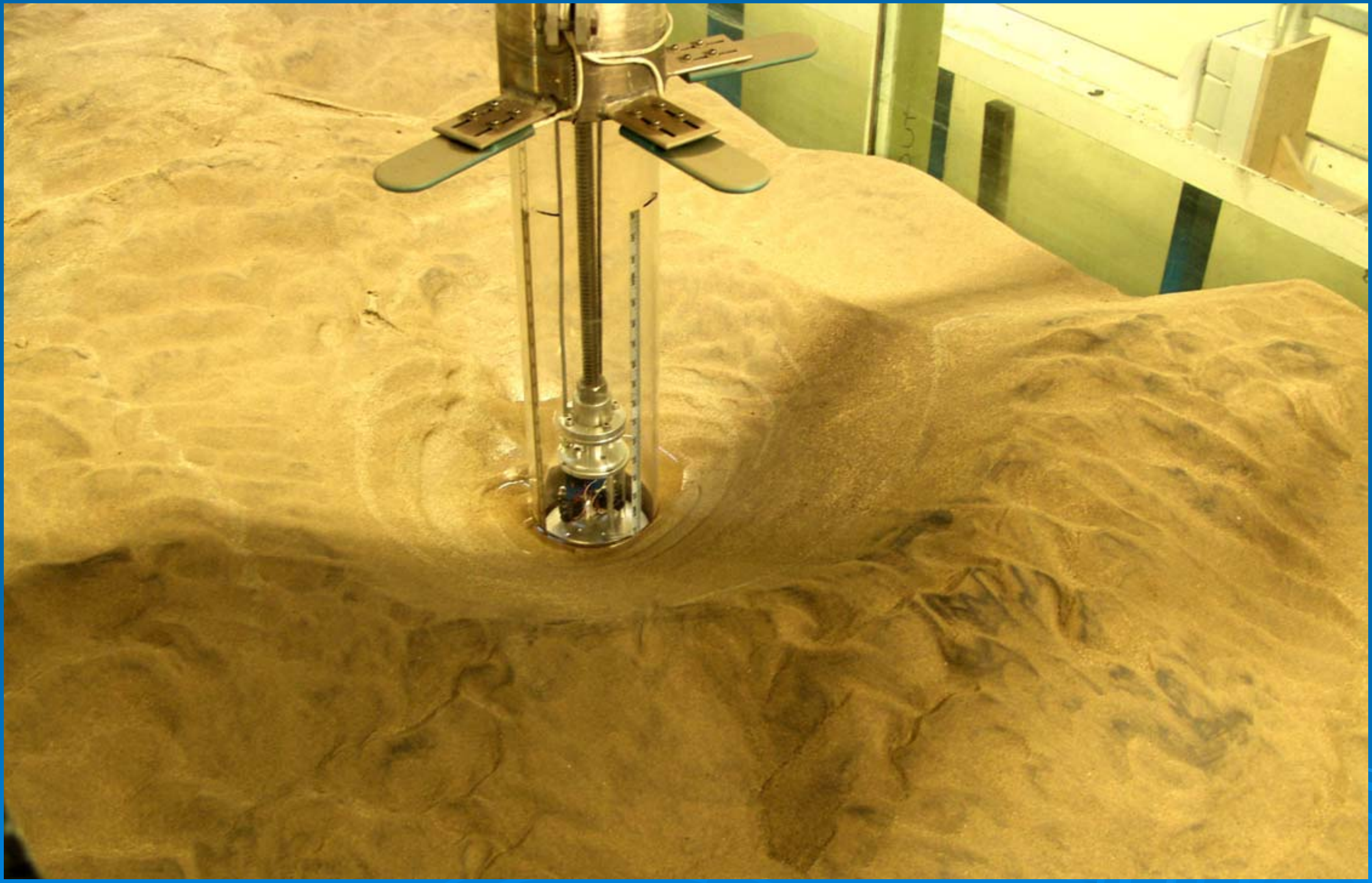
Live-Bed Scour Test



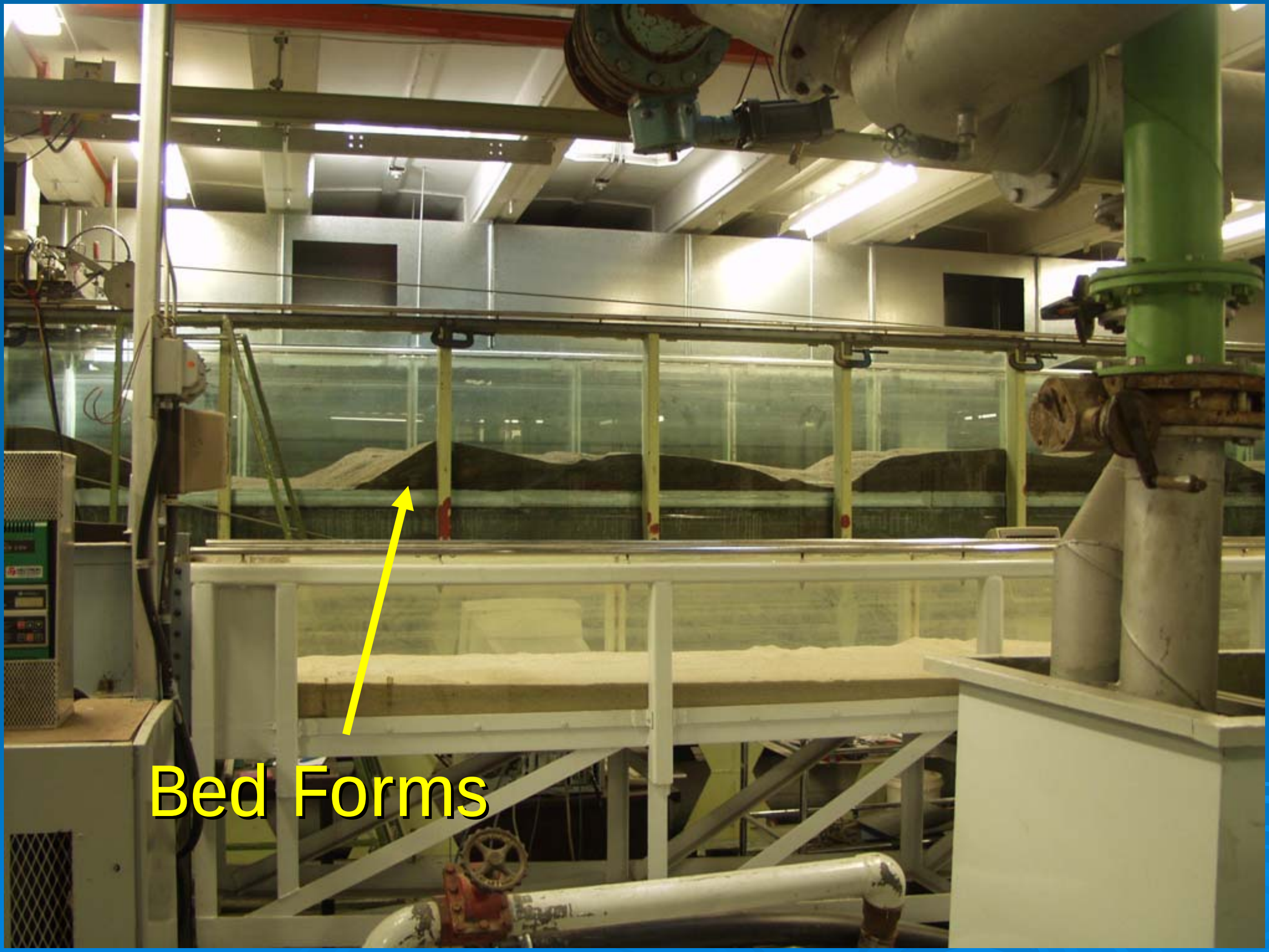
University of Auckland Flume
Test 14

$D = 0.152$ m	$V_c = 0.41$ m/s
$D_{50} = 0.84$ mm	$V_{lp} = 2.1$ m/s
$Y_0 = 0.38$ m	$V/V_c = 2.95$
$V = 1.21$ m/s	$V_{lp}/V_c = 5.1$

Live Bed Scour Hole



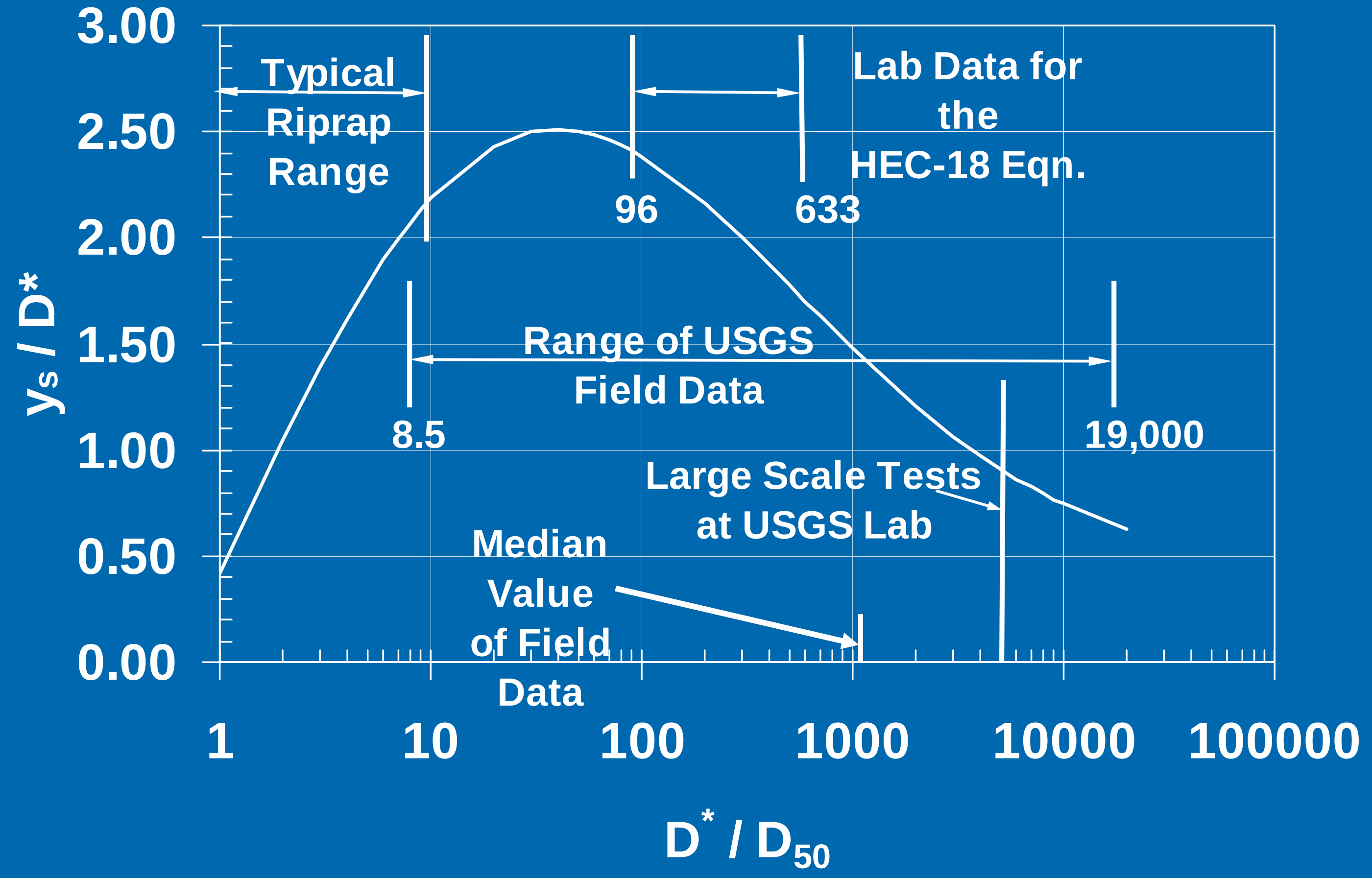
Bed Forms



Section Break

Test Results

Sheppard's Scour Equations



November 2005

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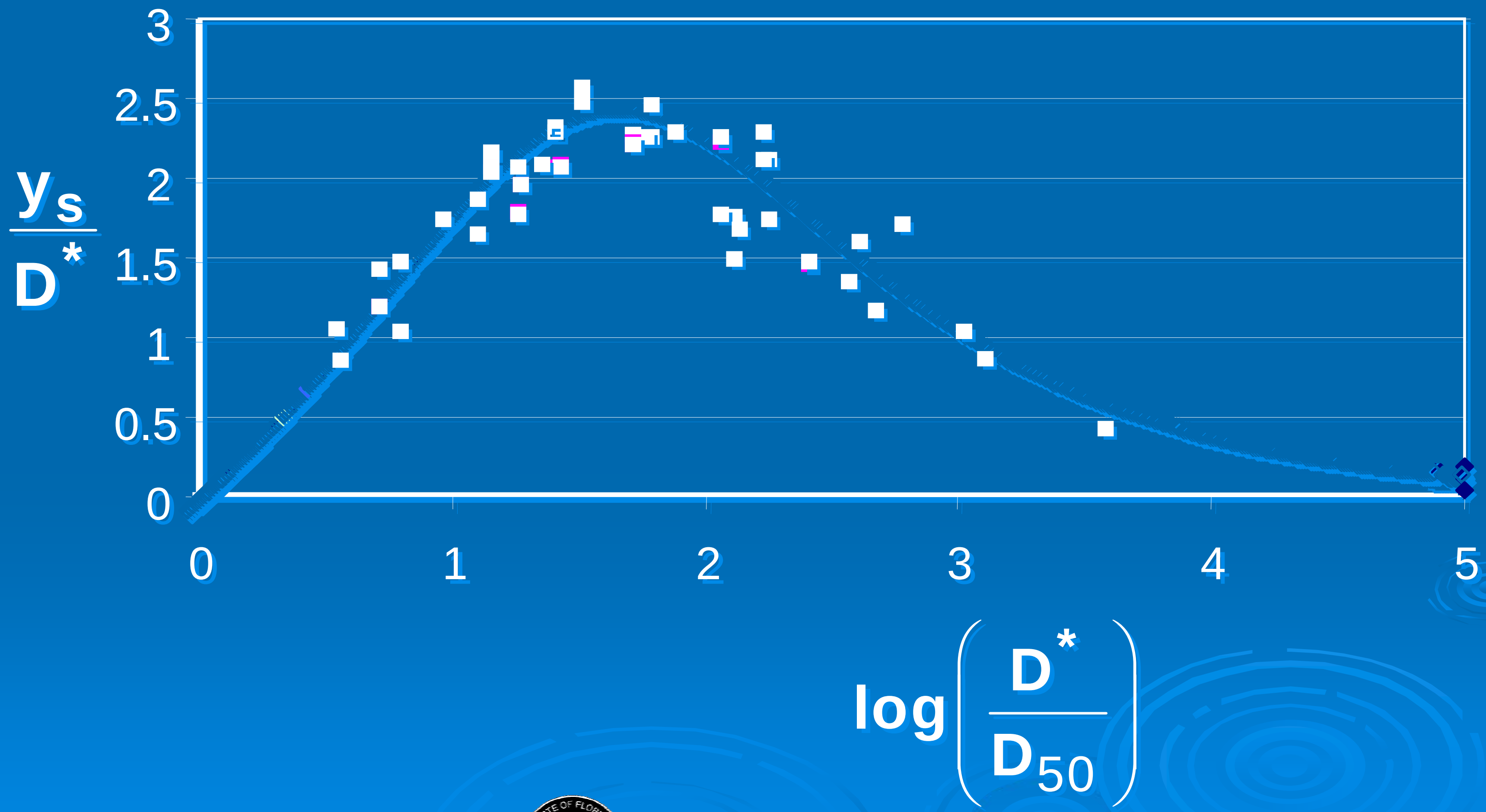
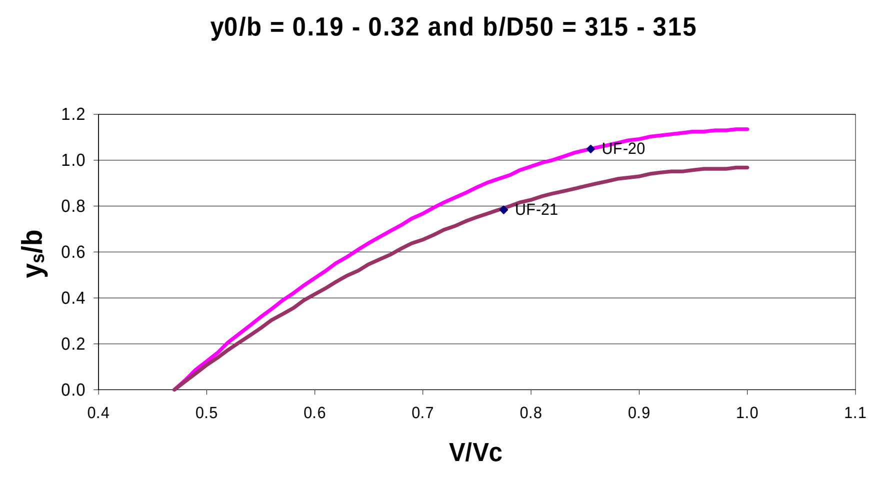
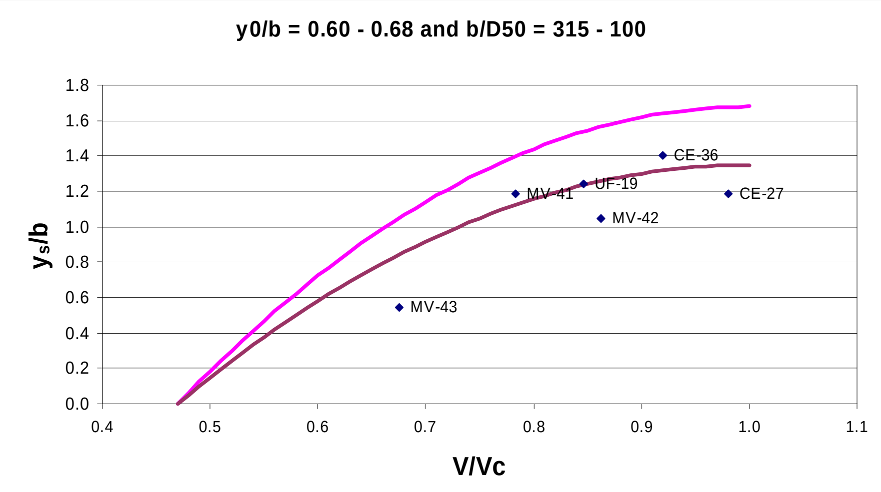
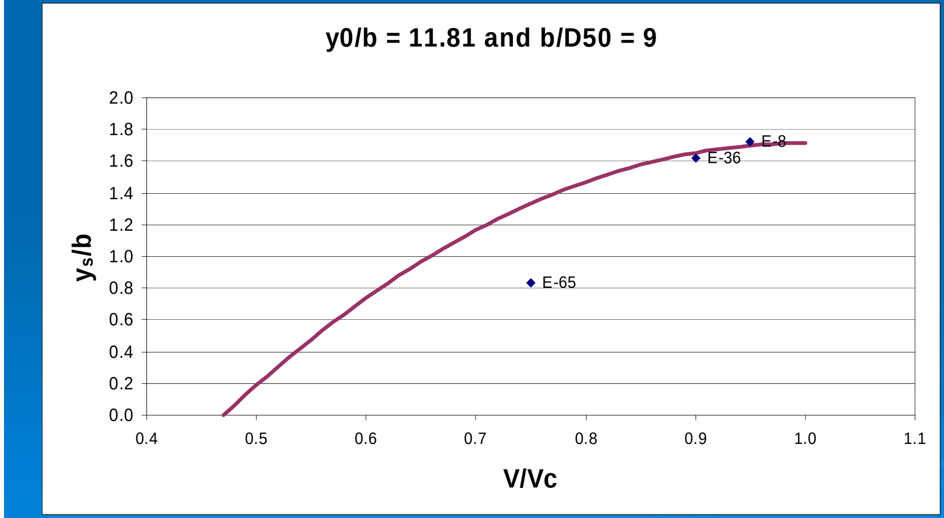
For $0.9 \le \dfrac{V}{V_c} < 1.0$ and $\dfrac{y_0}{D^*} \ge 2.0$

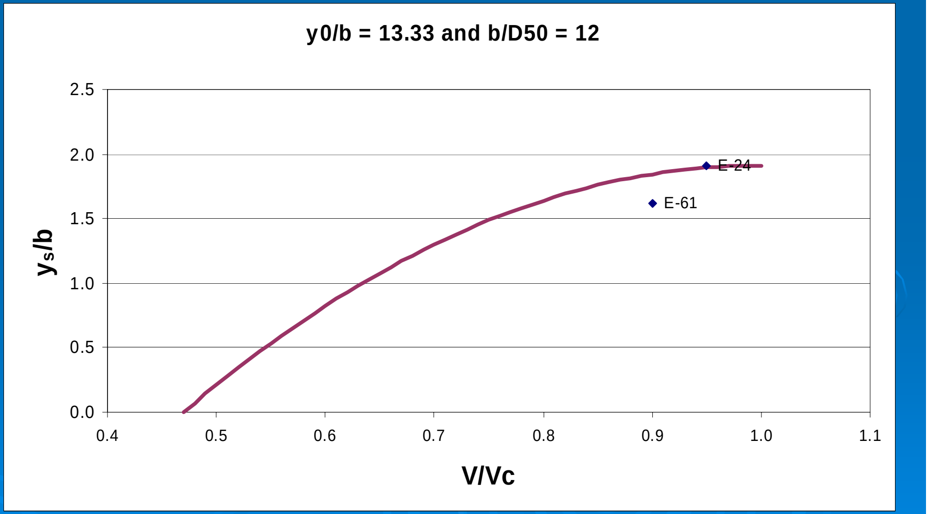


Predicted and Measured Laboratory Data

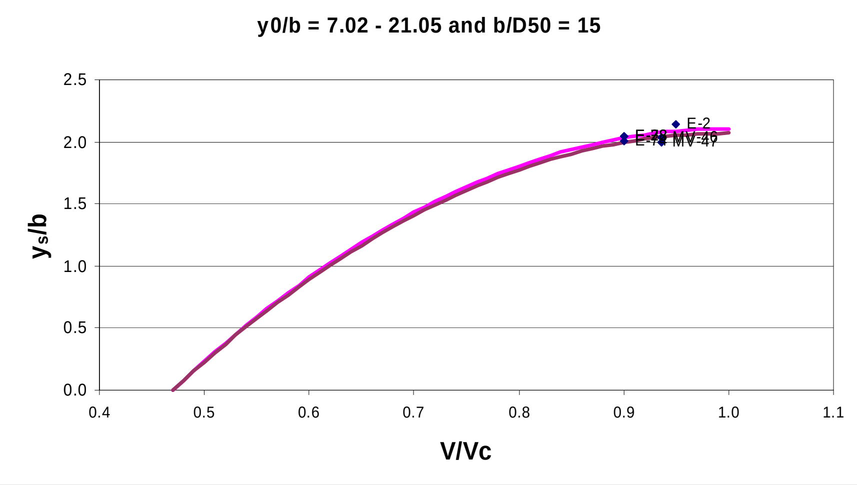

y0/b = 0.19 - 0.32 and b/D50 = 315 - 315

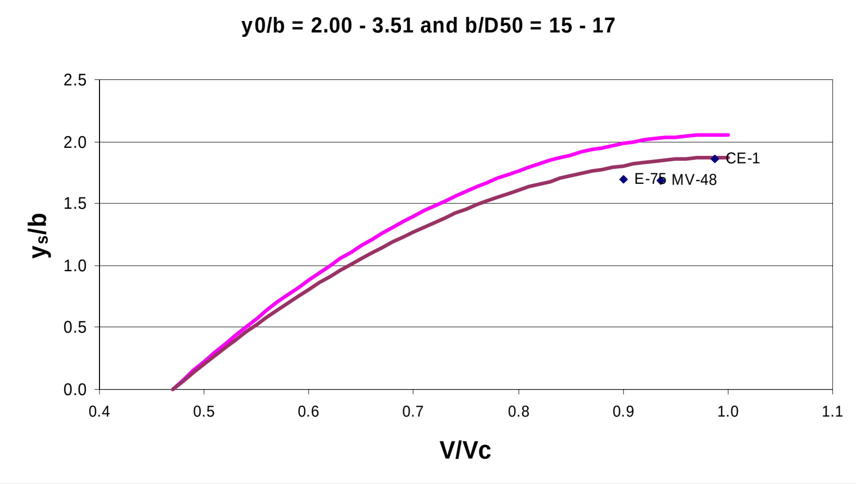

y0/b = 0.60 - 0.68 and b/D50 = 315 - 100

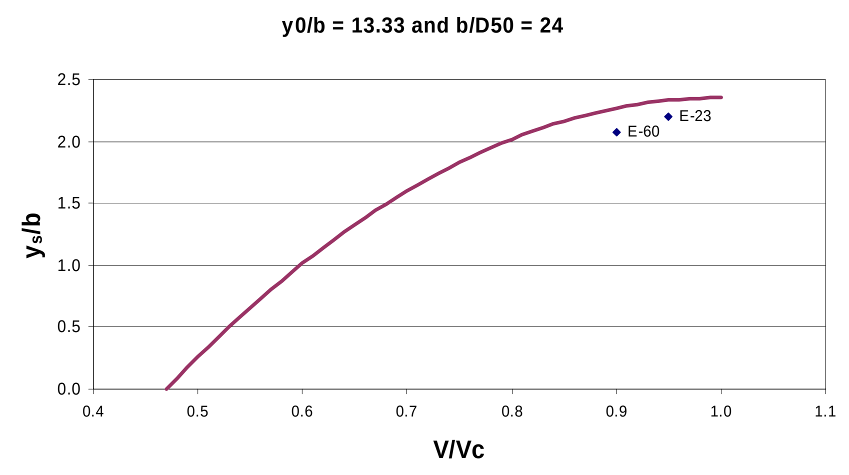

y0/b = 11.81 and b/D50 = 9

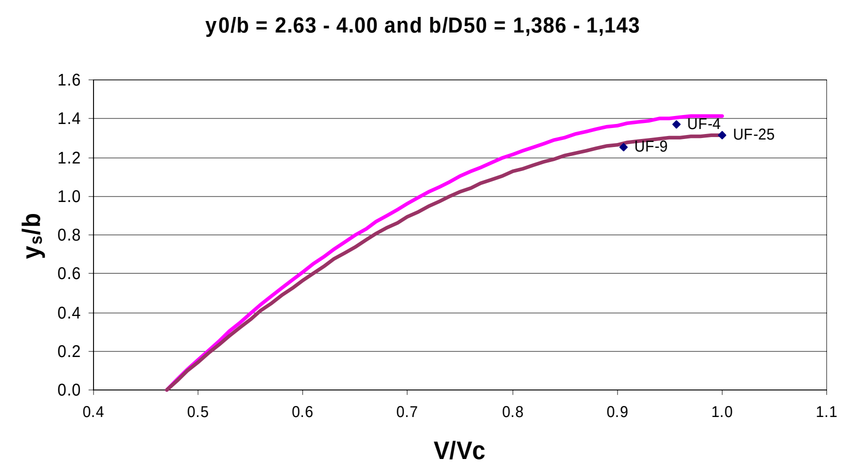

y0/b = 13.33 and b/D50 = 12

Predicted and Measured Laboratory Data

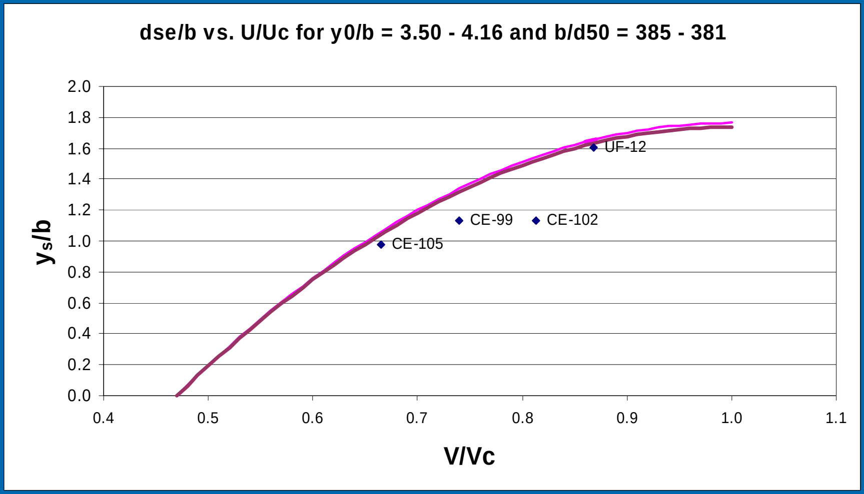

y0/b = 7.02 - 21.05 and b/D50 = 15

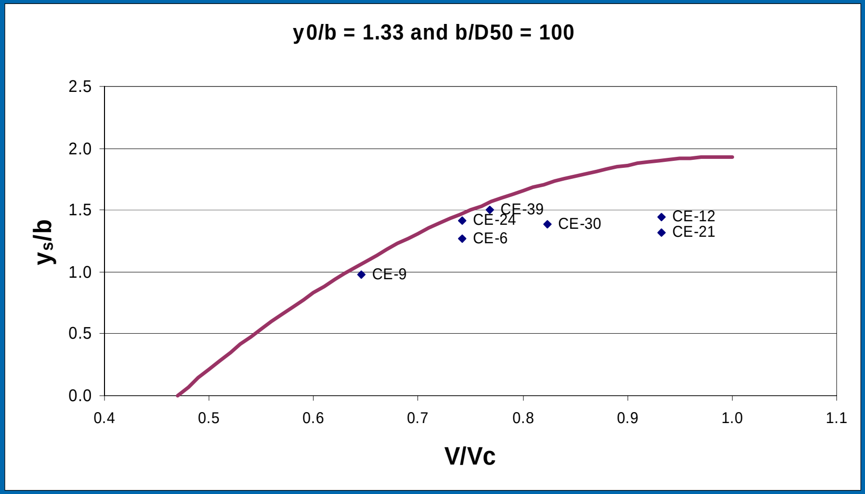

y0/b = 2.00 - 3.51 and b/D50 = 15 - 17

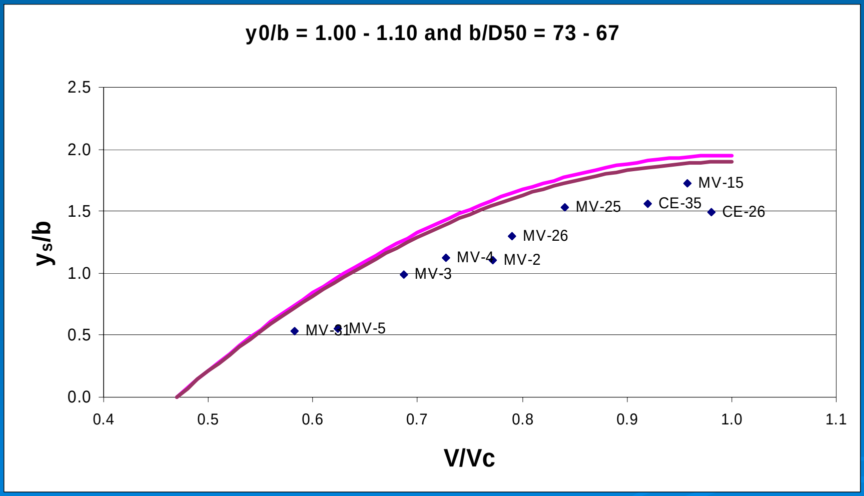

y0/b = 13.33 and b/D50 = 24

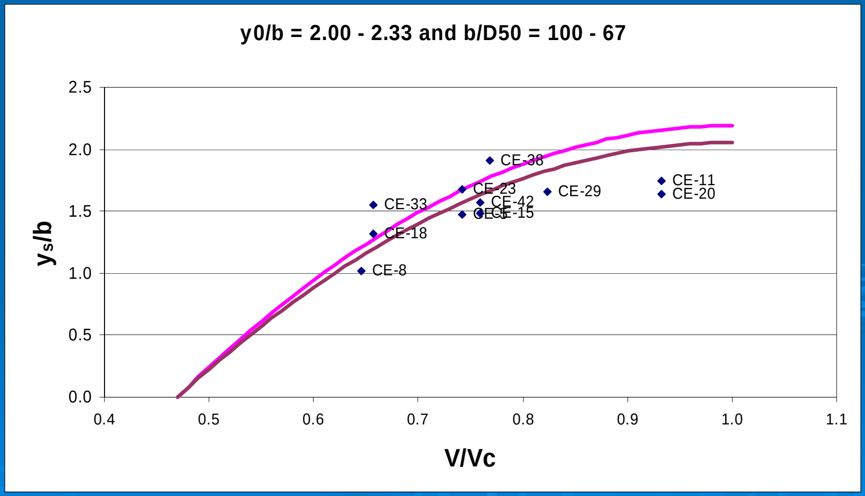

y0/b = 2.63 - 4.00 and b/D50 = 1,386 - 1,143

Predicted and Measured Laboratory Data

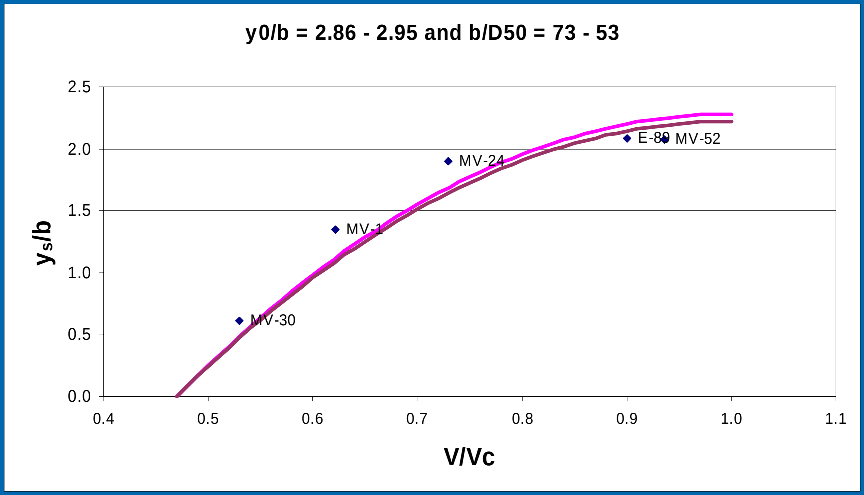

dse/b vs. U/Uc for y0/b = 3.50 - 4.16 and b/d50 = 385 - 381

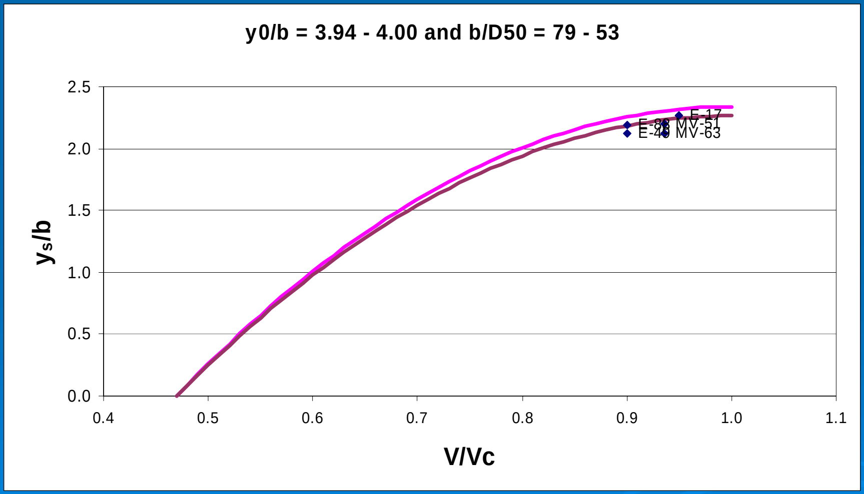

y0/b = 1.33 and b/D50 = 100

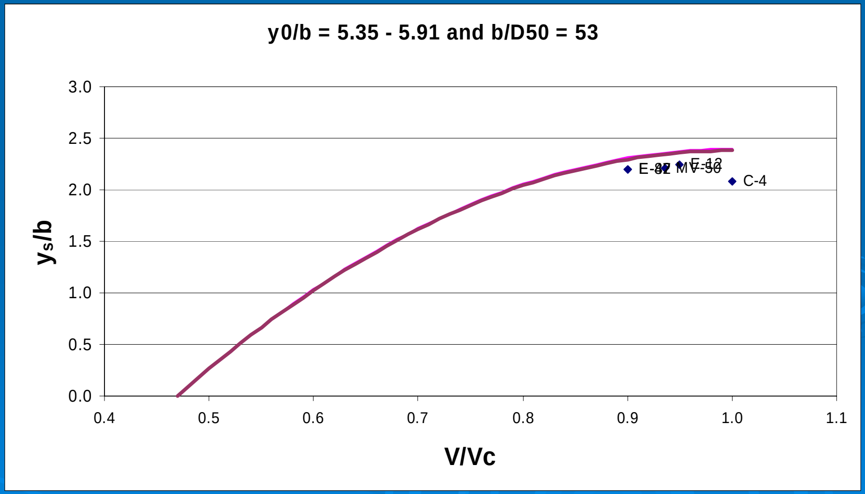

y0/b = 1.00 - 1.10 and b/D50 = 73 - 67


y0/b = 2.00 - 2.33 and b/D50 = 100 - 67

Predicted and Measured Laboratory Data


y0/b = 2.86 - 2.95 and b/D50 = 73 - 53


y0/b = 3.94 - 4.00 and b/D50 = 79 - 53


y0/b = 5.35 - 5.91 and b/D50 = 53

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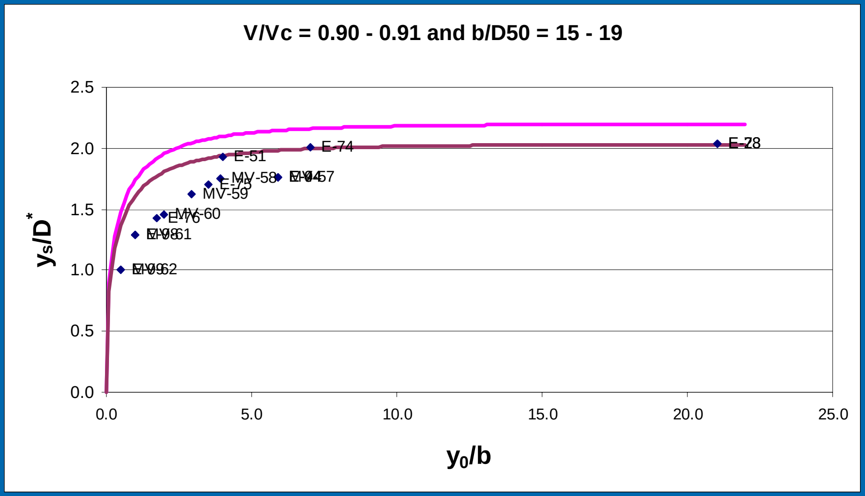
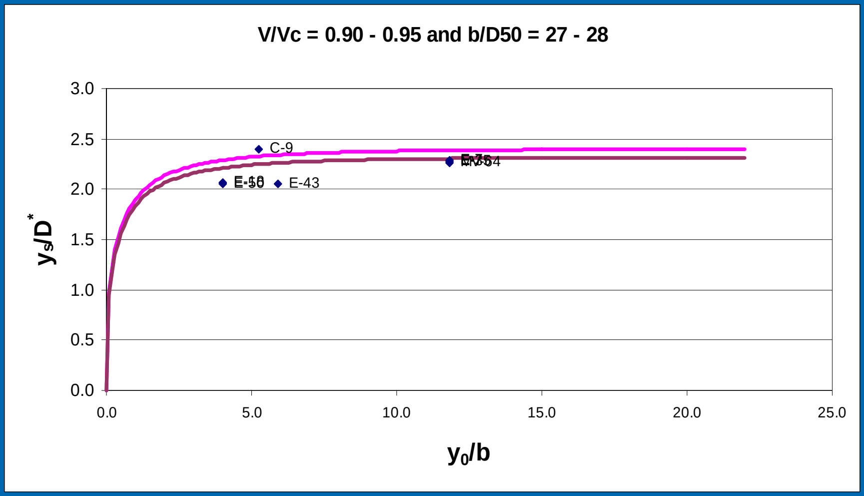
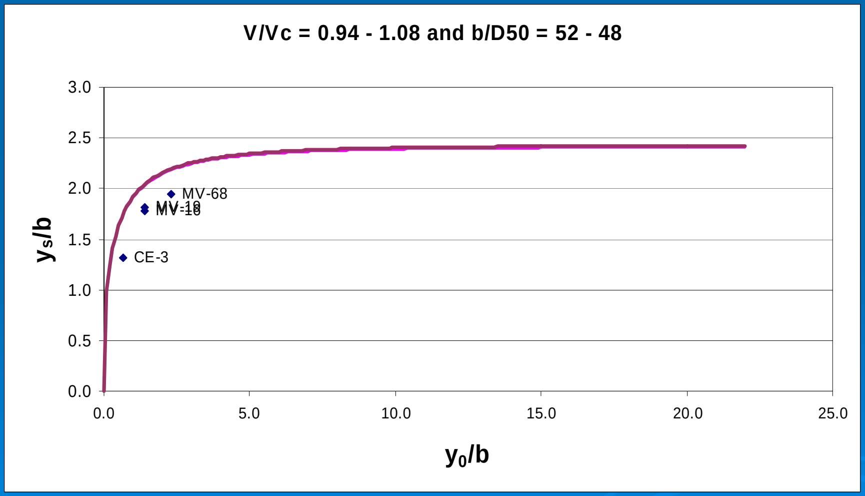
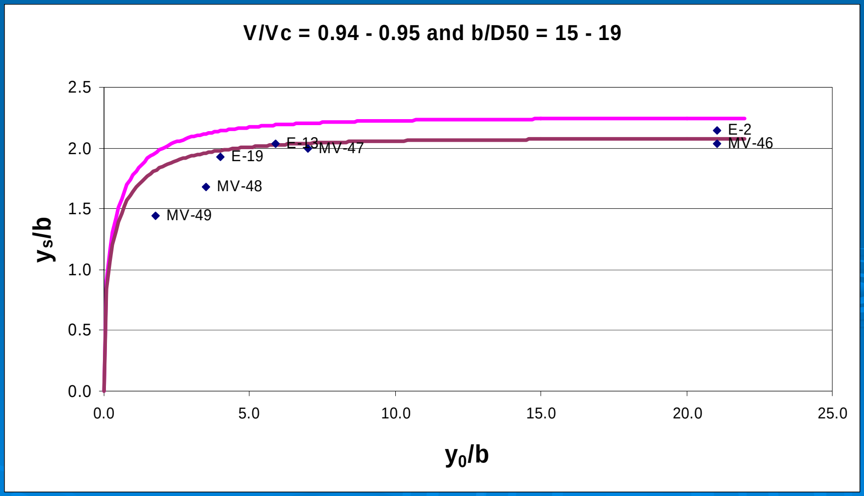
Predicted and Measured Laboratory Data


