Scour Prediction and Protection at Inlets

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Florida Shore and Beach Preservation Association
4th Annual Technology-Transfer Workshop

Contents

- Overview of Scour at Inlets
- Inlet Scour
- Scour Prediction
- Scour Protection
- Recent / Planned CIRP Developments
- Conclusions

Definition of Scour

Scour is the removal by hydrodynamic forces of granular bed material in the vicinity of Coastal Structures.

Note: ***Scour*** is a specific form of the more general term ***"erosion."***

Scour Problems at Tidal Inlets

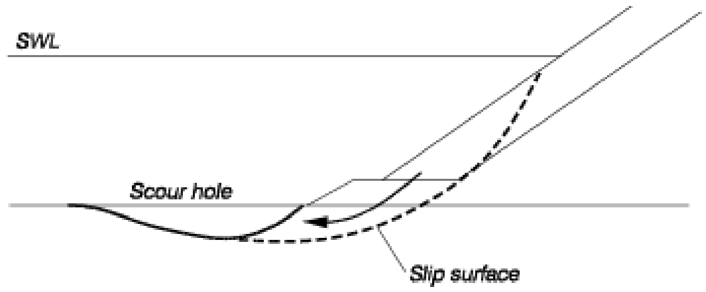
Consequences of Scour Holes…

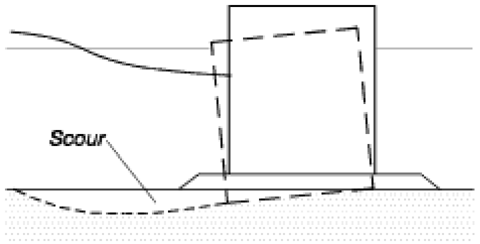
- Undermining of toe protection
- Damage to rubble-mound armor slopes
- Loss of jetty length
- Navigation problems

Design Questions Related to Scour

- Where will scour occur?
- How much scour?
- When to repair?
- Scour blanket design?

Typical Scour Failures





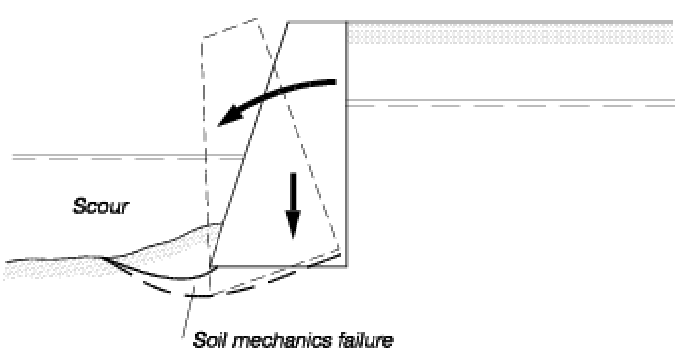
Sliding of main armour due to seabed scour

- *Formation of scour hole close to the foot of the structure due to wave and current action. The toe is functioning as support for the main armour as long as the toe erosion does not cause undermining of the armour.*
- *Reduced stabilizing forces causes slip failure to occur which results in sliding of armour.*

Scour in seabed, seaward tilt and settlement

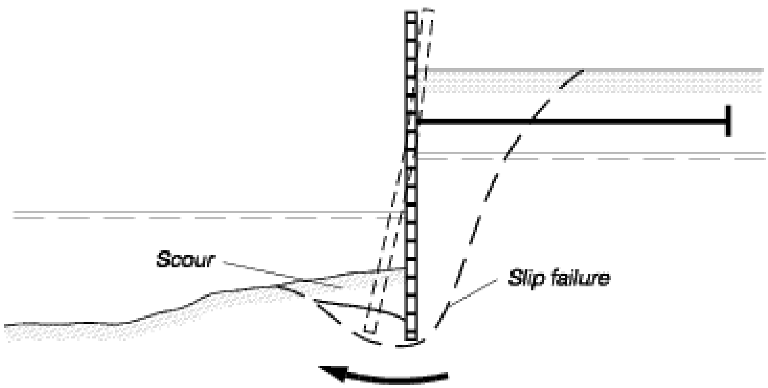
- *Scour in front of a caisson due to waves and currents might cause seaward tilt and settlement of the caisson.*
- *The critical wave load situations are when deep wave troughs occur at the caisson front.*

Typical Scour Failures



Seaward overturning and settlement of gravity wall

- Scour in front of the wall reduces both the passive resistance and the bearing capacity of the foundation soil.
- The resulting load from the active backfill pressure, the high groundwater table and the weight of the wall cause a bearing capacity failure in the soil resulting in a foreward overturning and some settlement of the wall.



Toe scour undercut and rotation of sheet wall

- Toe scour and undercut reduces/eliminates the passive pressure from the soil.
- Subsequent rotation of the wall when the loads from the active soil pressure and the pressure from the groundwater exceeds the passive pressure.

Negative Aspects of Scour-Related Damage to Structures

- Project functionality is decreased
- Repair and replacement costs
- Damage to upland property / flood damage
- Client's confidence in project decreased

Physical Processes of Scour

Scour occurs whenever...

Hydrodynamic **Bottom Shear Stress**	$>$	Sediment **Critical Shear Stress**

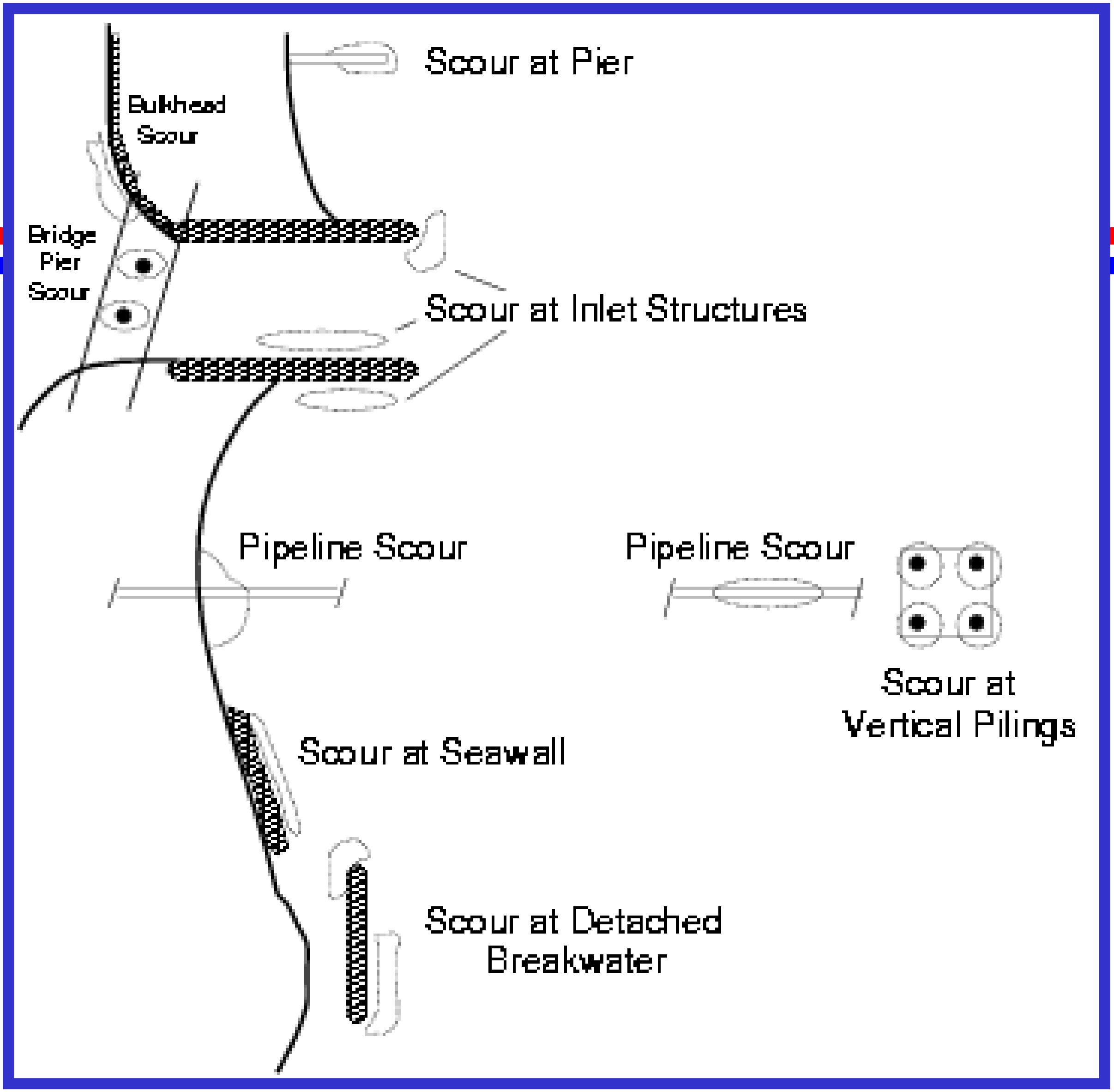
***Clear Water Scour* :** Sediment motion is localized

***Live Bed Scour* :** Entire bottom is mobilized with locally higher stresses

Hydrodynamic Conditions

Scour results from any of the following (acting singularly or in combination)

- Localized orbital velocity increases due to reflected waves
- Focusing of wave energy by structures that induces breaking
- Structure alignments that redirect currents and accelerate flows
- Flow constrictions that accelerate flow
- Downward directed breaking waves that mobilize sediment
- Flow separation and creation of vortices
- Transitions from hard bottom to erodible bed
- Wave pressure differentials and groundwater flow producing "quick" condition



Common Scour Problems

Other Scour Occurrences

- Any structure founded on the seafloor can experience scour at downstream side (surge barriers, sills, etc.)
- Small pad footings can be undermined
- Structure transition and termination points can have local accelerations
- Scour in advance of new construction