V/Vc = 0.90 - 0.91 and b/D50 = 15 - 19


V/Vc = 0.90 - 0.95 and b/D50 = 27 - 28


V/Vc = 0.94 - 1.08 and b/D50 = 52 - 48


V/Vc = 0.94 - 0.95 and b/D50 = 15 - 19

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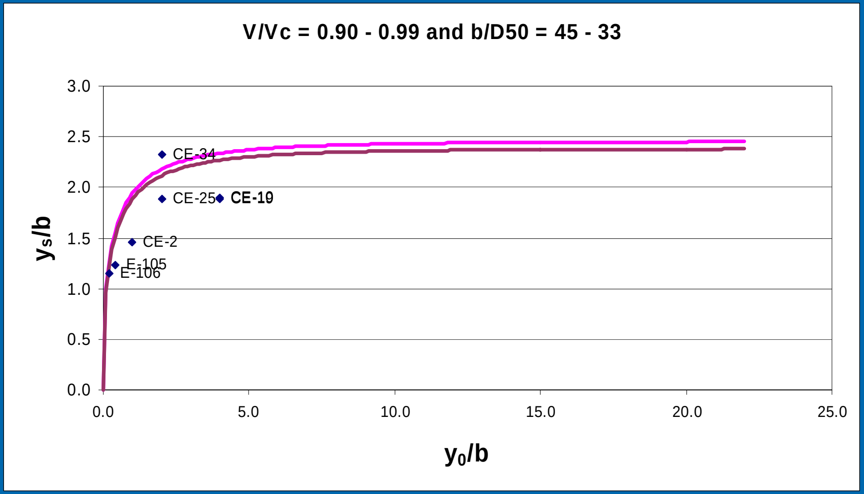
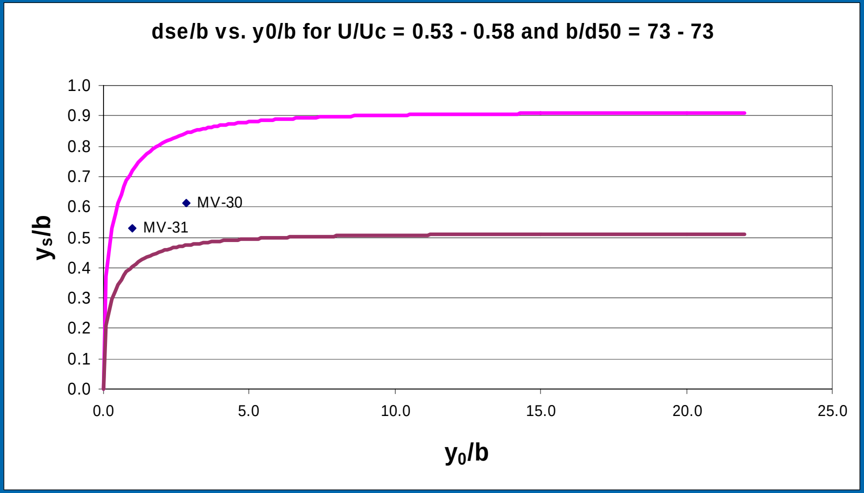
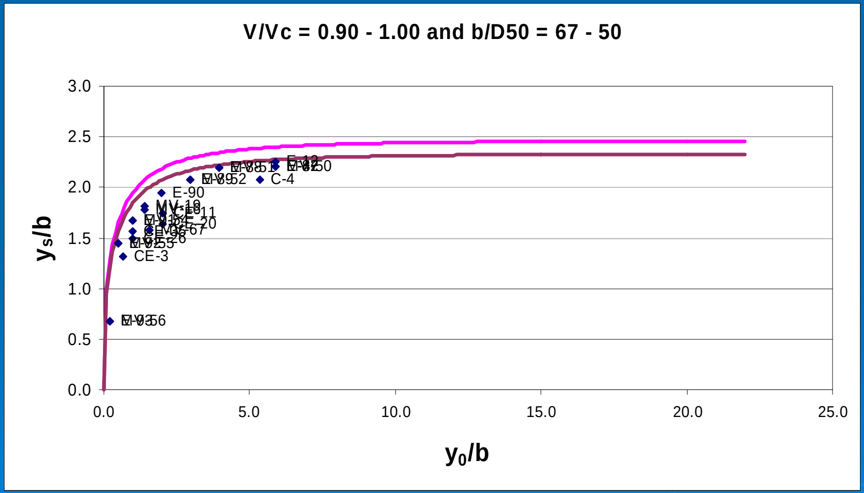
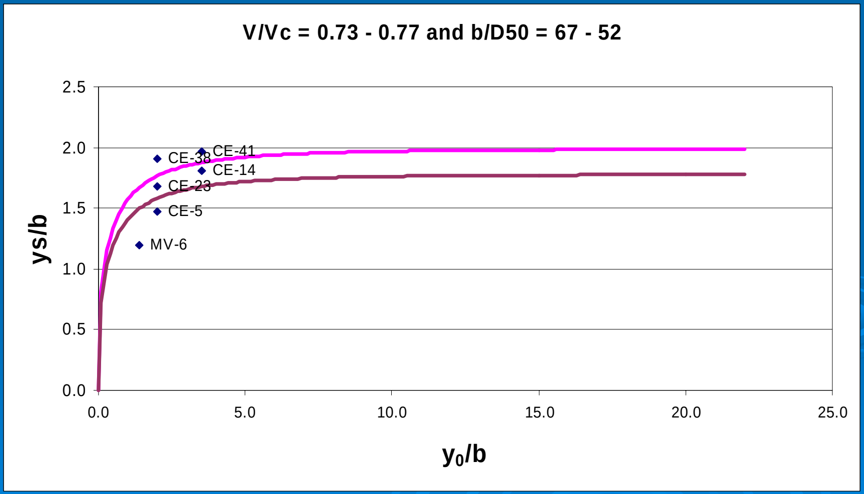
Predicted and Measured Laboratory Data

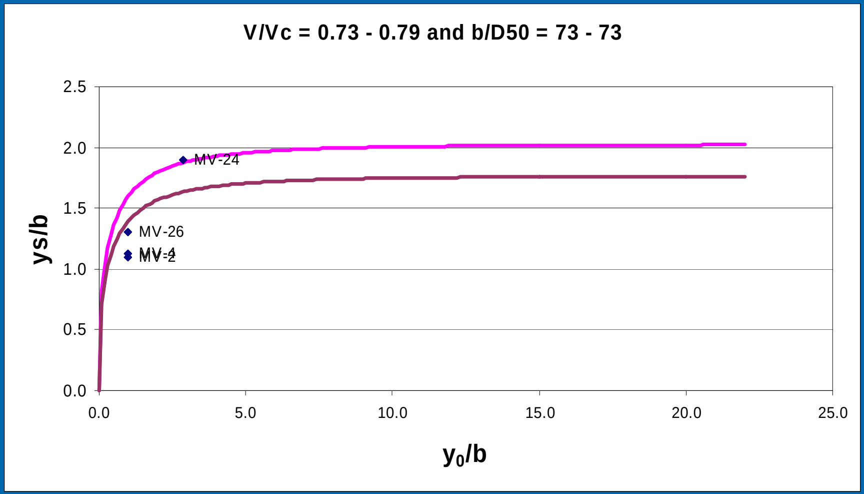

V/Vc = 0.90 - 0.99 and b/D50 = 45 - 33

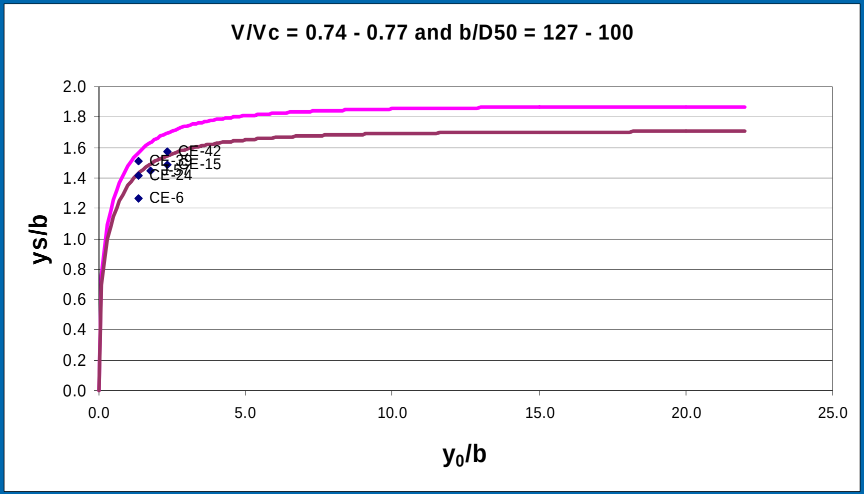

dse/b vs. y0/b for U/Uc = 0.53 - 0.58 and b/d50 = 73 - 73

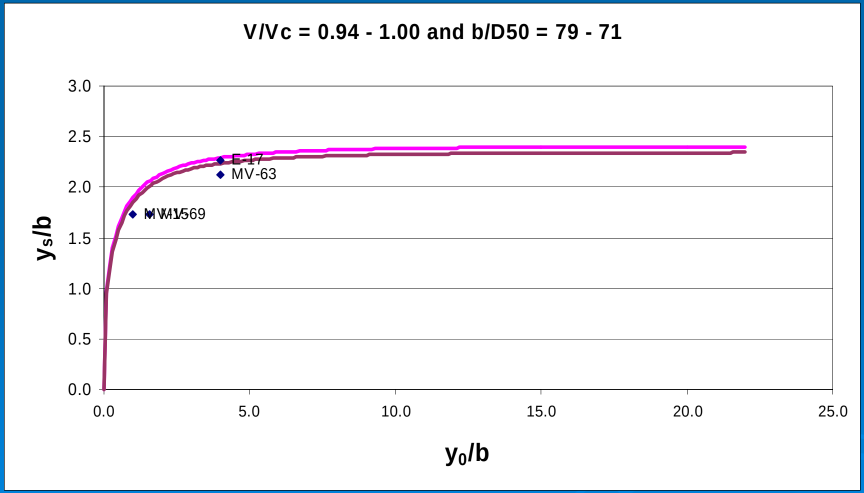

V/Vc = 0.90 - 1.00 and b/D50 = 67 - 50

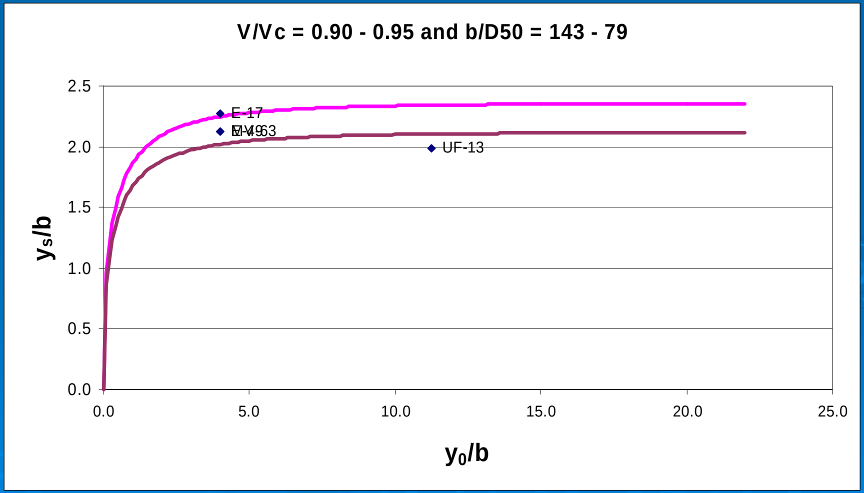

V/Vc = 0.73 - 0.77 and b/D50 = 67 - 52

Predicted and Measured Laboratory Data

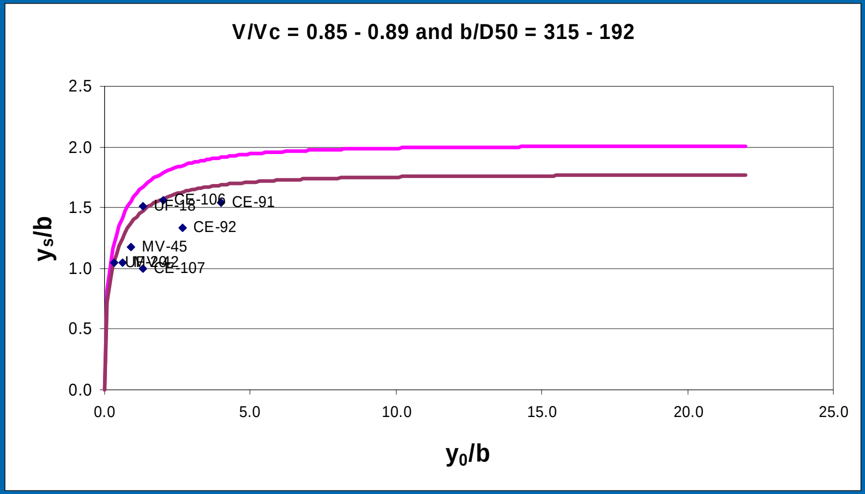




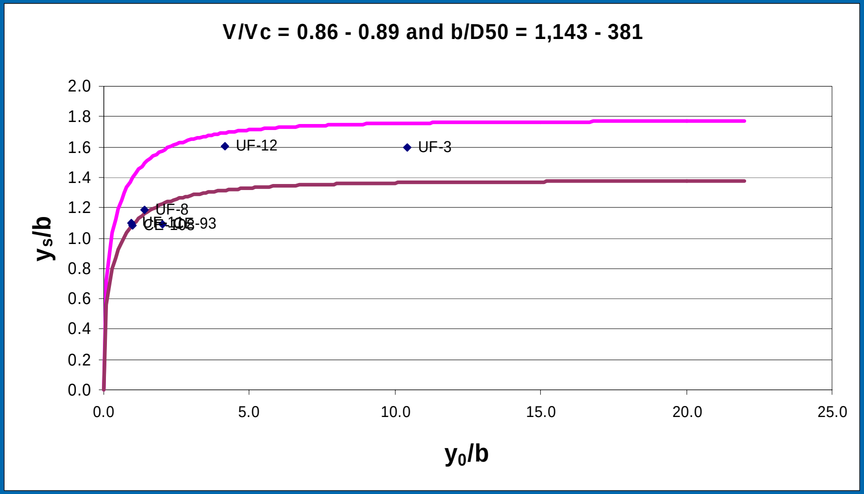




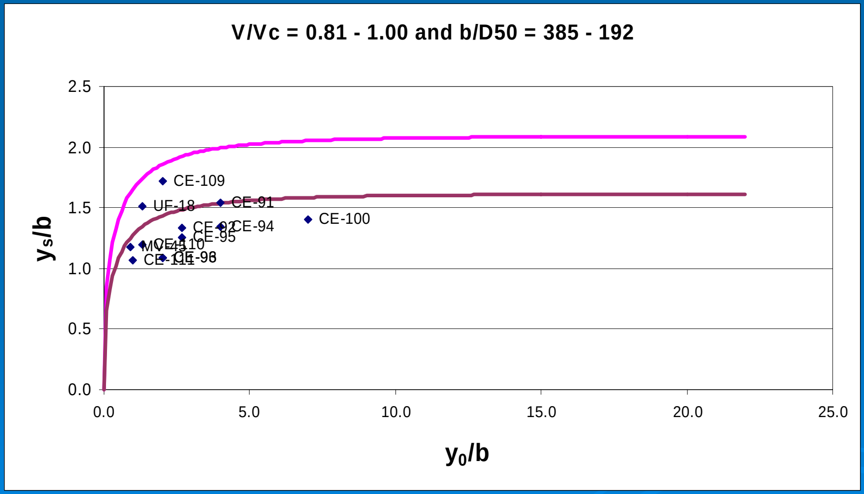
Predicted and Measured Laboratory Data



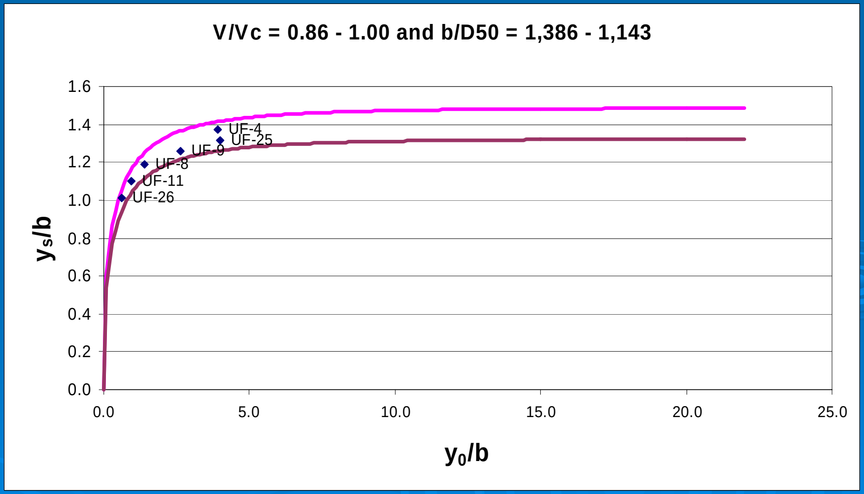
V/Vc = 0.85 - 0.89 and b/D50 = 315 - 192



V/Vc = 0.86 - 0.89 and b/D50 = 1,143 - 381



V/Vc = 0.81 - 1.00 and b/D50 = 385 - 192



V/Vc = 0.86 - 1.00 and b/D50 = 1,386 - 1,143

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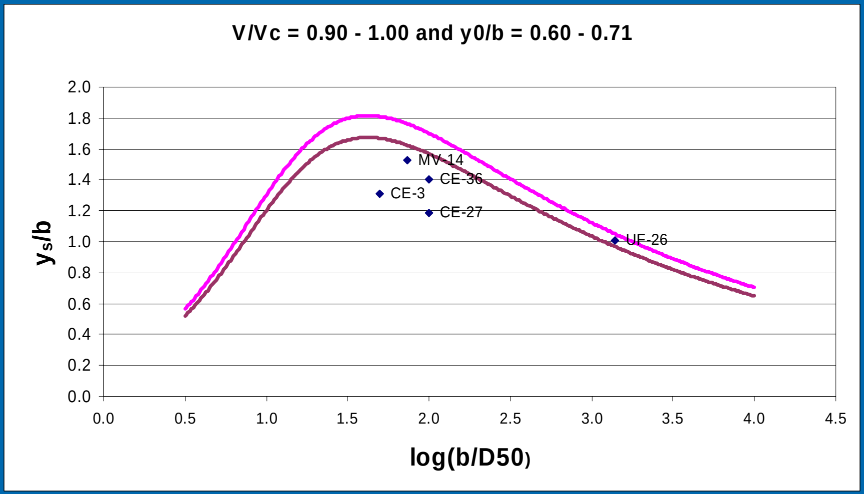
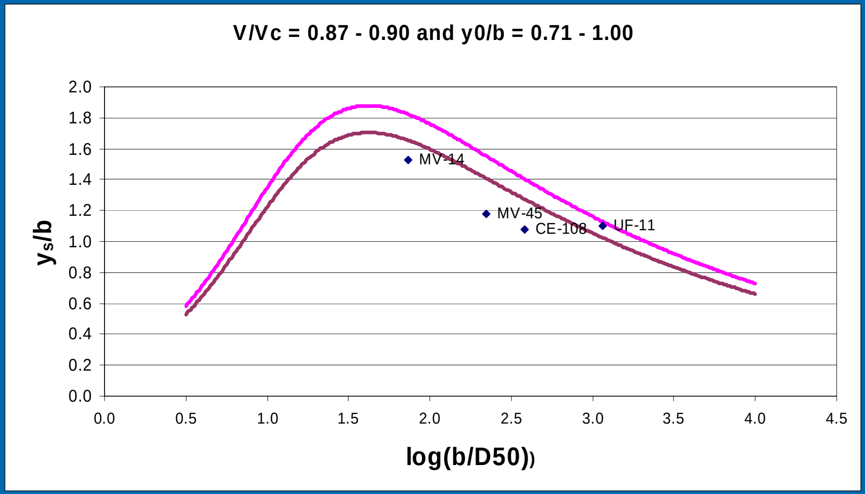
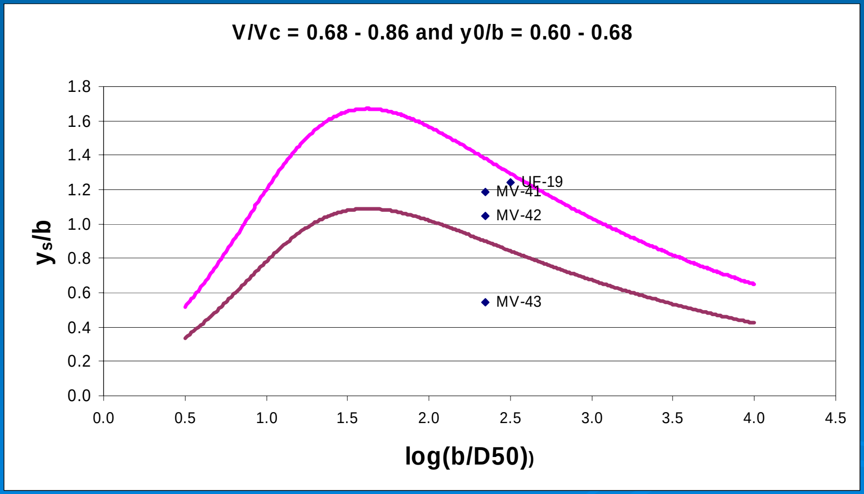
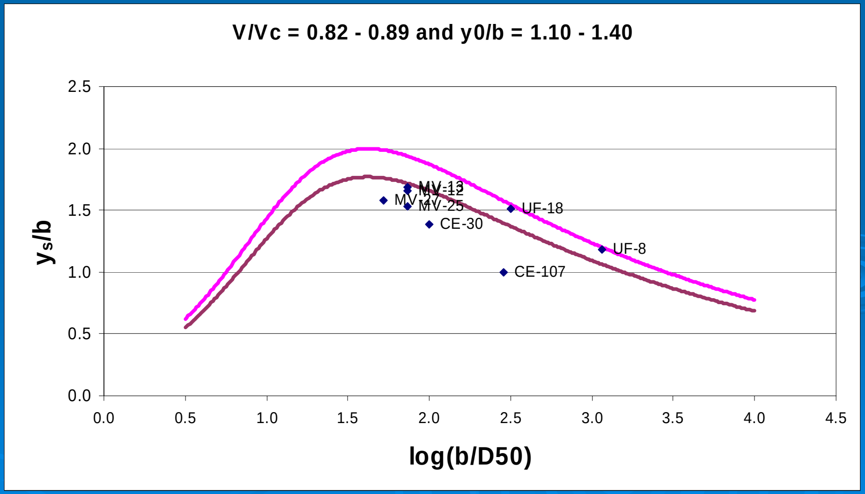
Predicted and Measured Laboratory Data

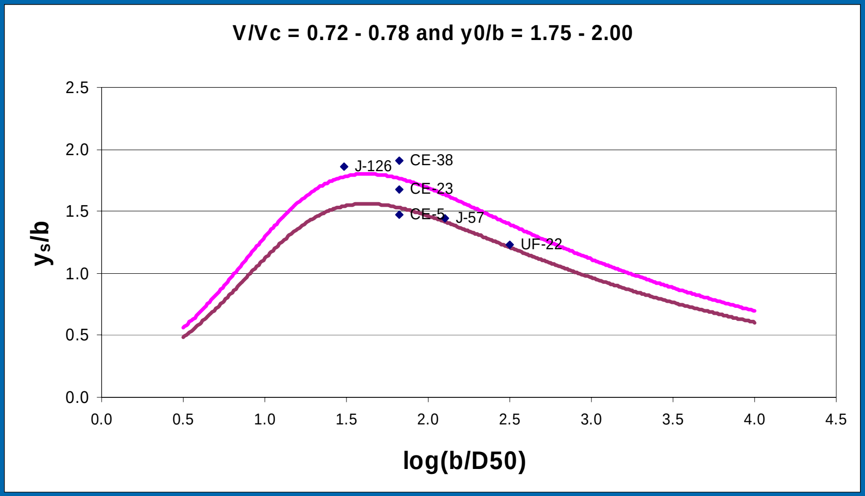


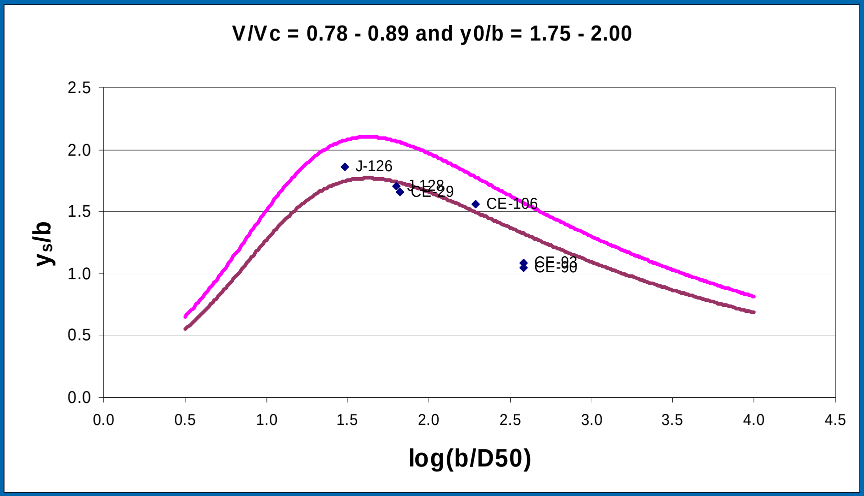


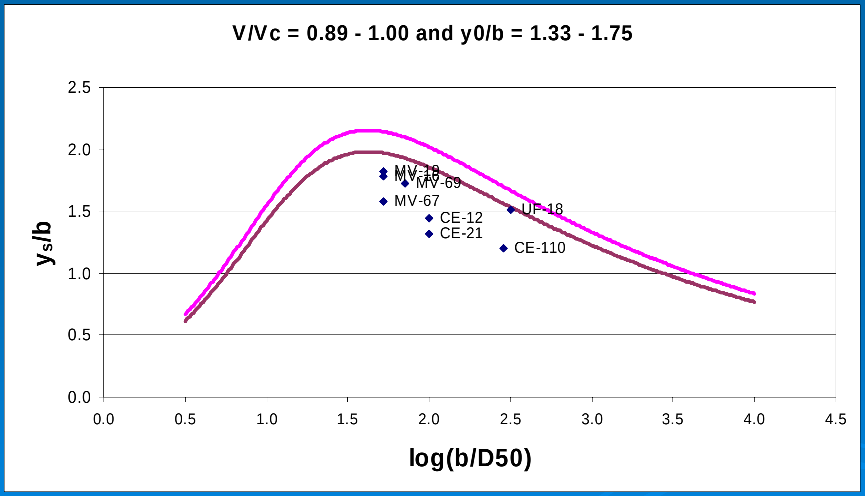


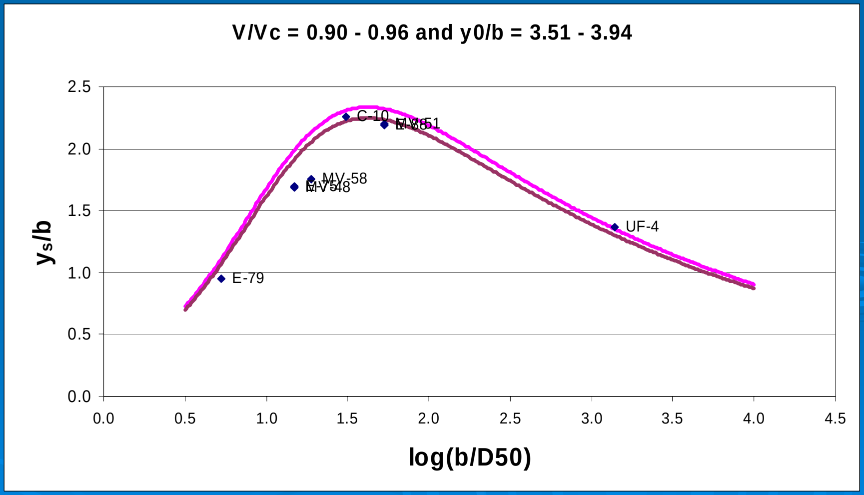


Predicted and Measured Laboratory Data









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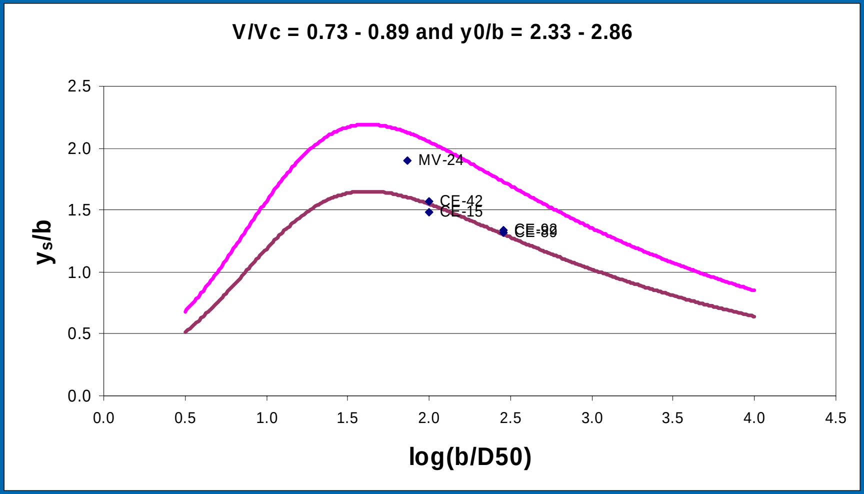
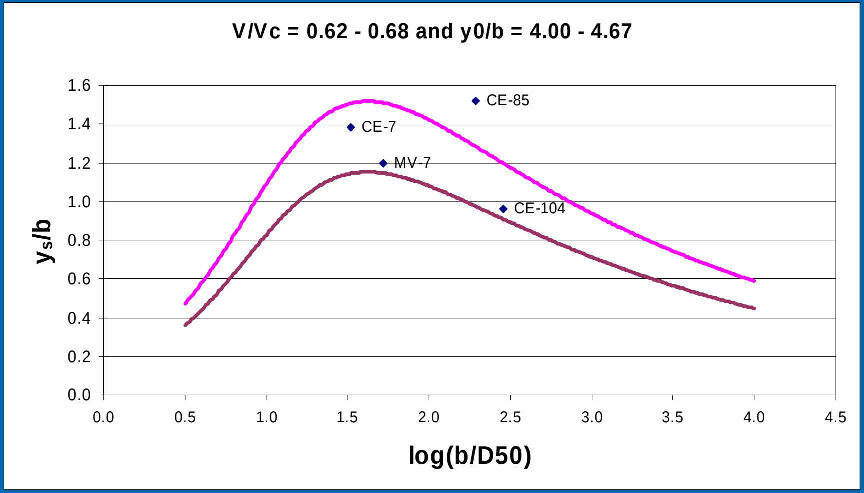
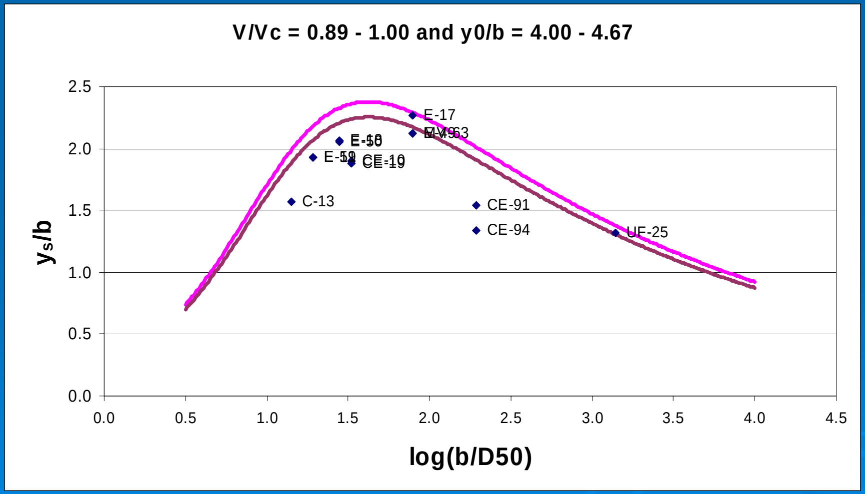
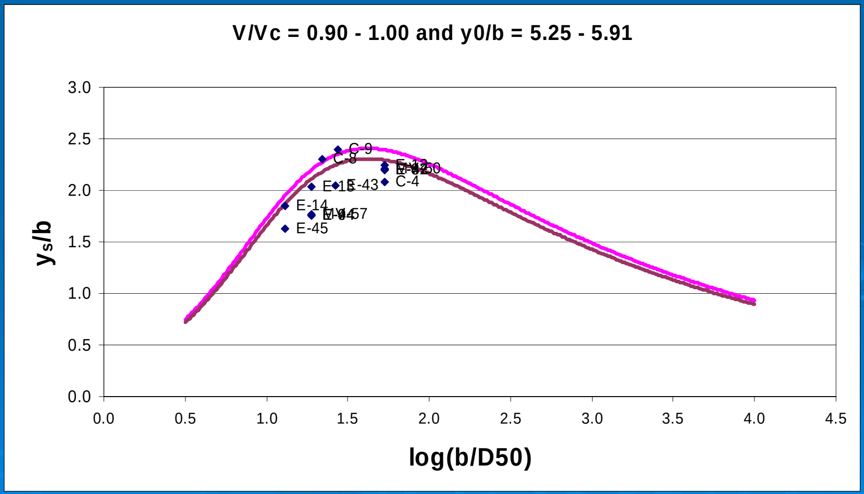
Predicted and Measured Laboratory Data


V/Vc = 0.73 - 0.89 and y0/b = 2.33 - 2.86


V/Vc = 0.62 - 0.68 and y0/b = 4.00 - 4.67


V/Vc = 0.89 - 1.00 and y0/b = 4.00 - 4.67


V/Vc = 0.90 - 1.00 and y0/b = 5.25 - 5.91

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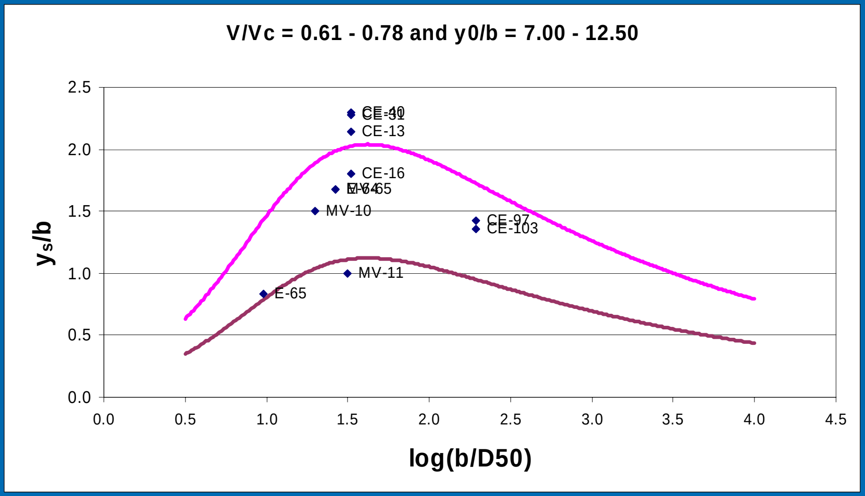
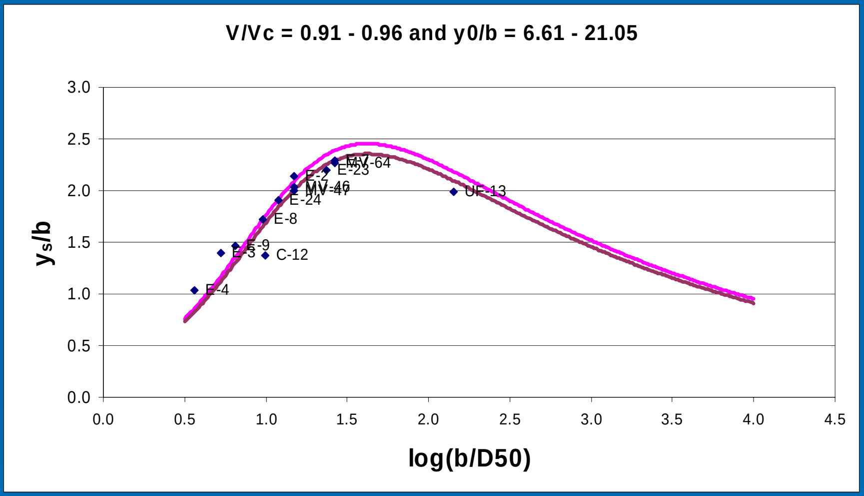
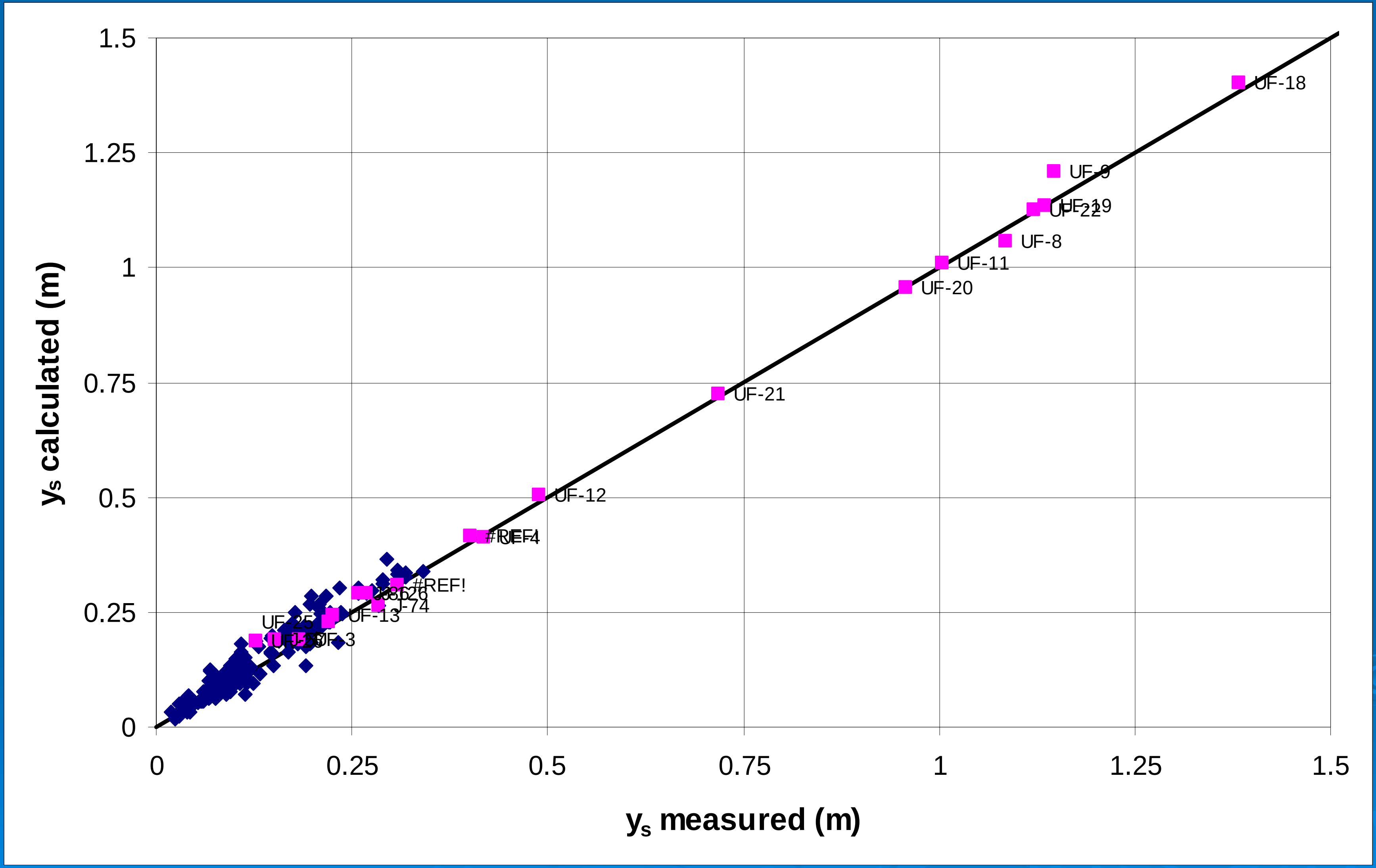
Predicted and Measured Laboratory Data





Predicted Versus Measured Laboratory Data



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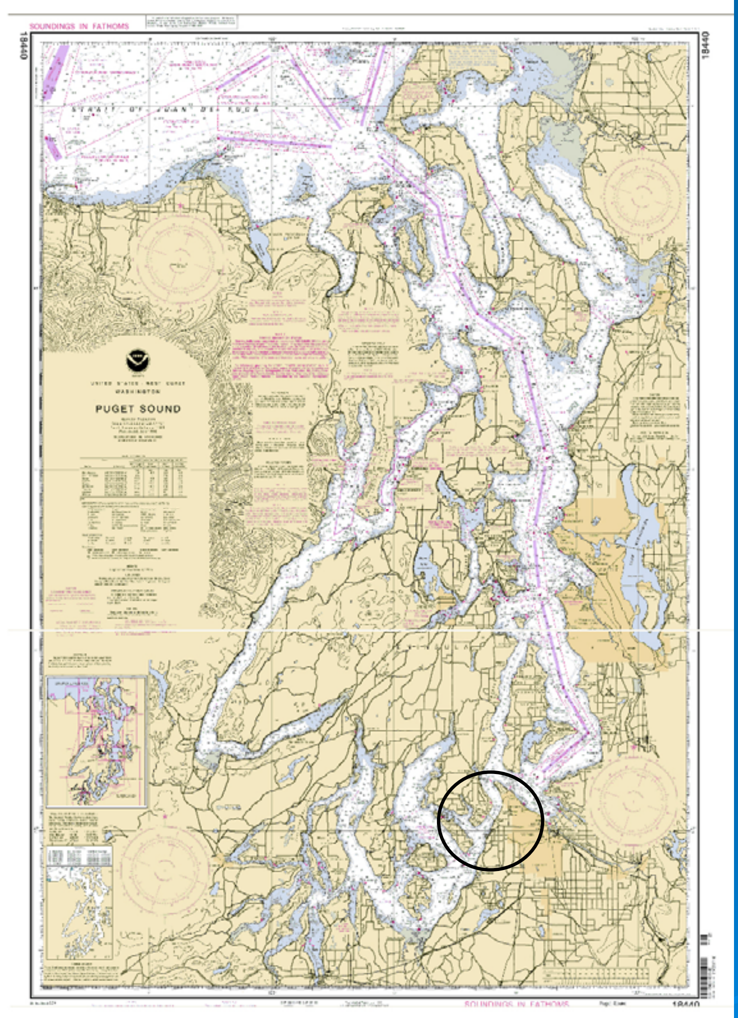
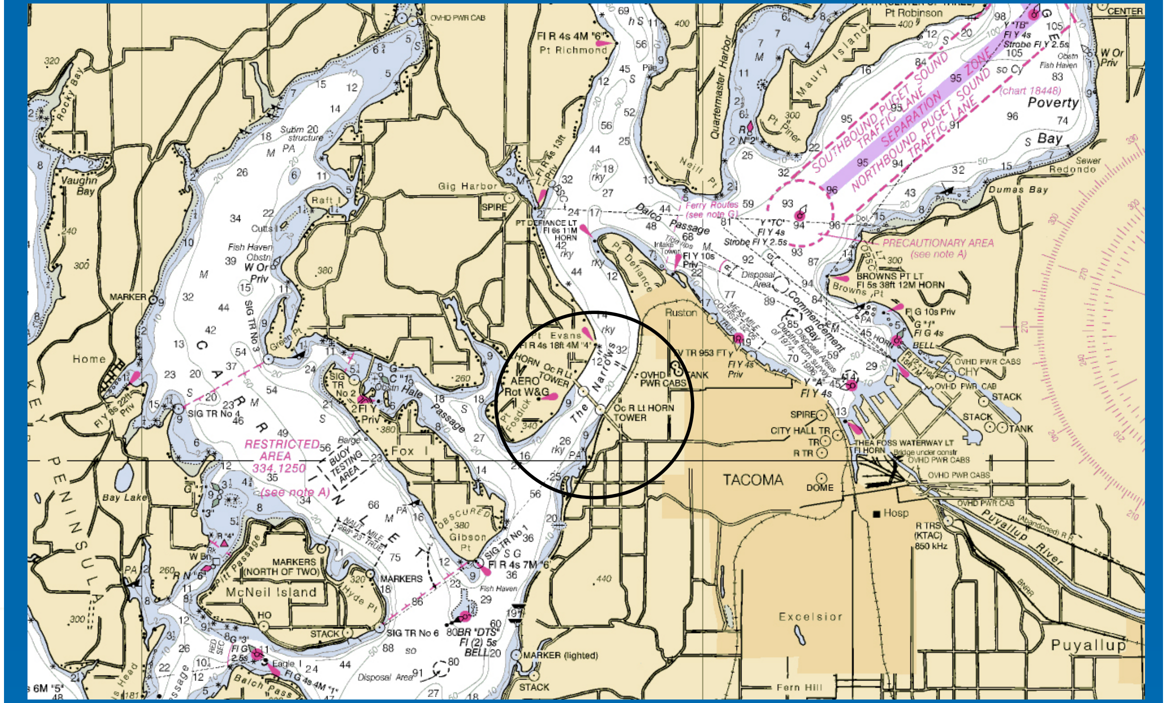
Prototype Pier

Tacoma Narrows Bridge
Tacoma, Washington

Tacoma Narrows Bridges





Existing and New Tacoma Narrows Bridges

Existing and New Tacoma Narrows Bridges

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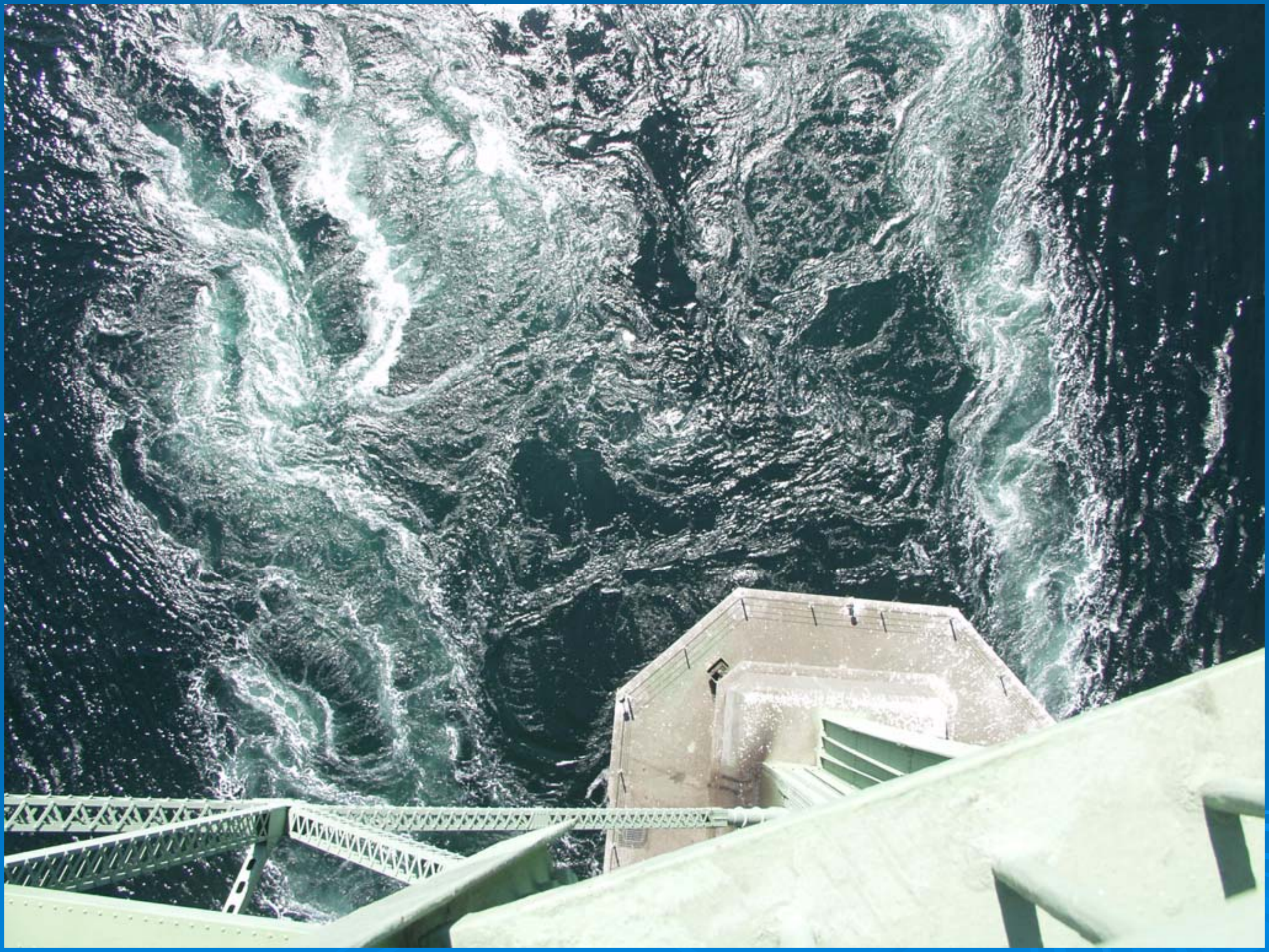
Existing and New Tacoma Narrows Bridges

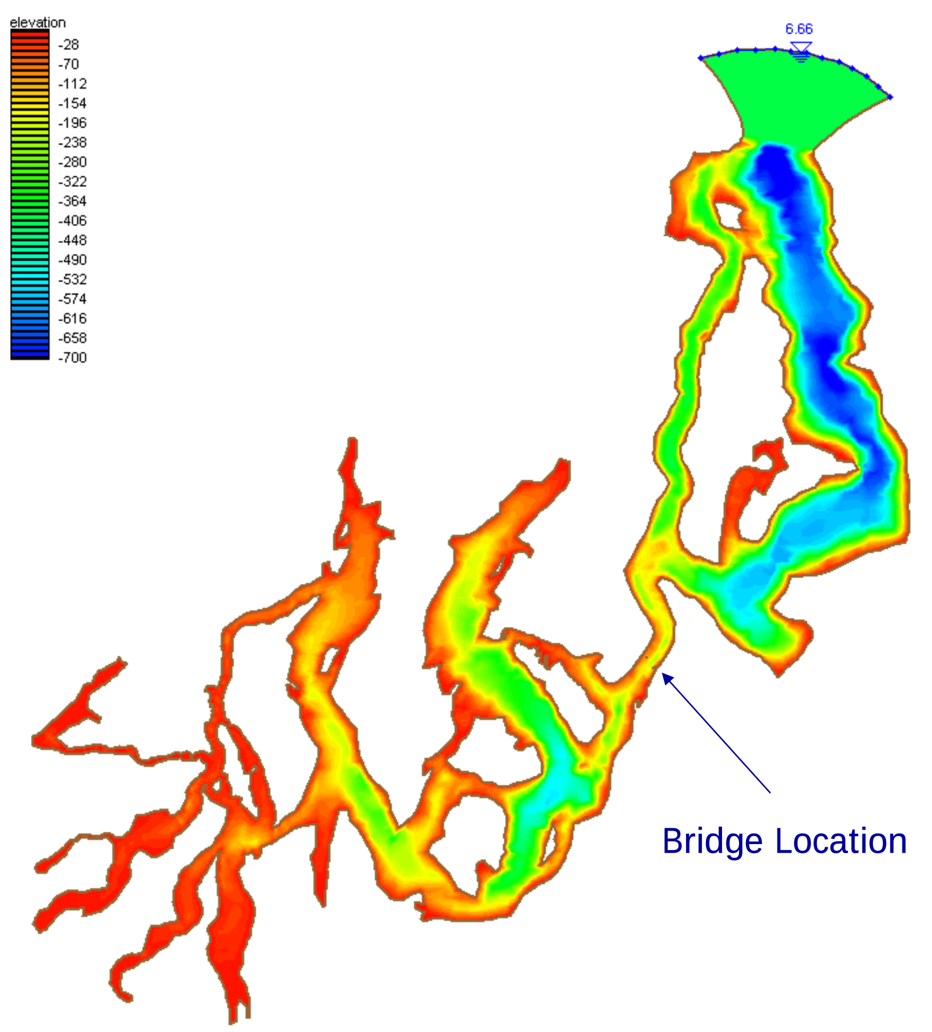


Wake Downstream of TN Bridge Pier

Flow and Sediment

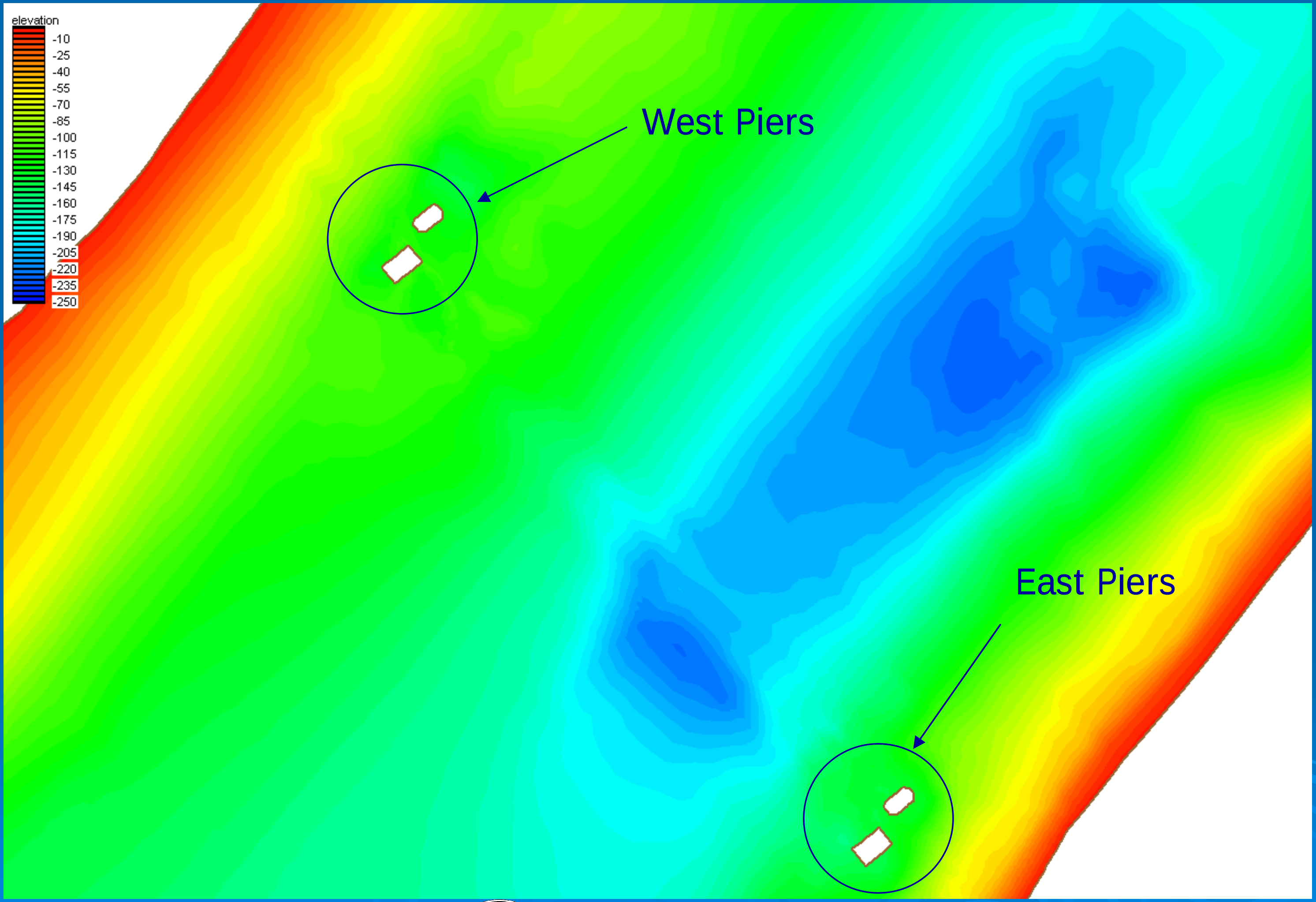
- Sediment
  - Fine sediment,
  - Large grain size distribution
- Design flow
  - Due to astronomical tides
  - Near design flow twice per month
  - Over 60 years of design flows

2D Depth-Averaged Flow Model

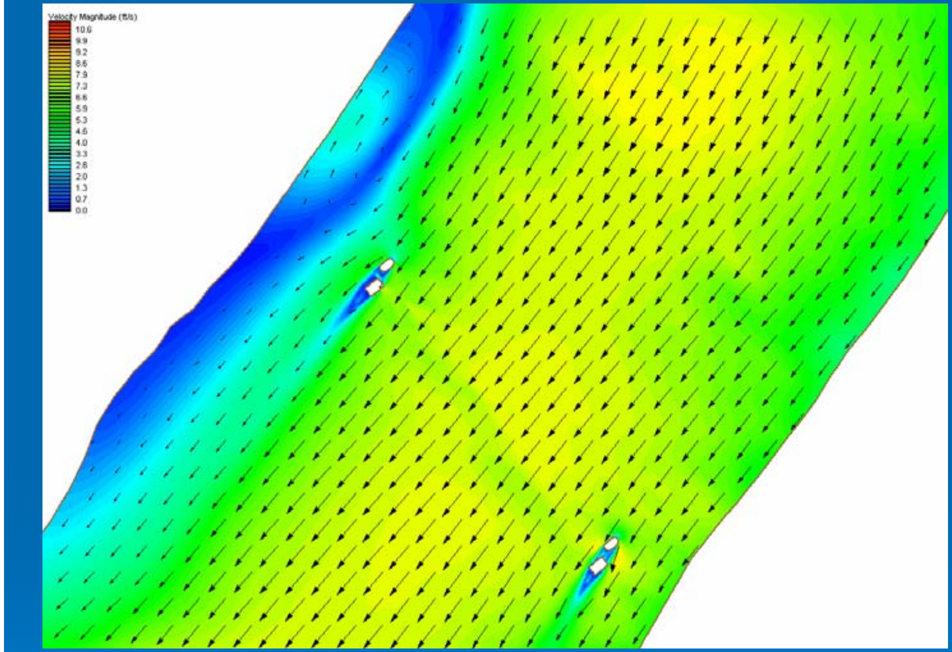


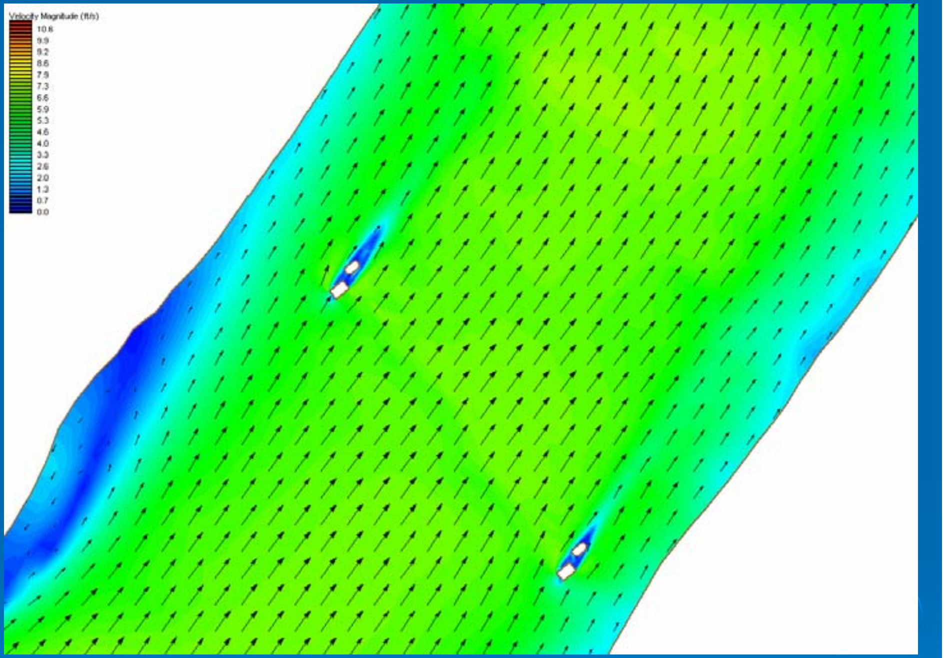
Bridge Location

2D Depth-Averaged Flow Model



2D Depth-Averaged Flow Model

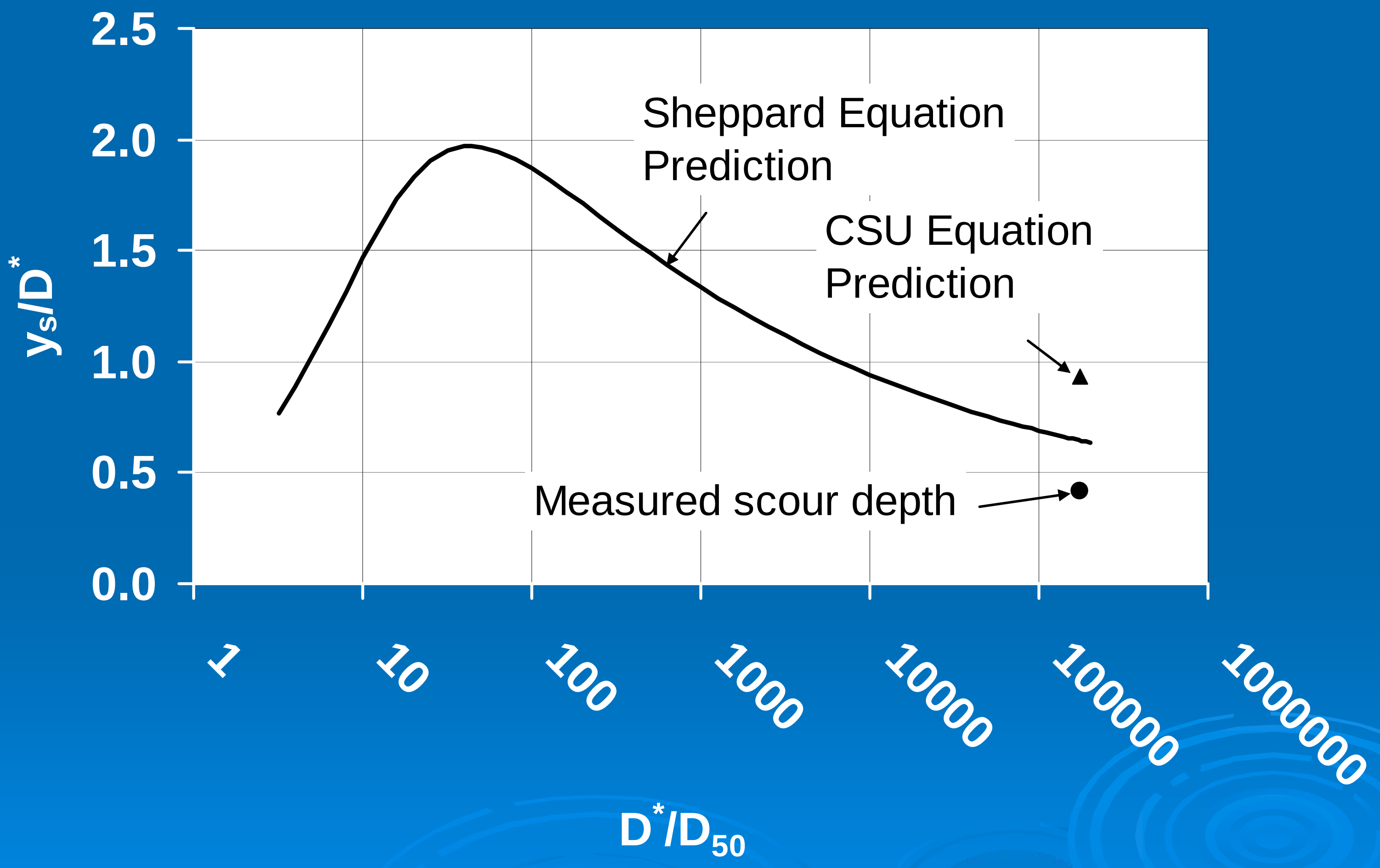




2D Depth-Averaged Flow Model

Event	Pier	Median Sediment Grain Diameter D_{50} (mm)	Flow	Water Depth (ft)	Flow Velocity (ft/s)	Computed Skew Angle (deg)	Prototype Effective Diameter (ft)
100 Year	East	0.15	Flood	126	**12.5**	16	96
		0.15	Ebb	123	9.1	20	94
	West	0.15	Flood	106	**11.1**	19	85
		0.15	Ebb	104	9.6	16.5	87
500 Year	East	0.15	Flood	125	11.7	16	96
		0.15	Ebb	121	9.9	20	94
	West	0.15	Flood	105	10.3	19	85
		0.15	Ebb	101	10	16.5	87
Check	East	0.15	Flood	126	15	16	96
		0.15	Edd	123	10.9	20	94
	West	0.15	Flood	106	13.4	19	85
		0.15	Ebb	104	11.4	16.5	87

Tacoma Narrows Bridge Pier



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Section Break

Local Scour at Piers with Complex Geometries

Methodology

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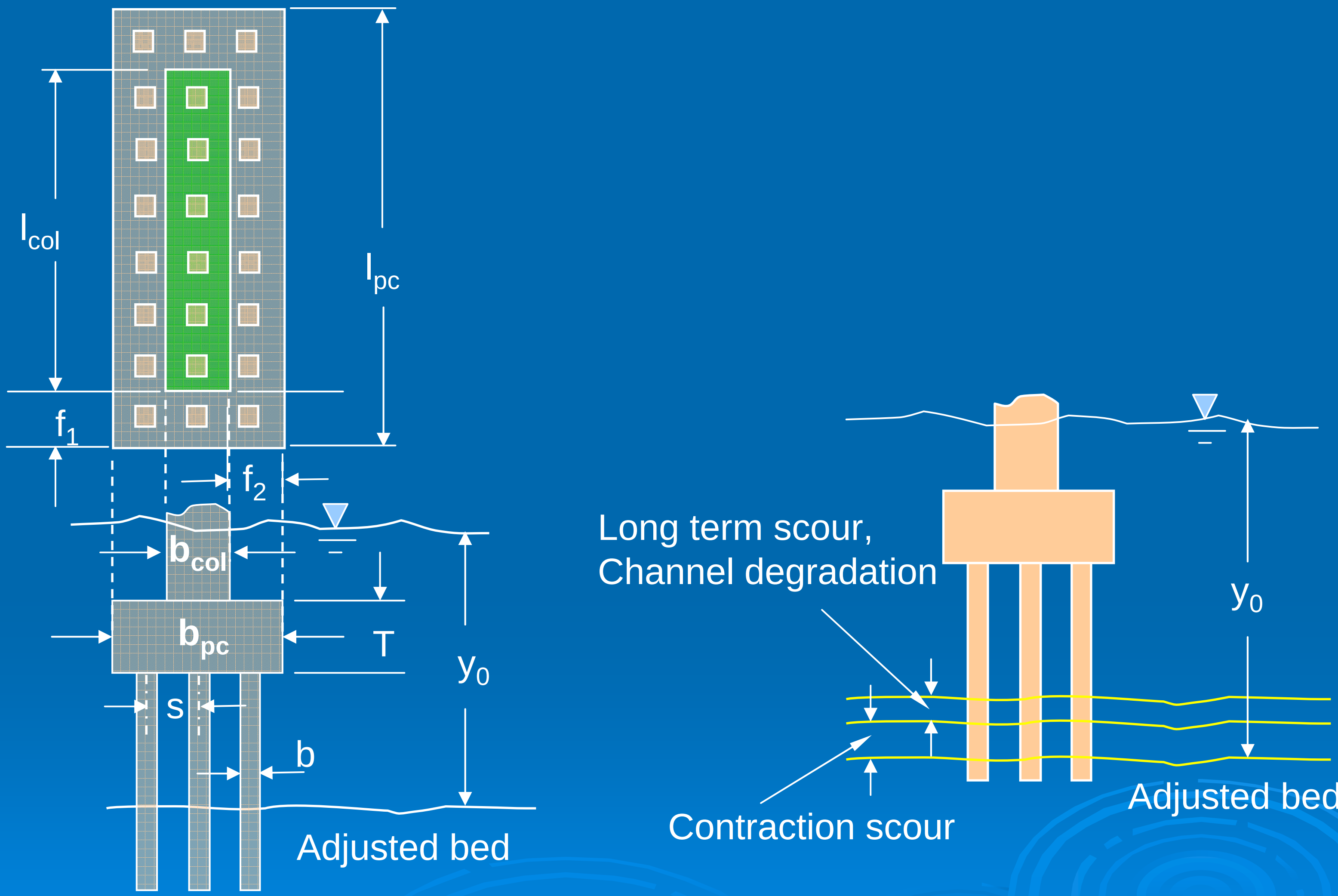
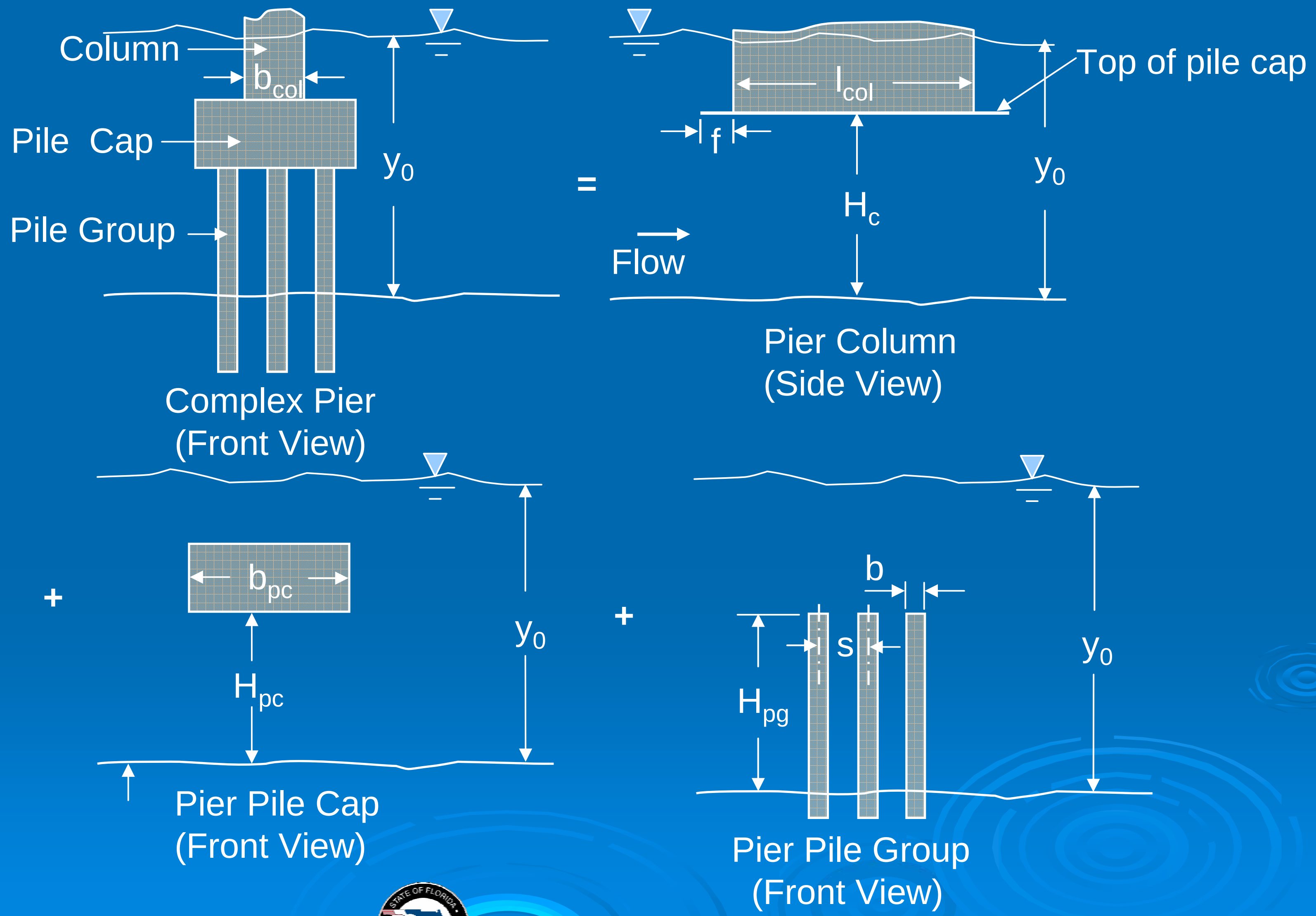
Complex Pier Geometries

- Many bridge piers have complex geometries
- Methodology presented here is suitable for piers that can be approximated by the pier shown in the following figures
- Physical model studies are recommended for piers that deviate significantly from the piers presented here

Complex Pier Definition Diagram



Complex Pier Scour Methodology



Complex Pier
(Front View)

Pier Column
(Side View)

Pier Pile Cap
(Front View)

Pier Pile Group
(Front View)

Complex Pier Classification

Case 1

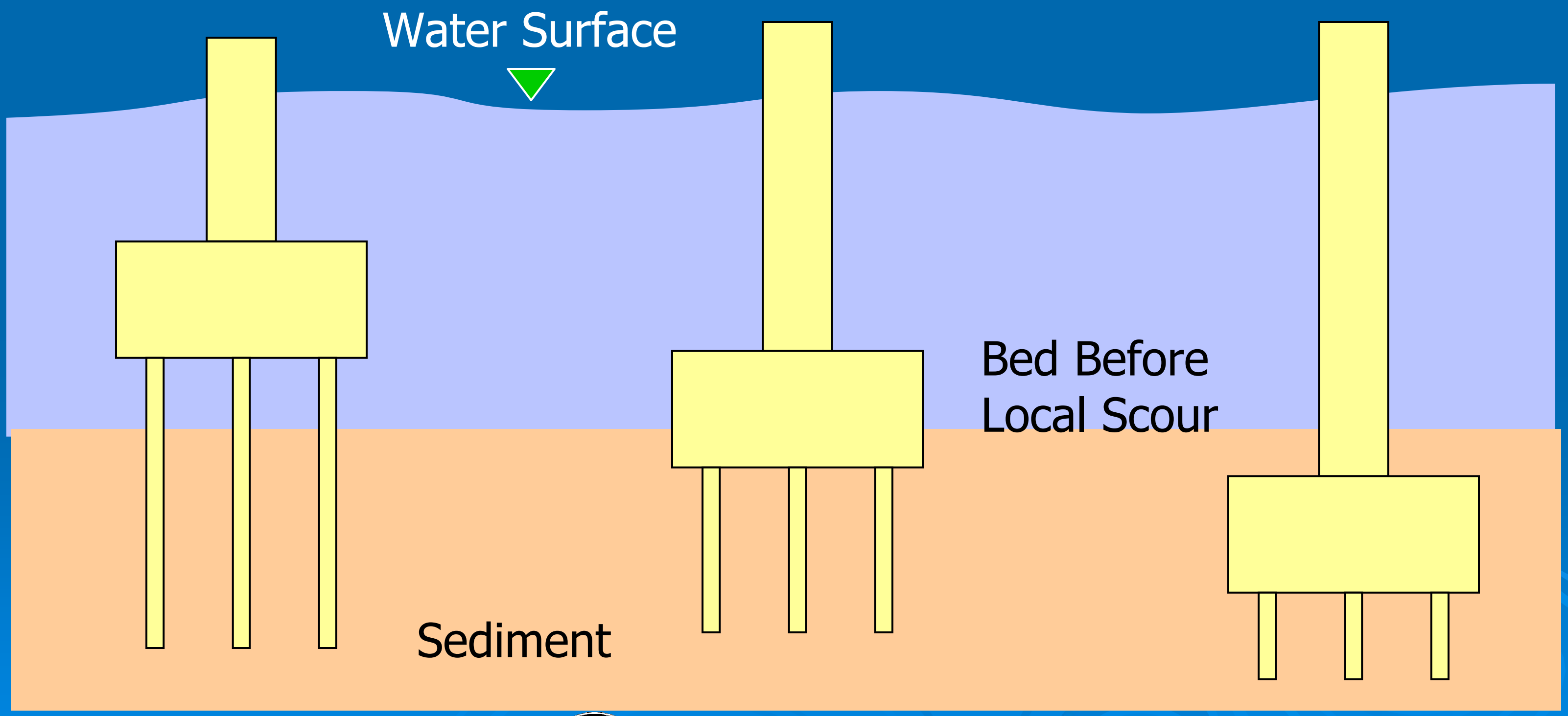
Pile Cap Above the Bed

Case 2

Partially Buried Pile Cap

Case 3

Buried Pile Cap



Complex Pier Scour Methodology

- Compute the effective diameter, D*, of the complex structure

$$D^* = D^*_{col} + D^*_{pc} + D^*_{pg}$$

where

$D^*_{col} \equiv$ effective diameter of the column

$D^*_{pc} \equiv$ effective diameter of the pile cap

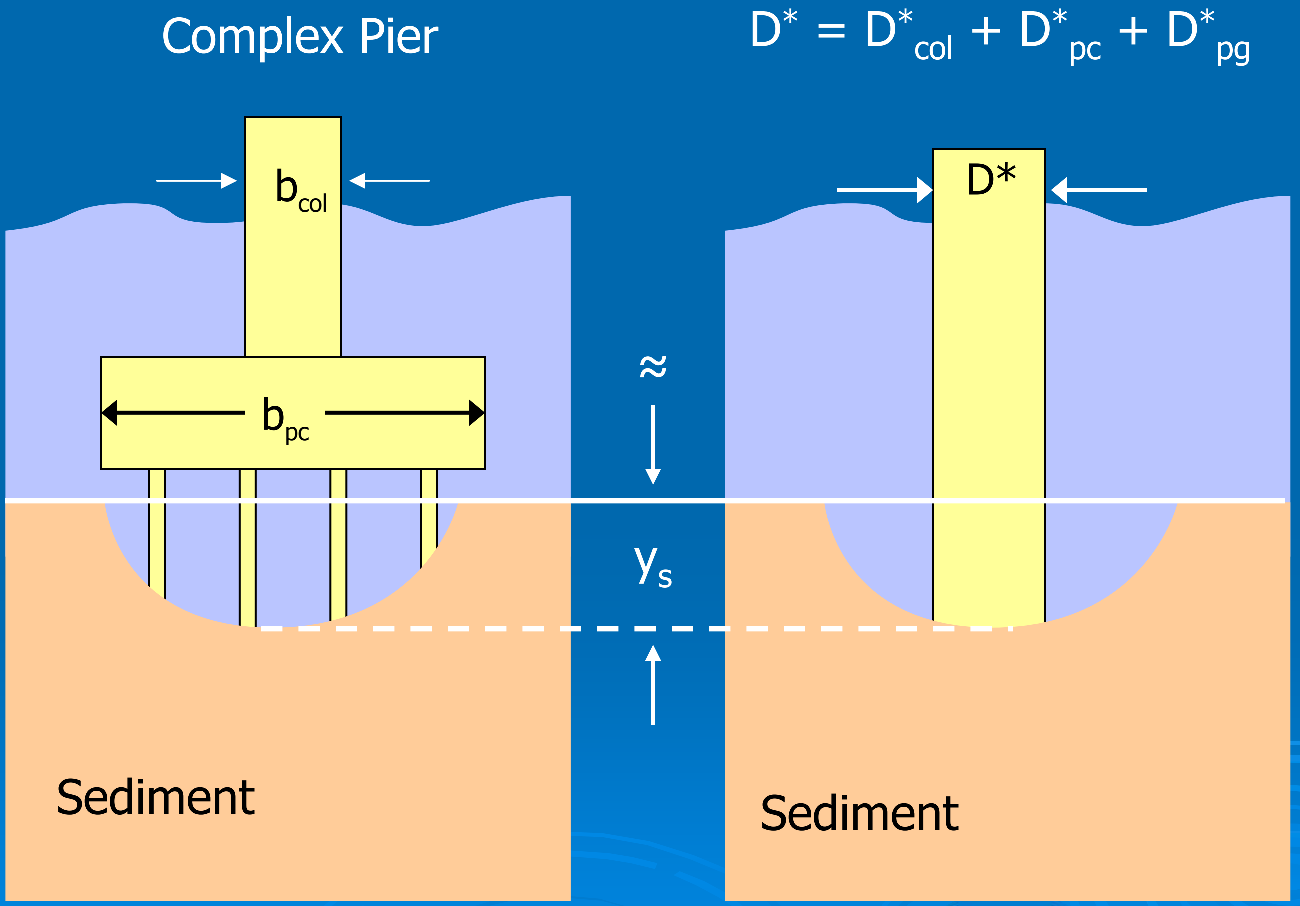
$D^*_{pg} \equiv$ effective diameter of the pile group

Complex Pier Scour Methodology

- Effective Diameter:

  Diameter of a water surface circular pile that will experience the same equilibrium scour depth as the structure of interest under the same sediment/flow conditions