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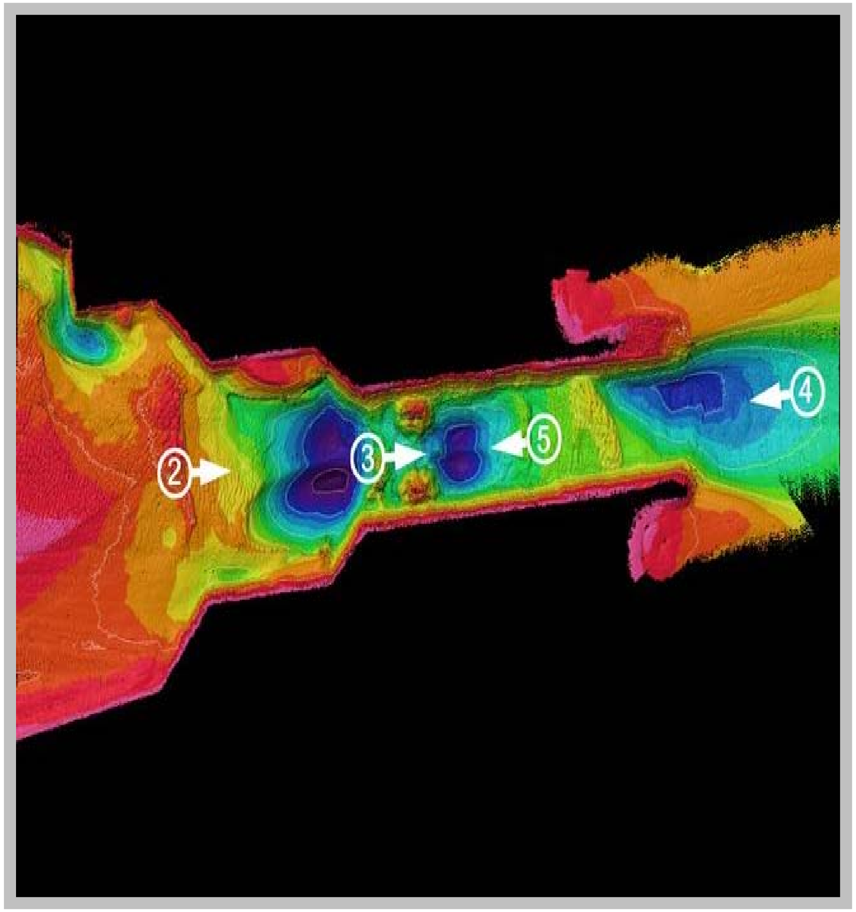
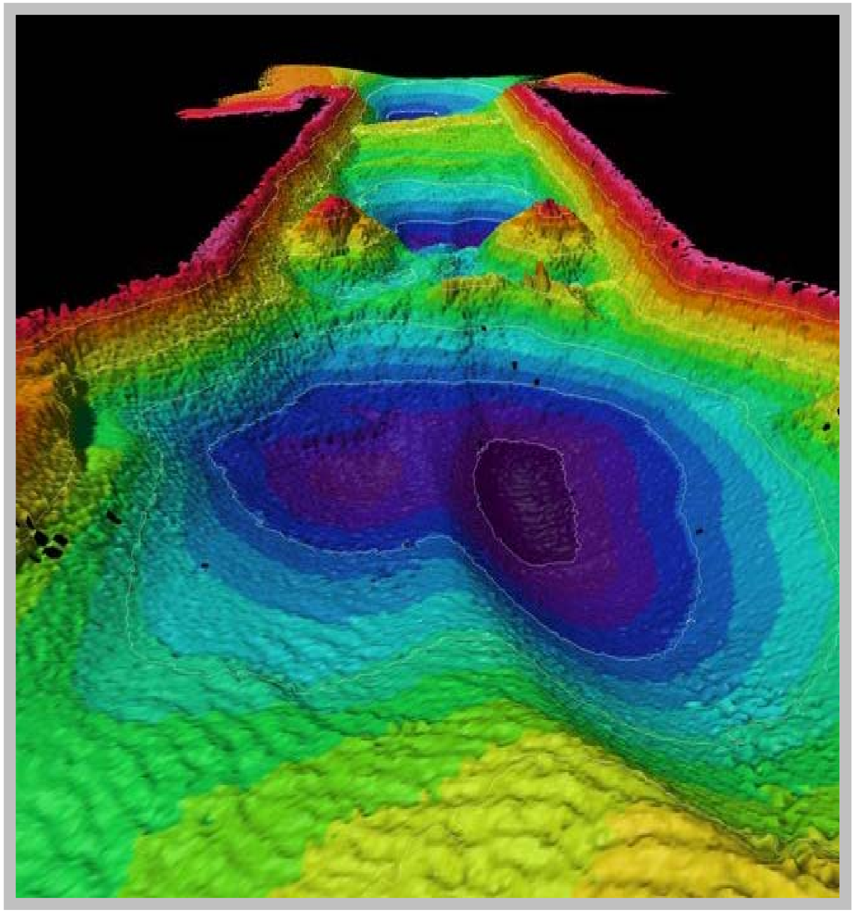
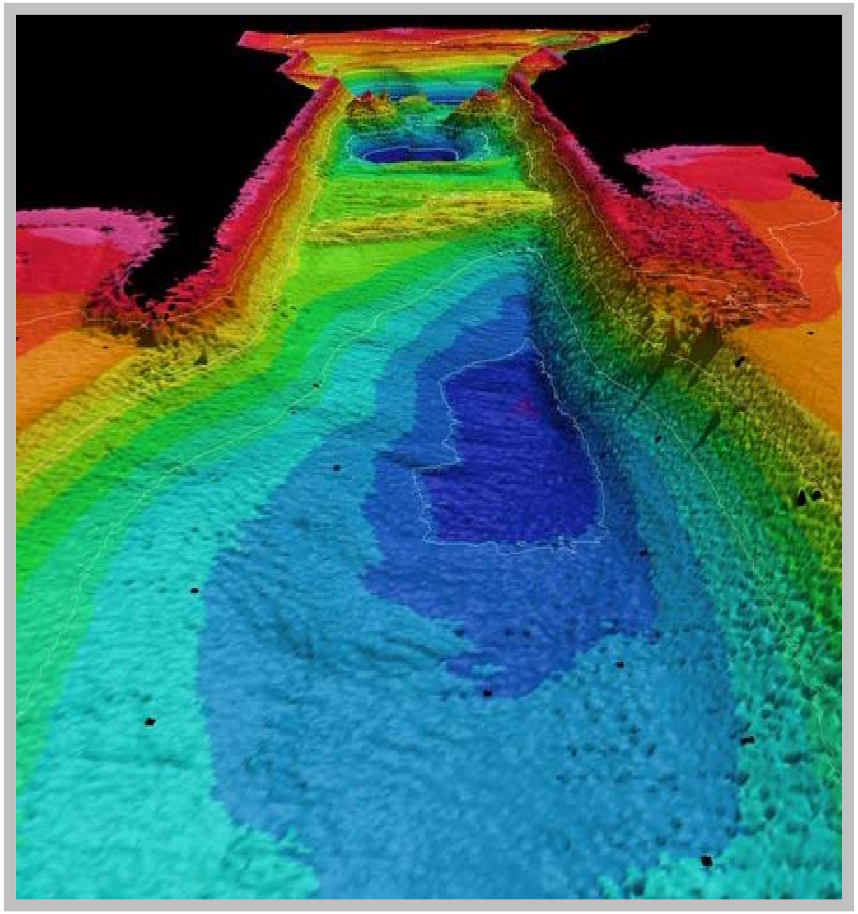
Indian River Inlet, Delaware

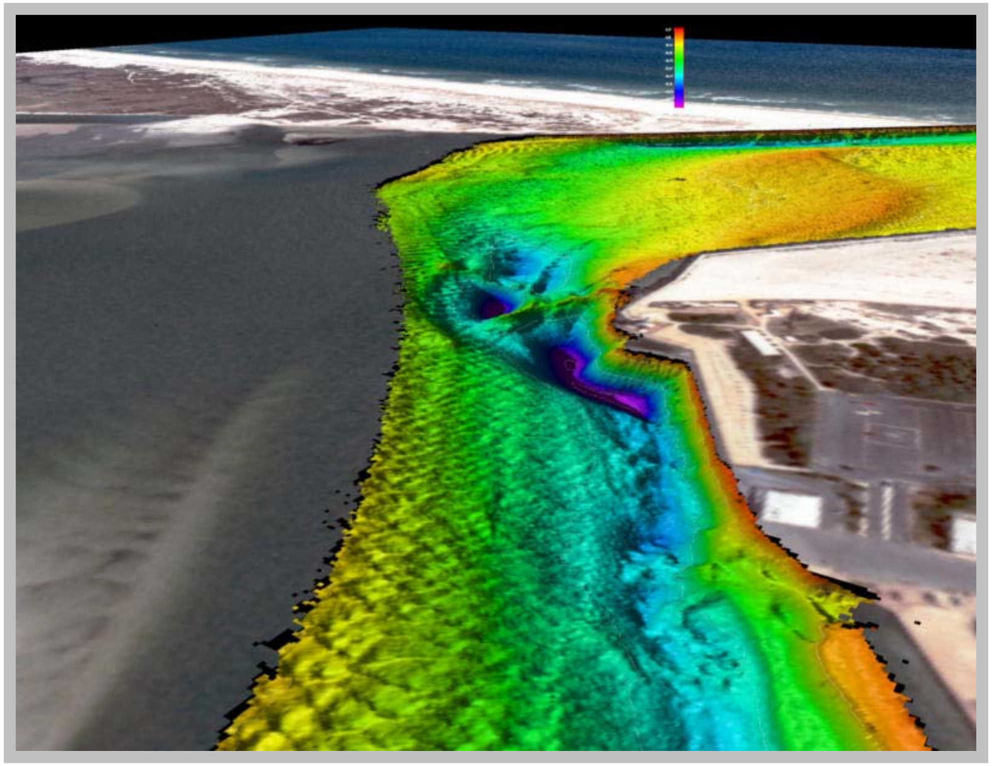


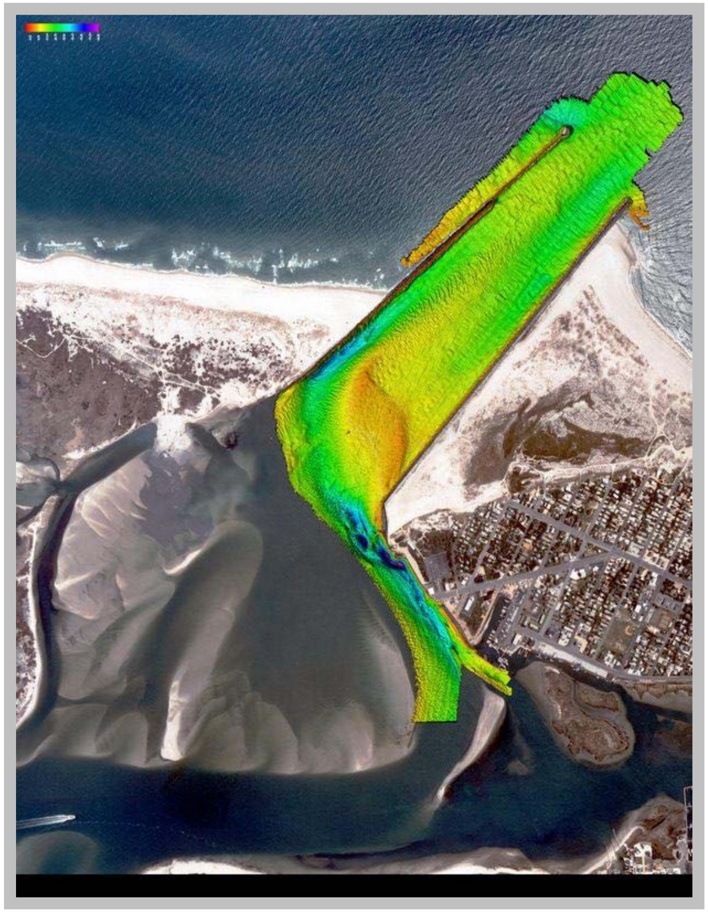
Indian River Inlet, Delaware



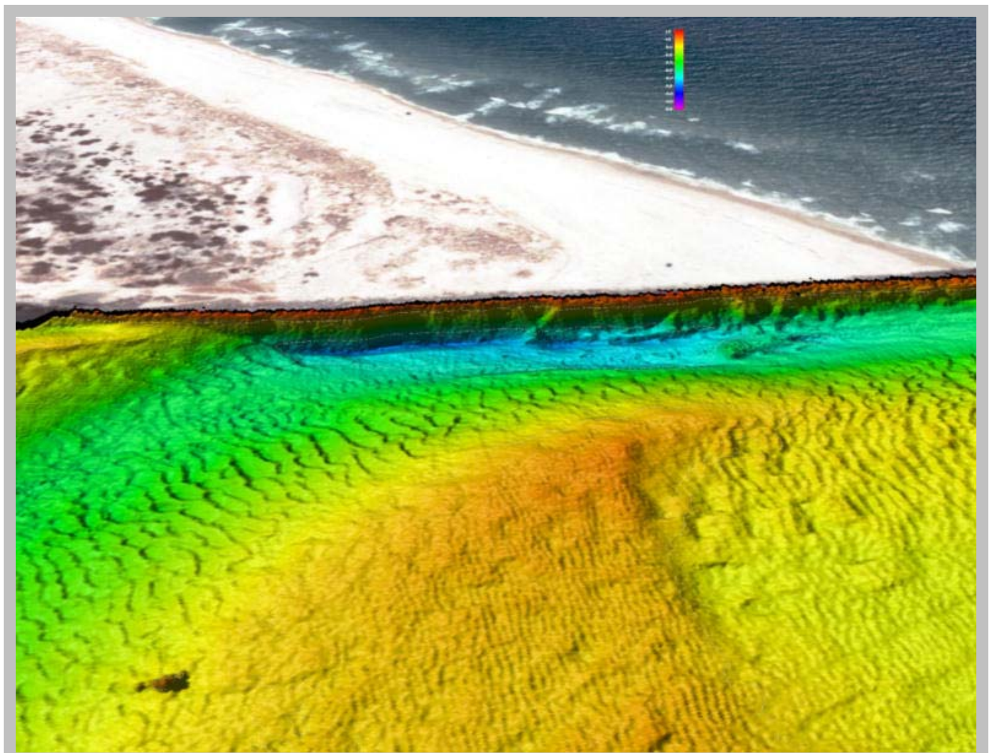


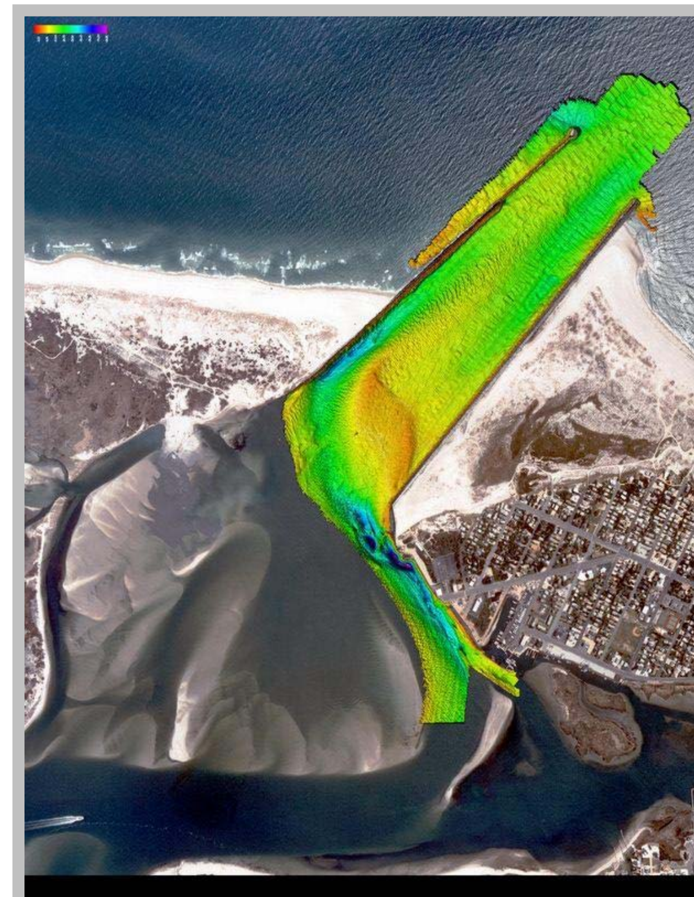
Barnegat Inlet, New Jersey



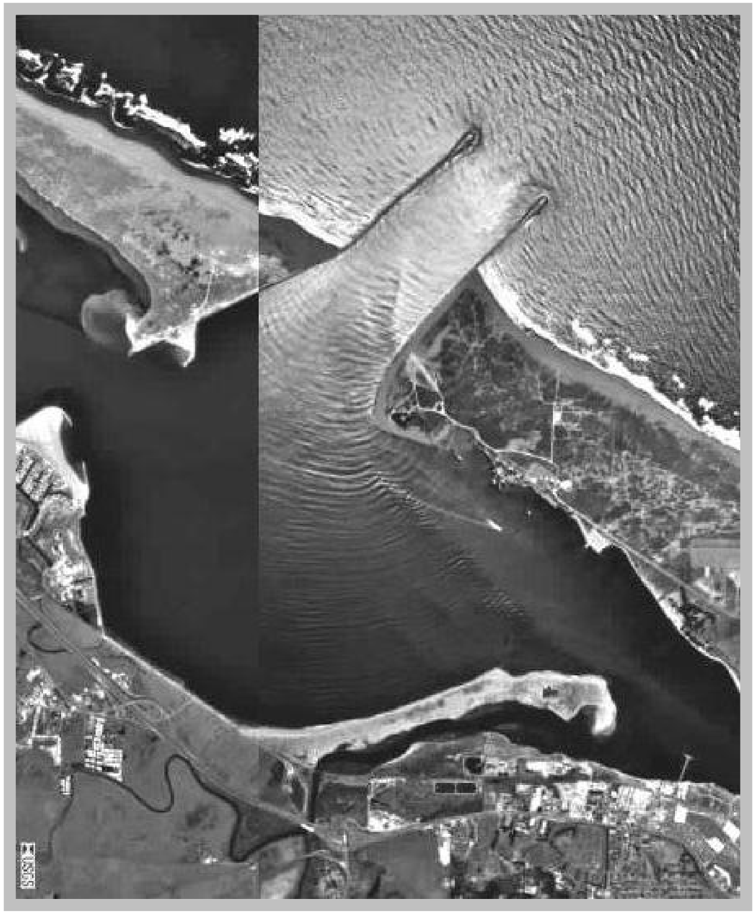


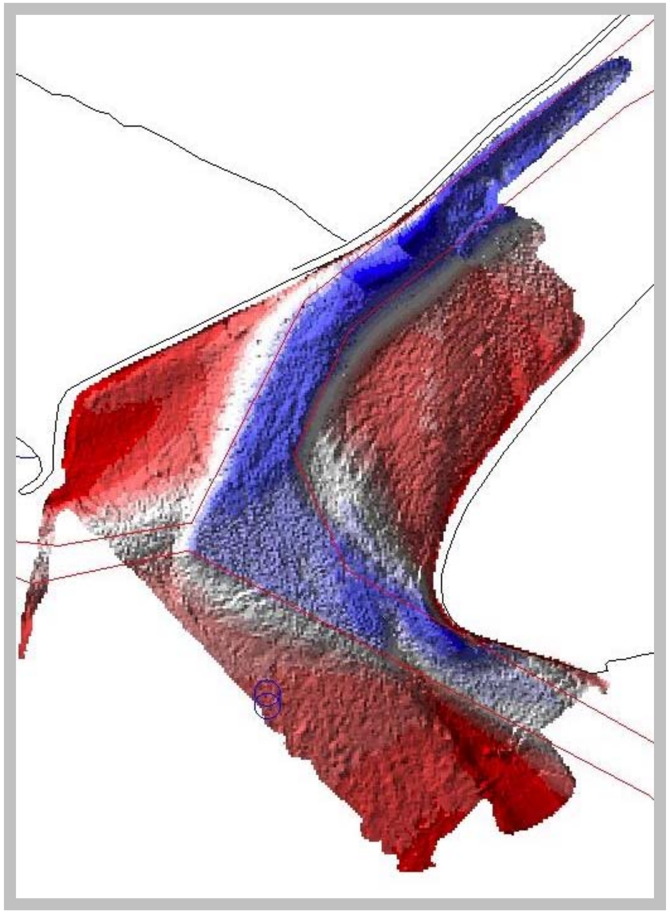
Barnegat Inlet, New Jersey



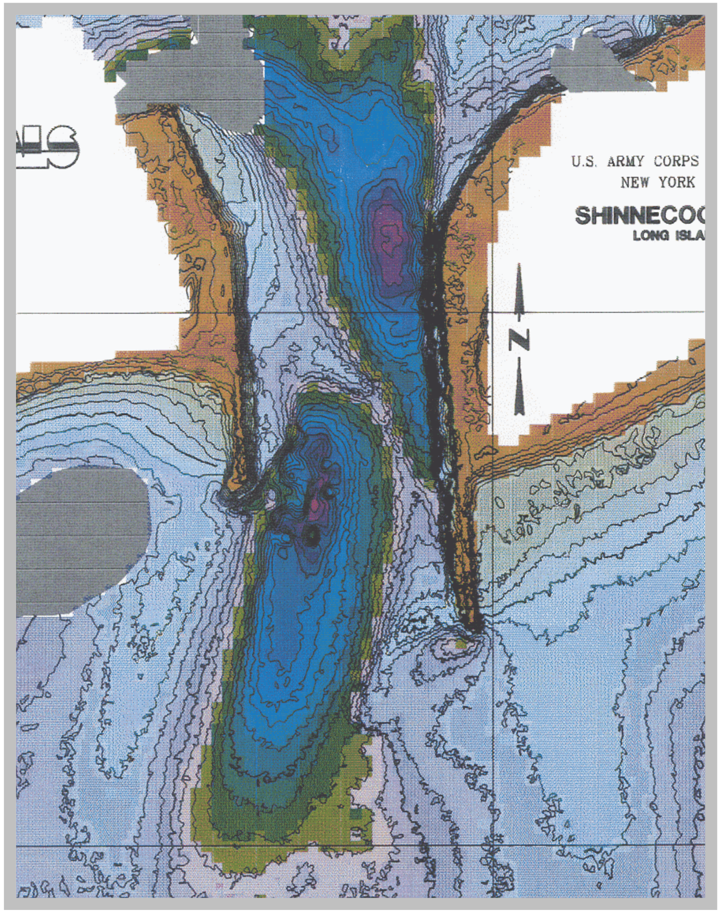


Humboldt Bay, California



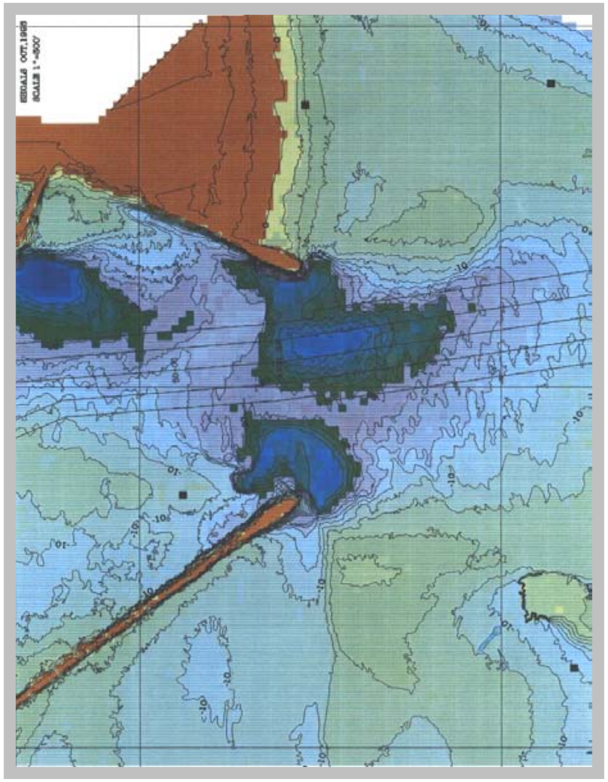


Shinnecock Inlet, New York

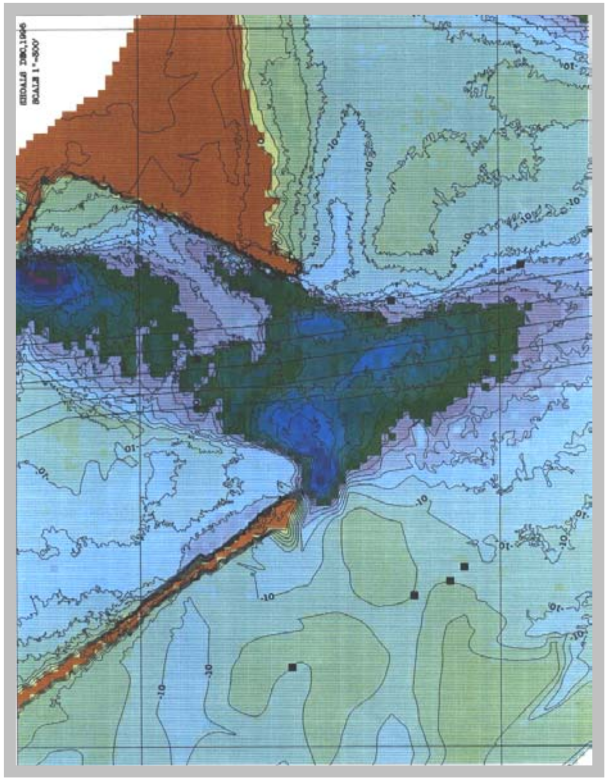


Overview | Inlet Scour | Prediction | Protection | Current Work

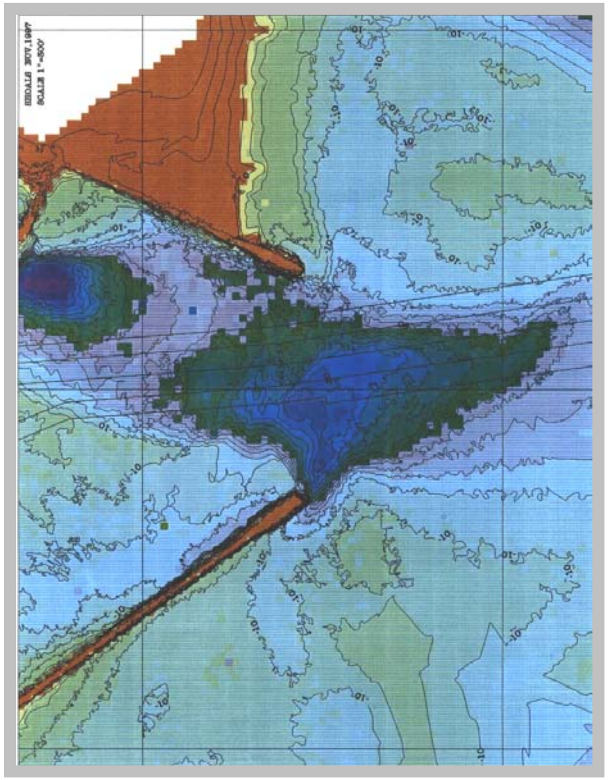
East Pass, Florida



1995



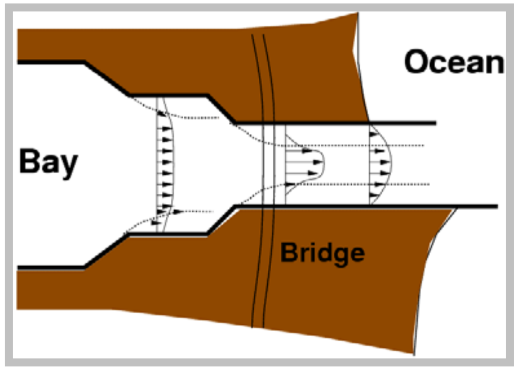
1996



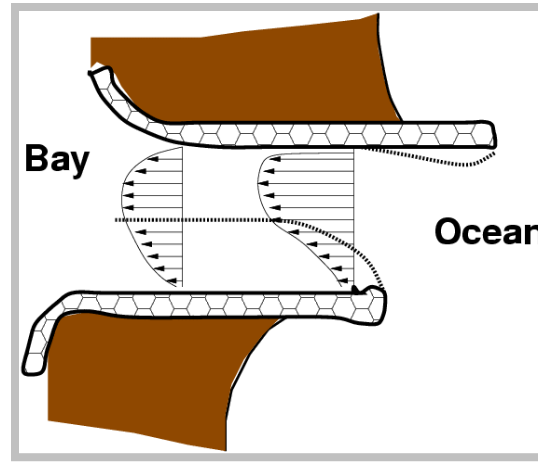
1997

Jet Scour at Tidal Inlets

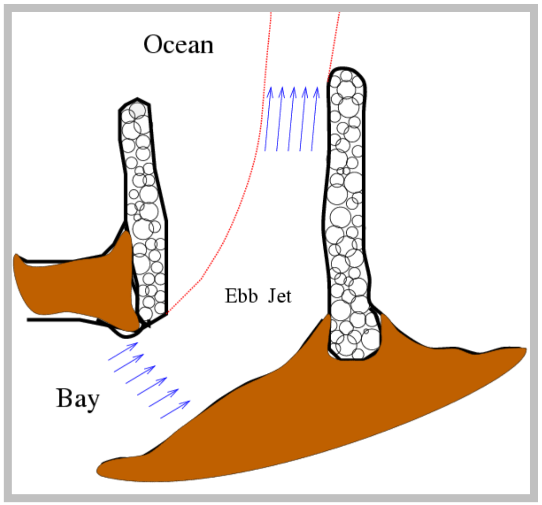
Examples of Inlet Jets



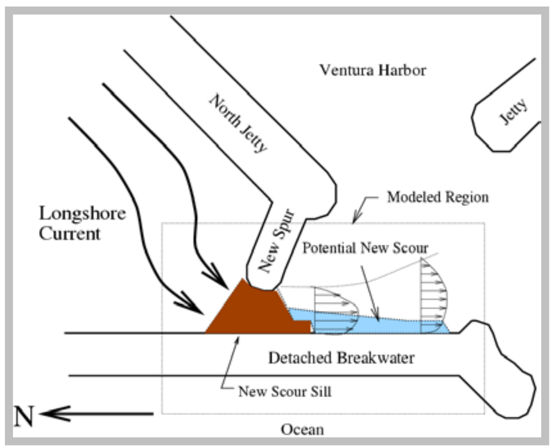
Nozzle Constriction Jet



Uneven Jetties Flood Jet



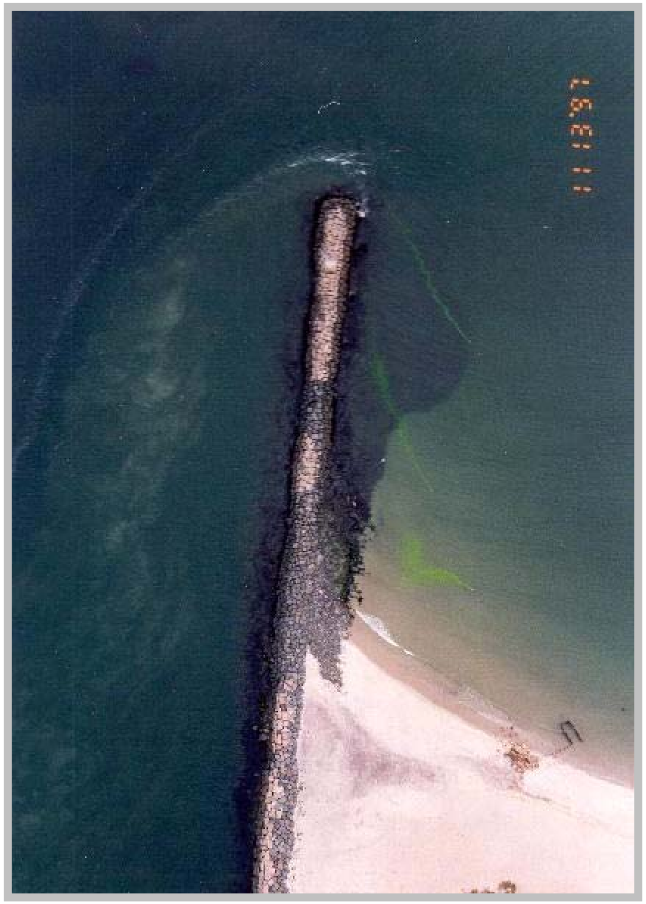
Deflected Ebb Jet

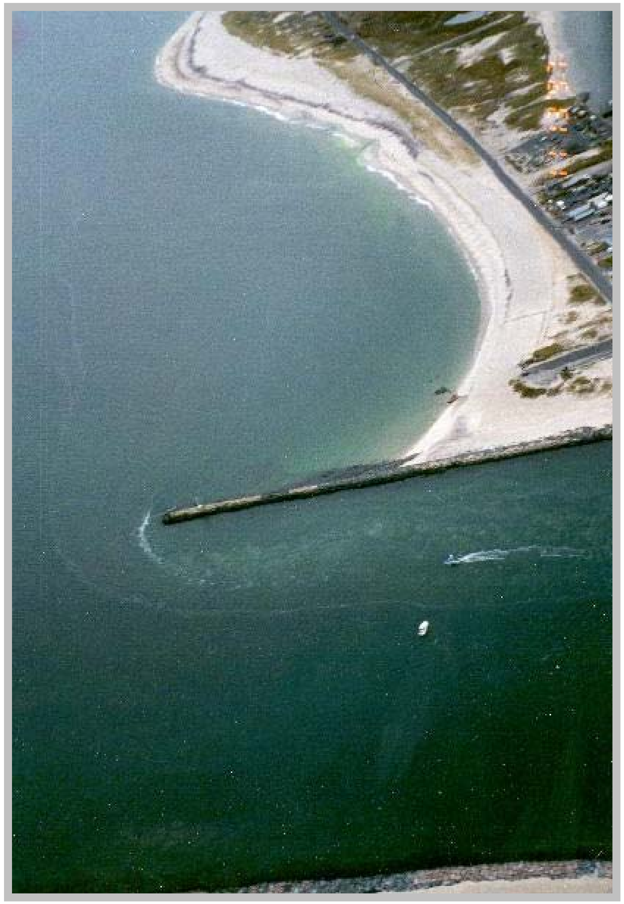