Complex Pier Scour Methodology



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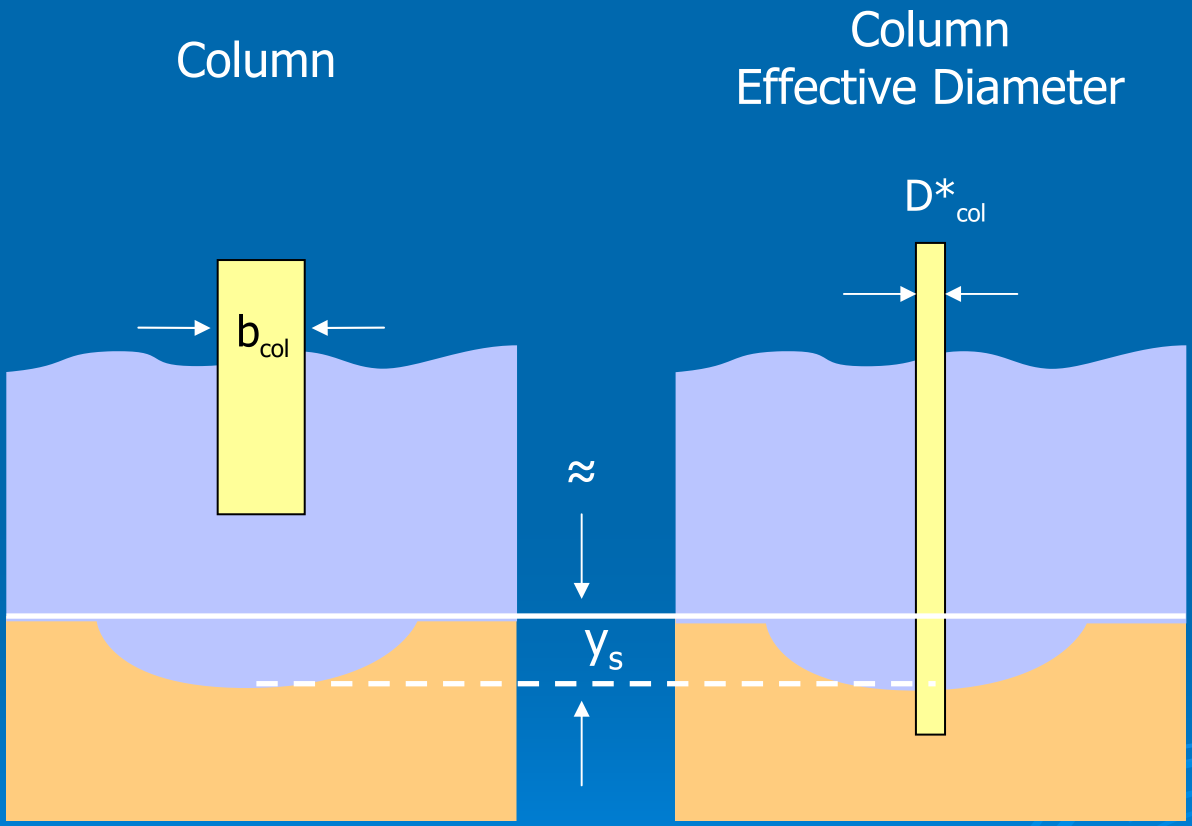
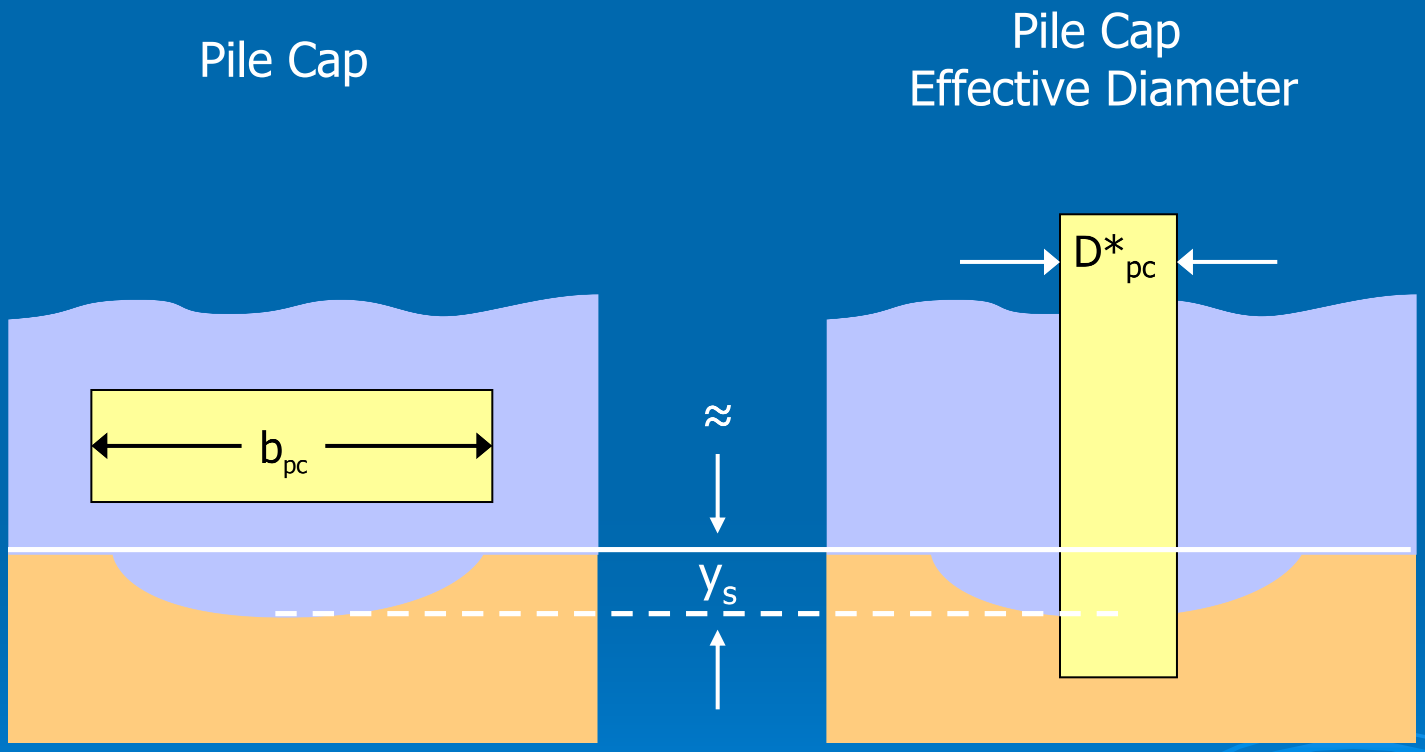
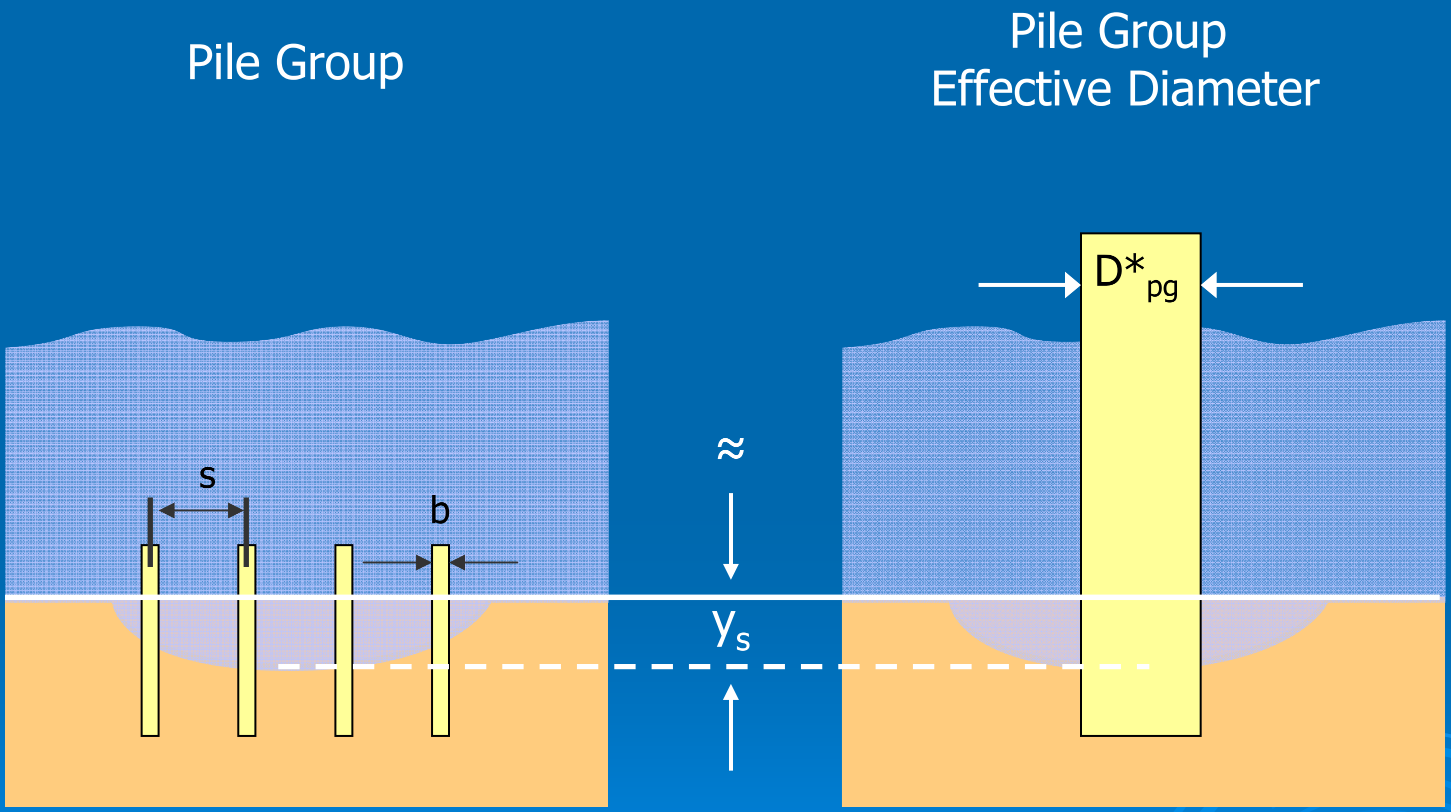
Complex Pier Scour Methodology



Complex Pier Scour Methodology



Complex Pier Scour Methodology



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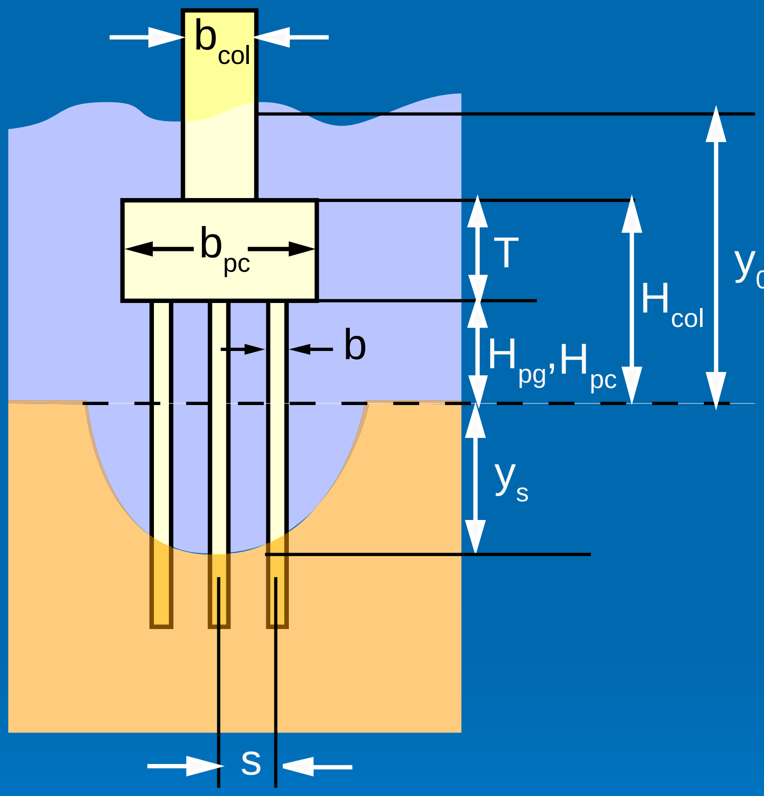
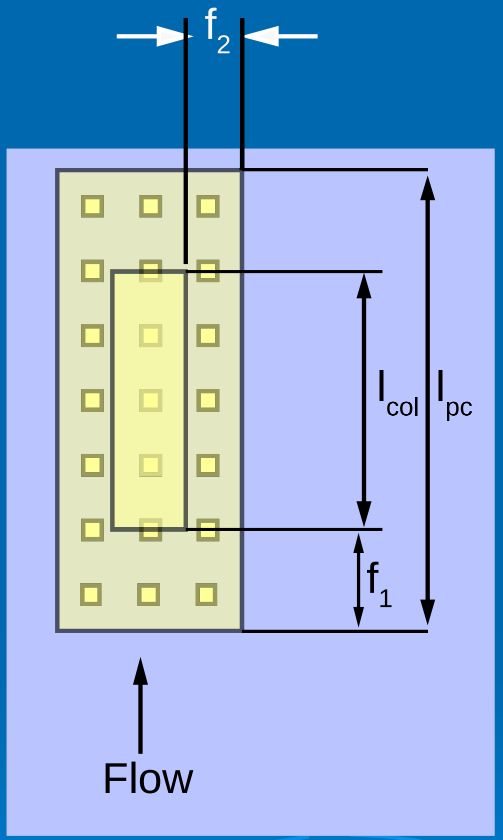
Complex Pier Definition Sketch





n = number of piles normal to the flow = 3

m = number of piles parallel with the flow = 7

Complex Pier Scour Methodology

$$D^*_{col} = f\left(b_{col}, l_{col}, y_0, f_1, f_2, \alpha, H_{col}\ \text{Col. Shape,}\right)$$

$$D^*_{pc} = f\left(b_{pc}, l_{pc}, y_0, \alpha, f_1, f_2, T, H_{pc}, D^*_{col}, \text{Pile Cap Shape,}\right)$$

$$D^*_{pg} = f\begin{pmatrix} b, y_0, \alpha, H_{pg}, n, m, D^*_{col}, D^*_{pc}, s, \\ \text{Pile Shape, Pile Array Shape} \end{pmatrix}$$

Complex Pier Scour Methodology

- Once the effective diameter has been established, equilibrium scour depth can be computed using single structure scour equations

Changes From HEC-18 Methodology

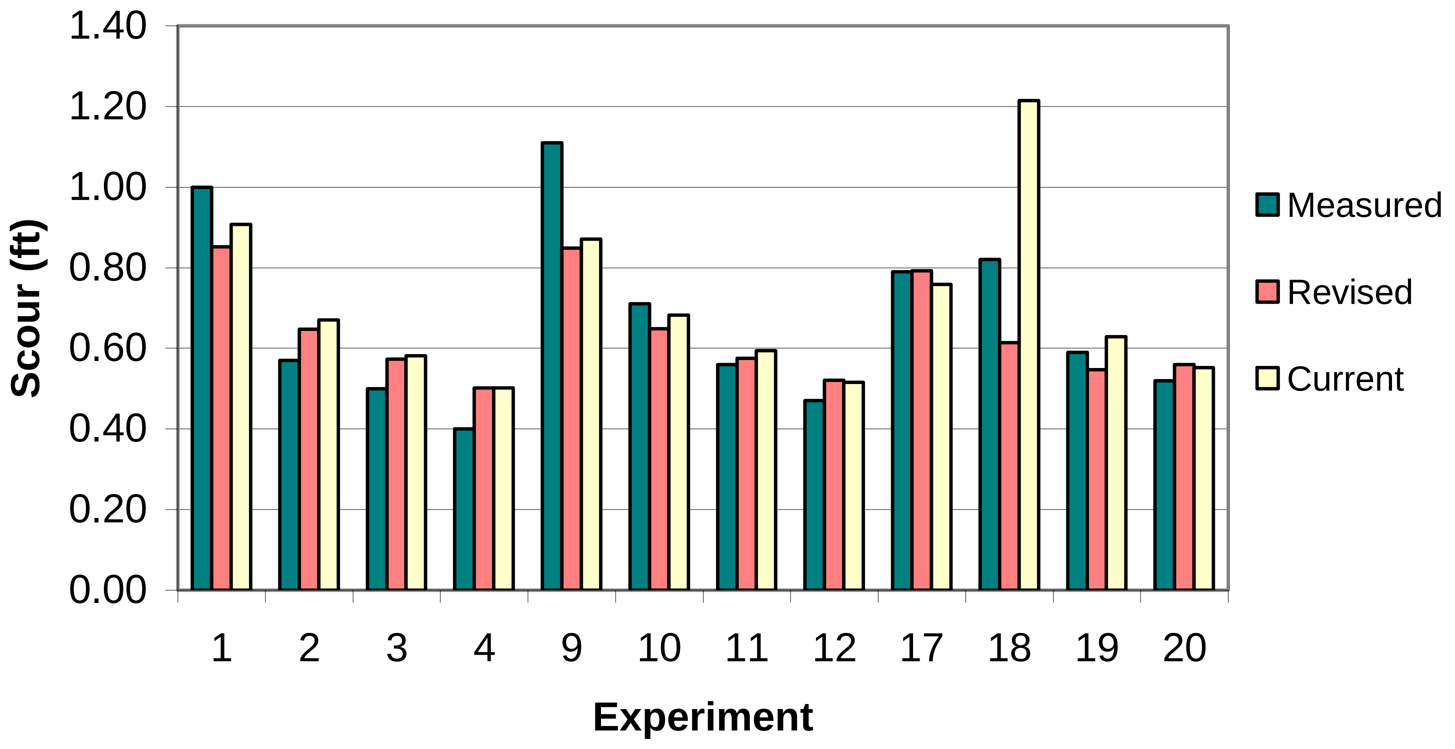
- Additional Data Available (Including Partially Buried and Buried Pile Caps)
- Use of Entire Structure Effective Diameter
- No Adjustments to Flow Velocity Required
- Flow Skew Angles Accounted For in Effective Diameter
- Methodology Extended to Include:
  - Partially Buried Pile Caps
  - Buried Pile Caps

New Laboratory Data

- Tests Conducted by Max Sheppard in Hydraulics Lab at the University of Auckland
- Tests Conducted by Sterling Jones at FHWA Lab
- Tests Conducted by Stephen Coleman in Hydraulics Lab at the University of Auckland

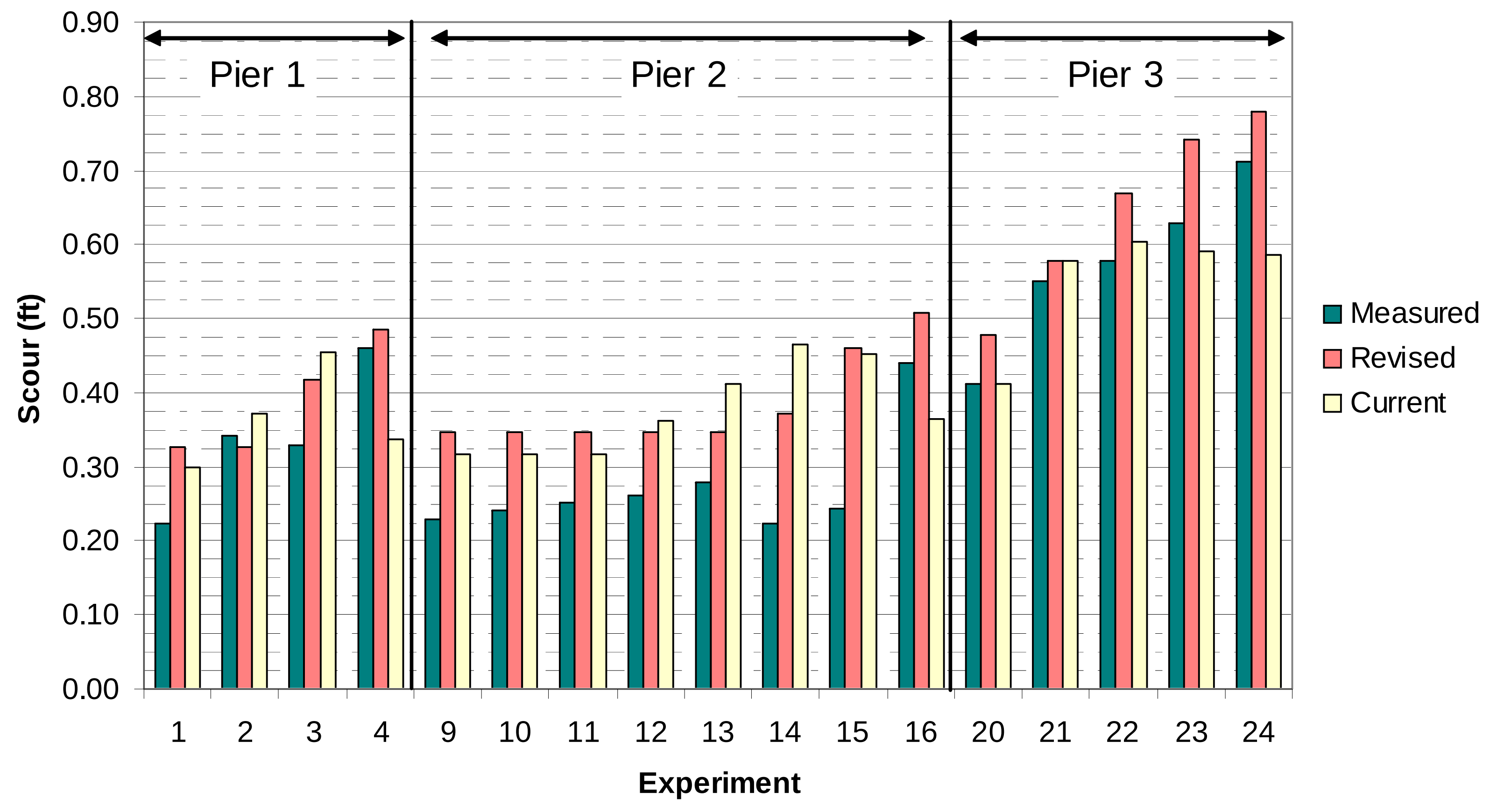
Existing, New and Measured

Jones' Data



Existing, New and Measured

Coleman’s Data



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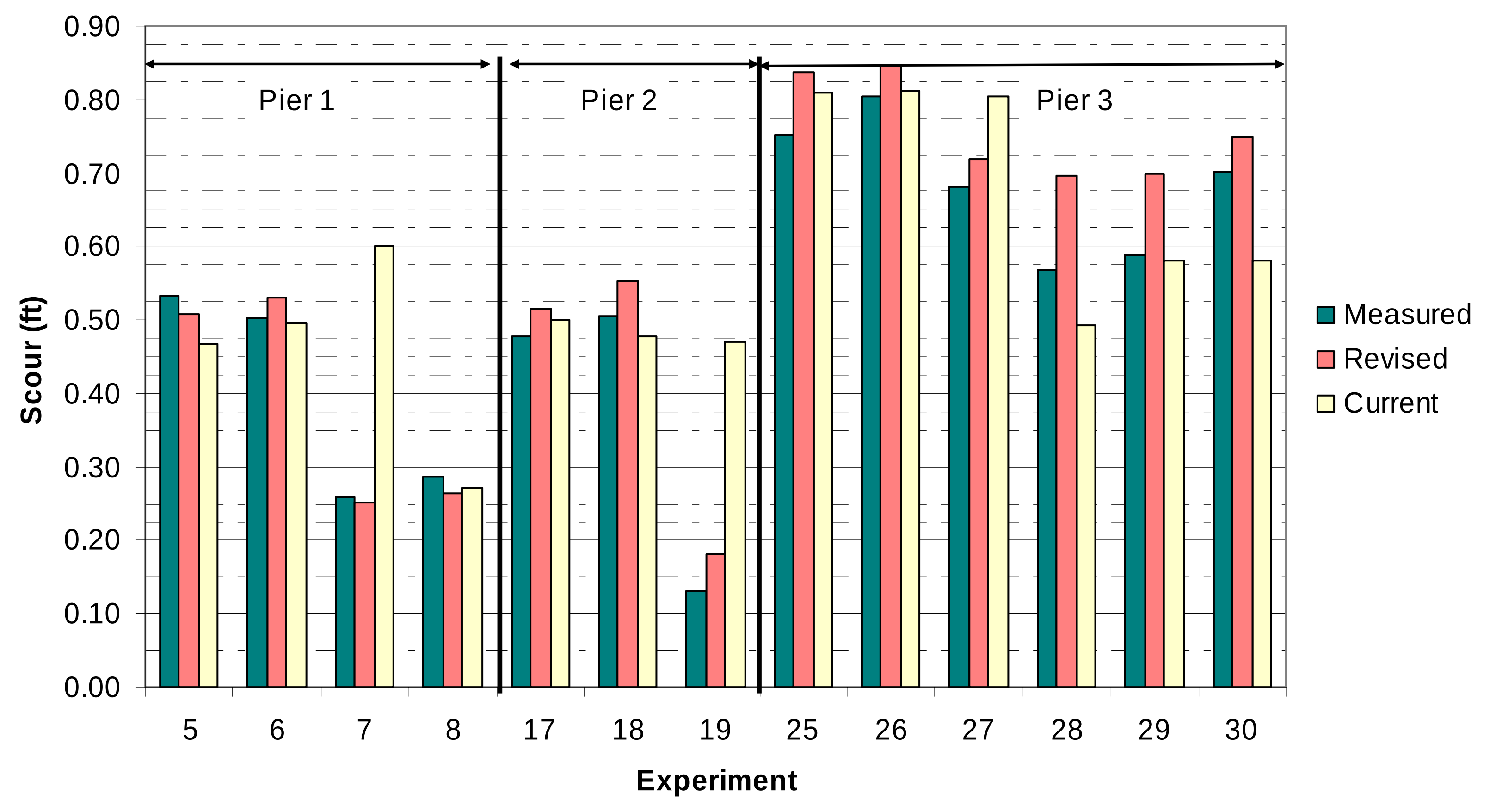
Existing, New and Measured

Coleman’s Data



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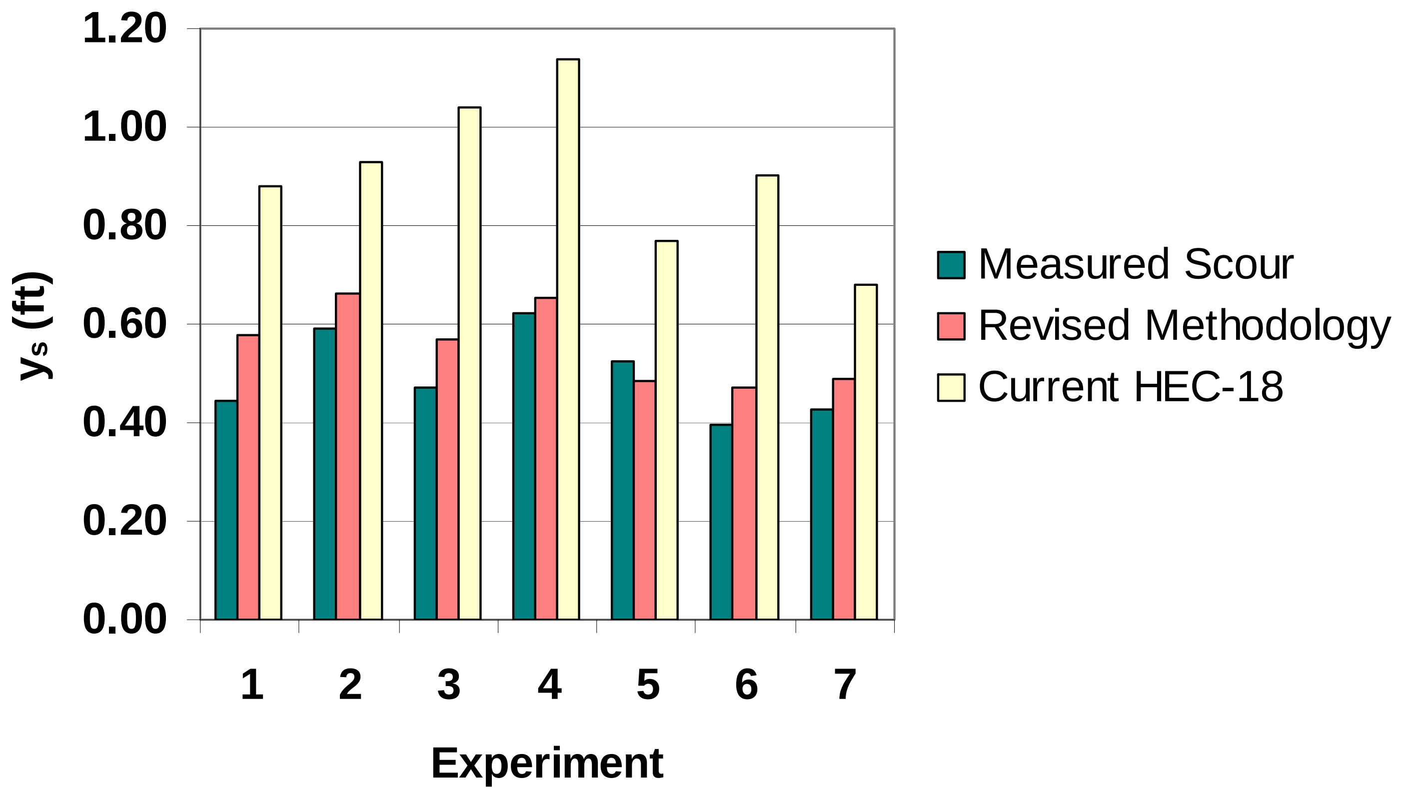
Livebed Data

Sheppard's Data



General Procedure

- Procedure divides the complex pier into its components and treats each component separately
- There are, however, interactions between the components that must be taken into consideration
  - Example: Pile cap impact on effective diameter of column

Section Break

Complex Pier Scour Methodology

Case 1 Complex Pier

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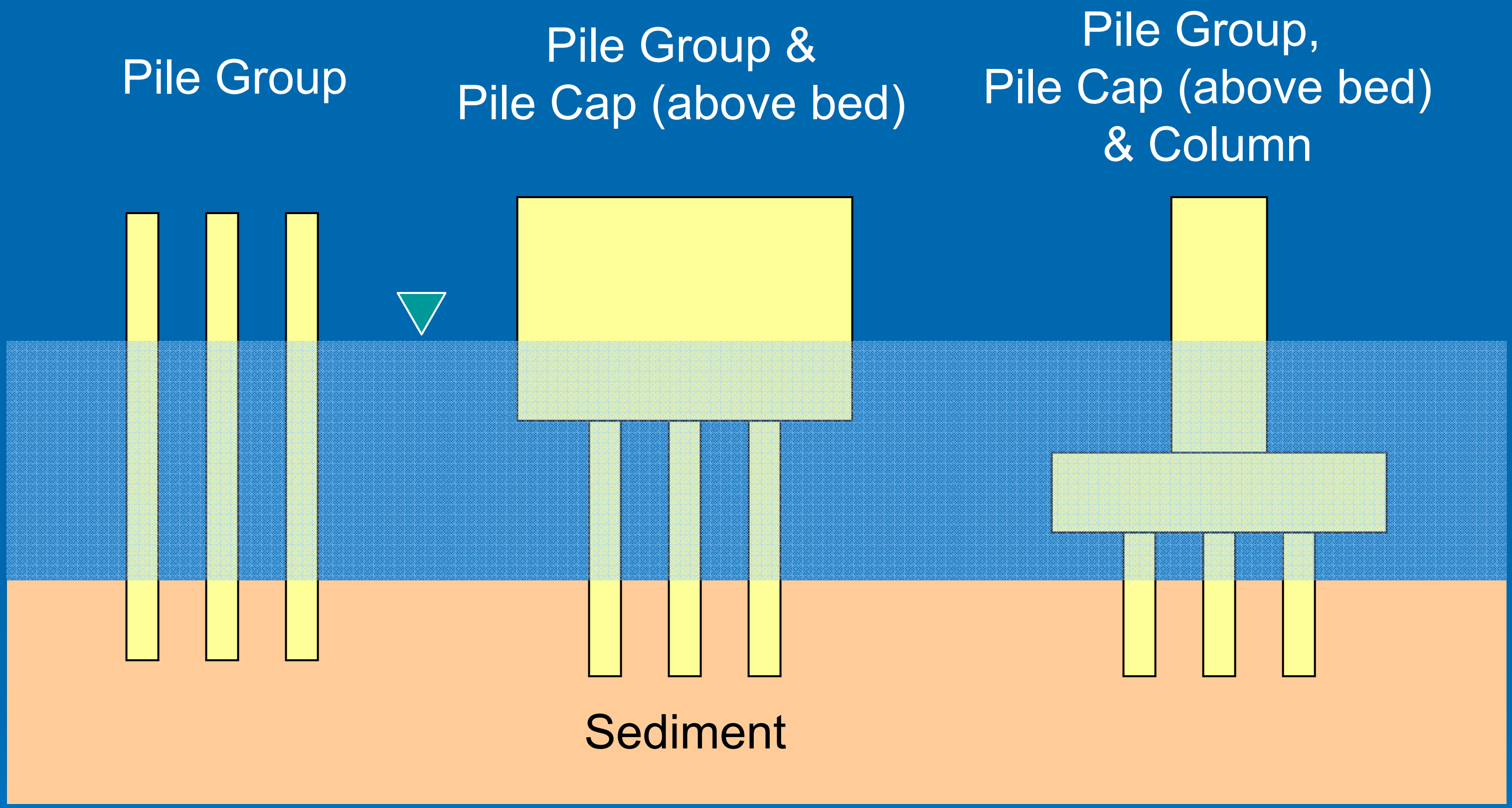
Case 1 Complex Piers

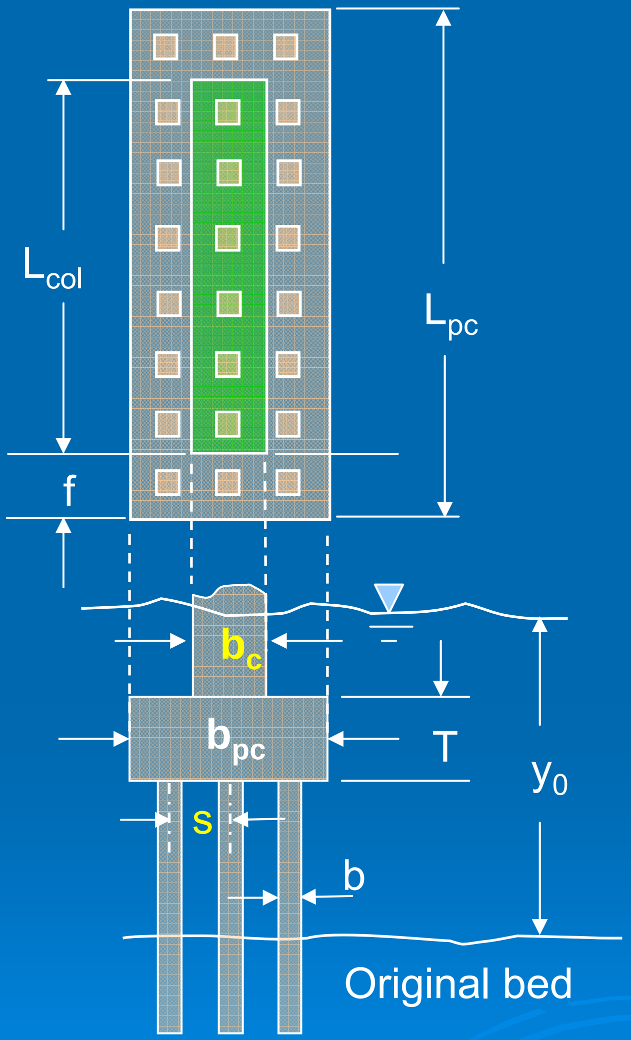


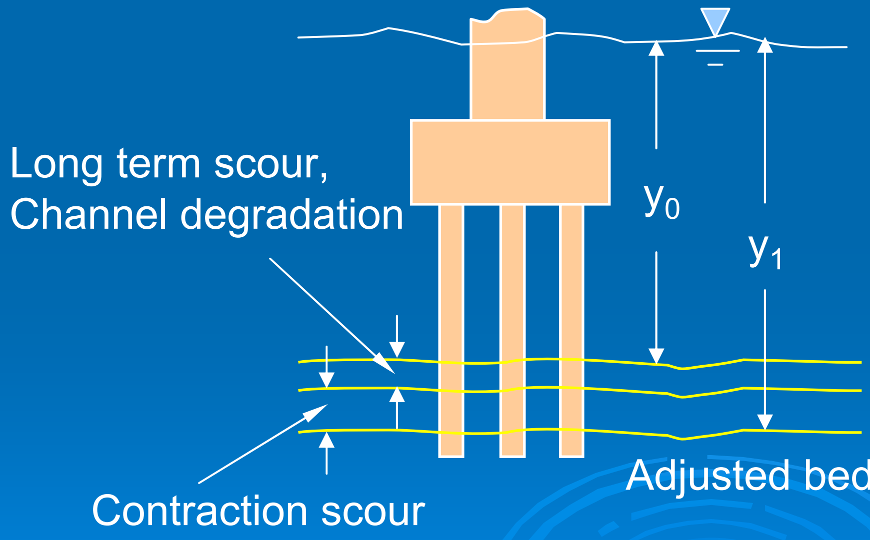
Piers Covered in this Case

Case 1 Procedure Outline

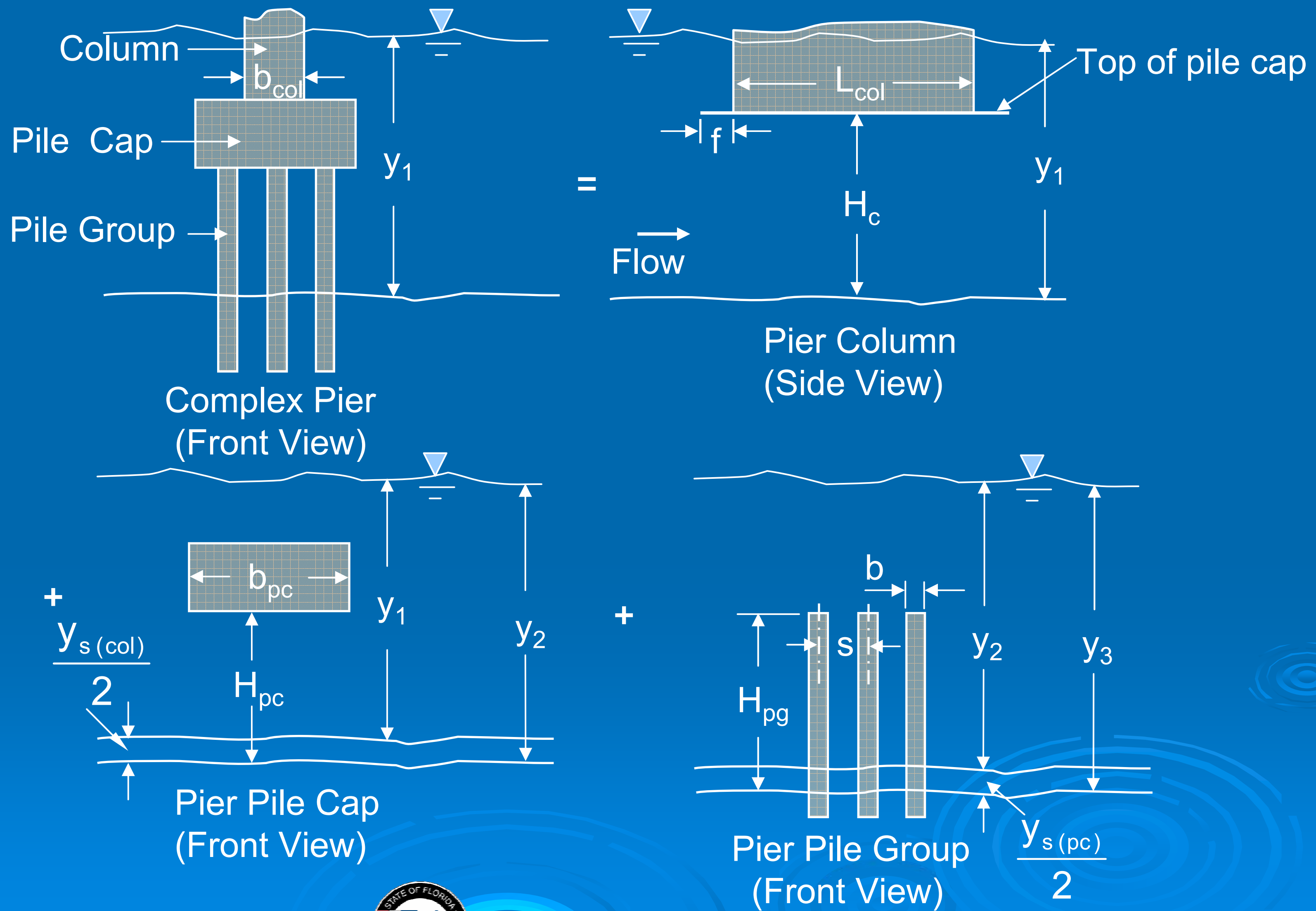
- Compute Column Effective Diameter, D^*_{col}
- Compute Pile Cap Effective Diameter, D^*_{pc}
- Compute Pile Group Effective Diameter, D^*_{pg}
- Calculate Complex Pier Effective Diameter
  - $D^* = D^*_{col} + D^*_{pc} + D^*_{pg}$
- Compute Complex Pier Scour Depth, y_s, using the simple, single structure equations

Pier Definition Diagram





Pier Definition Diagram



Compute Column Effective Diameter , D^*_{col}

- Calculate $y_{0(max)}$ for the Column

$$y_{0(max)} = \begin{cases} 5b_{col} & \text{for } y_o \geq 5b_{col} \\ y_o & \text{for } y_o < 5b_{col} \end{cases}$$

- Calculate the Column Shape Factor, K_s

$$K_s = \begin{cases} 1 & \text{for circular columns} \\ 0.86 + 0.97\left|\alpha \dfrac{\pi}{180^o} - \dfrac{\pi}{4}\right|^4 & \text{for square columns} \end{cases}$$

Column Effective Diameter (cont.)

- Calculate the Column Skew Factor, K_α

$$K_\alpha = \frac{b_{col}\cos(\alpha) + l_{col}\sin(\alpha)}{b_{col}}$$

- Calculate the Pile Cap Extension, f

$$f = \begin{cases} \dfrac{3f_1 + f_2}{4} & \text{for } \alpha \leq \dfrac{\pi}{4} \\ \dfrac{3f_2 + f_1}{4} & \text{for } \alpha > \dfrac{\pi}{4} \end{cases}$$

Column Effective Diameter (cont.)