Flow Constriction Jet

Jet Scour at Tidal Inlets

Mission Support
Technology Transfer
CIRP
Research & Development





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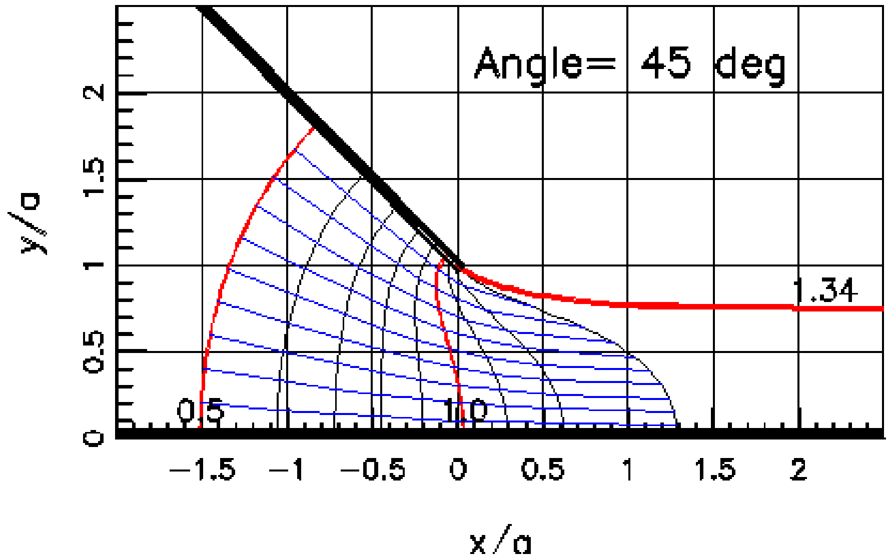
Quantifying Discharge Distribution

Jet Theory Assumes:

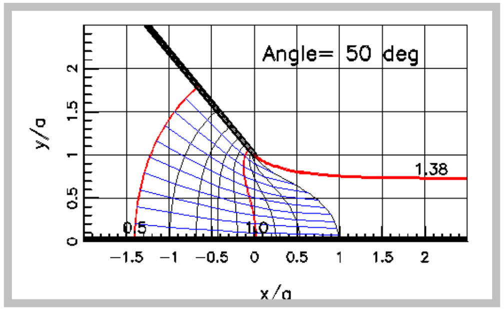
- Incompressible, Ideal Fluid
- Steady Flow
- Nonrotational Flow
- Vertical Solid Boundaries
- No Flow Across Streamlines

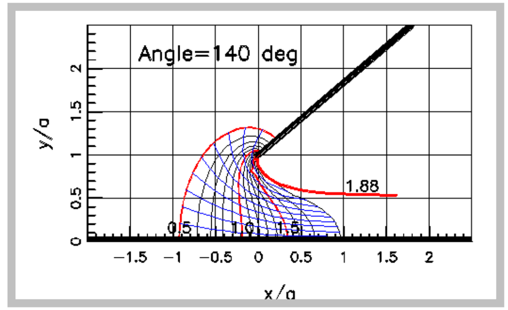
Jet Theory Provides:

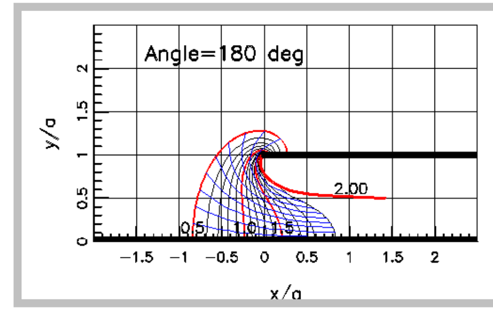


Plan View Flow Maps

Half Plane Solutions

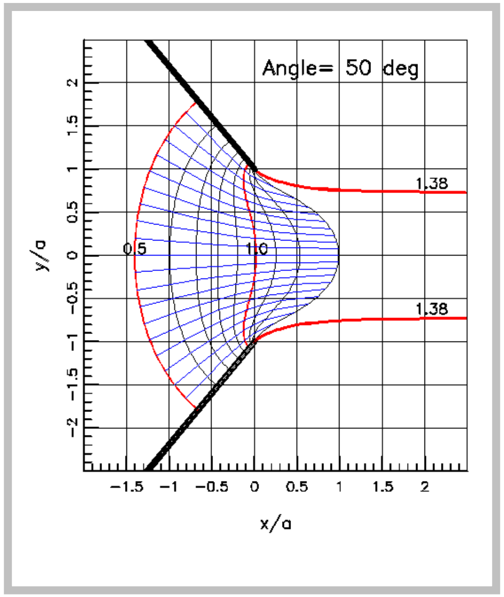




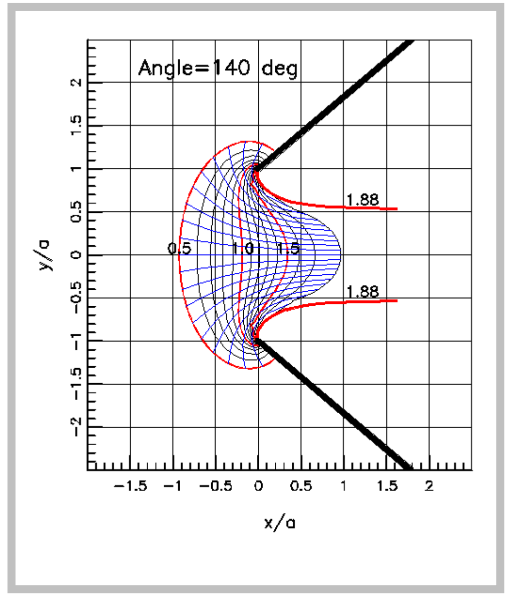


Typical Flow Constriction Solutions

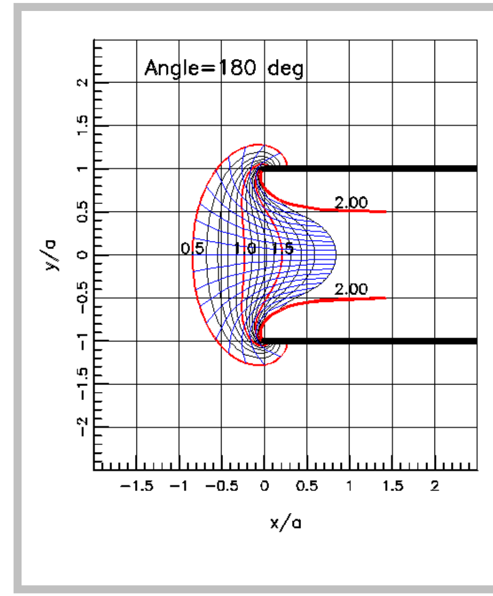
Symmetric Solutions



Ebb at Arrowhead Jetty System



Flood at Arrowhead Jetty System



Flood at Equal Length Jetties

Flow Map Interpretation

Required Input:

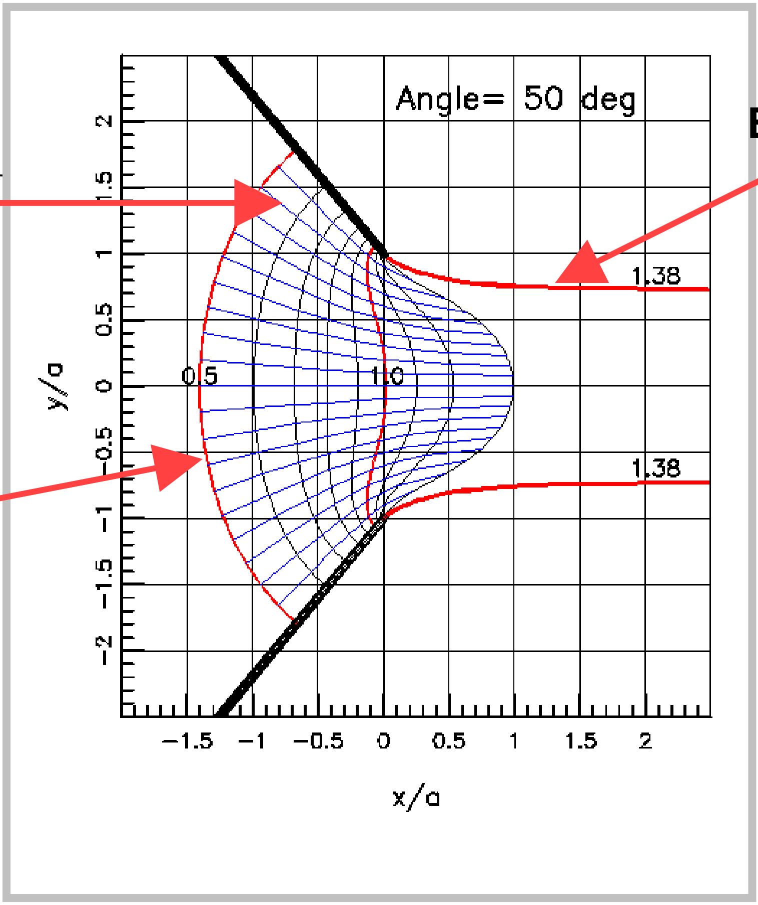
- Geometry
- Dimension "**a**"
- Total Discharge, "**Q**"