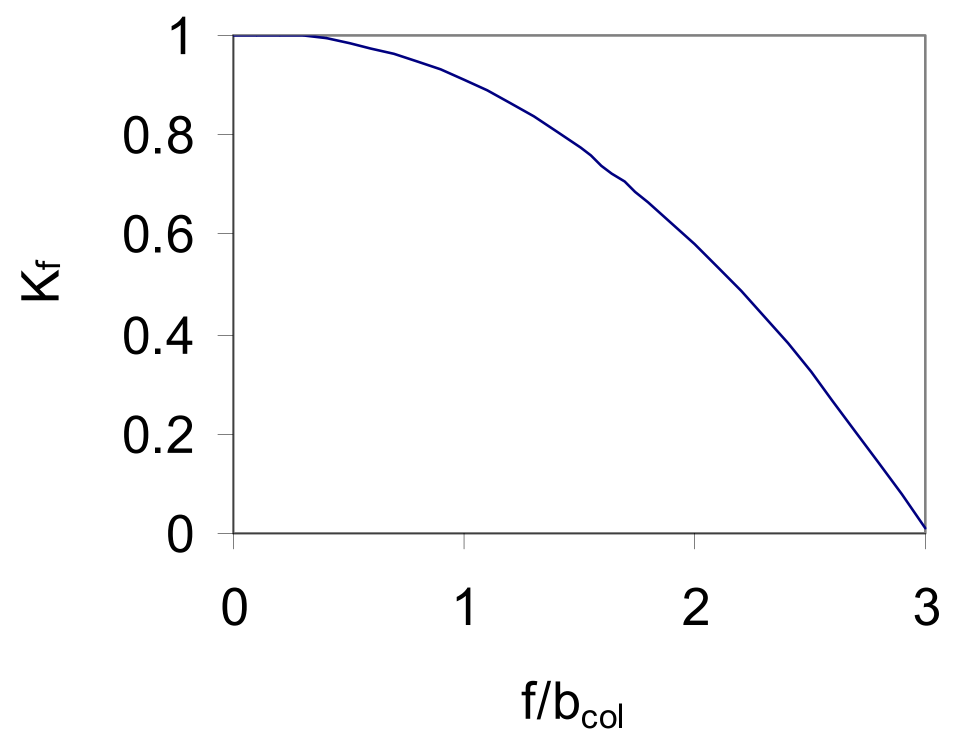
- Calculate the Pile Cap Extension Coefficient, K_f

$$K_f = \left\{ \begin{array}{ll} -0.12\left(\dfrac{f}{b_{col}}\right)^2 + 0.03\left(\dfrac{f}{b_{col}}\right) + 1 & \text{for } 0 \le \left(\dfrac{f}{b_{col}}\right) \le 3 \\ 0 & \text{for } \left(\dfrac{f}{b_{col}}\right) > 3 \end{array} \right\}$$

Note: If α >45 degrees, rotate structure 90 degrees

Column Effective Diameter (cont.)

- Calculate the Pile Cap Extension Coefficient, K_f



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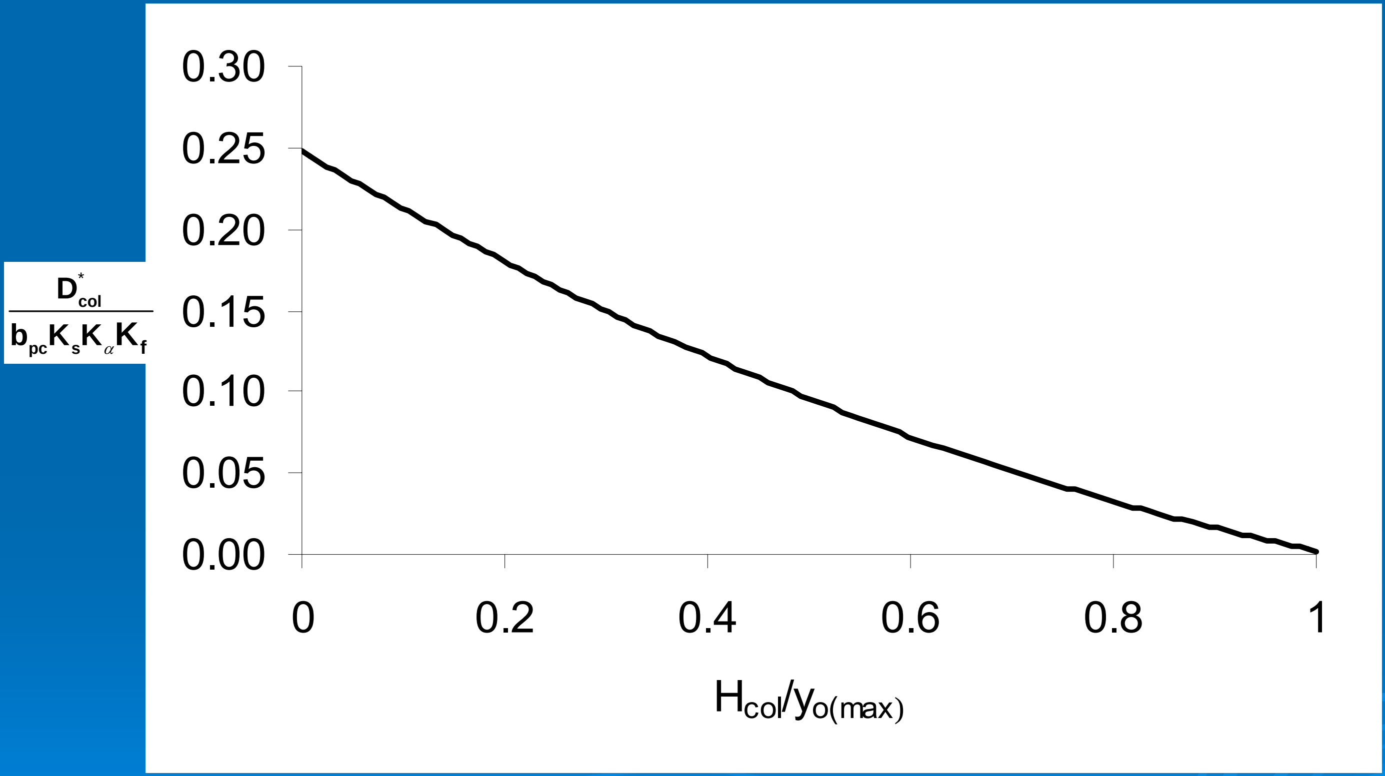
Column Effective Diameter (cont.)

- Calculate the Column Effective Diameter , D^*_{col}

$$D^*_{col} = K_s K_\alpha K_f b_{col} \left[0.116 \left(\frac{H_{col}}{y_{0\,(max)}} \right)^2 - 0.362 \left(\frac{H_{col}}{y_{0\,(max)}} \right) + 0.248 \right]$$

Column Effective Diameter (cont.)

- Calculate the Column Effective Diameter , D^*_{col}



Compute Pile Cap Effective Diameter

- Calculate $y_{0(max)}$ for the Pile Cap

$$y_{0(max)} = \begin{Bmatrix} 1.64\left(T\left(K_s b_{pc}\right)^{\frac{5}{2}}\right)^{\frac{2}{7}} & y_o \geq 1.64\left(T\left(K_s b_{pc}\right)^{\frac{5}{2}}\right)^{\frac{2}{7}} \\ y_o & y_o < 1.64\left(T\left(K_s b_{pc}\right)^{\frac{5}{2}}\right)^{\frac{2}{7}} \end{Bmatrix}$$

Pile Cap Effective Diameter (cont.)

- Calculate the Pile Cap Shape Factor, K_s

$$K_s = \begin{cases} 1 & \text{for circular columns} \\ 0.86+0.97\left|\alpha\dfrac{\pi}{180^o}-\dfrac{\pi}{4}\right|^4 & \text{for square columns} \end{cases}$$

- Calculate the Pile Cap Skew Factor, K_α

$$K_\alpha = \frac{b_{pc}cos\left(\alpha\right)+l_{pc}sin\left(\alpha\right)}{b_{pc}}$$

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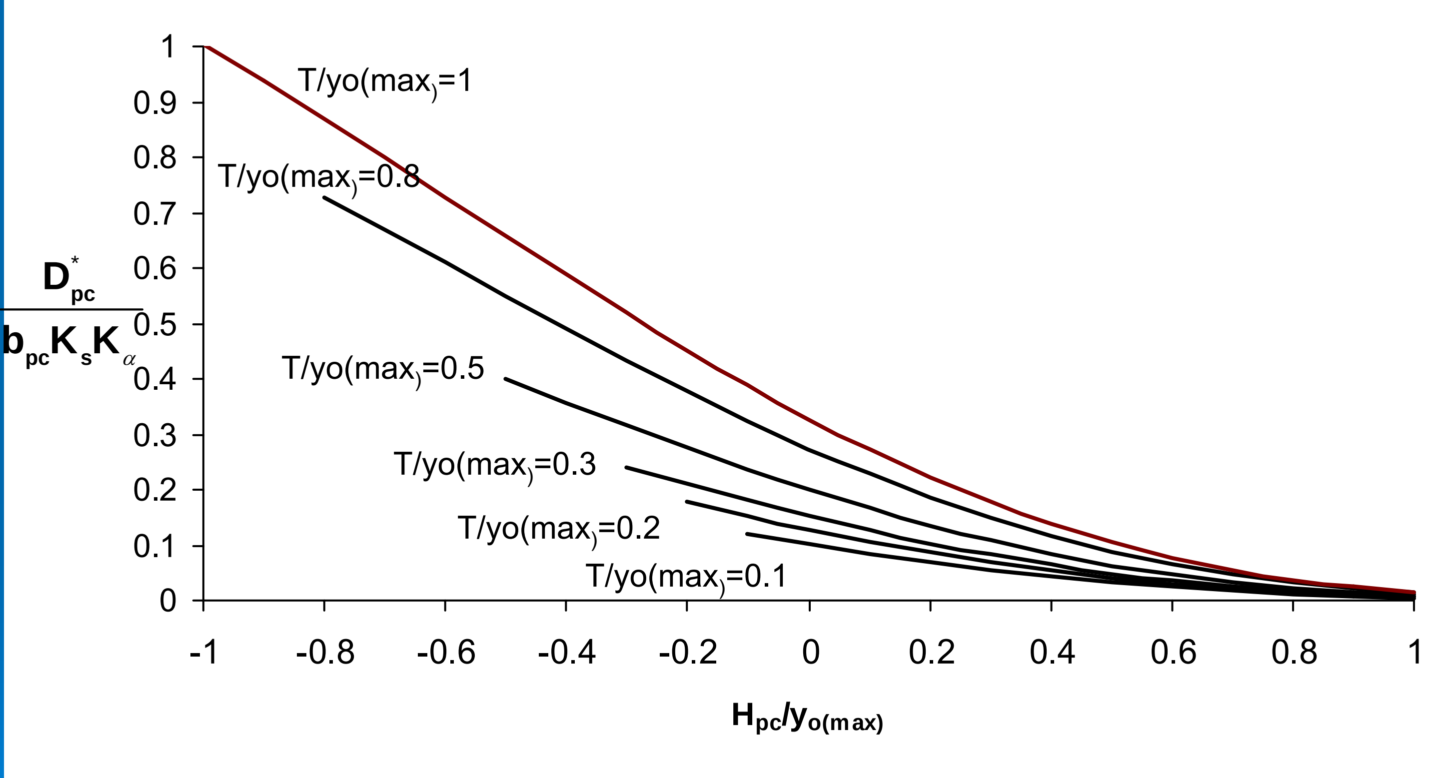
Pile Cap Effective Diameter (cont.)

- Compute the Pile Cap Effective Diameter

$$D^{*}_{pc} = K_s K_\alpha b_{pc}\, exp\left[-1.04 - 1.77\, exp\left(\frac{H_{pc}}{y_{0(max)}}\right) + 1.70\left(\frac{T}{y_{0(max)}}\right)^{\frac{1}{2}}\right]$$

Pile Cap Effective Diameter (cont.)

- Compute the Pile Cap Effective Diameter



Pile Group Effective Diameter

- Compute the Scour caused by the Column and Pile Cap, $y_{s(col+pc)}$

$$D^* = D^*_{col} + D^*_{pc}$$

- Shift the bed Down by $y_{s(col+pc)}$

$$\overline{H}_{pg} = H_{pg} + y_{s\,(col\,+\,pc)} \quad \text{and}$$

$$\overline{y}_o = y_o + y_{s\,(col\,+\,pc)}$$

Pile Group Effective Diameter (cont.)

- Compute Pile Group Shape Factor, K_s

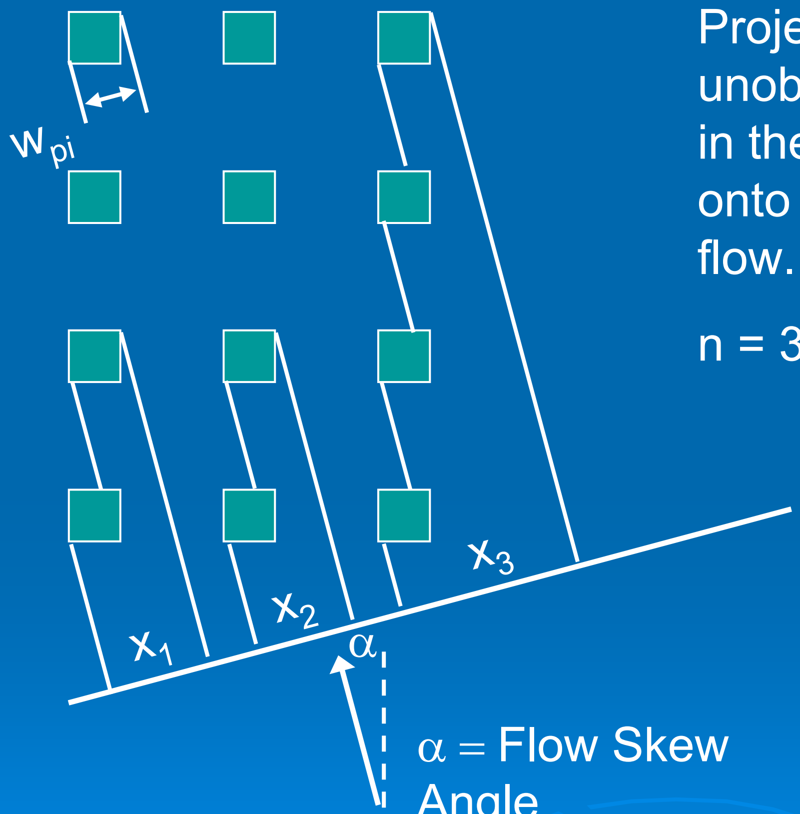
$$K_s = \frac{K_{s\,(\text{pile})} - K_{s\,(\text{pile group})}}{9}\left(\frac{s}{b}\right) + K_{s(\text{pile})} - \frac{10}{9}\left(K_{s\,(\text{pile})} - K_{s\,(\text{pile group})}\right)$$

Where

$$K_{s\,(\text{pile or Pile Group})} = \begin{Bmatrix} 1 & \text{for circular piles} \\ 0.86 + 0.97\left|\alpha\dfrac{\pi}{180^{o}} - \dfrac{\pi}{4}\right|^{4} & \text{for square piles} \end{Bmatrix}$$

Pile Group Effective Diameter (cont.)

- Compute W_p



α = Flow Skew Angle

Projected width is the sum of the unobstructed projections of the piles in the first two rows and first column onto a vertical plane normal to the flow.

n = 3, m = 4

$$W_p = X_1 + X_2 + X_3$$

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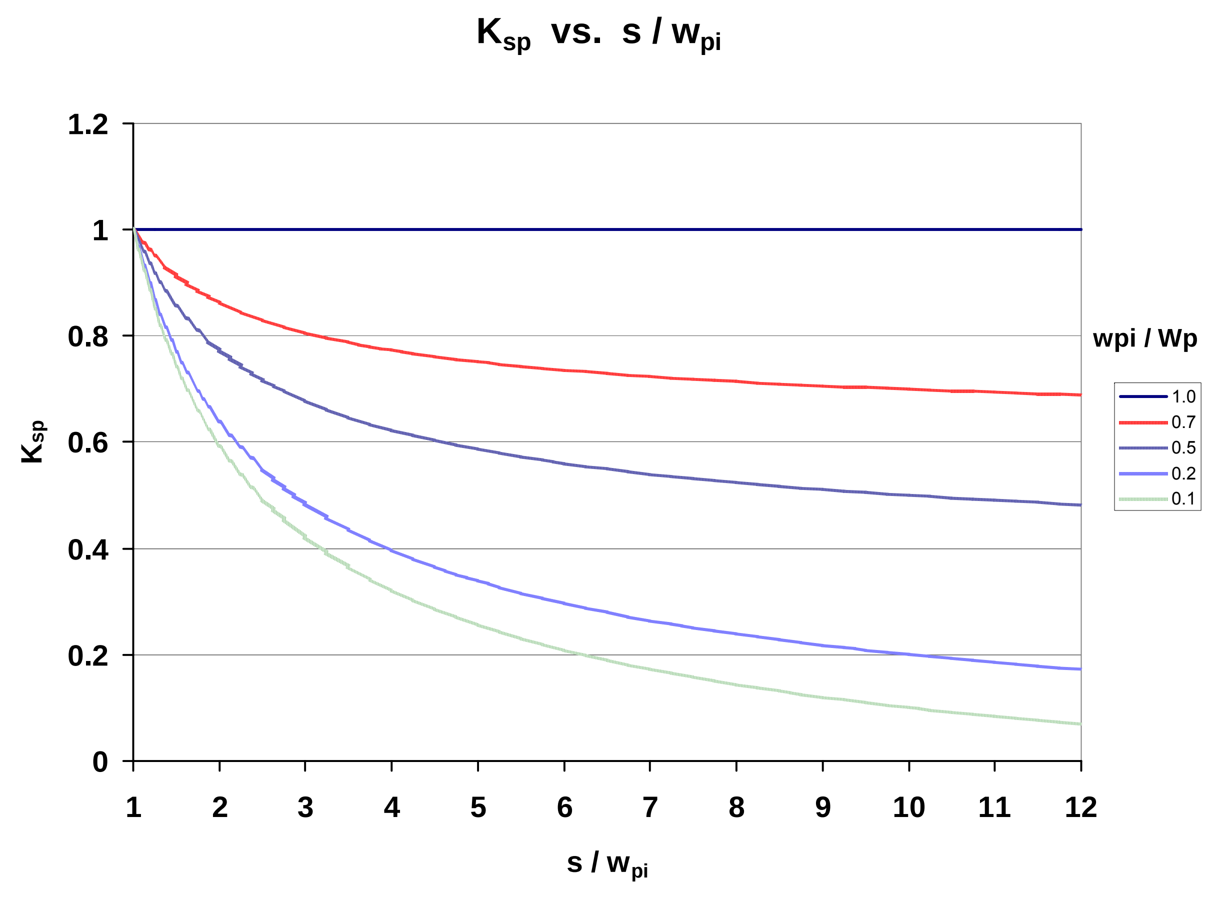
Pile Group Effective Diameter (cont.)

- Compute the Pile Spacing Coefficient, K_{sp}

$$K_{sp} = 1 - \frac{4}{3}\left(1 - \frac{w_{pi}}{W_p}\right)\left(1 - \frac{1}{\left(\frac{s}{w_{pi}}\right)^{0.6}}\right)$$

Pile Group Effective Diameter (cont.)

- Compute the Pile Spacing Coefficient, K_{sp}



Pile Group Effective Diameter (cont.)

- Compute K_m, a Coefficient that Accounts for the Number of Piles Inline With the Flow

$$K_m = \begin{cases} 0.045(m) + 0.96 & |\alpha| < 5^o, \text{and } m \le 5 \\ 1.19 & |\alpha| < 5^o, \text{and } m > 5 \\ 1 & |\alpha| \ge 5^o \end{cases}$$

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Pile Group Effective Diameter (cont.)

- Compute $y_{o(max)}$ for the Pile Group

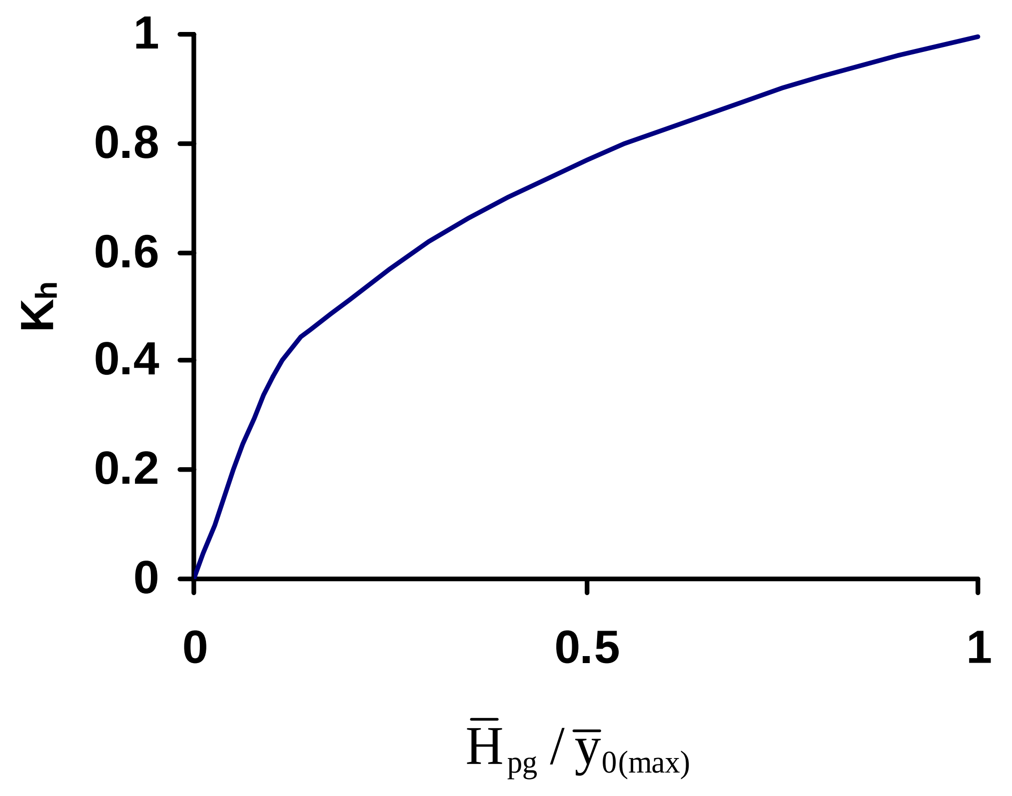
$$y_{0(\max)} = \left\{ \begin{array}{ll} \bar{y}_0 & \text{for } \bar{y}_0 \le 2K_sW_pK_{sp}K_m \\ 2\,K_sW_pK_{sp}K_m & \text{for } \bar{y}_0 > 2K_sW_pK_{sp}K_m \end{array} \right\}$$

- Compute the Pile Height Coefficient, K_h

$$K_h = \left\{ \begin{array}{ll} 1.5\,\tanh\left(0.8\sqrt{\dfrac{\bar{H}_{pg}}{y_{0(\max)}}}\right) & \bar{H}_{pg} \le y_{0(\max)} \\ 1 & \bar{H}_{pg} > y_{0(\max)} \end{array} \right\}$$

Pile Group Effective Diameter (cont.)

- Compute the Pile Height Coefficient, K_h



Pile Group Effective Diameter (cont.)

- Compute the Effective Diameter for the Pile Group

$$D^{*}_{pg} = K_{sp} K_{h} K_{m} K_{s} W_{p}$$

Complex Pier Effective Diameter

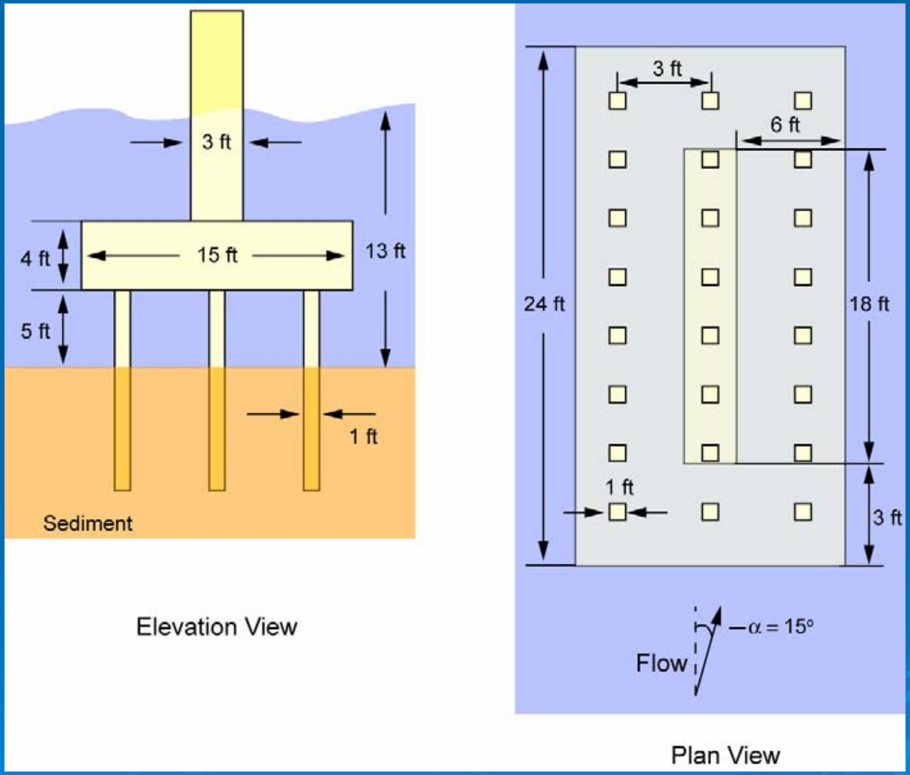
- Compute D^* and y_s

$$D^* = D^*_{col} + D^*_{pc} + D^*_{pg}$$

- The equilibrium scour depth, y_s, for the complex structure can now be computed by substituting D^* into the single structure equations

Case 1 Example Problem

- Consider the complex pier shown in the figure



Case 1 Example Problem (cont.)

Skew Angle Degrees	Velocity (ft/s)	Critical Velocity (ft/s)	Live Bed Peak Velocity (ft/s)	Water Depth (ft)	Temp (F°)	Salinity (ppt)	D_{50} (mm)
15	11.0	1.16	16.36	13	65	35	0.20

Calculate $y_{0(max)}$ for the column

$$y_{0(max)} = \begin{Bmatrix} 5b_{col} & \text{for } y_0 \geq 5b_{col} \\ y_0 & \text{for } y_0 < 5b_{col} \end{Bmatrix}$$

$$5b_{col} = 5(3\text{ ft}) = 15\text{ ft} \quad \text{and } y_0 = 13\text{ ft}$$

$$\text{Since } y_0 < 5b_{col}, \quad y_{0(max)} = y_0 = 13\text{ ft}$$

Case 1 Example Problem (cont.)

Compare the column's base height, H_{col}, to $y_{0(max)}$. If $H_{col} < y_{0(max)}$ continue

$$H_{col} = 9\text{ ft},\quad y_{0(max)} = 13\text{ ft}$$

$$\text{Since } H_{col} < y_{0(max)} \quad \text{continue}$$

Compute the shape factor for the square column, K_s

$$K_s = 0.86 + 0.97\left|15^{o}\frac{\pi}{180^{o}} - \frac{\pi}{4}\right|^{4} = 0.93$$

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Case 1 Example Problem (cont.)

Compute the column skew factor, K_α

$$K_\alpha = \frac{3\text{ ft } cos\left(15^{o}\right) + 18\text{ ft } sin\left(15^{o}\right)}{3\text{ ft}} = 2.52$$

Calculate the pile cap extension coefficient, K_f

$$f = \frac{3 f_1 + f_2}{4} \quad \text{for } \alpha \le 45^{0}$$

$$f = \frac{3\left(3\text{ ft}\right) + \left(6\text{ ft}\right)}{4} = 3.75\text{ ft}$$

Case 1 Example Problem (cont.)

Calculate the pile cap extension coefficient, K_f, (cont.)

$$K_f = -0.12\left(\frac{3.75\text{ ft}}{3\text{ ft}}\right)^2 + 0.03\left(\frac{3.75\text{ ft}}{3\text{ ft}}\right) + 1 = 0.85$$

Compute the column effective diameter, D^*_{col}

$$D^*_{col} = K_s K_\alpha K_f b_{col}\left[0.116\left(\frac{H_{col}}{y_{0\,(max)}}\right)^2 - 0.362\left(\frac{H_{col}}{y_{0\,(max)}}\right) + 0.248\right]$$

$$\boxed{D^*_{col} = (0.93)(2.52)(0.85)(3\text{ ft})\left[0.116\left(\frac{9\text{ ft}}{13\text{ ft}}\right)^2 - 0.362\left(\frac{9\text{ ft}}{13\text{ ft}}\right) + 0.248\right] = 0.32\text{ ft}}$$

Case 1 Example Problem (cont.)

Compute the shape factor for the square pile cap, K_s

$$K_s = 0.86 + 0.97\left|15^{\circ}\frac{\pi}{180^{\circ}} - \frac{\pi}{4}\right|^4 = 0.93$$

Compute the pile cap skew factor, K_α

$$K_\alpha = \frac{15\text{ ft}\,cos\left(15^{\circ}\right) + 24\text{ ft}\,sin\left(15^{\circ}\right)}{15\text{ ft}} = 1.38$$

Case 1 Example Problem (cont.)

Compute $y_{0(max)}$ for the pile cap

$$y_{0(max)} = \begin{cases} 1.64\left(T\left(K_s b_{pc}\right)^{\frac{5}{2}}\right)^{\frac{2}{7}} & y_0 \geq 1.64\left(T\left(K_s b_{pc}\right)^{\frac{5}{2}}\right)^{\frac{2}{7}} \\ y_0 & y_0 < 1.64\left(T\left(K_s b_{pc}\right)^{\frac{5}{2}}\right)^{\frac{2}{7}} \end{cases}$$

$$y_0 = 13 \text{ ft},$$

$$1.64\left(4\,\text{ft}\left(0.93 * 15\,\text{ft}\right)^{\frac{5}{2}}\right)^{\frac{2}{7}} = 16.0\,\text{ft}$$

Therefore,

$$y_{0(max)} = y_0 = 13 \text{ ft}$$

Case 1 Example Problem (cont.)

Determine if $H_{pc} < y_{o(max)}$

$$H_{pc} = 5 \text{ ft} < 13 \text{ ft} \quad \text{continue}$$

Compute pile cap effective diameter, D^*_{pc}

$$D^*_{pc} = K_s K_\alpha b_{pc}\, exp\left[-1.04 - 1.77\, exp\left(\frac{H_{pc}}{y_{0(max)}}\right) + 1.70\left(\frac{T}{y_{0(max)}}\right)^{\frac{1}{2}}\right]$$

$$D^*_{pc} = (0.93)(1.38)(15 \text{ ft})\, exp\left[-1.04 - 1.77\, exp\left(\frac{5 \text{ ft}}{13 \text{ ft}}\right) + 1.70\left(\frac{4 \text{ ft}}{13 \text{ ft}}\right)^{\frac{1}{2}}\right]$$

$$\boxed{D^*_{pc} = 1.29 \text{ ft}}$$

Case 1 Example Problem (cont.)

Next compute the effective diameter of the pile group

Calculate the scour created by the column and pile cap

$$D^*_{(col+pc)} = D^*_{col} + D^*_{pc} = 0.33\text{ ft} + 1.29\text{ ft} = 1.62\text{ ft}$$

$$\frac{y_s}{D^*_{(col+pc)}} = tanh\left[\left(\frac{y_o}{D^*_{(col+pc)}}\right)^{0.4}\right] \times \left[\begin{array}{l} 2.2\left(\dfrac{V/V_c - 1}{V_{lp}/V_c - 1}\right) + \\ 2.5\left\{\dfrac{D^*_{(col+pc)}/D_{50}}{0.4\left(D^*_{(col+pc)}/D_{50}\right)^{1.2} + 10.6\left(D^*_{(col+pc)}/D_{50}\right)^{-0.13}}\right\} \\ \left(\dfrac{V_{lp}/V_c - V/V_c}{V_{lp}/V_c - 1}\right) \end{array}\right]$$

Case 1 Example Problem (cont.)

$$\frac{y_s}{1.62\text{ ft}} = tanh\left[\left(\frac{13}{1.62}\right)^{0.4}\right] \times \left[\begin{array}{l} 2.2\left(\dfrac{11/1.16-1}{16.36/1.16-1}\right) + \\ 2.5\left\{\dfrac{1.62/(6.56\text{ x }10^{-4})}{0.4\left[1.62/(6.56\text{ x }10^{-4})\right]^{1.2}+10.6\left[1.62/(6.56\text{ x }10^{-4})\right]^{-0.13}}\right\} \\ \left(\dfrac{16.36/1.16-11/1.16}{16.36/1.16-1}\right) \end{array}\right]$$

$$y_{s(col+pc)} = 2.98\text{ ft}$$

Case 1 Example Problem (cont.)

Compute $\bar{H}_{pg}$, and $\bar{y}_0$

$$\bar{H}_{pg} = H_{pg} + y_{s\,(col + pc)} \quad = 5\text{ ft} + 2.98\text{ ft} = 7.98\text{ ft}$$

$$\bar{y}_0 = y_0 + y_{s\,(col + pc)} \quad = 13\text{ ft} + 2.98\text{ ft} = 15.98\text{ ft}$$

Compute pile group shape factor

$$K_s = \frac{K_{s\,(pile)} - K_{s\,(pile\ group)}}{9}\left(\frac{s}{b}\right) + K_{s(pile)} - \frac{10}{9}\left(K_{s\,(pile)} - K_{s\,(pile\ group)}\right)$$

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Case 1 Example Problem (cont.)

$$K_{s(\text{pile or pile group})} = \begin{Bmatrix} 1 & \text{for circular piles or pile group arrays} \\ 0.86+0.97\left|\alpha\dfrac{\pi}{180^{\circ}} - \dfrac{\pi}{4}\right|^{4} & \text{for square piles or pile group arrays} \end{Bmatrix}$$

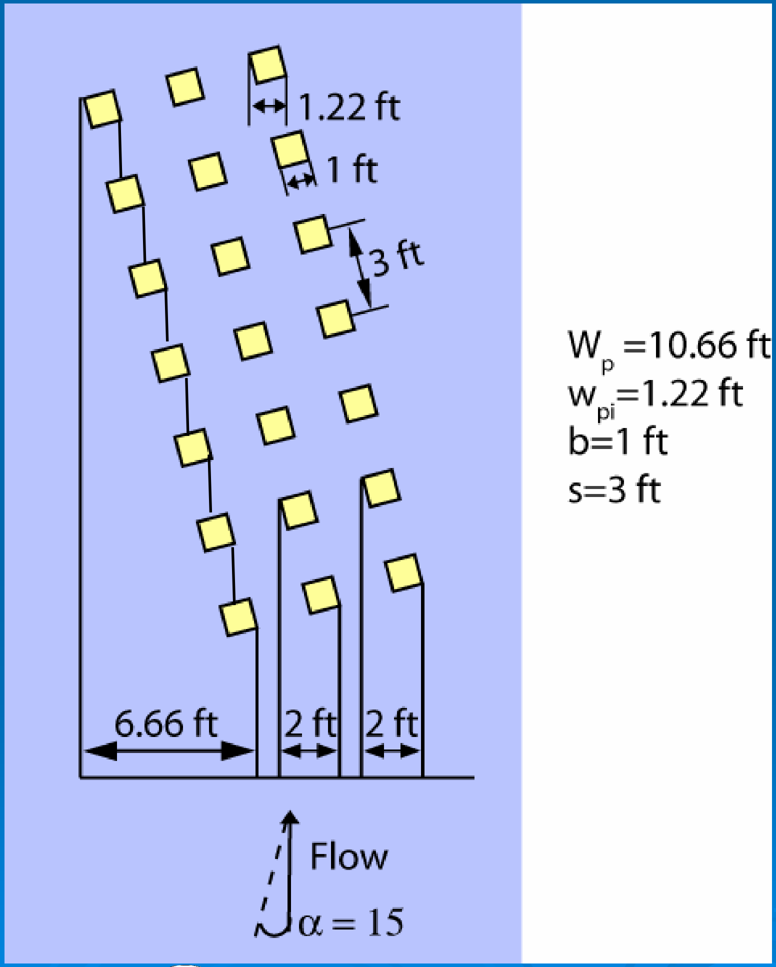
$$K_{s(\text{pile})} = 0.86 + 0.97\left|15^{\circ}\frac{\pi}{180^{\circ}} - \frac{\pi}{4}\right|^{4} = 0.93$$

$$K_{s(\text{pilegroup})} = 0.86 + 0.97\left|15^{\circ}\frac{\pi}{180^{\circ}} - \frac{\pi}{4}\right|^{4} = 0.93$$

$$K_{s} = \frac{0.93 - 0.93}{9}\left(\frac{6\text{ ft}}{2\text{ ft}}\right) + 0.93 - \frac{10}{9}(0.93 - 0.93) = 0.93$$

Case 1 Example Problem (cont.)

Compute the projected width of the pile group



$W_p = 10.66$ ft
$w_{pi} = 1.22$ ft
$b = 1$ ft
$s = 3$ ft

Case 1 Example Problem (cont.)

Compute the pile spacing coefficient

$$K_{sp} = 1 - \frac{4}{3}\left(1 - \frac{w_{pi}}{W_p}\right)\left(1 - \frac{1}{\left(\frac{s}{w_{pi}}\right)^{0.6}}\right) = 1 - \frac{4}{3}\left(1 - \frac{1.22\text{ ft}}{10.66\text{ ft}}\right)\left(1 - \frac{1}{\left(\frac{3\text{ ft}}{1.22\text{ ft}}\right)^{0.6}}\right) = 0.51$$

Case 1 Example Problem (cont.)

Compute the coefficient that accounts for the number of piles in line with the flow, K_m

$$K_m = \begin{cases} 0.045(m) + 0.96 & |\alpha| < 5^\circ,\ \text{and } m \le 5 \\ 1.19 & |\alpha| < 5^\circ,\ \text{and } m > 5 \\ 1 & |\alpha| \ge 5^\circ \end{cases}$$

$$\alpha = 15^\circ,\ \text{therefore } K_m = 1$$

Case 1 Example Problem (cont.)

Compute $\bar{y}_{0(\max)}$ for the pile group

$$\bar{y}_{0(\max)} = \begin{cases} \bar{y}_0 & \text{for } \bar{y}_0 \le 2K_s W_p K_{sp} K_m \\ 2K_s W_p K_{sp} K_m & \text{for } \bar{y}_0 \ge 2K_s W_p K_{sp} K_m \end{cases}$$

$$2K_s W_p K_{sp} K_m = 2(0.93)(10.66\ \text{ft})(0.51)(1) = 10.11\ \text{ft}$$

$$\bar{y}_0 = 15.98\ \text{ft},$$

therefore,

$$\bar{y}_{0(\max)} = 10.11\ \text{ft}$$

Case 1 Example Problem (cont.)

Compute the submerged pile coefficient, K_h

$$K_h = 1.5\,\tanh\left(0.8\sqrt{\frac{8\text{ ft}}{10.11\text{ ft}}}\right) = 0.92$$

Compute the effective diameter of the pile group, D^*_{pg}

$$\boxed{D^*_{pg} = K_{sp}K_hK_mK_sW_p = (0.51)(0.92)(1)(0.93)(10.66\text{ ft}) = 4.65\text{ ft}}$$

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Case 1 Example Problem (cont.)

Compute the effective diameter of the complex pier, D^*

$$D^* \equiv D^*_{col} + D^*_{pc} + D^*_{pg}$$

$$\boxed{D^* = 0.32\,\text{ft} + 1.29\,\text{ft} + 4.65\,\text{ft} = 6.26\,\text{ft}}$$

Case 1 Example Problem (cont.)

Compute the equilibrium scour depth for the complex pier, y_s

$$\frac{y_s}{6.26\ \text{ft}} = tanh\left[\left(\frac{13}{6.26}\right)^{0.4}\right] \times \left[\begin{array}{l} 2.2\left(\dfrac{11/1.16 - 1}{16.36/1.16 - 1}\right) + \\ 2.5\left\{\dfrac{6.26/(6.56 \times 10^{-4})}{0.4\left[6.26/(6.56 \times 10^{-4})\right]^{1.2} + 10.6\left[6.26/(6.56 \times 10^{-4})\right]^{-0.13}}\right\} \\ \left(\dfrac{16.36/1.16 - 11/1.16}{16.36/1.16 - 1}\right) \end{array}\right]$$

$$\boxed{y_s = 9.69\ \text{ft}}$$

Section Break

Complex Pier Scour Methodology

Case 2 Complex Pier

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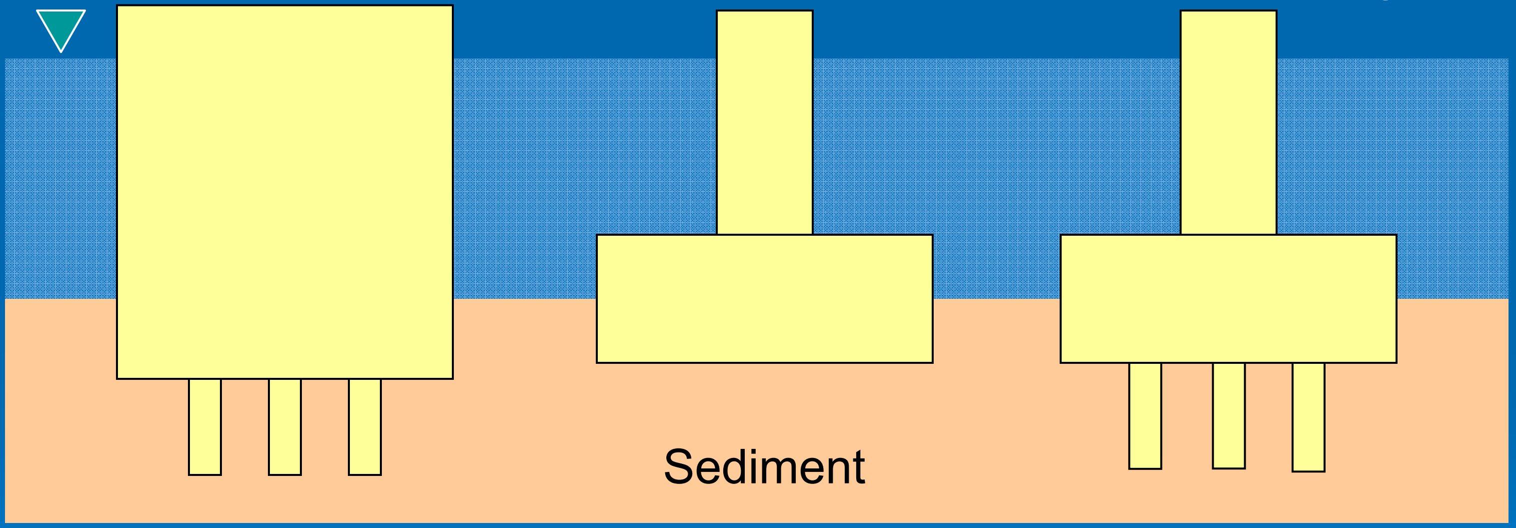
Case 2 Complex Piers



Pile Cap (partially buried) & Pile group

Column, Pile Cap (partially buried)

Column, Pile Cap (partially buried) & Pile group

Piers Covered in this Case

Case 2 Procedure Outline

- Compute Column Effective Diameter, D^{*}_{col}
- Compute Pile Cap Effective Diameter, D^{*}_{pc} Iteration required
- Compute Pile Group Effective Diameter, D^{*}_{pg}, if bottom of the pile cap is exposed
- Calculate Complex Pier Effective Diameter
  - $D^* = D^{*}_{col} + D^{*}_{pc} + D^{*}_{pg}$
- Compute Complex Pier Scour, y_s

Compute Column Effective Diameter, D^{*}_{col}

- Calculate $y_{0(max)}$ for the Column

$$y_{0(max)} = \begin{cases} 5b_{col} & \text{for } y_0 \geq 5b_{col} \\ y_0 & \text{for } y_0 < 5b_{col} \end{cases}$$

- If $H_{col} > y_{0(max)}$ set $D^{*}_{col} = 0$ start computation of D^{*}_{pc}
  otherwise continue

Compute Column Effective Diameter, D^{*}_{col} (cont.)