Contours are Lines of Constant Dimensionless DischargePer Unit Width Given by:

$$\frac{q}{(Q/2a)} = \text{Constant}$$

q – Dimensional discharge per unit width
Q – Total discharge
a – Jet width at exit

Streamlines



Jet Boundary

a
a

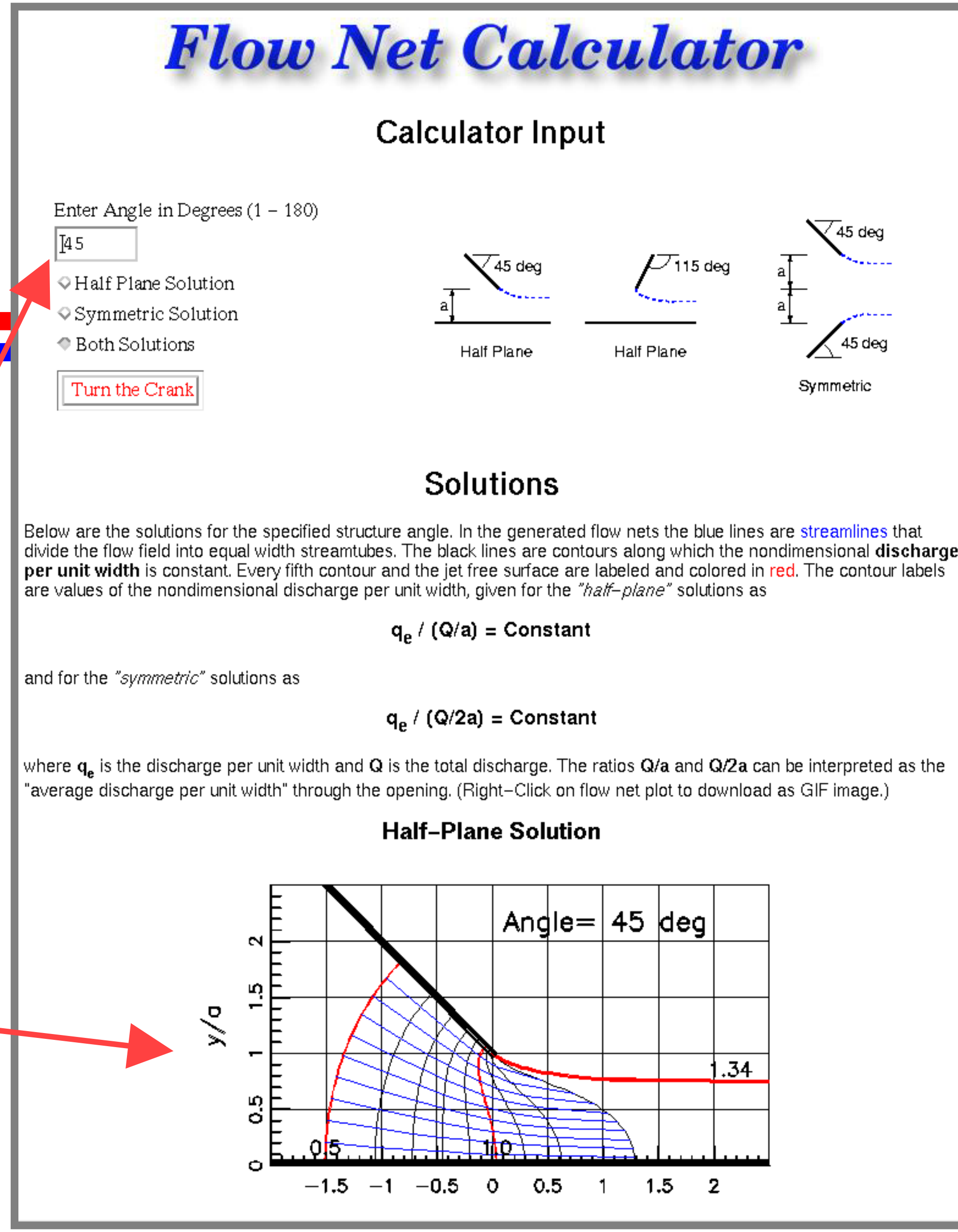
Constricted Jet Flow Web Application

CIRP Web Site Under "Products & Tools" Link

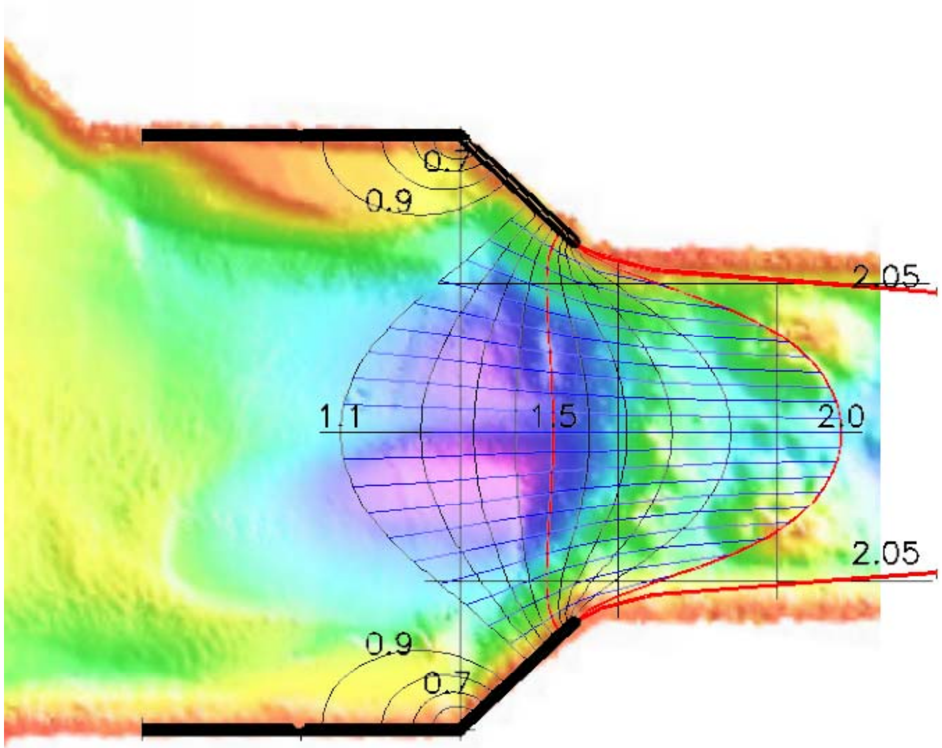
Enter Geometry Angle Here

Flow Map is Calculated and Updated Here

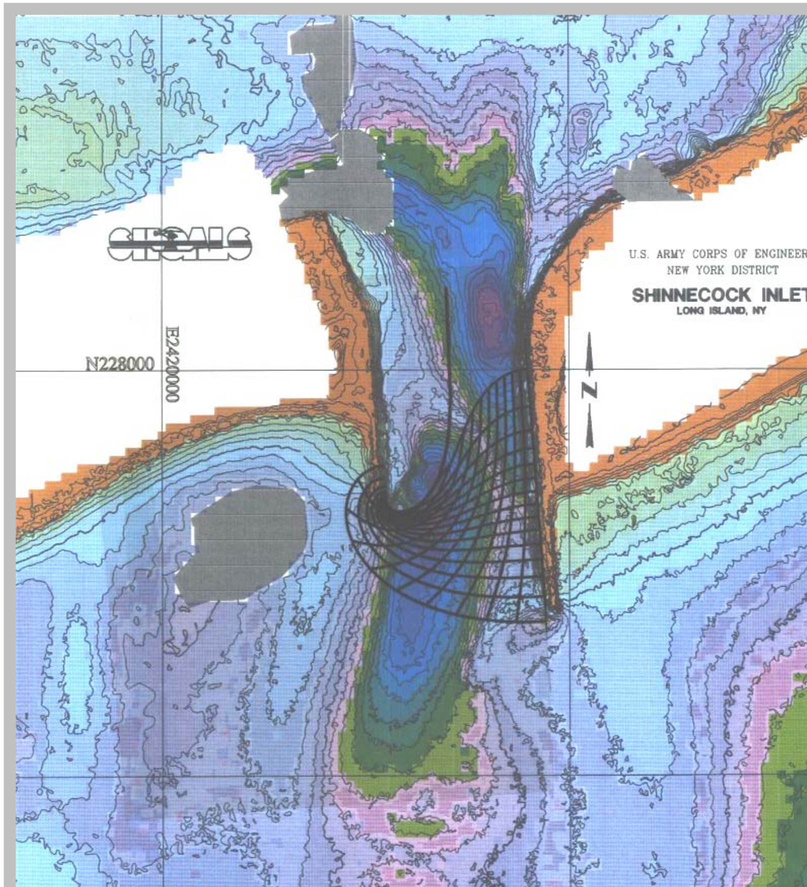
Available Now

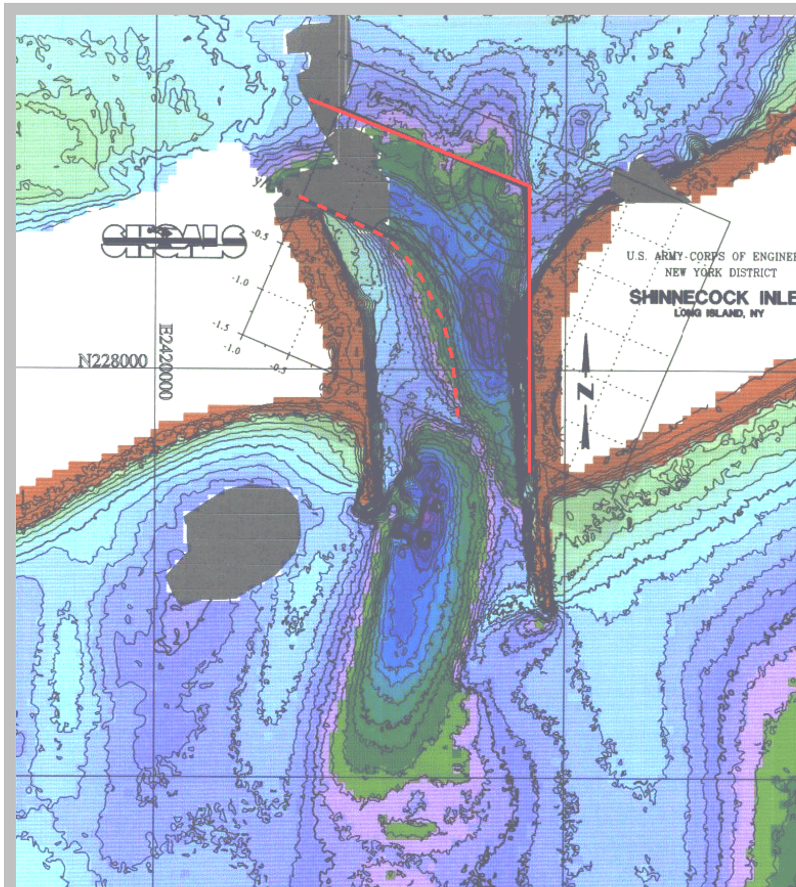


Indian River Inlet, Delaware

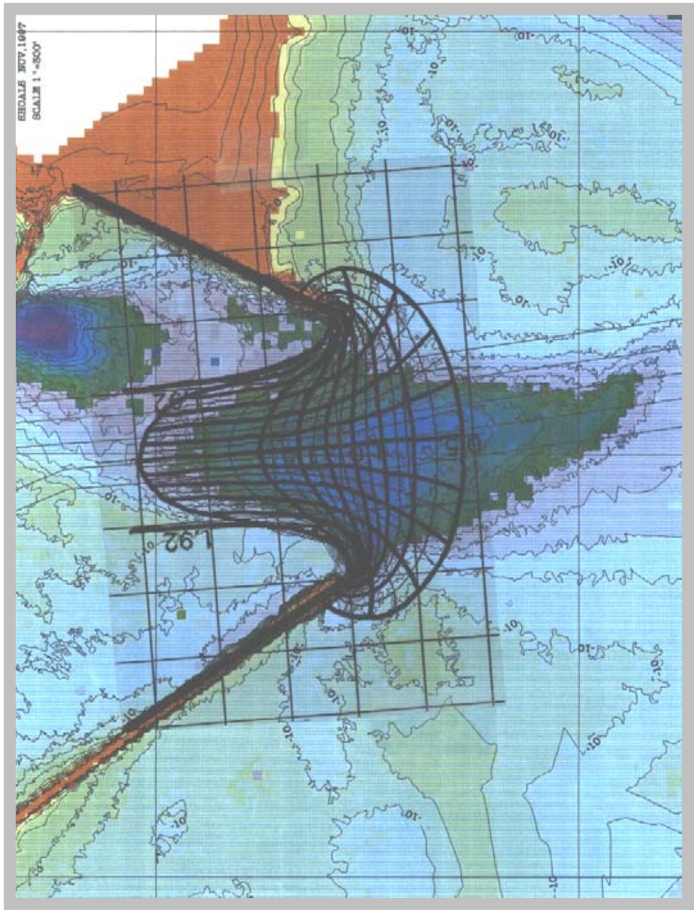


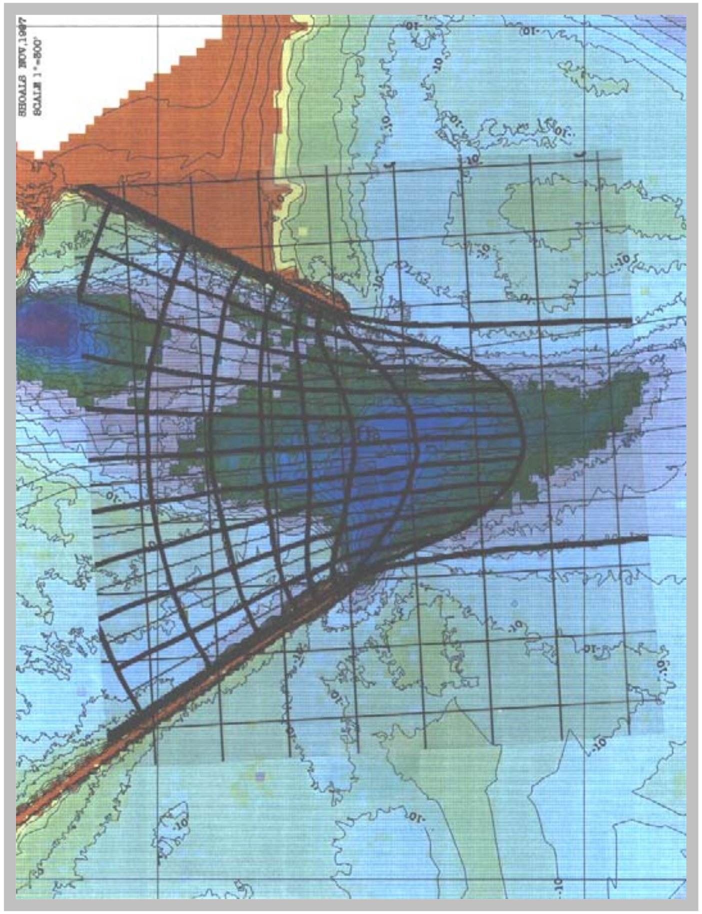
Shinnecock Inlet, New York





East Pass, Florida





Estimating Maximum Scour Depth

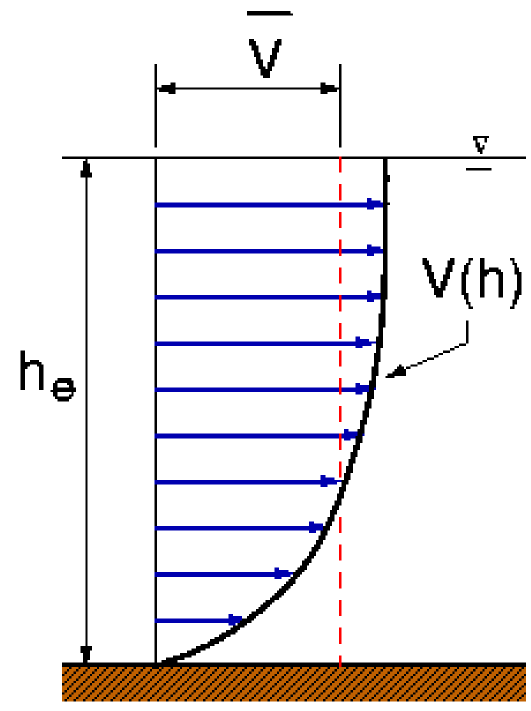
Assume:

- Turbulent boundary layer
- Shear stress proportional to bed critical shear stress

Result:

Equation with empirically evaluated coefficient

Reference: CETN IV-18:
Equilibrium Scour Depths at Inlets



Definition Sketch

Estimating Maximum Scour Depth

Empirical Equation for Equilibrium Discharge

$$q_e = 5.12 \left[g \left(S_s - 1 \right) \right]^{1/2} \; d_e^{3/8} \; h_e^{9/8}$$

where

q_e	–	equilibrium maximum discharge per unit width
S_s	–	sediment specific gravity [$= \rho_s/\rho_w$] (about 2.65 for quartz sand)
ρ_s	–	mass density of sediment
ρ_w	–	mass density of water
d_e	–	median grainsize diameter
h_e	–	equilibrium water depth at maximum discharge
g	–	acceleration of gravity