- Calculate the Column Shape Factor, K_s

$$K_s = \left\{ \begin{array}{ll} 1 & \text{for circular columns} \\ 0.86+0.97\left|\alpha \dfrac{\pi}{180^{o}} - \dfrac{\pi}{4}\right|^{4} & \text{for square columns} \end{array} \right\}$$

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Column Effective Diameter (cont.)

- Calculate the Column Skew Factor, K_α

$$K_\alpha = \frac{b_{col}\cos(\alpha) + l_{col}\sin(\alpha)}{b_{col}}$$

- Calculate the Pile Cap Extension, f

$$f = \left\{ \begin{array}{ll} \dfrac{3f_1 + f_2}{4} & \text{for } \alpha \leq 45^o \\ \dfrac{3f_2 + f_1}{4} & \text{for } \alpha > 45^o \end{array} \right\}$$

Column Effective Diameter (cont.)

- Calculate the Pile Cap Extension Coefficient, K_f

$$K_f = \left[\begin{array}{ll} -0.12\left(\dfrac{f}{b_{col}}\right)^2 - 0.03\left(\dfrac{f}{b_{col}}\right) + 1 & \text{for } 0 \le \dfrac{f}{b_{col}} \le 3 \\ 0 & \text{for } \dfrac{f}{b_{col}} > 3 \end{array} \right]$$

Column Effective Diameter (cont.)

- Calculate the Column Effective Diameter , D^{*}_{col}

$$D^{*}_{col} = \left\{ \begin{array}{ll} K_s K_\alpha K_f b_{col} \left[0.116 \left(\frac{H_{col}}{y_{0\,(max)}} \right)^2 - 0.362 \left(\frac{H_{col}}{y_{0\,(max)}} \right) + 0.248 \right] & \text{for } 0 \le \frac{H_{col}}{y_{0\,(max)}} \le 1 \\ 0 & \text{for } \frac{H_{col}}{y_{0\,(max)}} > 1 \end{array} \right\}$$

Compute Pile Cap Effective Diameter

- Calculate $y_{s(col)}$, Using the D^*_{col} Calculated in the Previous Section
- Calculate the Pile Cap Shape Factor, K_s

$$K_s = \begin{cases} 1 & \text{for circular pile caps} \\ 0.86+0.97\left|\alpha\dfrac{\pi}{180^\circ}-\dfrac{\pi}{4}\right|^4 & \text{for square pile caps} \end{cases}$$

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Pile Cap Effective Diameter (cont.)

- Calculate the Pile Cap Skew Factor, K_α

$$K_\alpha = \frac{b_{pc}\cos(\alpha) + l_{pc}\sin(\alpha)}{b_{pc}}$$

- Does $y_{s(col)}$ uncover bottom of pile cap?

$$\text{If}\ \left\{\begin{array}{ll} y_{s(col)} \ge \left|H_{pc}\right|, & \text{pile cap bottom is uncovered; compute } y_{0(max)} \text{ and } D^{*}_{pc} \\ y_{s(col)} < \left|H_{pc}\right|, & \text{start iterative computations} \end{array}\right\}$$

Pile Cap Effective Diameter (cont.)

- If $y_{s(col)} \geq |H_{pc}|$ Calculate D^{*}_{pc} and $y_{0(max)}$

$$y_{0(max)} = \begin{cases} 1.64\left[T(K_s b_{pc})^{\frac{5}{2}}\right]^{\frac{2}{7}} & \text{for } y_0 \geq 1.64\left[T(K_s b_{pc})^{\frac{5}{2}}\right]^{\frac{2}{7}} \\ y_0 & \text{for } y_0 < 1.64\left[T(K_s b_{pc})^{\frac{5}{2}}\right]^{\frac{2}{7}} \end{cases}$$

$$D^{*}_{pc} = K_s K_\alpha b_{pc}\, exp\left[-1.04 - 1.77\, exp\left(\frac{H_{pc}}{y_{0(max)}}\right) + 1.70\left(\frac{T}{y_{0(max)}}\right)^{\frac{1}{2}}\right]$$

Pile Cap Effective Diameter (cont.)

- If $y_{s(col)} < \left| H_{pc} \right|$ Calculate T' and H'_{pc}

$$H'_{pc} = -y_{s(col)}$$

$$T' = T + H_{pc} - H'_{pc}$$

- Calculate $y_{0(max)(i)}$

$$y_{0(max)(i)} = \begin{cases} 1.64\left[T'(K_s b_{pc})^{\frac{5}{2}}\right]^{\frac{2}{7}} & \text{for } y_0 \geq 1.64\left[T'(K_s b_{pc})^{\frac{5}{2}}\right]^{\frac{2}{7}} \\ y_0 & \text{for } y_0 < 1.64\left[T'(K_s b_{pc})^{\frac{5}{2}}\right]^{\frac{2}{7}} \end{cases}$$

Pile Cap Effective Diameter (cont.)

- Compute $D^{*}_{pc(i)}$

$$D^{*}_{pc(i)} = K_s K_\alpha b_{pc}\, exp\left[-1.04 - 1.77\; exp\left(\frac{H'_{pc}}{y_{0(max)(i)}} \right) + 1.70 \left(\frac{T'}{y_{0(max)(i)}} \right)^{\frac{1}{2}} \right]$$

- Compute the effective diameter of column and pile cap

$$D^{*}_{(col+pc)(i)} = D^{*}_{col} + D^{*}_{pc(i)}$$

Pile Cap Effective Diameter (cont.)

- Compute scour depth due to the column and portion of pile cap above bed, $Y_{s(col+pc)(i)}$ using single structure equations
- Recompute H'_{pc} and T'

$$H'_{pc} = \begin{cases} H_{pc} & \text{for } Y_{s(col+pc)(i)} \geq \left|H_{pc}\right| \\ -Y_{s(col+pc)(i)} & \text{for } Y_{s(col+pc)(i)} < \left|H_{pc}\right| \end{cases}$$

$$T' = \begin{cases} T & \text{for } Y_{s(col+pc)(i)} \geq \left|H_{pc}\right| \\ T + H_{pc} - H'_{pc} & \text{for } Y_{s(col+pc)(i)} < \left|H_{pc}\right| \end{cases}$$

Pile Cap Effective Diameter (cont.)

- If i = 1 compute $y_{0(max)(2)}$, $D^*_{pc(2)}$, $D^*_{(col+pc)(2)}$, and $Y_{s(col+pc)(2)}$
- If i > 1 check for convergence

$$\Delta \equiv \left| \frac{Y_{s(col+pc)(i)} - Y_{s(col+pc)(i-1)}}{Y_{s(col+pc)(i-1)}} \right|$$

$$\text{If} \left\{ \begin{array}{l} \Delta \le 0.05 \ \ \text{converged, set } D^*_{pc} = D^*_{pc(i)}; \\ \qquad\qquad\qquad\qquad\qquad D^*_{(col+pc)} = D^*_{(col+pc)(i)}; \\ \qquad\qquad\qquad\qquad\qquad y_{s(col+pc)} = Y_{s(col+pc)(i)} \\ \Delta > 0.05 \ \ \text{continue ineration} \end{array} \right\}$$

Determine if Pile Group is Exposed

$$\text{If} \quad \left\{ \begin{array}{ll} y_{s(col+pc)} \leq \left|H_{pg}\right|, & D^{*}_{pg} = 0 \\ y_{s(col+pc)} > \left|H_{pg}\right|, & \text{pile group exposed} \end{array} \right\}$$

Pile Group Effective Diameter

- Using computed scour depth due to column and pile cap, $y_{s(col+pc)}$ lower bed by that amount then compute

$$\overline{H}_{pg} = H_{pg} + y_{s\,(col\,+\,pc)} \quad \text{and}$$

$$\overline{y}_0 = y_0 + y_{s\,(col\,+\,pc)}$$

- Note that H_{pg} is < 0 and $\overline{H}_{pg} > 0$

Pile Group Effective Diameter (cont.)

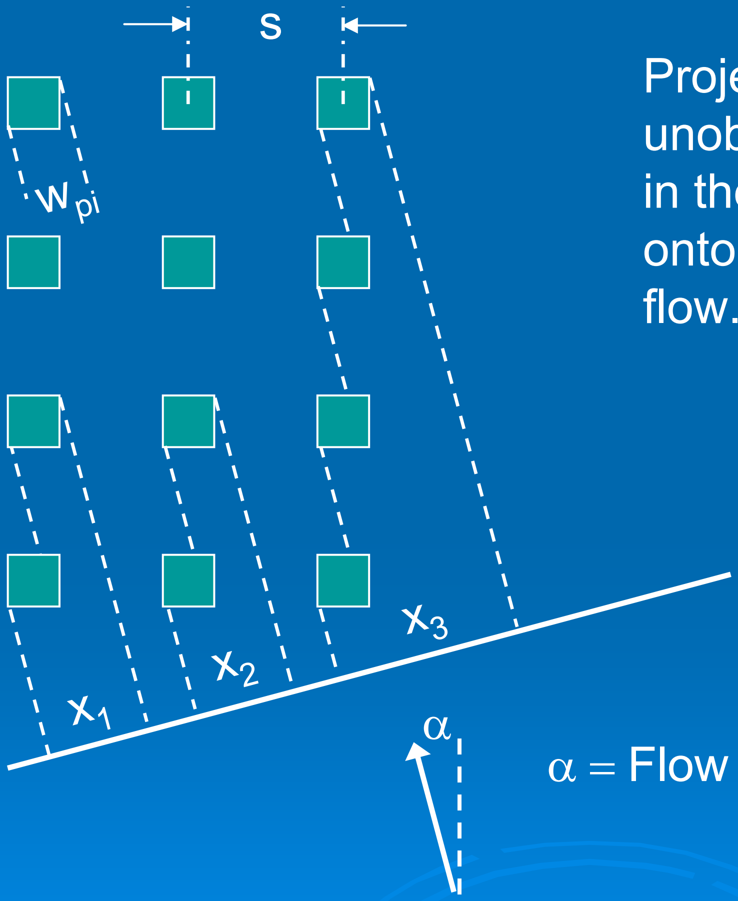
- Compute Pile Group Shape Factor, K_s

$$K_s = \frac{K_{s\,(pile)} - K_{s\,(pile\ group)}}{9}\left(\frac{s}{b}\right) + K_{s(pile)} - \frac{10}{9}\left(K_{s\,(pile)} - K_{s\,(pile\ group)}\right)$$

$$K_{s\,(pile\ or\ pile\ group)} = \begin{cases} 1 & \text{for circular piles} \\ 0.86+0.97\left|\alpha\frac{\pi}{180^{o}} - \frac{\pi}{4}\right|^{4} & \text{for square piles} \end{cases}$$

Pile Group Effective Diameter (cont.)

- Compute W_p



Projected width is the sum of the unobstructed projections of the piles in the first two rows and first column onto a vertical plane normal to the flow.

$$W_p = X_1 + X_2 + X_3$$

α = Flow skew angle

Pile Group Effective Diameter (cont.)

- Compute the Pile Spacing Coefficient, K_{sp}

$$K_{sp} = 1 - \frac{4}{3}\left(1 - \frac{w_{pi}}{W_p}\right)\left(1 - \frac{1}{\left(\frac{s}{w_{pi}}\right)^{0.6}}\right)$$

Pile Group Effective Diameter (cont.)

- Compute K_m, a coefficient that accounts for the number of piles inline with the flow

$$K_m = \begin{cases} 0.045(m) + 0.96 & \text{for } |\alpha| < 5^\circ, \text{ and } m \leq 5 \\ 1.19 & \text{for } |\alpha| < 5^\circ, \text{ and } m > 5 \\ 1 & \text{for } |\alpha| \geq 5^\circ \end{cases}$$

Pile Group Effective Diameter (cont.)

- Compute $\overline{y}_{0(\max)}$ for the pile group

$$y_{0(\max)} = \left\{ \begin{array}{ll} \overline{y}_0 & \text{for } \overline{y}_0 \leq 2\,K_s\,W_p\,K_{sp}\,K_m \\ 2\,W_p K_{sp} K_m & \text{for } \overline{y}_0 > 2\,K_s\,W_p\,K_{sp}\,K_m \end{array} \right\}$$

Pile Group Effective Diameter (cont.)

- Compute the Pile Height Coefficient, K_h

$$K_h = \begin{cases} 1.5\tanh\left(0.8\sqrt{\dfrac{\bar{H}_{pg}}{\bar{y}_{0(max)}}}\right) & \text{for } 0 \leq \dfrac{\bar{H}_{pg}}{\bar{y}_{0(max)}} \leq 1 \\ 0 & \text{for } \dfrac{\bar{H}_{pg}}{\bar{y}_{0(max)}} < 0 \\ 1 & \text{for } \dfrac{\bar{H}_{pg}}{\bar{y}_{0(max)}} > 1 \end{cases}$$

Pile Group Effective Diameter (cont.)

- Compute the Effective Diameter for the Pile Group

$$D^{*}_{pg} = K_{sp} K_{h} K_{m} K_{s} W_{p}$$

Complex Pier Effective Diameter

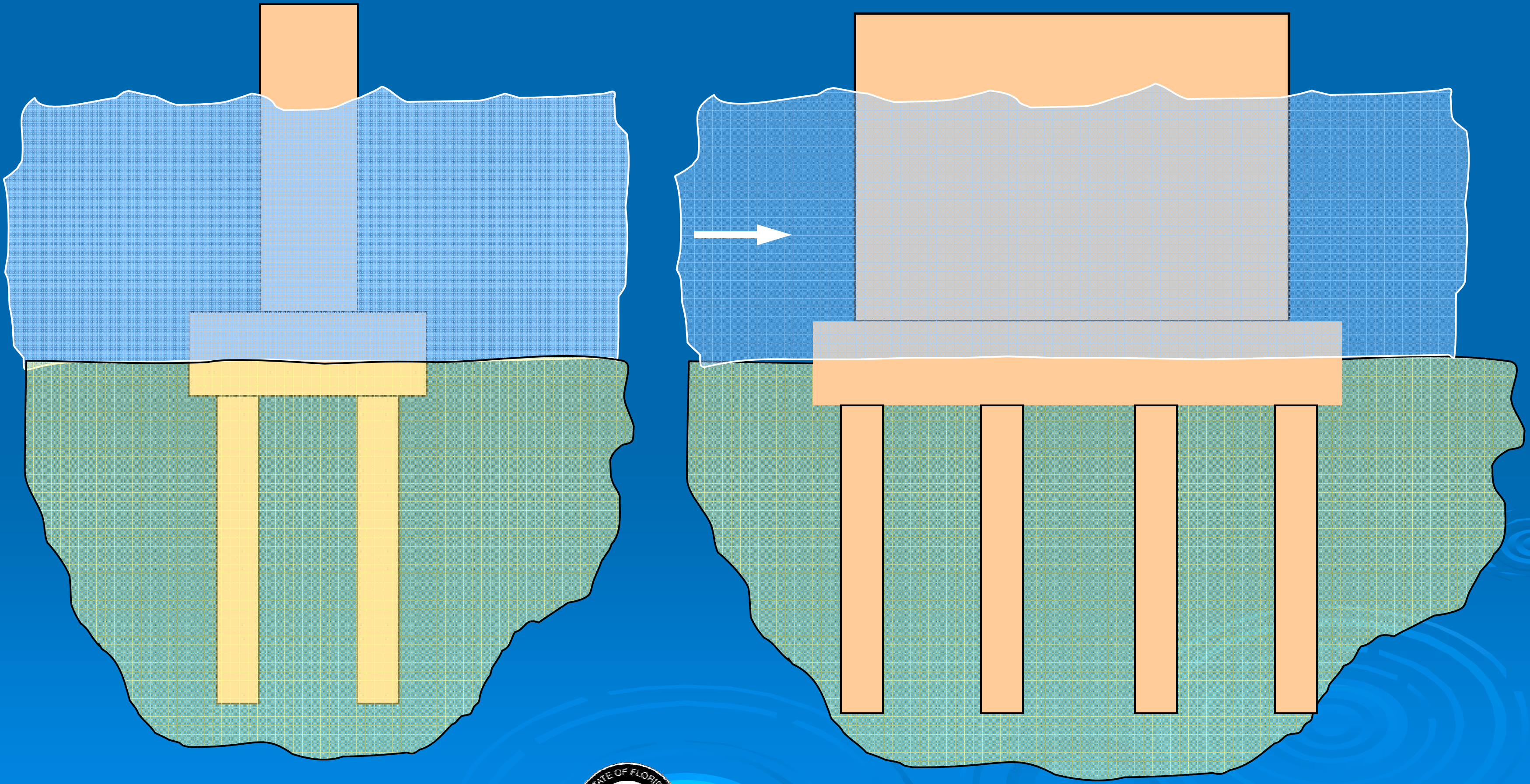
- Compute the Effective Diameter for the Complex Pier

$$D^* = D^*_{col} + D^*_{pc} + D^*_{pg}$$

- The equilibrium scour depth, y_s, for the complex structure can now be computed by substituting D^* into the single structure equations

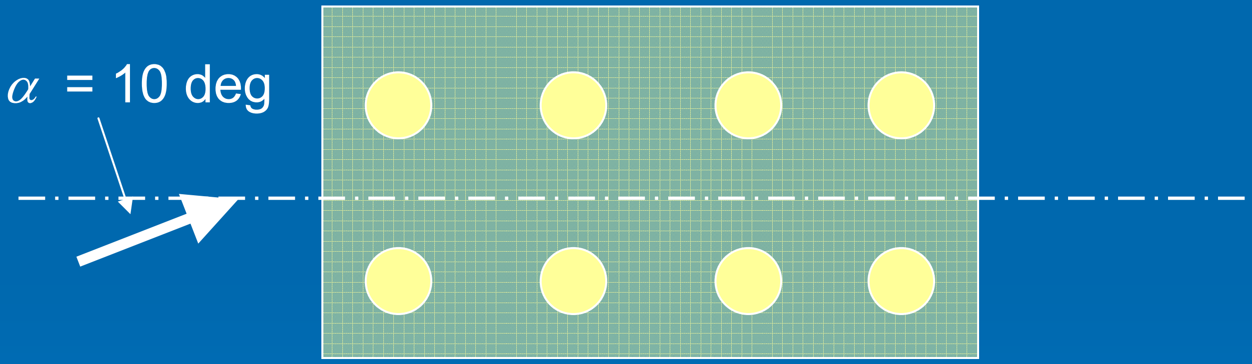
Case 2 Example Problem

- Compute the Equilibrium Scour Depth for the following pier/sediment/flow situation



Case 2 Example Problem

- Compute the Equilibrium Scour Depth for the following pier/sediment/flow situation



Case 2 Example Problem

- Compute the Equilibrium Scour Depth for the following pier/sediment/flow situation

Flow and Sediment

y_0 (ft)	V (ft/s)	V_c (ft/s)	V_{lp} (ft/s)	α (deg)	D_{50} (mm)
18	10	1.18	19.25	10	0.2

Structure - Column

H_{col} (ft)	b_{col} (ft)	l_{col} (ft)
3	10	23

Case 2 Example Problem

- Compute the Equilibrium Scour Depth for the following pier/sediment/flow situation

Structure - Column

H_{pc} (ft)	T (ft)	b_{pc} (ft)	f_1 (ft)	f_2 (ft)	l_{pc} (ft)
-3	6	14	3	2	29

Structure – Pile Group

b (ft)	s (ft)	n	m	w_{pi} (ft)	W_p (ft)
2.5	7.5	2	4	2.5	10.2

Case 2 Example Problem – Solution

Critical Velocity and Live Bed Peak Velocity		
	y_o (ft)	18
	Water density (lb/ft^3)	62.29
	Kinematic Viscosity (ft^2/s)	0.000010492
	D_{50} (mm)	0.2
	u_{*c} (ft/s)	0.041
	V_c (ft/s)	1.18
	V_{lp} (ft/s)	19.25
	V/V_c	8.47
	V_{lp}/V_c	16.31

Case 2 Example Problem – Solution (cont.)

Case 2 Column Calculations		
A	Calculate $y_{0(max)}$ (ft)	18
B	Is $H_{col} > y_{0(max)}$	Continue on to step C
C	Calculate K_s	1
D	Calculate K_α	1.38
E	Calculate the pile cap extension coefficient, K_f	
	f (ft)	2.75
	f/b_{col}	0.28
	K_f	1
F	Calculate D^*_{col} (ft)	2.63

Case 2 Example Problem – Solution (cont.)

Pile Cap Calculations		
A	Calculate $y_{s(col)}$	
	$y_0/D^*_{col(max)}$	6.84
	D^*/D_{50}	4009.15
	$f_1(y_0/D^*)$	0.97
	$f_2(D^*/D_{50})$	0.48
	$y_{s(col)}$ (ft)	4.31
B	Calculate K_s	1
C	Calculate K_a	1.34
D	Check to see if the scour depth due to the column, y_{scol}, uncovers the bottom of the pile cap	Continue to step E.

Case 2 Example Problem – Solution (cont.)

E	Calculate $y_{0(max)}$ and D^*_{pc}	
	$y_{0(max)}$ (ft)	18
	$H_{pc}/y_{0(max)}$	-0.17
	$T/y_{0(max)}$	0.33
	D^*_{pc} (ft)	3.94
F	Calculate T' and H'_{pc}	
	T' (ft)	NA
	H'_{pc} (ft)	NA
G	Calculate $y_{0(max)(i)}$ (ft)	NA
H	Calculate $D^*_{pc(i)}$ (ft)	NA
	$H'_{pc}/y_{0(max)}$	NA
	$T'/y_{0(max)}$	NA
	D^*_{pc} (ft)	NA
I	Calculate $D^*_{(col+pc)(i)}$ (ft)	NA

Case 2 Example Problem – Solution (cont.)

J	Calculate $y_{s(col+pc)(i)}$	NA
	$y_o/D^*_{(col+pc)(i)}$	NA
	$D^*/D_{50(i)}$	NA
	$f_1(y_0/D^*)(i)$	NA
	$f_2(D^*/D_{50})(i)$	NA
	$Y_{s(col+pc)(i)}$ (ft)	NA
K	Calculate T' and H'_{pc}	NA
	T' (ft)	NA
	H'_{pc} (ft)	NA
L	Check for convergence	NA
M	Pile cap summary	
	D^*_{pc} (ft)	3.94
	Calculate $D^*_{(col+pc)}$ (ft)	6.57
	Calculate $y_{s(col+pc)}$ (ft)	9.39
N	Determine if the Pile Group is exposed	Yes

Case 2 Example Problem – Solution (cont.)

Case 2 Pile Group Calculations		
A	Calculate $y_{s(col+pc)}$	
	$D^*_{(col+pc)}$ (ft)	6.57
	$y_o/D^*_{col(max)}$	2.74
	D^*/D_{50}	10015.24
	$f_1(y_o/D^*)$	0.9
	$f_2(D^*/D_{50})$	0.4
	$y_{s(col+pc)}$ (ft)	9.39
B	Calculate $\overline{H}_{pg}$ and $\overline{y}_0$ (ft)	
	$\overline{H}_{pg}$ (ft)	27.39
	$\overline{y}_0$ (ft)	6.39
C	Calculate the shape factor for the pile group, K_s	
	s/b	1.2
	$K_{s(pile)}$	1
	$K_{s(pile\ group)}$	1
	K_s	1

Case 2 Example Problem – Solution (cont.)

D	Calculate W_p (ft)	10.2
E	Calculate the pile spacing coefficient, K_{sp}	0.9
G	Calculate $\overline{y}_{0(max)}$ (ft)	18.36
H	Calculate K_h	0.66
I	Calculate D^*_{pg} (ft)	6.06

Case 2 Example Problem – Solution (cont.)

Case 2 Complex Pier Scour		
A	Calculate the overall effective diameter, D^*	10.89
B	Calculate $y_{s(col+pc+pg)}$	
	$D^*_{(col+pc+pg)}$ (ft)	10.89
	y_0/D^*	1.65
	D^*/D_{50}	16600
	$f_1(y_0/D^*)$	0.84
	$f_2(D^*/D_{50})$	0.36
	$y_{s(col+pc+pg)}$ (ft)	14.0

Section Break

Complex Pier Scour Methodology

Case 3 Complex Pier

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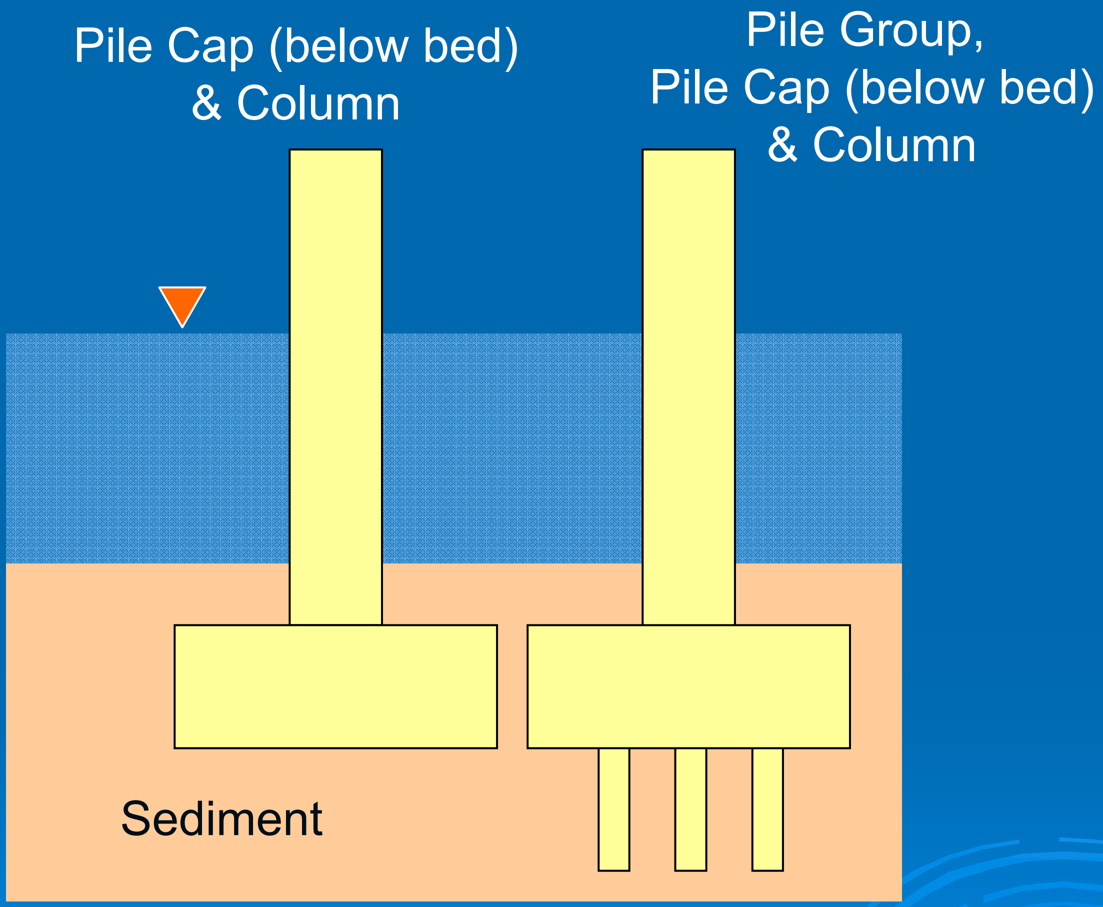
Case 3 Complex Piers



Pile Cap (below bed)
& Column

Pile Group,
Pile Cap (below bed)
& Column

Piers Covered in this Case

Case 3 Procedure Outline

- Compute column effective diameter, D^{*}_{col}
- If exposed determine if the scour caused by the column uncovers the top of the pile cap
- Compute pile cap effective diameter, D^{*}_{pc} iteratively

Case 3 Procedure Outline (cont.)

- Compute pile group effective diameter, D^*_{pg}, if the pile group is exposed
- Calculate complex pier effective diameter
  - $D^* = D^*_{col} + D^*_{pc} + D^*_{pg}$
- Compute complex pier equilibrium scour depth, $y_s(D^*)$

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Column Effective Diameter

- Calculate the column shape factor, K_s

$$K_s = \begin{cases} 1 & \text{for circular columns} \\ 0.86+0.97\left|\alpha\dfrac{\pi}{180^{o}}-\dfrac{\pi}{4}\right|^{4} & \text{for square columns} \end{cases}$$

- Calculate the column skew factor, K_α

$$K_\alpha = \frac{b_{col}\,cos(\alpha)+l_{col}\,sin(\alpha)}{b_{col}}$$

Column Effective Diameter (cont.)

- Compute the scour depth for the column, $y_{s(col)(max)}$, as if the column extends indefinitely deep, by substituting $D^{*}_{col(max)}$ into the single structure scour equations
- Compare this scour depth with distance to the bottom of the column

$$\text{If}\left\{\begin{array}{lll} y_{s(col)(max)} & \leq \; \left|H_{col}\right| & D^{*}\text{ for complex pier} = D^{*}_{col} \\ y_{s(col)(max)} & > \; \left|H_{col}\right| & \text{pile cap is exposed} \end{array}\right\}$$

Column Effective Diameter (cont.)

- Compute effective diameter required to scour to top of pile cap
- Set $y_s = |H_{col}|$ in the single structure scour equations and solve for the effective diameter, $D^*_{col(min)}$

Column Effective Diameter (cont.)

- Calculate the pile cap weighted average extension, f

$$f = \left\{ \begin{array}{ll} \dfrac{3f_1 + f_2}{4} & \text{for } \alpha \le 45^\circ \\[2ex] \dfrac{3f_2 + f_1}{4} & \text{for } \alpha > 45^\circ \end{array} \right\}$$

Column Effective Diameter (cont.)

- Calculate the Pile Cap Extension Coefficient, K_f

$$K_f = \begin{cases} -0.12\left(\frac{f}{b_{col}}\right)^2 + 0.03\left(\frac{f}{b_{col}}\right) + 1 & \text{for } 0 < \left(\frac{f}{b_{col}}\right) \leq 3 \\ 0 & \text{for } \left(\frac{f}{b_{col}}\right) > 3 \end{cases}$$

Column Effective Diameter (cont.)

- Calculate the, $D^*_{col(f)}$

$$D^*_{col(f)} = K_f D^*_{col(max)} \left[-0.75 \left(\frac{H_{col}}{y_{s(col)(max)}} \right) + 0.25 \right]$$

Column Effective Diameter (cont.)

- Compute the effective diameter of the column,

$$D^*_{col} = \begin{cases} D^*_{col(f)} & \text{if } D^*_{col(f)} \geq D^*_{col(min)} \\ D^*_{col(min)} & \text{if } D^*_{col(f)} < D^*_{col(min)} \end{cases}$$

Pile Cap Effective Diameter

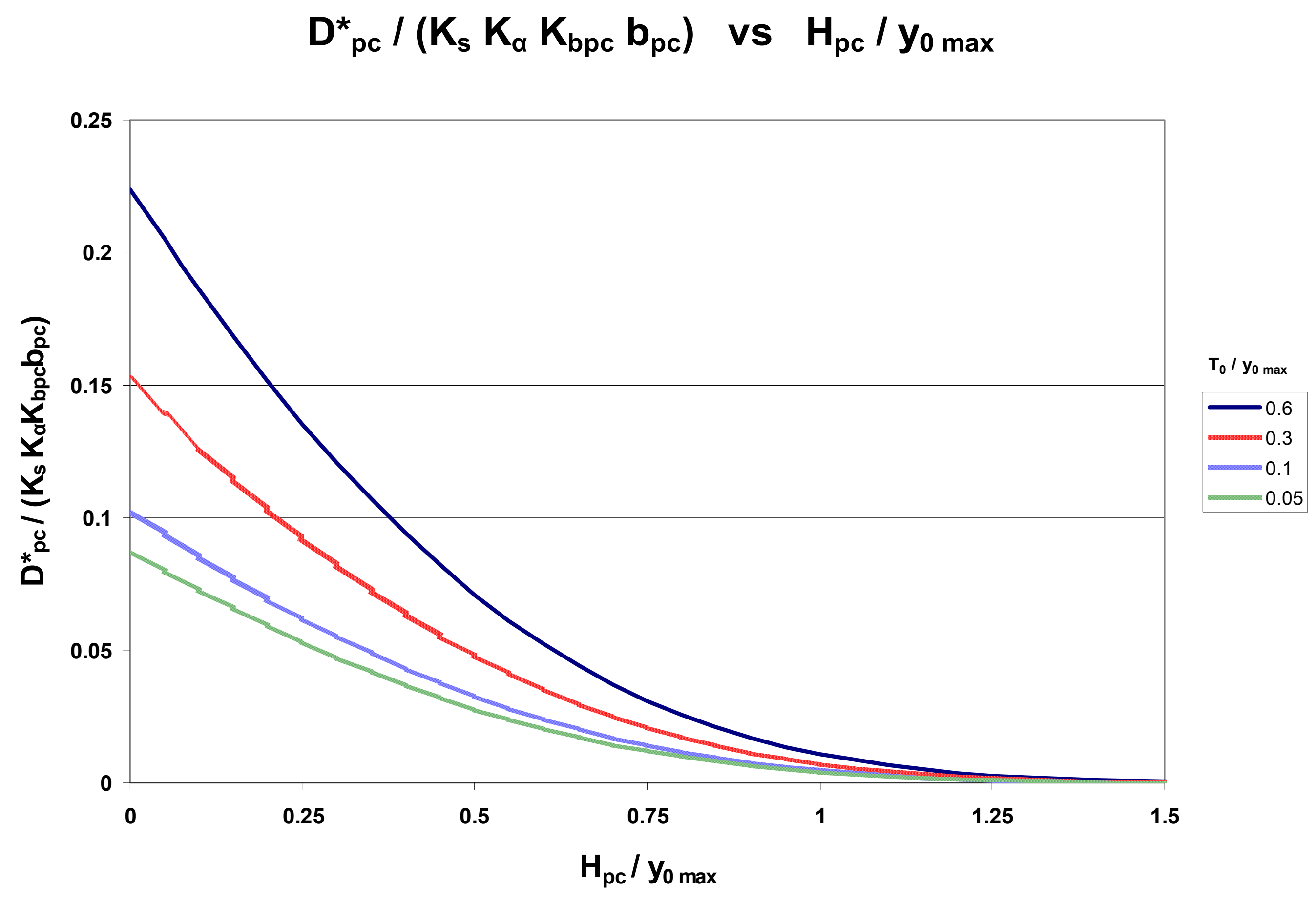
- Compute $y_{s(col)}$, using the D^{*}_{col} from the column section
- Compute the coefficient that accounts for the position of the pile cap in the scour hole, K_{bpc}

$$K_{bpc} = \left\{ \begin{array}{ll} (A)(B) & \text{for} \quad 0 \le \dfrac{-H_{col}}{y_{s(col)}} \le 1 \text{ and } 0 \le \dfrac{f}{b_{col}} \le 3 \\ 0 & \text{otherwise} \end{array} \right\}$$

$$A = -1.166\left(\frac{-H_{col}}{y_{s(col)}}\right)^{2} + 0.166\left(\frac{-H_{col}}{y_{s(col)}}\right) + 1$$

$$B = -0.333\left(\frac{f}{b_{col}}\right) + 1$$

Pile Cap Effective Diameter



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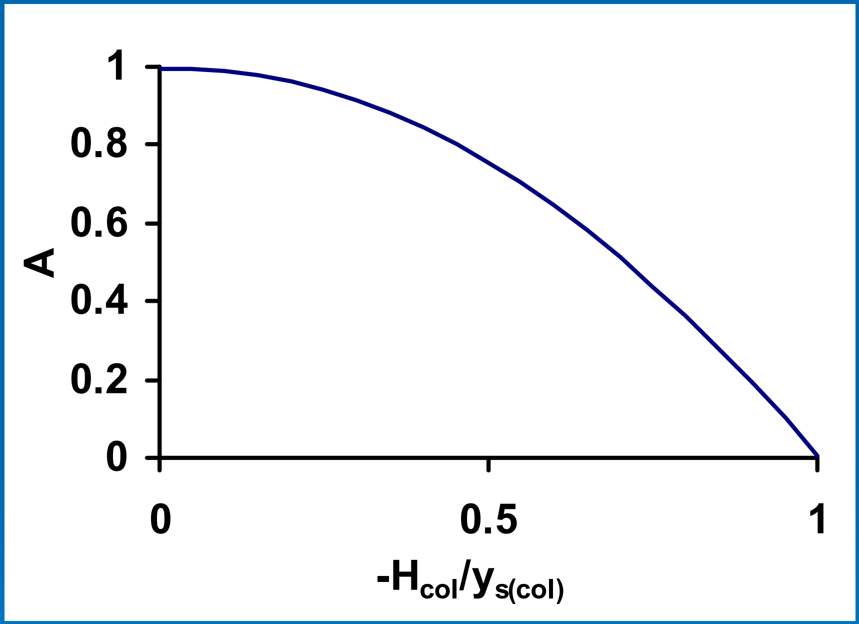
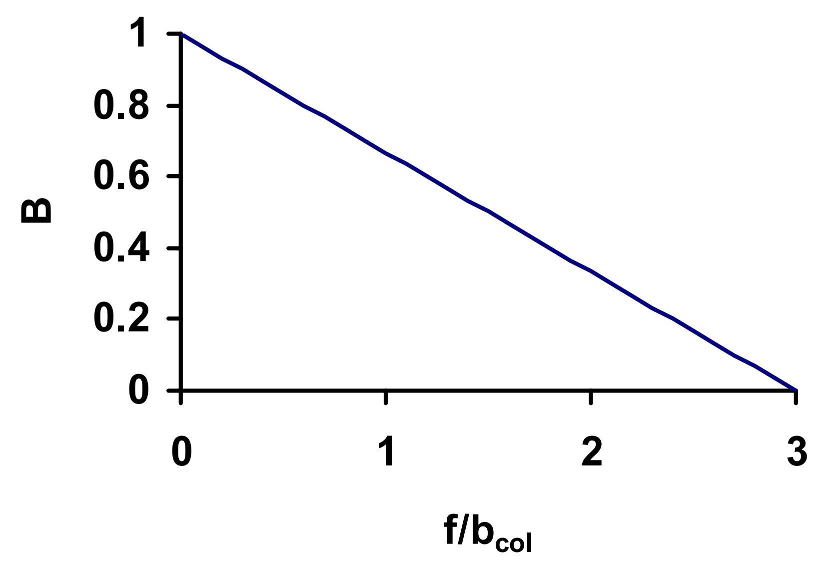
Pile Cap Effective Diameter





Pile Cap Effective Diameter (cont.)

- Compute the pile cap shape factor, K_s

$$K_s = \begin{cases} 1 & \text{for circular pile caps} \\ 0.86 + 0.97\left|\alpha\dfrac{\pi}{180^\circ} - \dfrac{\pi}{4}\right|^4 & \text{for square pile caps} \end{cases}$$

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Pile Cap Effective Diameter (cont.)

- Compute pile cap skew angle factor, K_α

$$K_\alpha = \frac{b_{pc}\cos(\alpha) + l_{pc}\sin(\alpha)}{b_{pc}}$$

- Does column scour COMPLETELY uncover bottom of pile cap?

$$\text{If}\left\{\begin{array}{l} y_{s(col)} \ \geq \ |H_{pc}|, \text{ pile cap bottom uncovered} \\ \qquad\qquad\qquad \text{compute } y_{0(max)}, \text{and } D^{*}_{pc} \text{ directly} \\ y_{s(col)} \ < \ |H_{pc}|, \text{ iterative computations required} \end{array}\right\}$$

Pile Cap Effective Diameter (cont.)

- Pile cap COMPLETELY uncovered

  Compute $y_{0(max)}$

$$y_{0(max)} = \begin{cases} 1.64\left(T(K_s b_{pc})^{\frac{5}{2}}\right)^{\frac{2}{7}} & \text{for } y_0 \geq 1.64\left(T(K_s b_{pc})^{\frac{5}{2}}\right)^{\frac{2}{7}} \\ y_0 & \text{for } y_0 < 1.64\left(T(K_s b_{pc})^{\frac{5}{2}}\right)^{\frac{2}{7}} \end{cases}$$

Pile Cap Effective Diameter (cont.)

- Pile cap COMPLETELY uncovered

  Compute D^*_{pc}

$$D^*_{pc} = K_s K_\alpha b_{pc}\, exp\left[-1.04 \;-\; 1.77\, exp\left(\frac{H_{pc}}{y_{0(max)}}\right) + 1.70\left(\frac{T}{y_{0(max)}}\right)^{\frac{1}{2}}\right]$$

Pile Cap Effective Diameter (cont.)

- Pile cap NOT COMPLETELY uncovered

Compute T' and H'_{pc}

$$T' = (T + H_{pc}) + y_{s(col)}$$

$$H'_{pc} = -y_{s(col)}$$

Pile Cap Effective Diameter (cont.)