Physical Interpretation

$$q_e = 5.12\left[g\left(S_s - 1\right)\right]^{1/2}\ d_e^{3/8}\ h_e^{9/8}$$

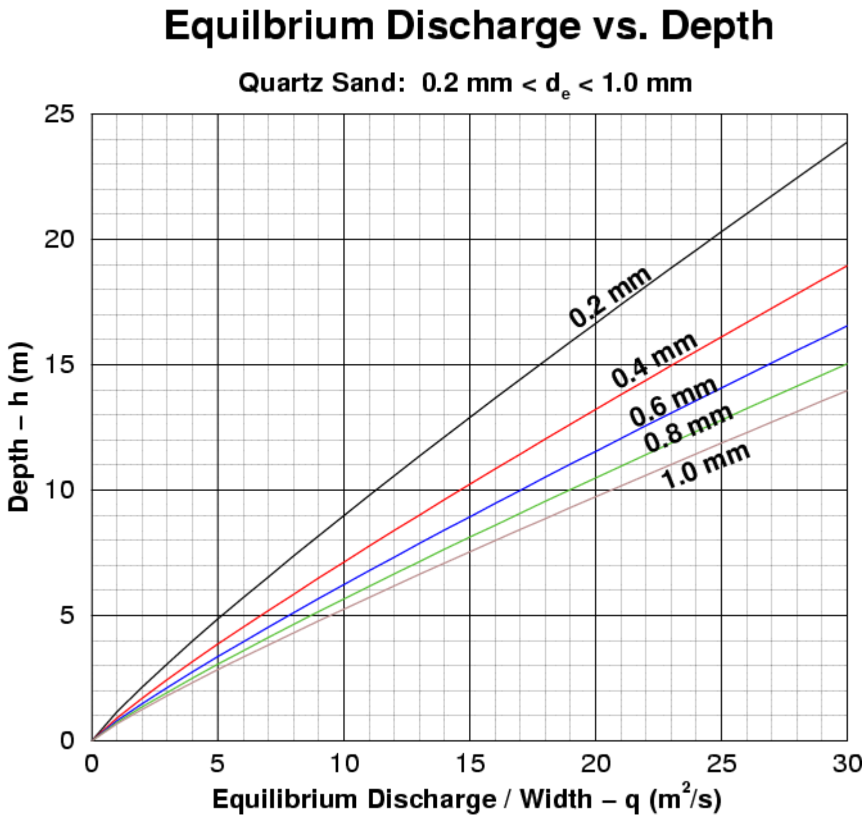
At equilibrium scour depth, a sand bed of a given grain size can tolerate up to a certain discharge per unit width without additional scouring.

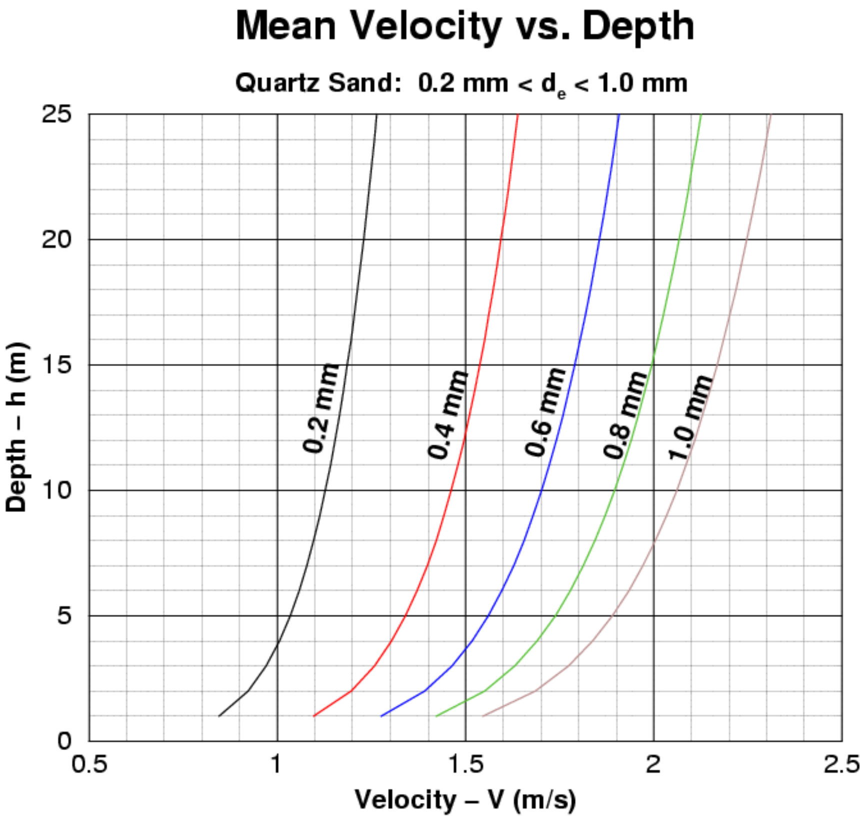
Rearranging into the form

$$h_e = \frac{0.234\ q_e^{8/9}}{\left[g(S_s - 1)\right]^{4/9}\ d_e^{1/3}}$$

Gives the ***maximum depth*** associated with a specified ***maximum discharge***

Estimating Maximum Scour Depth





Estimating Maximum Scour Depth

Equilibrium Scour Depth

Online Calculator

The *"equilibrium scour depth"* refers to depth where no additional scour will occur for a given maximum **equilibrium discharge per unit width (q_e)**.

The table below solves the equilibrium parameters for a given sediment grain size. Specify the known parameter in the appropriate column, and the other parameters in that column will be calculated. Grain size must be specified for all columns. The equations and a definition sketch are given below the table.

Variable	Solve for q_e , V_m	Solve for h_e , V_m	Solve for h_e , q_e
Water Depth (meters)	m	0.0 m	0.00 m
Equilibrium Discharge (m^2/s)	0.00 m^2/s	m^2/s	0.00 m^2/s
Mean Velocity (m/s)	0.00 m/s	0.00 m/s	/s
Maximum Velocity (m/s)	0.00 m/s	0.00 m/s	0.00 m/s
Sand Grain Size (millimeters)		mm	
		Compute!	

Methodology development is described in the CETN Equilibrium Scour Depth at Inlets (**PDF** file).

Equations Solved in Above Calculations

- **Solve for q_e , V_m**

$$V_m = 5.12\,[g\,(S_s - 1)]^{1/2}\,d_e^{3/8}\,h_e^{1/8}$$

Vmax

Equilibrium Discharge Web Application

CIRP Web Site Under "Products & Tools" Link

Choose Column and Enter Value of Parameter

Enter Grain Size

Available Now

Estimating Maximum Scour Depth

Application Caveats:

- Restricted to regions of tidal flow scour
- Actual scour depth will be less than estimated
- Wave action may increase scour over estimates
- Intended only as reasonable estimate for planning

Matagorda Ship Channel, Texas

Problem:

Flow constriction during flood tide

Scour to nearly 100 feet depth in narrow section

Questionable jetty toe stability in narrow section

Scour Estimate from Jet Map

Given:

$$\begin{aligned} L &= 305 \text{ m} \\ a &= 158 \text{ m} \\ Q_T &= 7{,}185 \text{ m}^3/\text{s} \end{aligned}$$

Find:

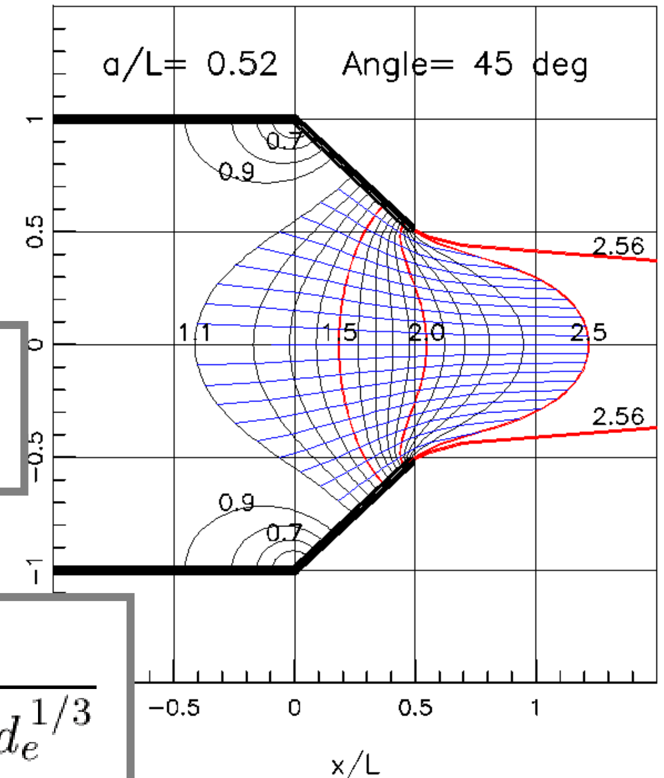
Discharge distribution across **x/L**=0.5 using

$$\frac{q}{(Q_T/2L)} = \text{constant}$$

Estimate:

Scour depth profile across **x/L**=0.5 using

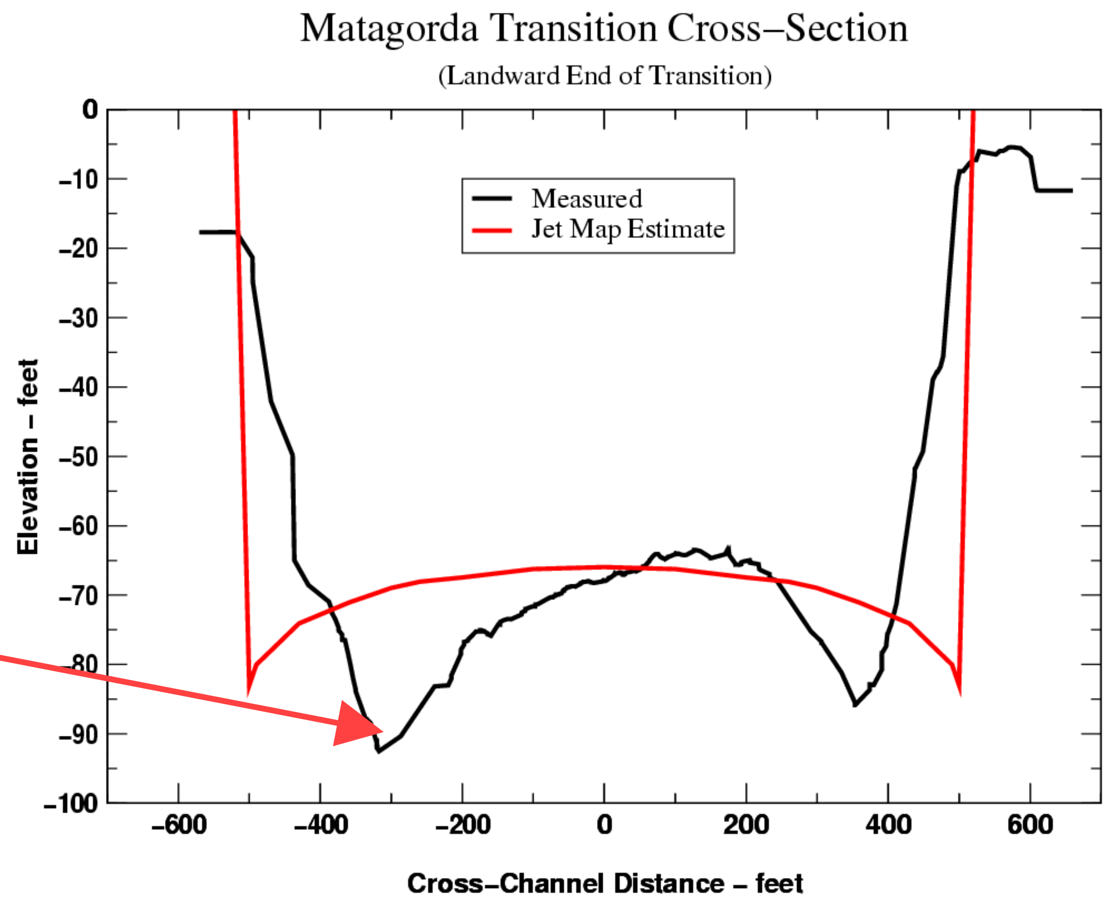
$$h_e = \frac{0.234\, q_e^{8/9}}{[g(S_s-1)]^{4/9}\, d_e^{1/3}}$$



Scour Estimate from Jet Map

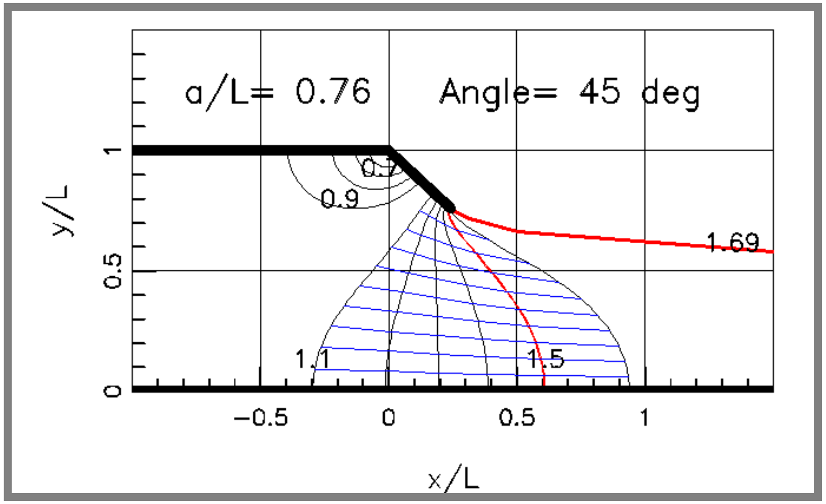
Using Only:
- Geometry
- Total Discharge
- Grain Size

Probably scoured by rotating flows caused by flow separation



Matagorda Ship Channel, Texas

Removing one side of the transition yields this flow map



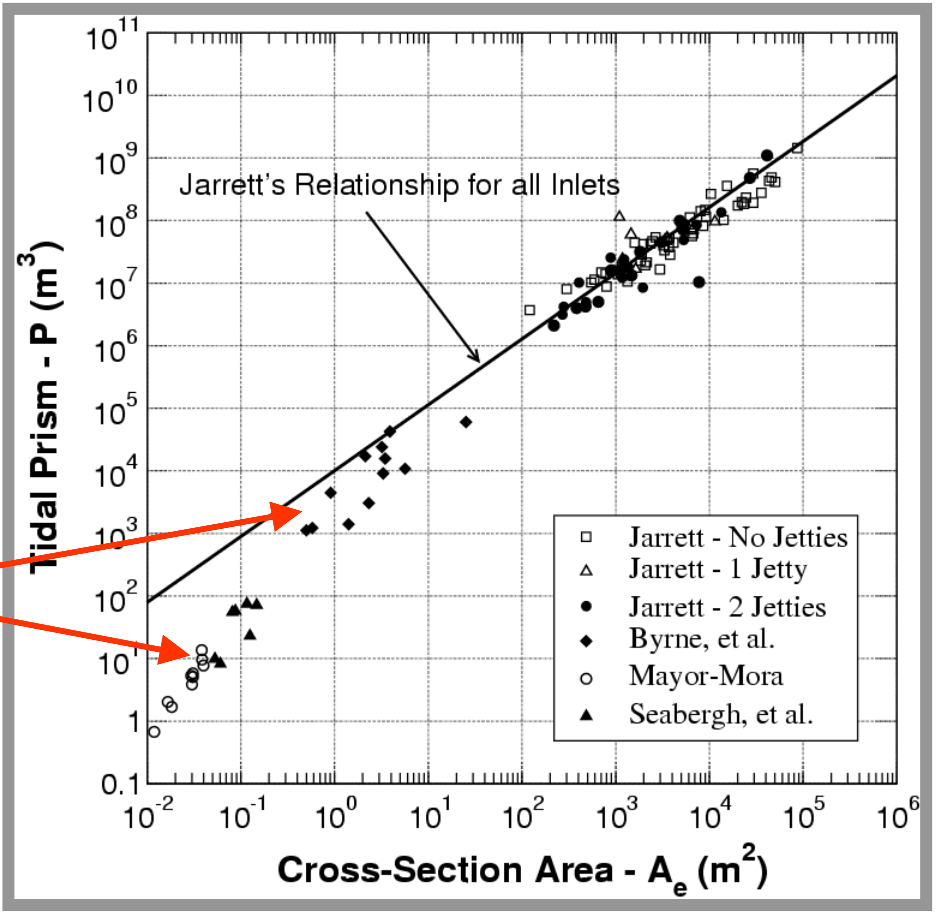
For the same discharge, cross-section depth will vary between

14 -17 m (46 -57 ft)

Equilibrium Inlet Cross Section

Jarrett's Relationship

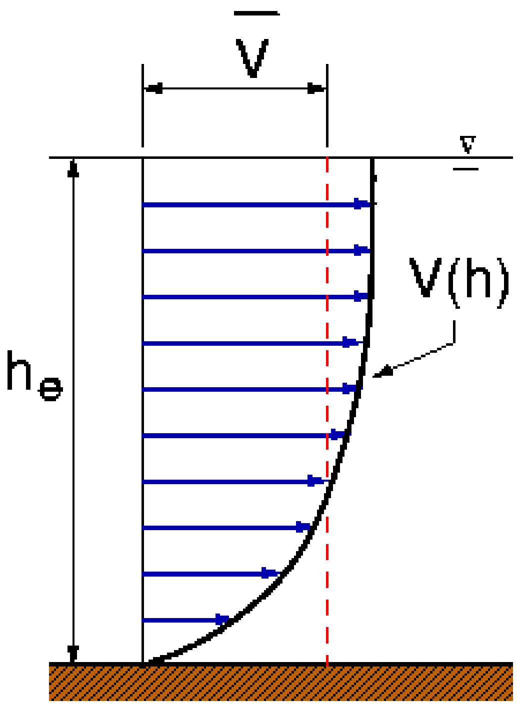
Note: Smaller inlets and laboratory data do not follow the trend.



New Tidal Prism vs. Cross-Section Area Relationship

- Assume that the equilibrium depth of scour exists everywhere
- Integrate the formula across the minimum inlet cross section (arbitrary profile)

Reference: Hughes, “Equilibrium Cross Sectional Area at Tidal Inlets,” *Journal of Coastal Research*, Vol. 18, No. 1, 2002.



Definition Sketch

New Tidal Prism vs. Cross-Section Area Relationship

$$A_e = 0.87 \left[\frac{W^{1/9}}{[\,g(S_s - 1)]^{4/9} \, d_e^{1/3} \, T^{8/9}} \right] P^{8/9}$$

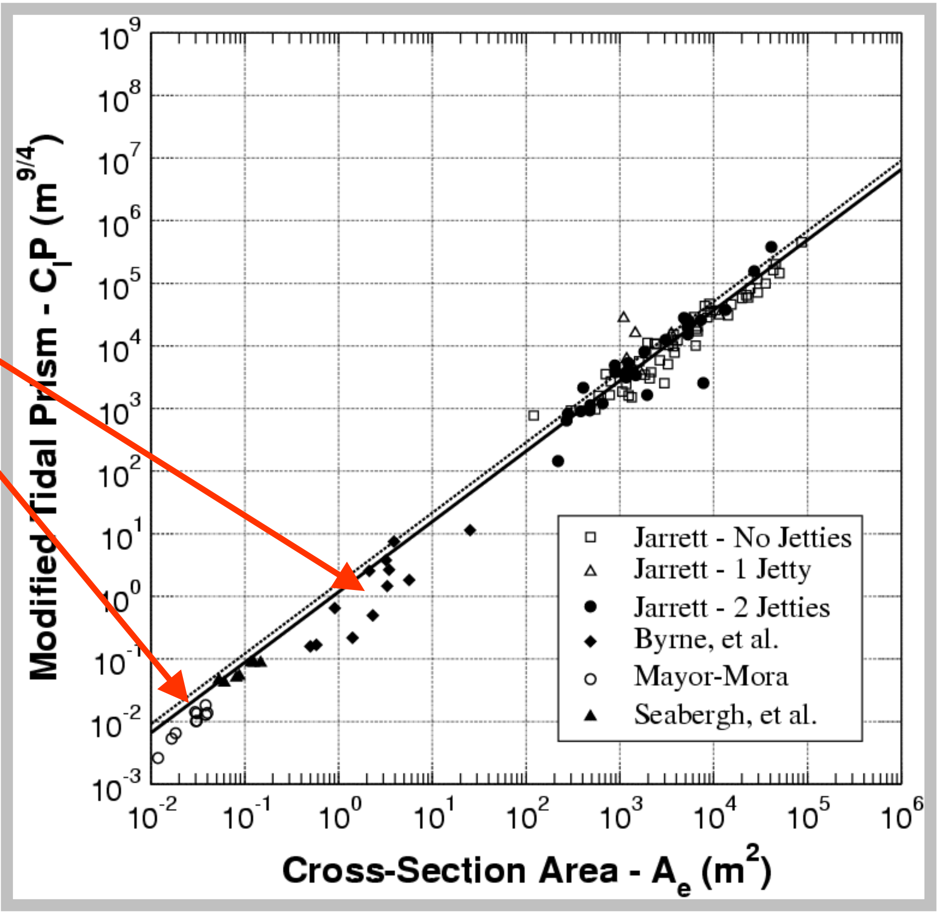
where

A_e	–	minimum equilibrium cross-sectional area
W	–	equilibrium channel width at minimum cross section
g	–	gravitational acceleration
S_s	–	sediment specific gravity $[= \rho_s/\rho_w]$
d_e	–	median grain-size diameter
T	–	tidal period
P	–	tidal prism

New Tidal Prism vs. Cross-Section Area Relationship

Result: Smaller inlets and laboratory data more closely follow the trend.