- Pile cap NOT COMPLETELY uncovered

Compute $y_{0(max)(i)}$

$$y_{0(max)(i)} = \left\{ \begin{array}{ll} 1.64\left(T^{'}(K_s b_{pc})^{\frac{5}{2}}\right)^{\frac{2}{7}} & \text{for } y_0 \geq 1.64\left(T^{'}(K_s b_{pc})^{\frac{5}{2}}\right)^{\frac{2}{7}} \\ y_0 & \text{for } y_0 < 1.64\left(T^{'}(K_s b_{pc})^{\frac{5}{2}}\right)^{\frac{2}{7}} \end{array} \right\}$$

Pile Cap Effective Diameter (cont.)

- Pile cap NOT COMPLETELY uncovered

  Compute $D^{*}_{pc(i)}$

$$D^{*}_{pc} = K_s K_\alpha b_{pc}\, exp\left[-1.04 - 1.77\, exp\left(\frac{H'_{pc}}{y_{0(max)(i)}}\right) + 1.70\left(\frac{T'}{y_{0(max)(i)}}\right)^{2}\right]^{\frac{1}{2}}$$

Pile Cap Effective Diameter (cont.)

- Pile cap NOT COMPLETELY uncovered

  Compute $D^*_{(col+pc)(i)}$

$$D^*_{(col+pc)(i)} = D^*_{col} + D^*_{pc(i)}$$

- Compute scour depth due to column and pile cap above bed, $Y_{s(col+pc)(i)}$ using $D^*_{(col+pc)(i)}$ in the single structure equations

Pile Cap Effective Diameter (cont.)

- Pile cap NOT COMPLETELY uncovered

Compute H'_{pc} and T'

$$H'_{pc} = \left\{ \begin{array}{lll} H_{pc} & \text{for } Y_{s(col+pc)(i)} \geq \left| H_{pc} \right| \\ -Y_{s(col+pc)(i)} & \text{for } Y_{s(col+pc)(i)} < \left| H_{pc} \right| \end{array} \right\}$$

$$T' = \left\{ \begin{array}{ll} T & \text{for } Y_{s(col+pc)(i)} \geq \left| H_{pc} \right| \\ T + H_{pc} - H'_{pc} & \text{for } Y_{s(col+pc)(i)} < \left| H_{pc} \right| \end{array} \right\}$$

Pile Cap Effective Diameter (cont.)

- Pile cap NOT COMPLETELY uncovered

  If i = 1 proceed with iteration;

  if i > 1 check for convergence

$$\Delta \equiv \left| \frac{Y_{s(col+pc)(i)} - Y_{s(col+pc)(i-1)}}{Y_{s(col+pc)(i-1)}} \right|$$

$$\text{If} \begin{cases} \Delta \leq 0.05 & D^{*}_{pc} = D^{*}_{pc(i)} \\ \Delta > 0.05 & \text{proceed with iteration} \end{cases}$$

Pile Cap Effective Diameter (cont.)

- Pile cap NOT COMPLETELY uncovered

  Continue iteration until converges, then

$$D^*_{pc} = D^*_{pc(i)}$$

$$D^*_{(col+pc)} = D^*_{(col+pc)(i)}$$

$$y_{s(col+pc)} = Y_{s(col+pc)(i)}$$

Determine if pile group is exposed

$$\text{If}\left\{\begin{array}{llll} y_{s(col+pc)} & \leq & \left|H_{pg}\right| & \text{then } D^{*}_{pg} = 0 \\ y_{s(col+pc)} & > & \left|H_{pg}\right| & \text{pile group is exposed} \end{array}\right\}$$

Pile Group Effective Diameter

- Compute $\overline{H}_{pg}$, and $\overline{y}_0$

$$\overline{H}_{pg} = H_{pg} + y_{s(col+pc)}$$

$$\overline{y}_0 = y_0 + y_{s(col+pc)}$$

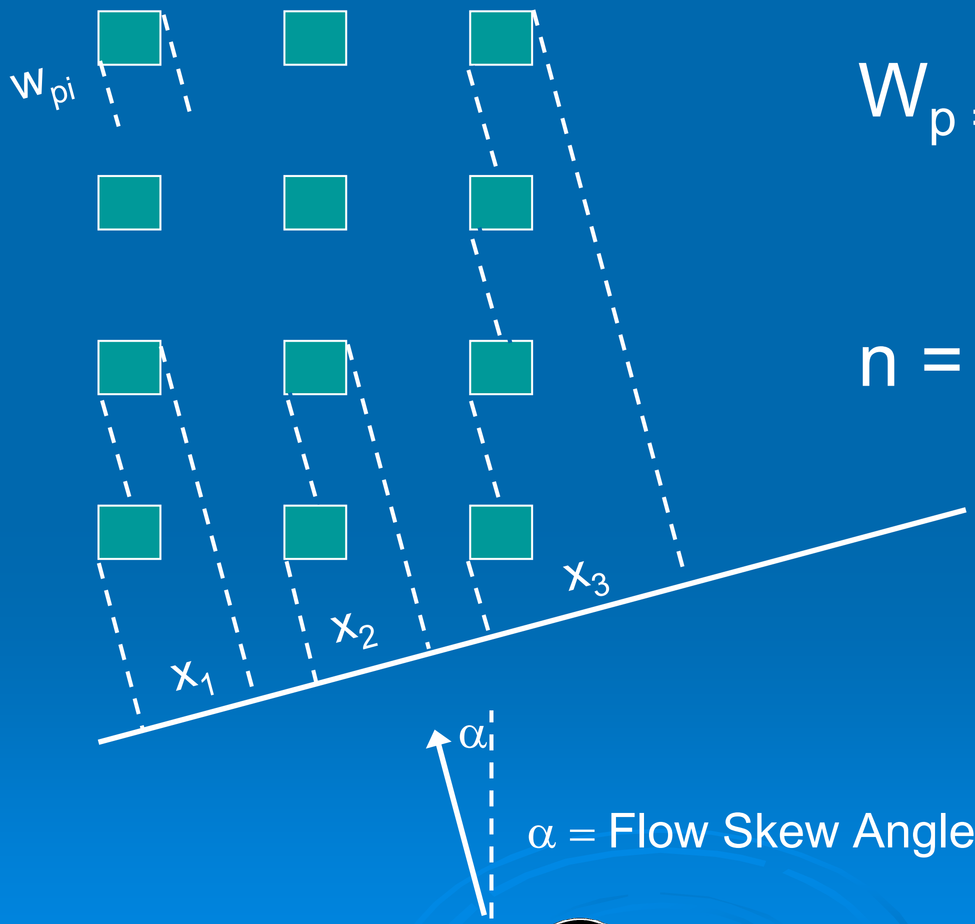
Pile Group Effective Diameter (cont.)

- Compute Pile Group Shape Factor, K_s

$$K_s = \frac{K_{s\,(pile)} - K_{s\,(pile\ group)}}{9}\left(\frac{s}{b}\right) + K_{s(pile)} - \frac{10}{9}\left(K_{s\,(pile)} - K_{s\,(pile\ group)}\right)$$

- Compute the Projected Width of the Pile Group, W_p

Pile Group Effective Diameter (cont.)



α = Flow Skew Angle

$$W_{p} = X_1 + X_2 + X_3$$

$$n = 3,\ m = 4$$

Pile Group Effective Diameter (cont.)

- Compute the pile spacing coefficient, K_{sp}

$$K_{sp} = 1 - \frac{4}{3}\left(1 - \frac{w_{pi}}{W_p}\right)\left(1 - \frac{1}{\left(\frac{s}{w_{pi}}\right)^{0.6}}\right)$$

Pile Group Effective Diameter (cont.)

- Compute K_m, a Coefficient that Accounts for the Number of Piles Inline with the Flow

$$K_m = \begin{cases} 0.045(m) + 0.96 & |\alpha| < 5^\circ \text{ and } m \leq 5 \\ 1.19 & |\alpha| < 5^\circ \text{ and } m > 5 \\ 1 & |\alpha| \geq 5^\circ \end{cases}$$

Pile Group Effective Diameter (cont.)

- Compute $\bar{y}_{0(\max)}$ for the pile group

$$\bar{y}_{0(\max)} = \begin{cases} \bar{y}_0 & \text{for } \bar{y}_0 \le 2 W_p K_{sp} K_m \\ 2 W_p K_{sp} K_m & \text{for } \bar{y}_0 \ge 2 W_p K_{sp} K_m \end{cases}$$

Pile Group Effective Diameter (cont.)

- Compute the pile height coefficient, K_h

$$K_h = \left\{ \begin{array}{lll} 1.5\,tanh\left(0.8\sqrt{\dfrac{\overline{H}_{pg}}{\overline{y}_{0(max)}}}\right) & \text{for } 0 \leq \dfrac{\overline{H}_{pg}}{\overline{y}_{0(max)}} \leq 1 \\ 0 & \text{for } \dfrac{\overline{H}_{pg}}{\overline{y}_{0(max)}} < 0 \\ 1 & \text{for } \dfrac{\overline{H}_{pg}}{\overline{y}_{0(max)}} > 1 \end{array} \right\}$$

Pile Group Effective Diameter (cont.)

- Compute the buried pile group attenuation coefficient, K_{bpg}

$$K_{bpg} = \frac{\overline{H}_{pg}}{y_{s(col+pc)}}$$

- Compute the effective diameter of the pile group

$$D^{*}_{pg} = K_{sp} K_h K_m K_s K_{bpg} W_p$$

Complex Pier Effective Diameter

- Compute D^* and y_s

$$D^* = D^*_{col} + D^*_{pc} + D^*_{pg}$$

- The equilibrium scour depth, y_s, for the complex structure can now be computed by substituting D^* into the single structure equations

Section Break

Other Scour Issues

Time Rate of Scour

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Time Rate of Scour

- Many design flow events are not sufficient in duration for the sediment scour to reach equilibrium
- This particularly true for the following situations:
  - Local scour at large structures where design flow is due to hurricanes
  - Contraction scour due to hurricane generated flow

Time Rate of Local Scour

- The effective shear stress near a structure (and thus the rate at which sediment is removed) changes as the scour hole develops

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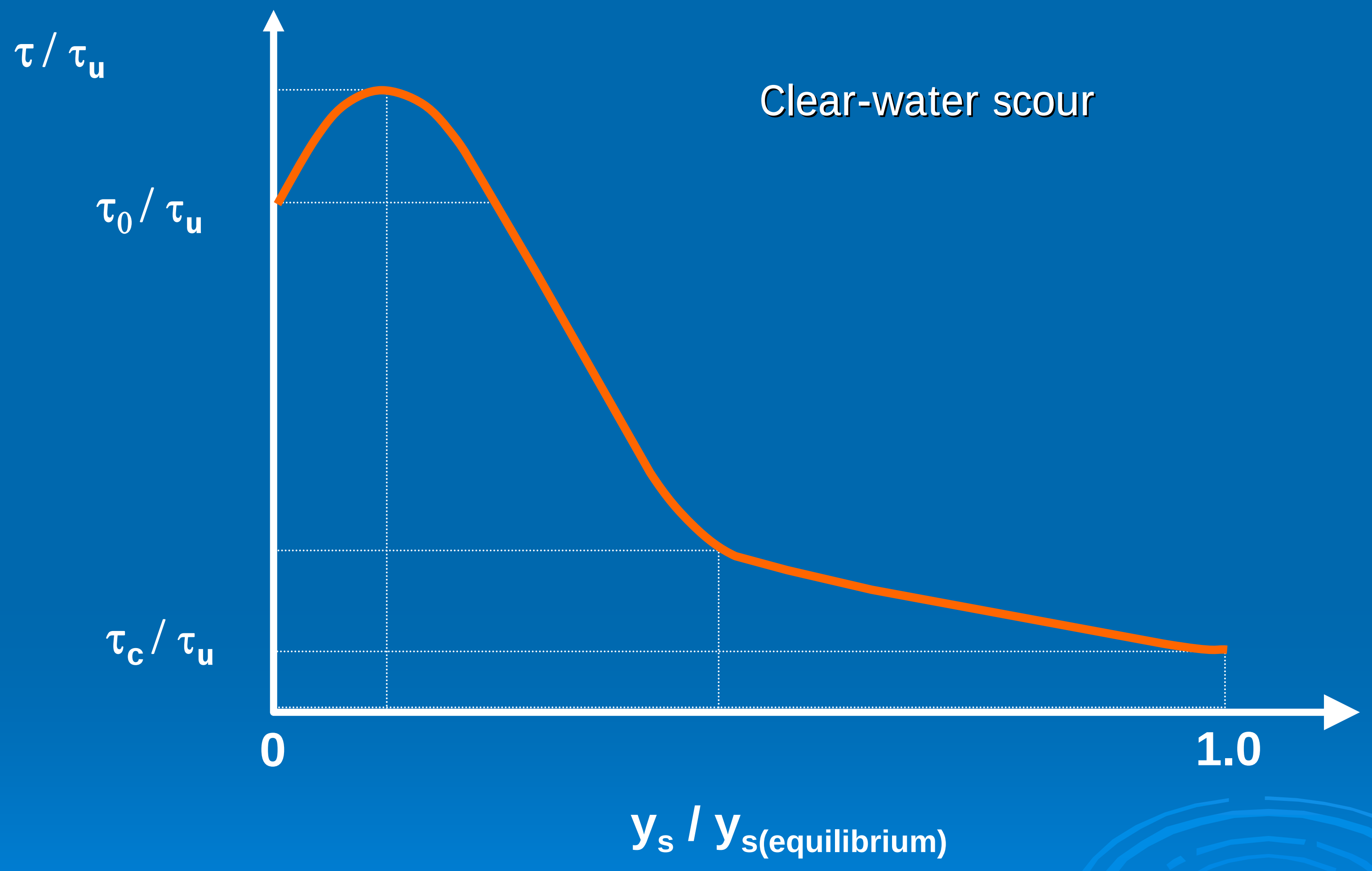
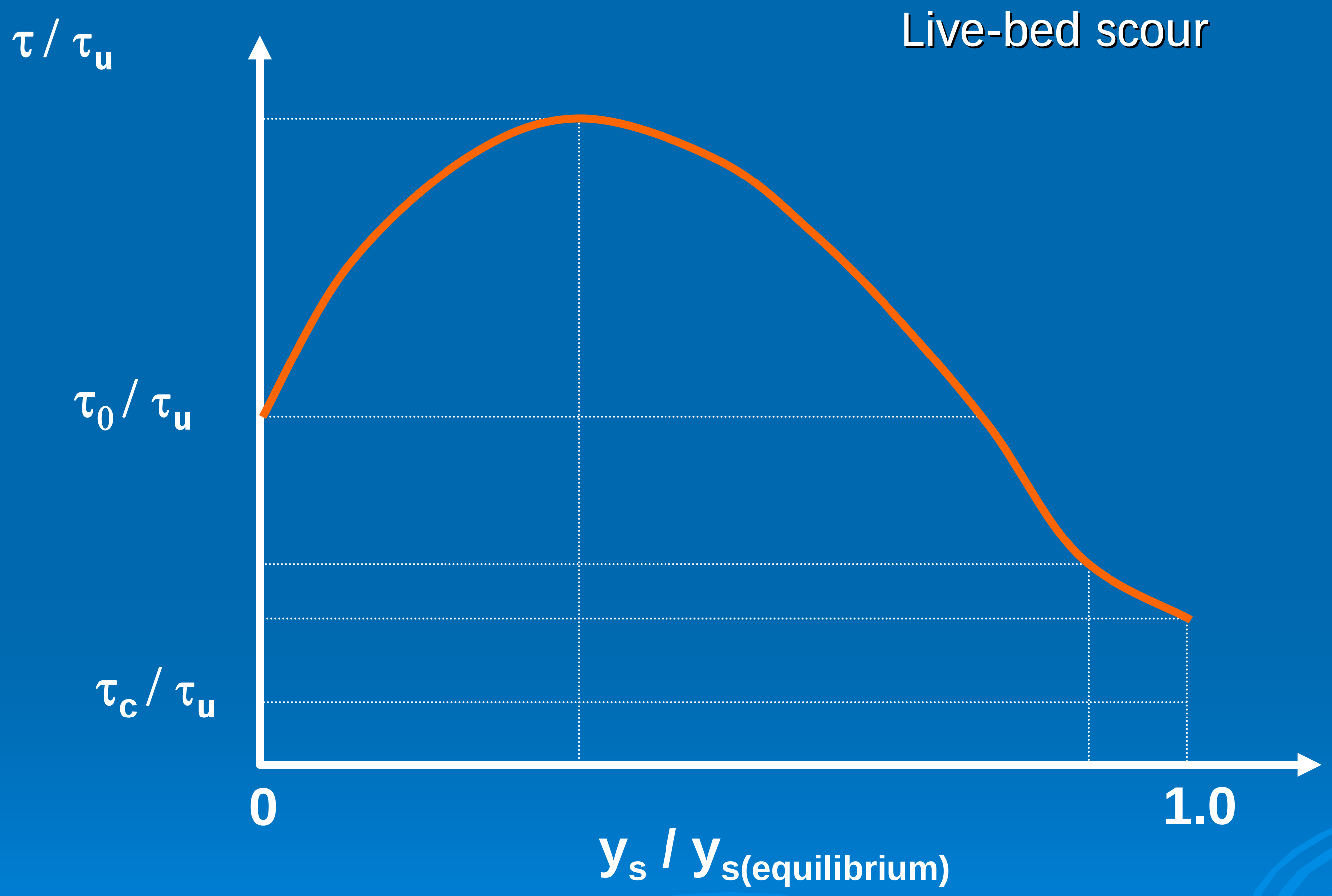
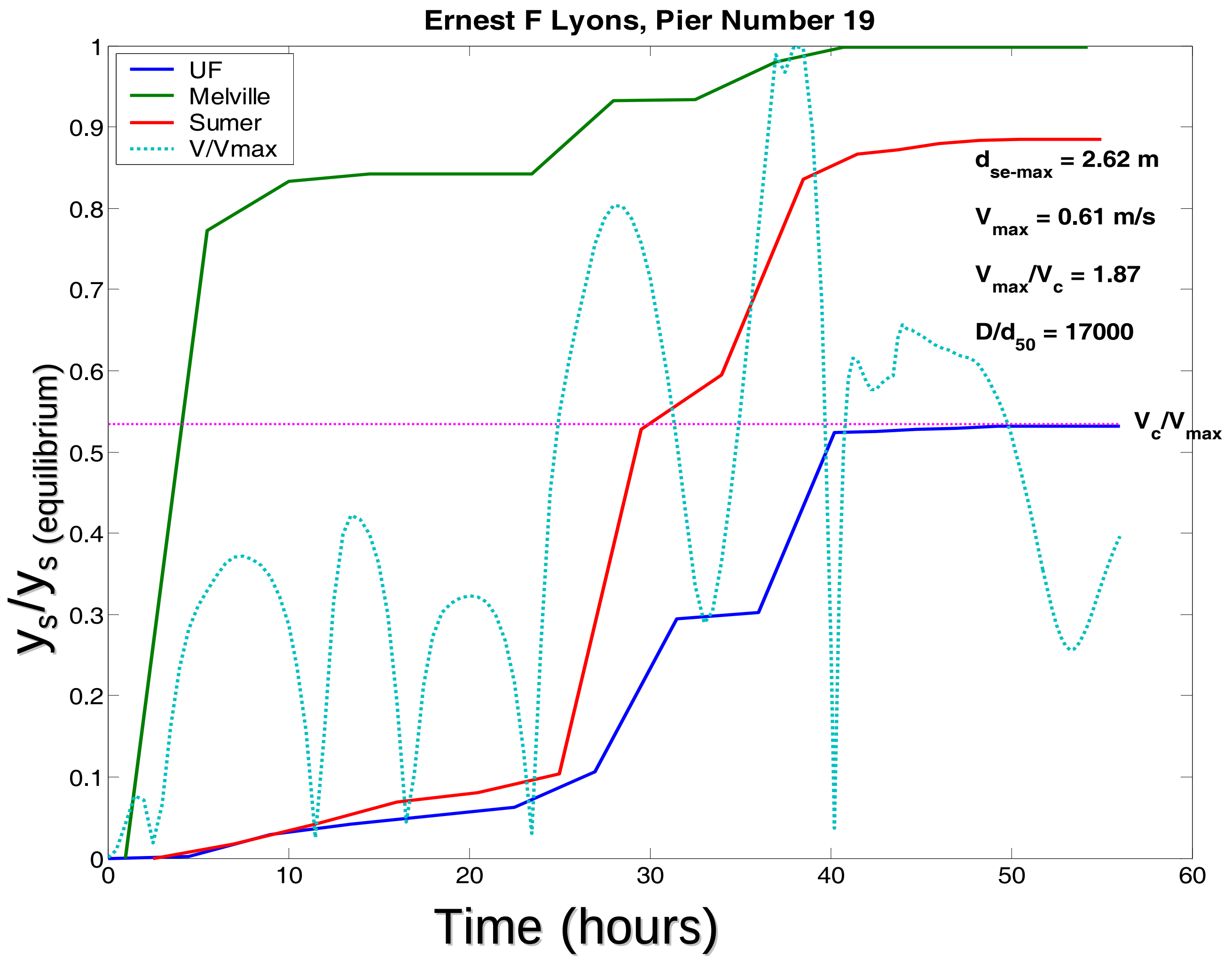
Time Rate of Scour



Time Rate of Scour



Time Rate of Scour



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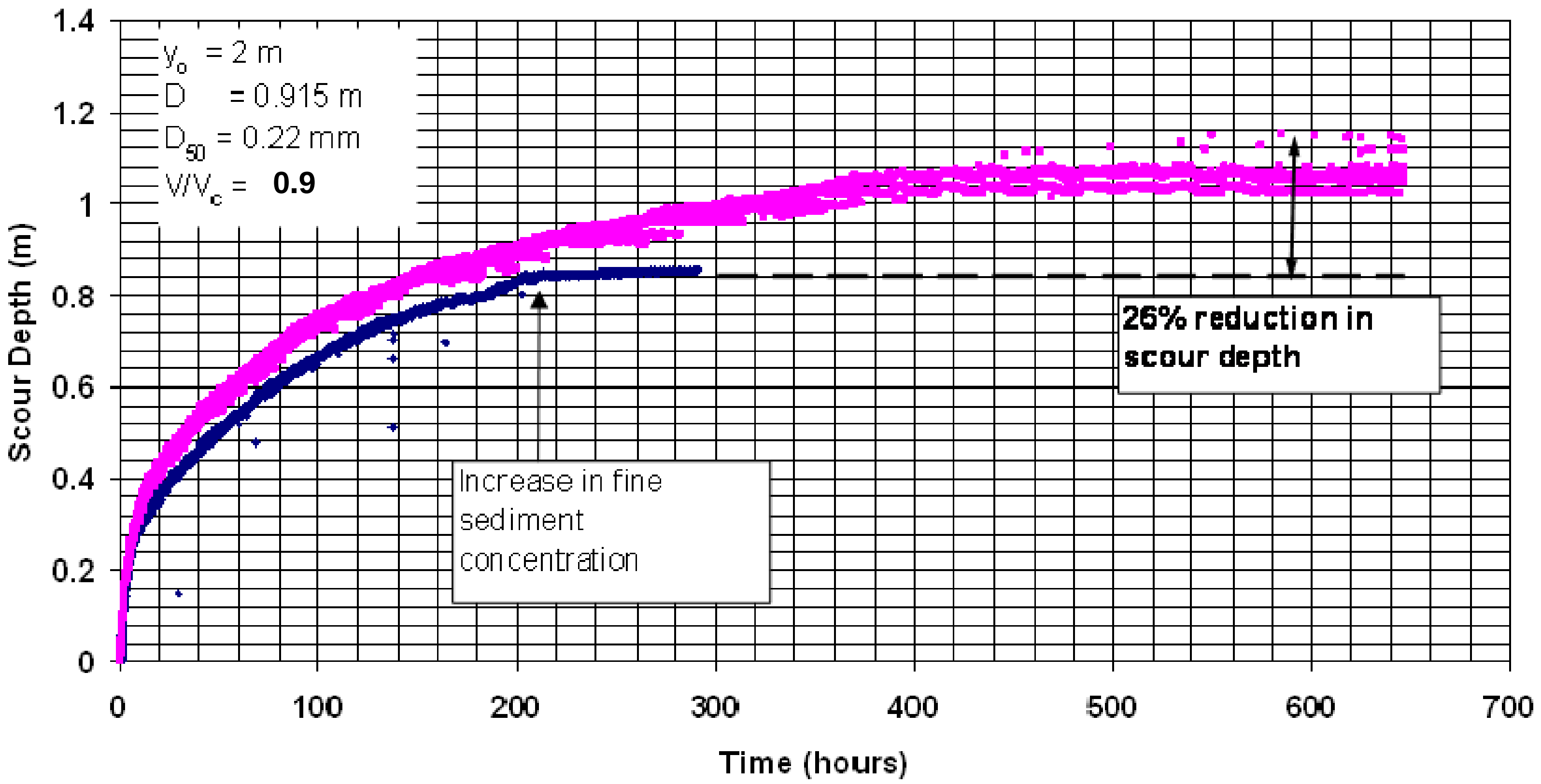
Effects of Suspended Fine Sediment

Effects of Suspended Fine Sediment

- The presence of suspended fine sediment can reduce equilibrium scour depths
  - Laboratory studies indicate that the presence of suspended fine sediment can reduce equilibrium scour depths
  - UF researchers think that this may be due to a reduction in bed shear stress
  - More research needed to quantify effects

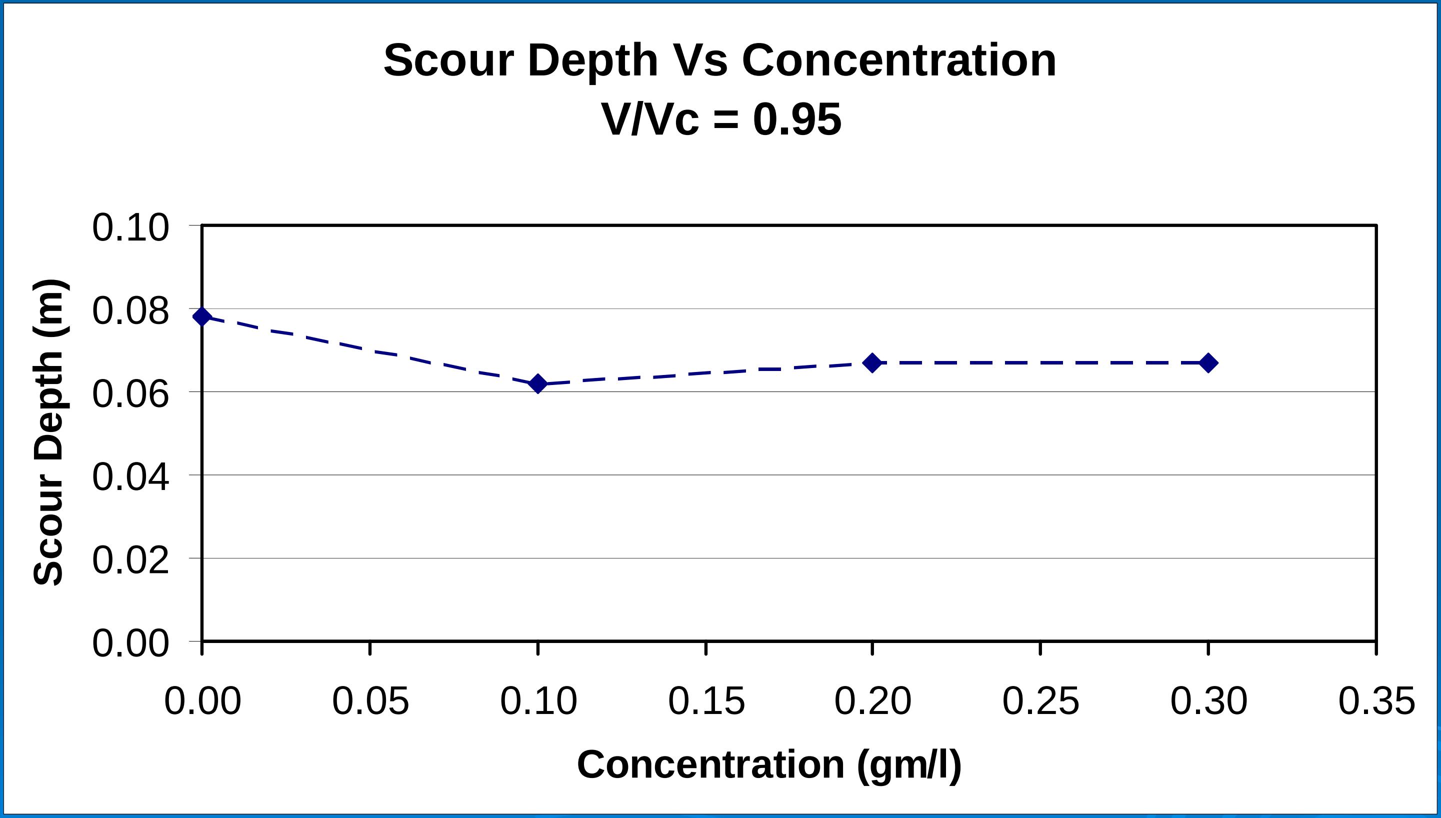
Effects of Suspended Fine Sediment



Increase in fine sediment concentration

26% reduction in scour depth

Effects of Suspended Fine Sediment



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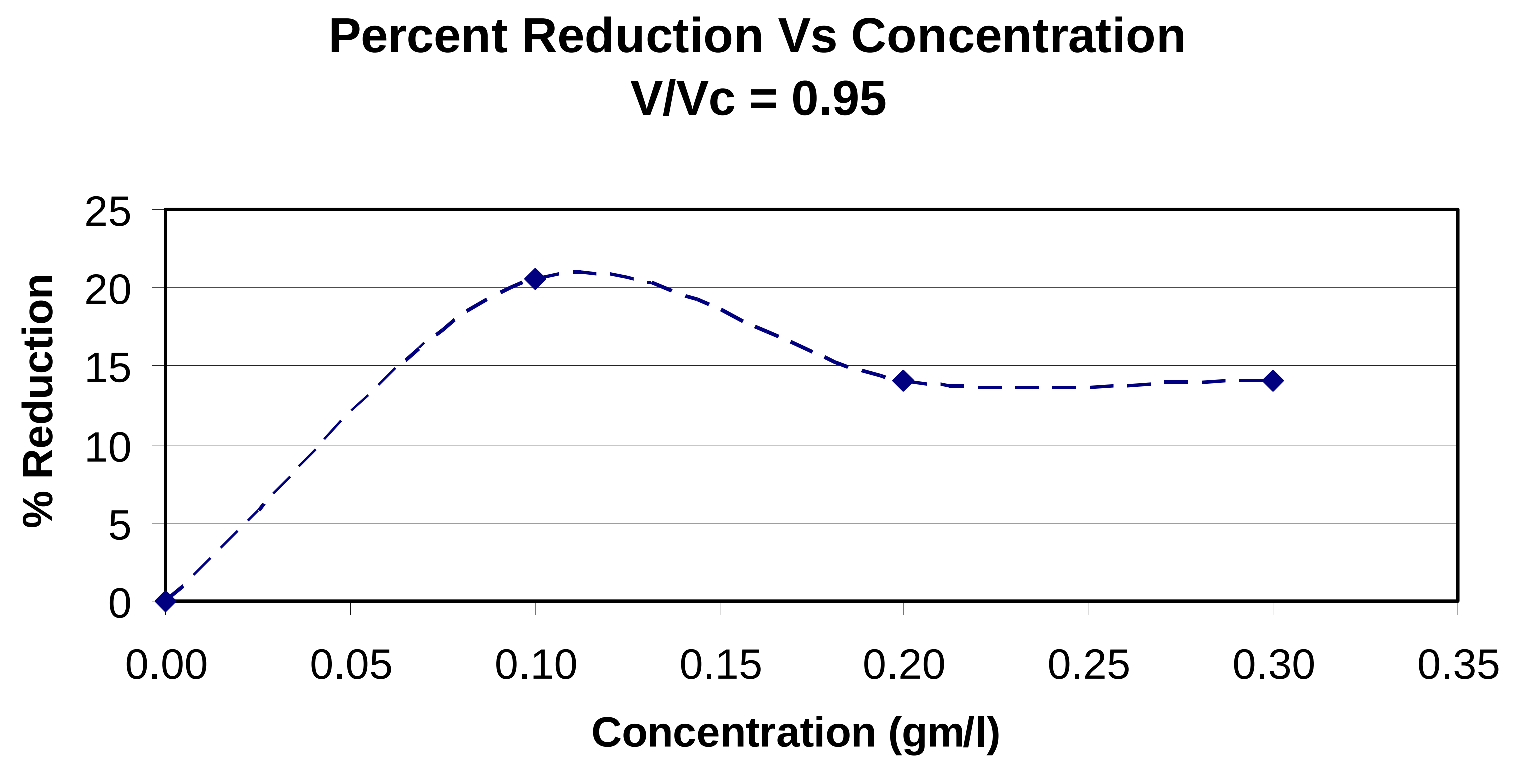
Effects of Suspended Fine Sediment



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Piers in Close Proximity to Other Structures

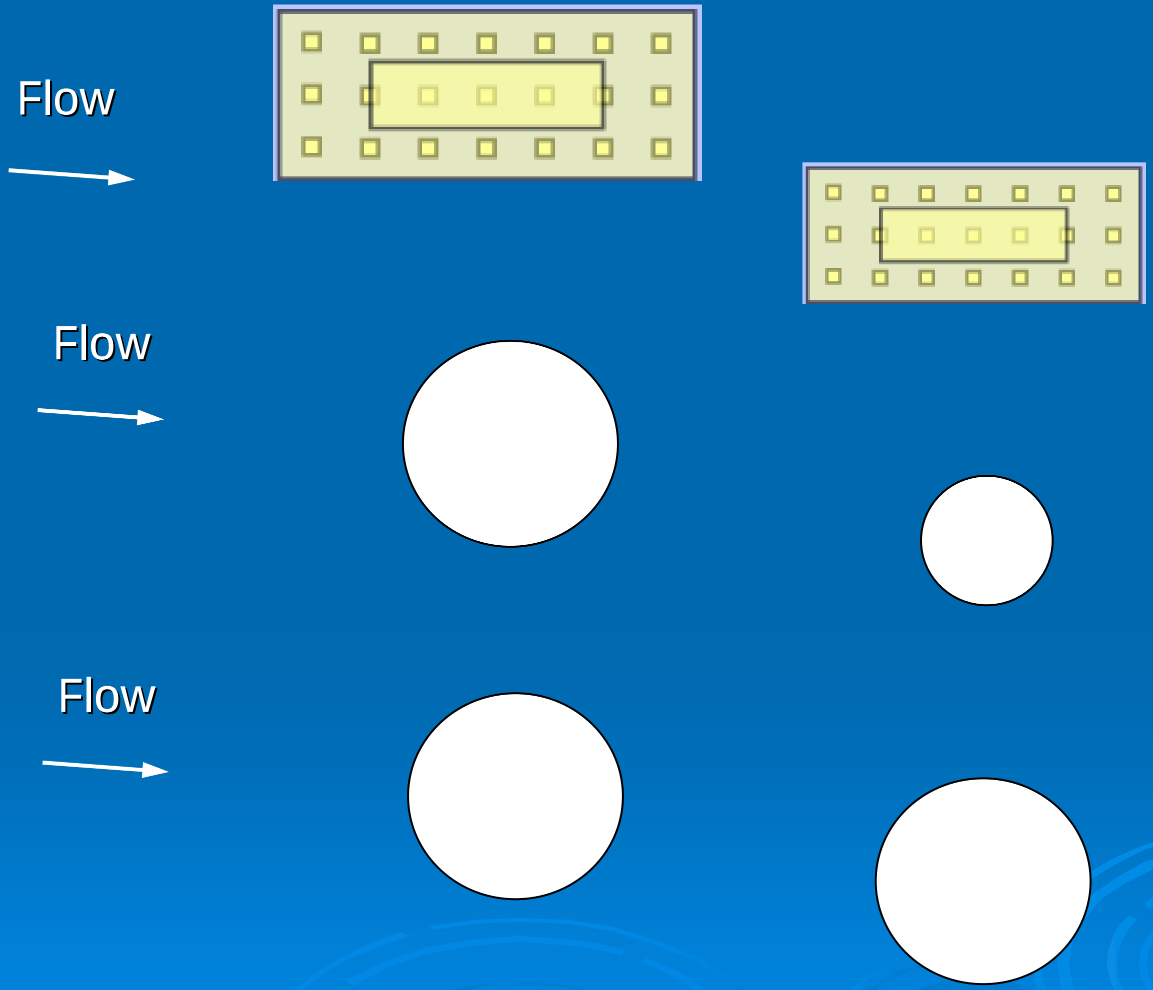
Piers in Close Proximity to Other Structures

- Bridge piers are often constructed near another structure
- When time and resources permit it is best to conduct a physical model study to determine the design scour depth
- An estimate of the scour depth can be obtained using the following procedure

Piers in Close Proximity to Other Structures

- Compute the effective diameters of the two structures using the complex pier scour procedure
- Replace the two structures with circular cylinders with their effective diameters
- Treat the two cylinders as a pile group and compute the scour (using the complex pier scour method)

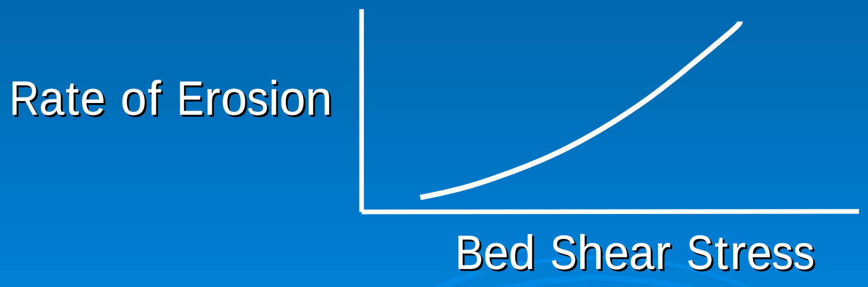
Piers in Close Proximity to Other Structures



Cohesive Sediments and Erosive Rock

Cohesive Sediments and Erosive Rock

- Cohesive sediments and erodible rock erode at different rates than sand
- Two different apparatus have been developed at the University of Florida for measuring Rate of Erosion as a function of Shear Stress



Cohesive Sediments and Erosive Rock

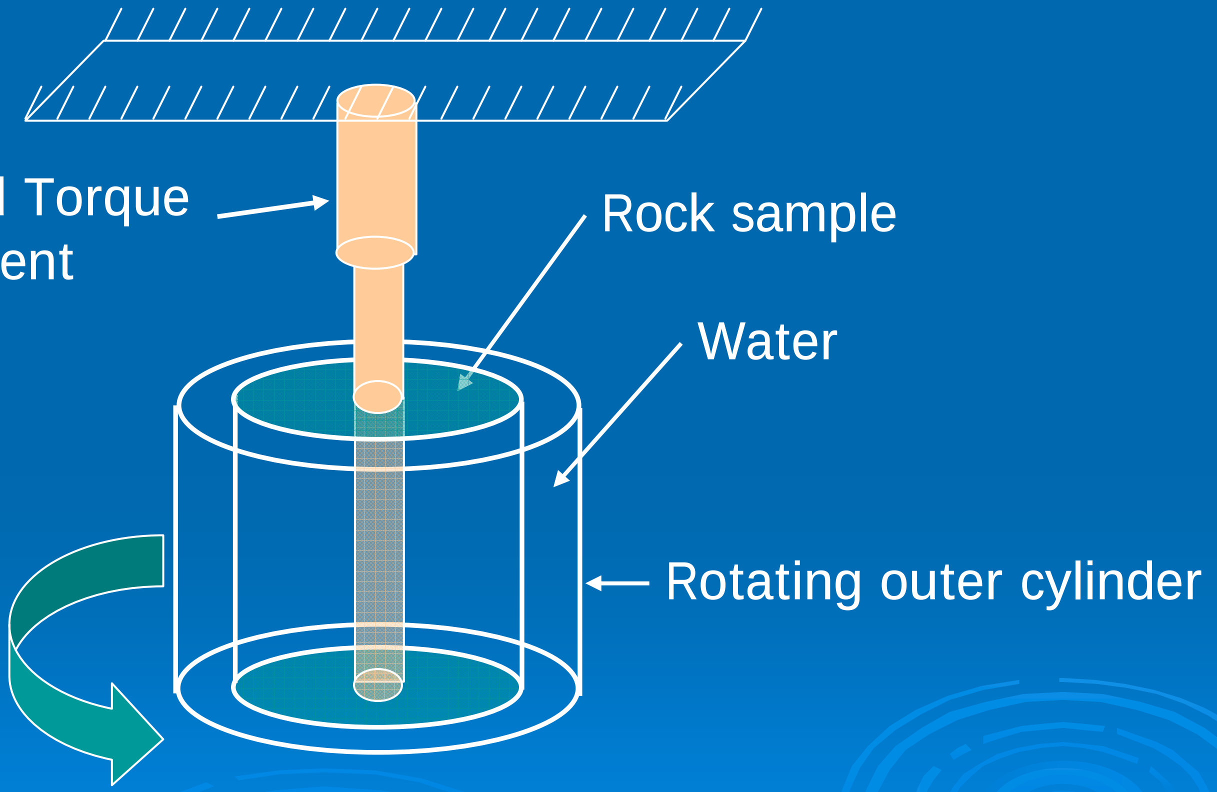
- Core samples (either 2.4” or 4” diameter) must be taken from the site for testing in the RETA or SERF
- The test results along with predicted flow information at the site can be used to estimate design scour depths

Rotating Erosion Test Apparatus (RETA)

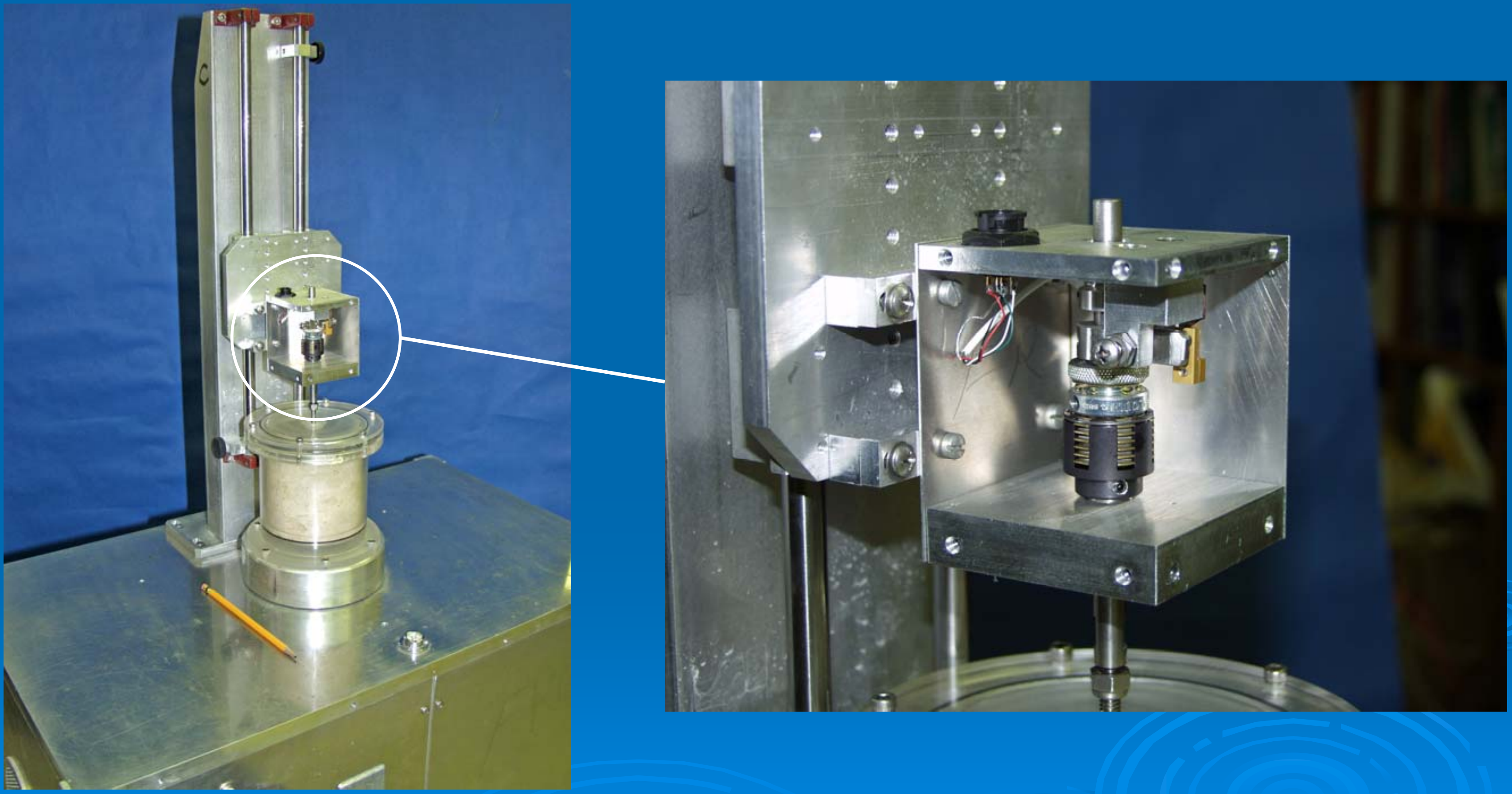
Cohesive Sediments and Erosive Rock - RETAs

- Rotating Erosion Test Apparatus (RETA)
  - FDOT Materials Laboratory in Gainesville has 4 RETAs
  - UF Civil and Coastal Engineering has 1 RETA
  - Requires 4” long x 2.4” (or 4”) diameter sample
  - RETA best for testing Unfractured Rock

Cohesive Sediments and Erosive Rock - RETAs



Cohesive Sediments and Erosive Rock - RETAs



Cohesive Sediments and Erosive Rock - RETAs

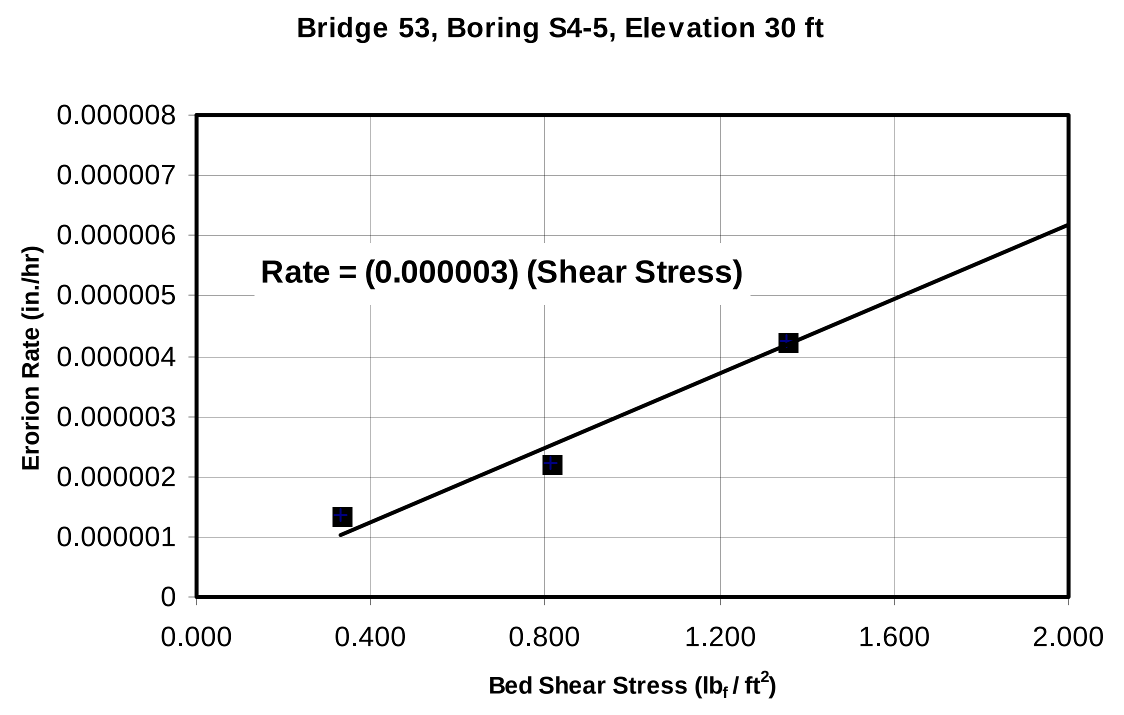
RETAs

Cohesive Sediments and Erosive Rock - RETAs

Wet saw used for cutting
Rock samples

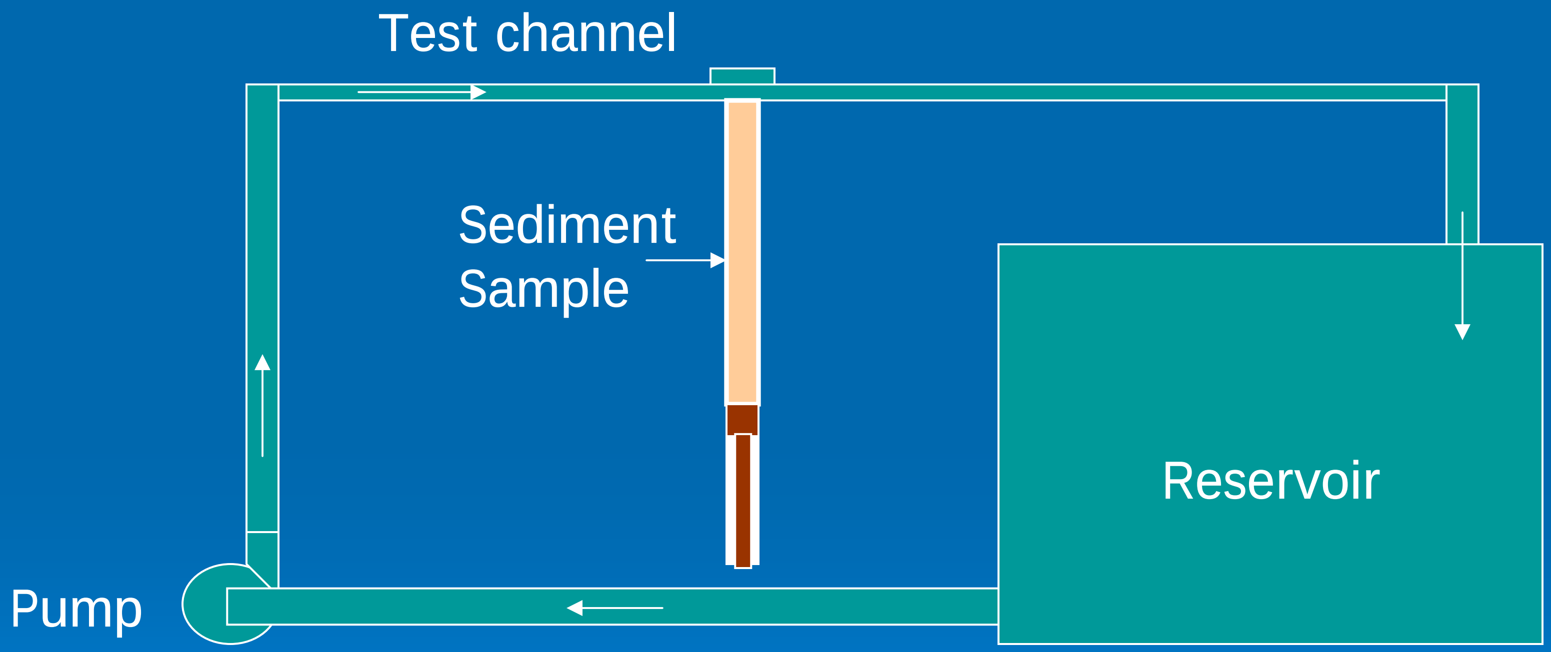
Cohesive Sediments and Erosive Rock - RETAs

Cohesive Sediments and Erosive Rock - RETA



Scour Erosion Rate Flume
(SERF)

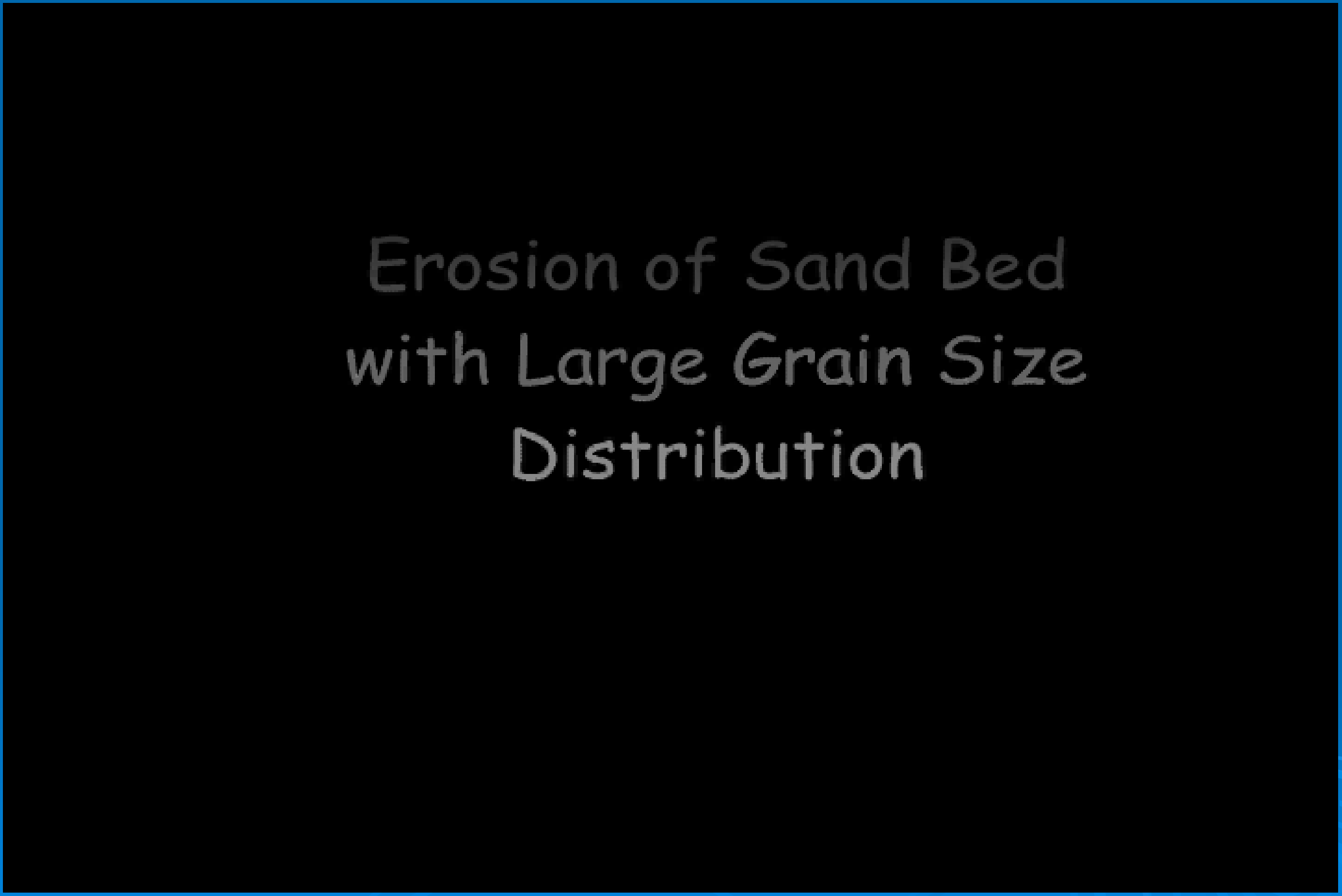
Cohesive Sediments and Erosive Rock - SERF



Cohesive Sediments and Erosive Rock - SERF

Cohesive Sediments and Erosive Rock - SERF

Cohesive Sediments and Erosive Rock - SERF



Erosion of Sand Bed
with Large Grain Size
Distribution

Current FDOT Approved Procedure When Cohesive Sediments/Erosive Rock is Encountered

Cohesive Sediments and Erosive Rock

- Current Procedure when Rock/Clay is encountered
  - Contact FDOT District Drainage Engineer
  - In consultation with State Hydraulics Engineer determine if core samples should be obtained and tested
  - If yes, obtain samples and send to FDOT Materials Lab in Gainesville, FL
  - FDOT State Hydraulics Engineer to oversee analysis of test results

Section Break

SCOUR BOOT CAMP

1. US1 JEWFISH CREEK BRIDGE

Table 1 Flow and Sediment Inputs

Skew Angle	Velocity (ft/s)	D_{50} (mm)	Water Depth (ft)	Pile Group Projected Width, W_p (ft)
7	8	0.20	20	18.5

The top of the pile cap resides at + 3.75 ft. The pile cap thickness is 8 ft and the bed elevation is at -16.25 ft.

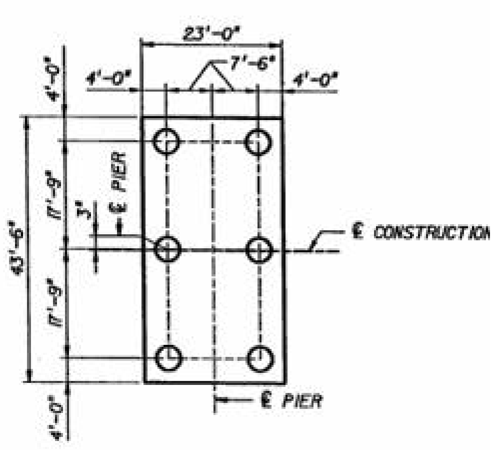


Figure 1 US1 Jewfish Creek Substructure with 6 ft Drilled Shafts

2. SR30 HATHAWAY BRIDGE

Table 2 Flow and Sediment Inputs

Skew Angle	Velocity (ft/s)	D_{50} (mm)	Water Depth (ft)	Pile Group Projected Width, W_p (ft)
0	8	0.20	30	15

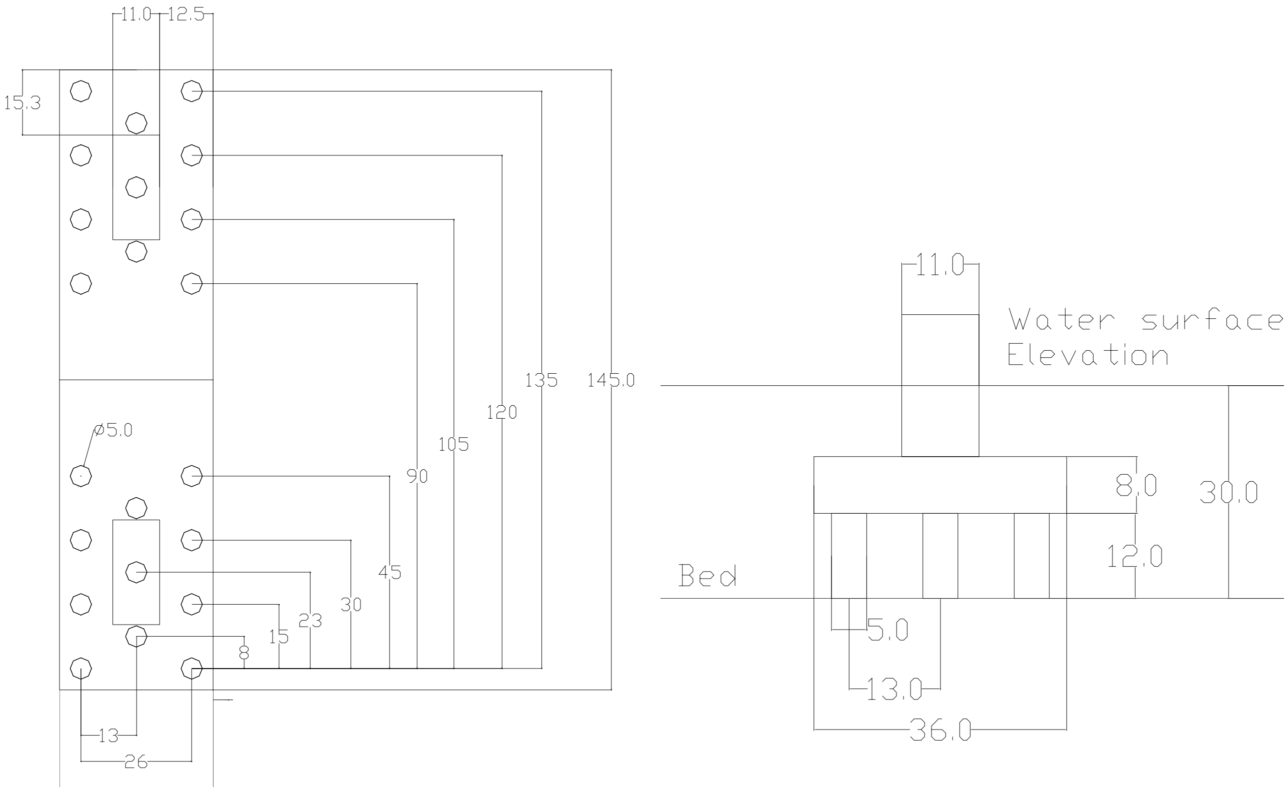


Figure 2 SR30 Hathaway Bridge Pier

3. I-10 BRIDGE OVER ESCAMBIA BAY

Table 3 Flow and Sediment Inputs

Skew Angle	Velocity (ft/s)	D_{50} (mm)	Water Depth (ft)	Pile Group Projected Width, W_p (ft)
10	4	0.11	24	21.4

The elevation of the bed is about -18 ft. The water surface elevation at the time of maximum velocity is + 6 ft; equaling a water depth of 24 ft. The flow skew angle relative to the bent is 10 degrees and the pile group's corresponding projected width, W_p, is 21.4 ft.

Column Info:

Column consist of two 6 ft circular cylinders

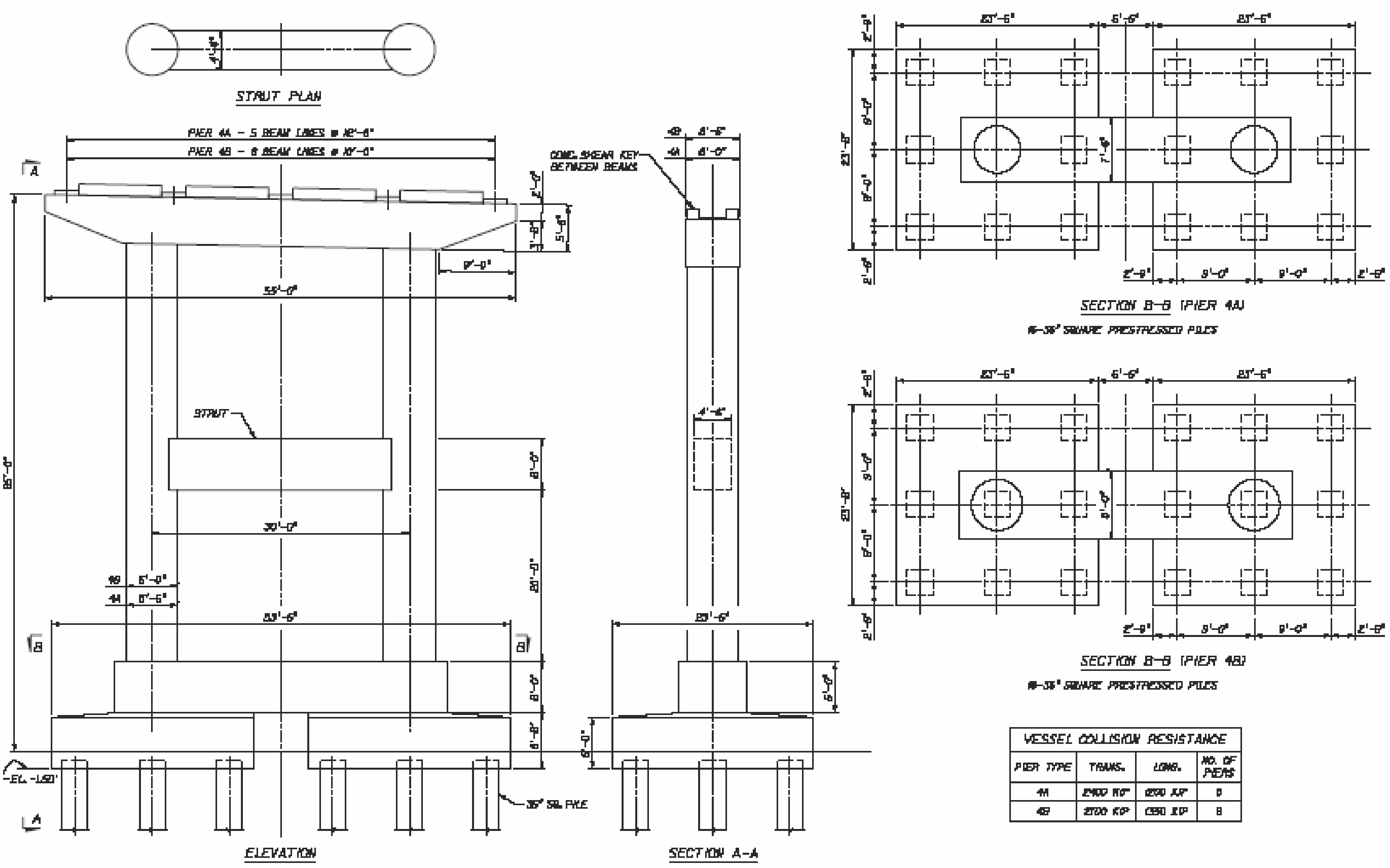
Pile Cap Info (2 Caps):

Pile cap width = 23.5 ft, Length = 23.5 ft, Thickness = 6.5 ft, Height of the pile cap = 0.

Pile Group Info:

The pile group is composed of 3 ft square piles spaced 9 ft apart in both directions

Figure 3 I-10 Bridge after Hurricane Ivan



VESSEL COLLISION RESISTANCE			
PIER TYPE	TRANS.	LONG.	NO. OF PIERS
4A	2400 KIP	1290 KIP	8
4B	2700 KIP	1390 KIP	8

Figure 4 I-10 Bridge Main Pier Dimensions

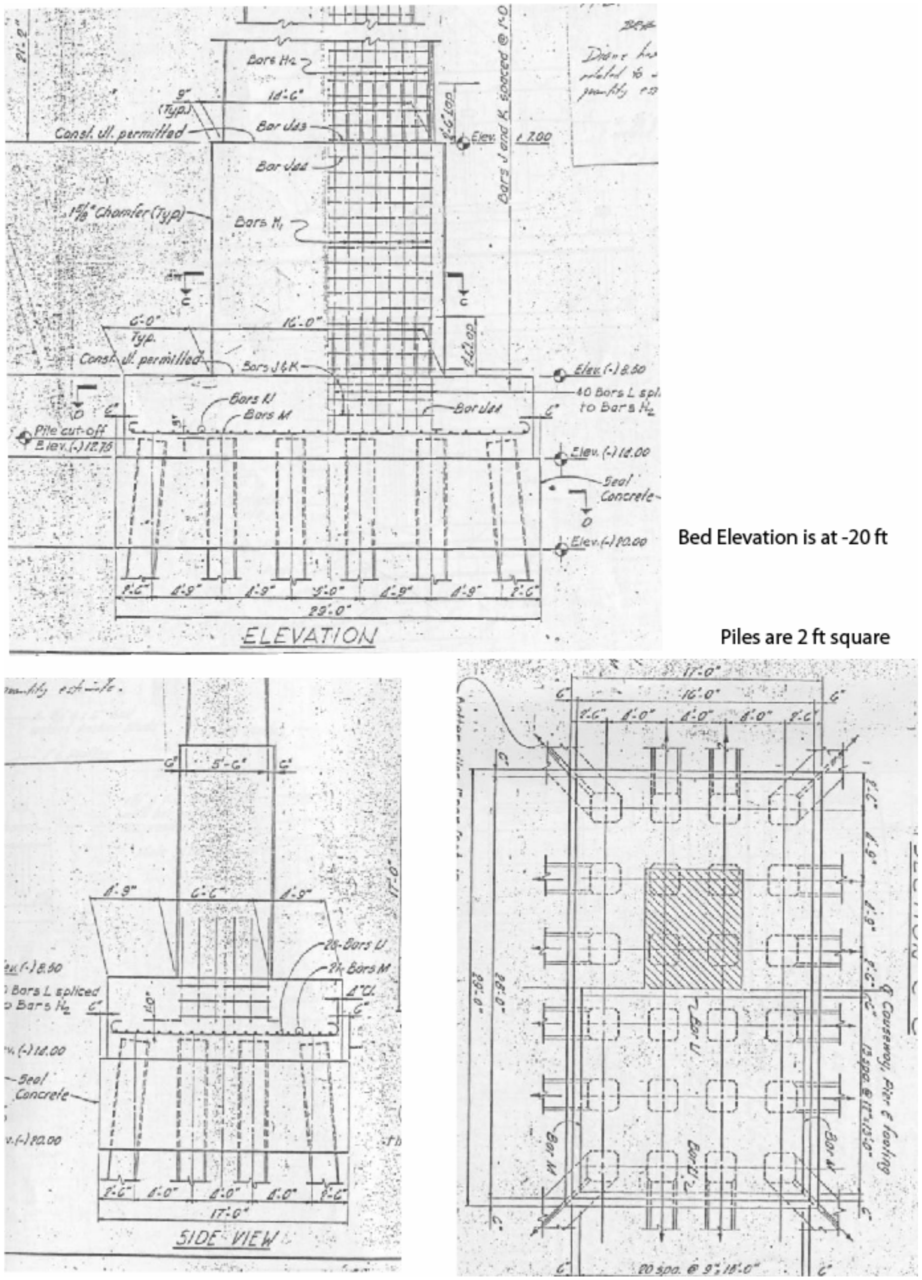
4. SR951 BRIDGE MARCO ISLAND

Table 4 Flow and Sediment Inputs

Skew Angle	Velocity (ft/s)	D_{50} (mm)	Water Depth (ft)	Pile Group Projected Width, W_p (ft)
10	8	0.20	30	18.2

The elevation of the bed is -20 ft.

Figure 5 SR951 over Big Marco Pass



Bed Elevation is at -20 ft

Piles are 2 ft square

Figure 6 SR951 over Big Marco Pass

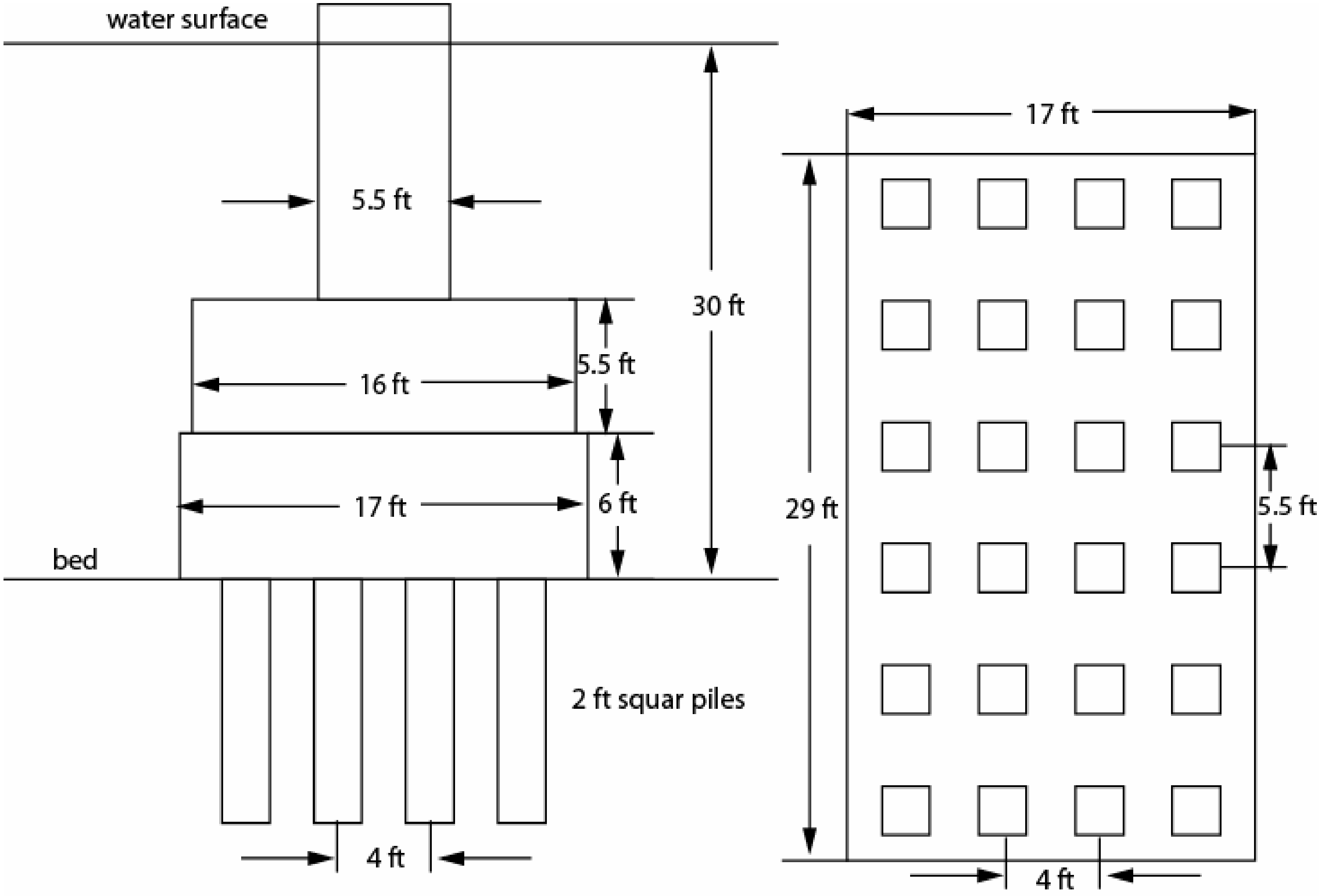


Figure 7 Plan and Elevation of the Main Channel Piers

5. JENSEN BEACH CAUSEWAY

Table 5 Flow and Sediment Inputs

Skew Angle	Velocity (ft/s)	D_{50} (mm)	Water Depth (ft)	Pile Group Projected Width, W_p (ft)
10	8	0.20	30	15.2

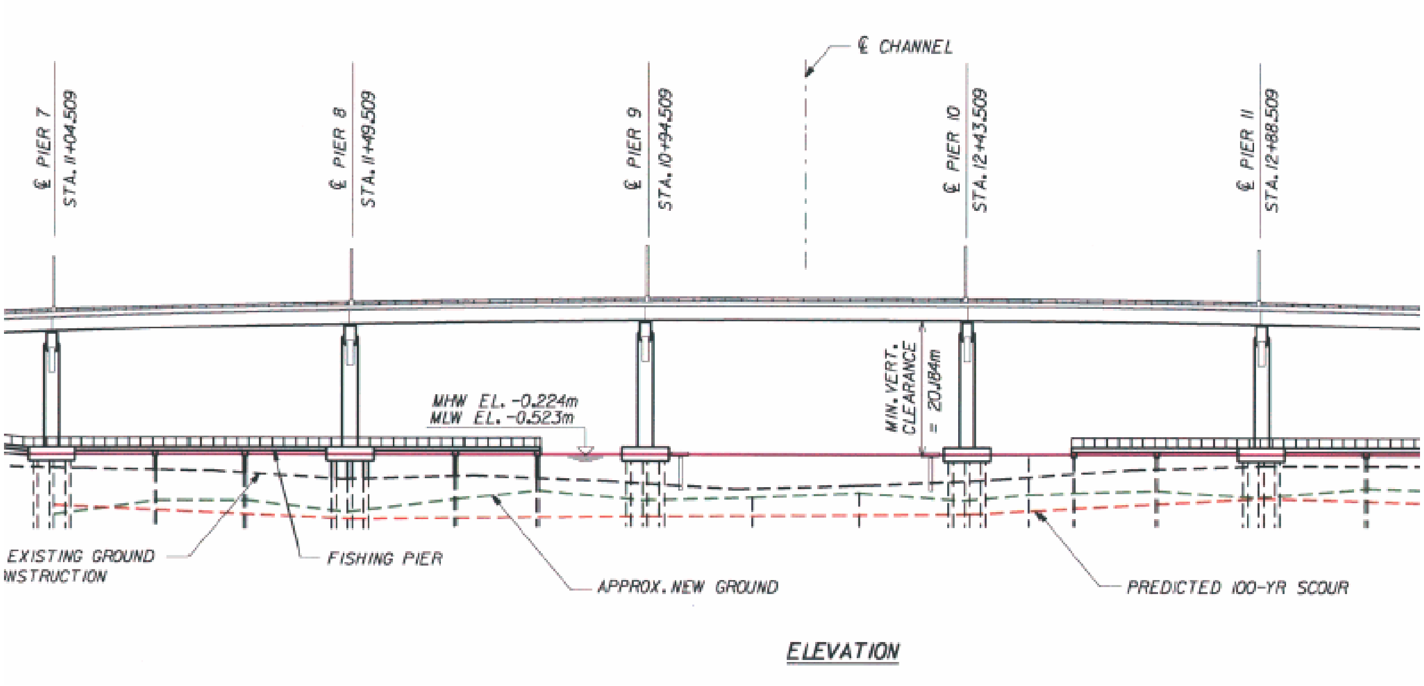


Figure 8 Jensen Beach Causeway over the Indian River Lagoon

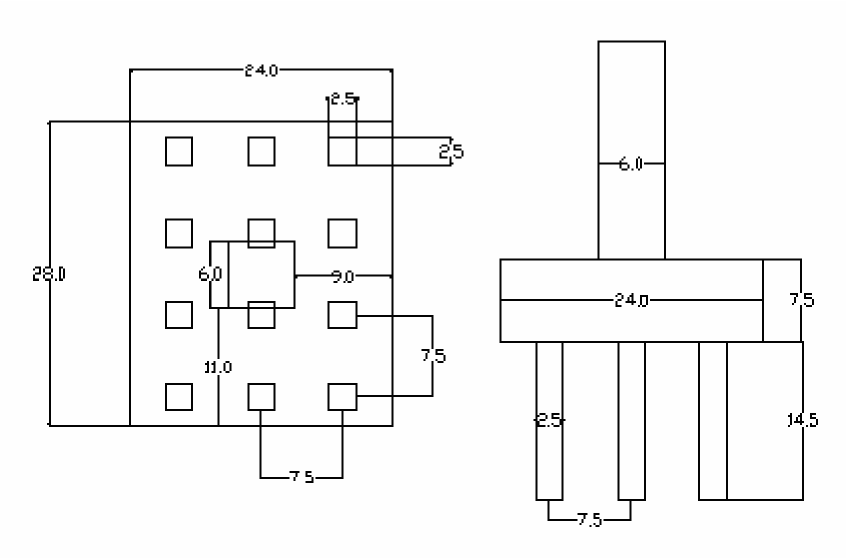


Figure 9 Plan and Elevation of the Jensen Beach Piers

6. TACOMA NARROWS

Table 6 Flow and Sediment Inputs

Skew Angle	Velocity (ft/s)	D_{50} (mm)	Water Depth (ft)	Pile Group Projected Width, W_p (ft)
22	9.1	0.11	123	NA

A 1 to 120 scale model test was performed using a water depth of 1.31 ft and a corresponding velocity of 0.9 ft/s. The measured scour depth at the end of the test was 1.12 ft. The sediment had a D_{50} of 0.75 mm with a sigma of 2.53.

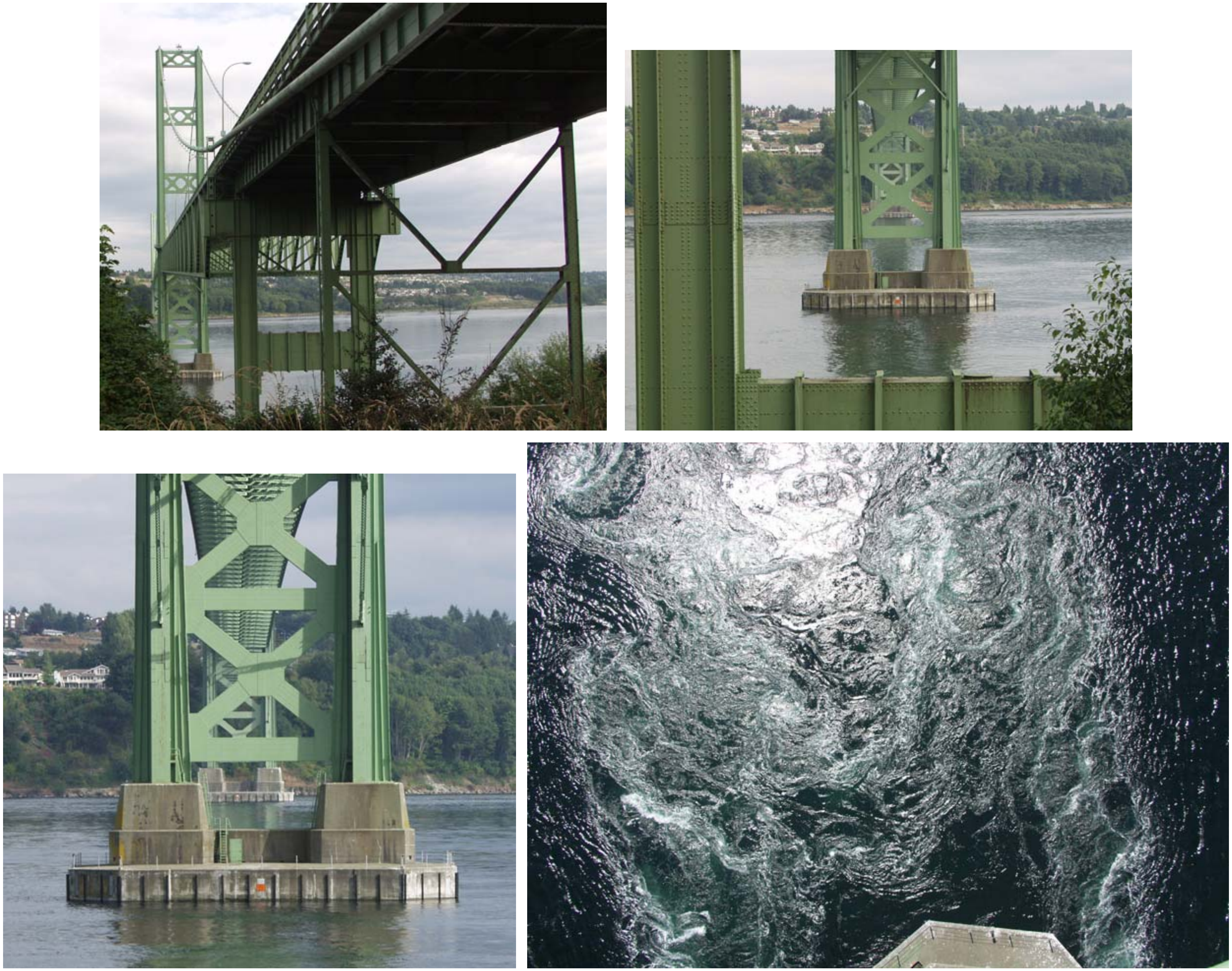


Figure 10 Tacoma Narrows Existing Bridge Piers

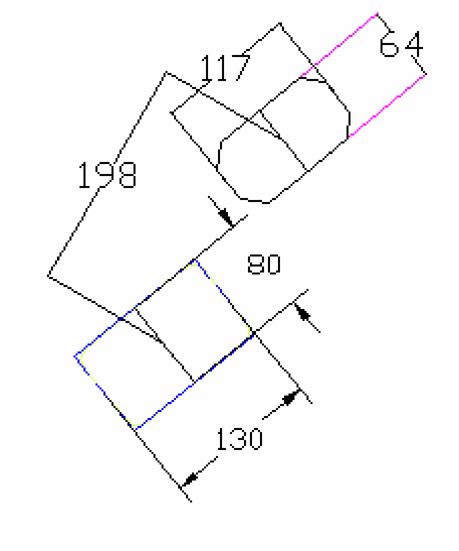


Figure 11 Tacoma Narrows Substructure Geometry

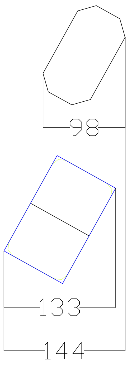


Figure 12 Projected Width of Structures at 22 Degrees of Skew