Spinoff: Basis for new scaling criteria for movable-bed inlet modeling.



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Repairing Damaged Inlet Structures

Problem:

- Scour is not recognized as a key factor leading to damage
- Structure is repaired without scour protection (usually bigger)
- Structure suffers more damage

Correct Approach:

- Determine if scour is contributing to damage
- Mitigate scour problem as part of structure repair
- Assess whether local mitigation might increase scour potential elsewhere

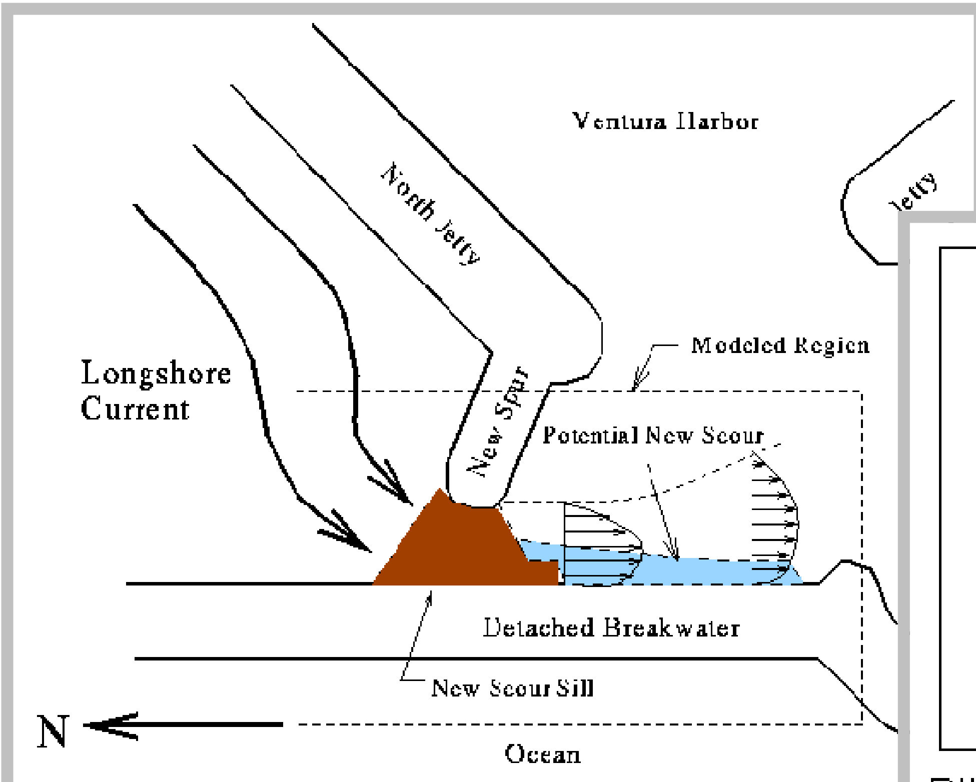
Repairing Damaged Inlet Structures

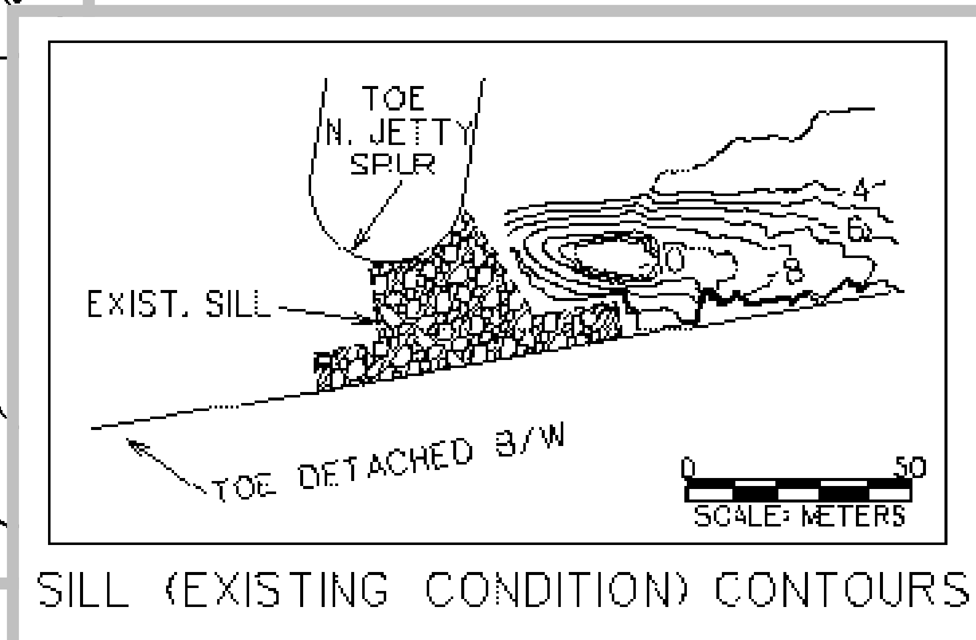
Ventura Harbor, California

Overview | Inlet Scour | Prediction | Protection | Current Work

Repairing Damaged Inlet Structures

Ventura Harbor, California





Overview	Inlet Scour	Prediction	Protection	Current Work

Scour Blankets in Current Fields

$$\frac{W_{30}}{w_a\, h^3} = \frac{\pi}{6}(S_f\, C_s)^3 \left[\left(\frac{w_w}{w_a - w_w}\right)^{1/2} \left(\frac{\bar{u}}{\sqrt{K_1 g h}}\right)\right]^{15/2}$$

With

$$K_1 = \sqrt{1 - \frac{\sin^2\theta}{\sin^2\phi}}$$

Where

- W_{30} – Weight at which 30% of stones are smaller by weight
- w_a – Specific weight of blanket stone
- w_w – Specific weight of water
- h – Water depth
- g – Gravity
- $\bar{u}$ – Mean current velocity over depth
- S_f – Safety factor (1.1 minimum)
- C_s – Stability coefficient (0.30 – angular stone; 0.38 – rounded stone)
- θ – Bottom slope angle
- ϕ – Blanket stone angle of repose ($\approx 40^o$)

Scour Blankets in Current Fields

Riprap Gradation

$$W_{50_{min}} = 1.7\, W_{30}$$

$$W_{100_{max}} = 8.5\, W_{30}$$

$$W_{100_{min}} = 3.4\, W_{30}$$

$$W_{50_{max}} = 2.6\, W_{30}$$

$$W_{15_{max}} = 1.3\, W_{30}$$

$$W_{15_{min}} = 0.5\, W_{30}$$

Blanket Thickness

Above water (minimum - 0.3 m)

$$r = 2.5 \left(\frac{W_{30}}{w_a} \right)^{1/3}$$

Below water (minimum - 0.5 m)

$$r = 3.8 \left(\frac{W_{30}}{w_a} \right)^{1/3}$$

Scour Blanket Design Example

- Depth = 20 ft
- Mean velocity = 8.2 ft/s
- Rounded stone
- Safety factor = 1.1
- Flat bottom

Blanket Thickness

$$r = 3.8\left(\frac{1.9\ lb}{165\ lb/ft^3}\right)^{1/3} = \underline{0.86\ ft}$$

Use r = 0.5 m = 1.6 ft

Riprap Gradation

$$W_{30} = 1.9\ lb$$

$$W_{100_{max}} = 16.4\ lb$$
$$W_{100_{min}} = 6.6\ lb$$

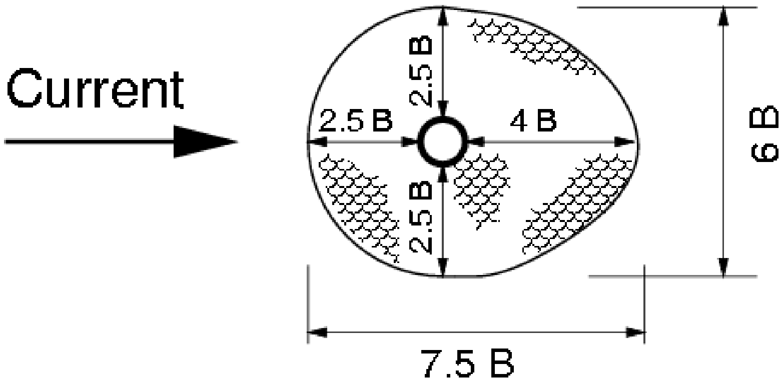
$$W_{50_{max}} = 5.0\ lb$$
$$W_{50_{min}} = 3.3\ lb$$

$$W_{15_{max}} = 2.5\ lb$$
$$W_{15_{min}} = 1.0\ lb$$

Blanket Design for Vertical Piles

Currents

Size stone according to scour blanket guidance



Waves

Rule of Thumb:

Blanket width about twice maximum scour depth

Toe Scour Apron Rules of Thumb

- Based on survey of successful field practice
- Often protection is extension of bedding or filter layer
- Minimum Apron Thickness: 0.6 to 1.0 m (1.0 to 1.5 m in NW)
- Minimum Apron Width: 1.5 m (3 m to 7.5 m in NW)
- Material: Quarrystone to 0.3 m diameter, gabions, mats, etc.

Rules of thumb are inadequate when:

1. depth < (2 x breaking wave height)
2. Reflection coefficient > 0.25 (about 1:3 slope)

Other Scour Guidance in CEM

- Wave-induced scour at vertical
- Wave-induced scour at sloping structures
- Wave- and current-induced scour at small- and large-diameter vertical piles
- Wave- and current-induced scour at submerged pipelines
- Design of jetty toe protection
- Design of pipeline scour protection

Scour Prediction and Protection at Inlets

Contents

Major Research Thrusts

Scour Numerical Model

- Contract
- Flow Construction Only
- Part of SMS

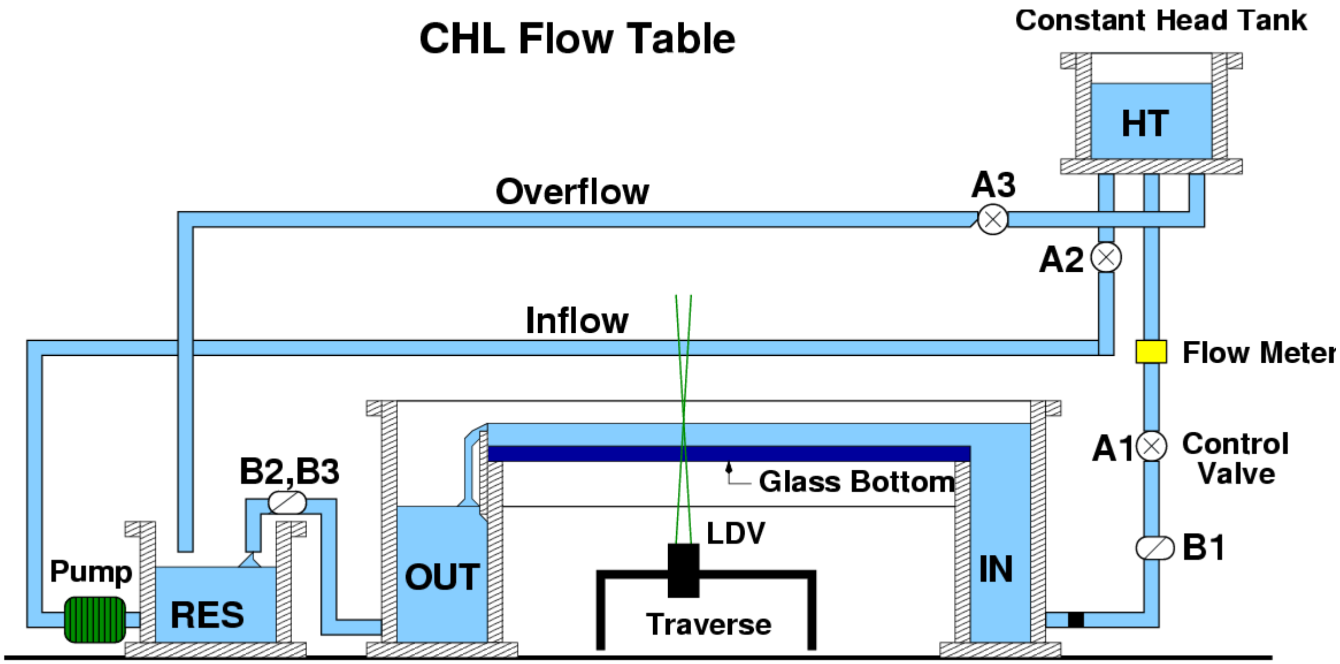
Inlet Structures

- One-Layer Armor Repairs
- Scour Risk to Jetties

Inlet Hydraulics

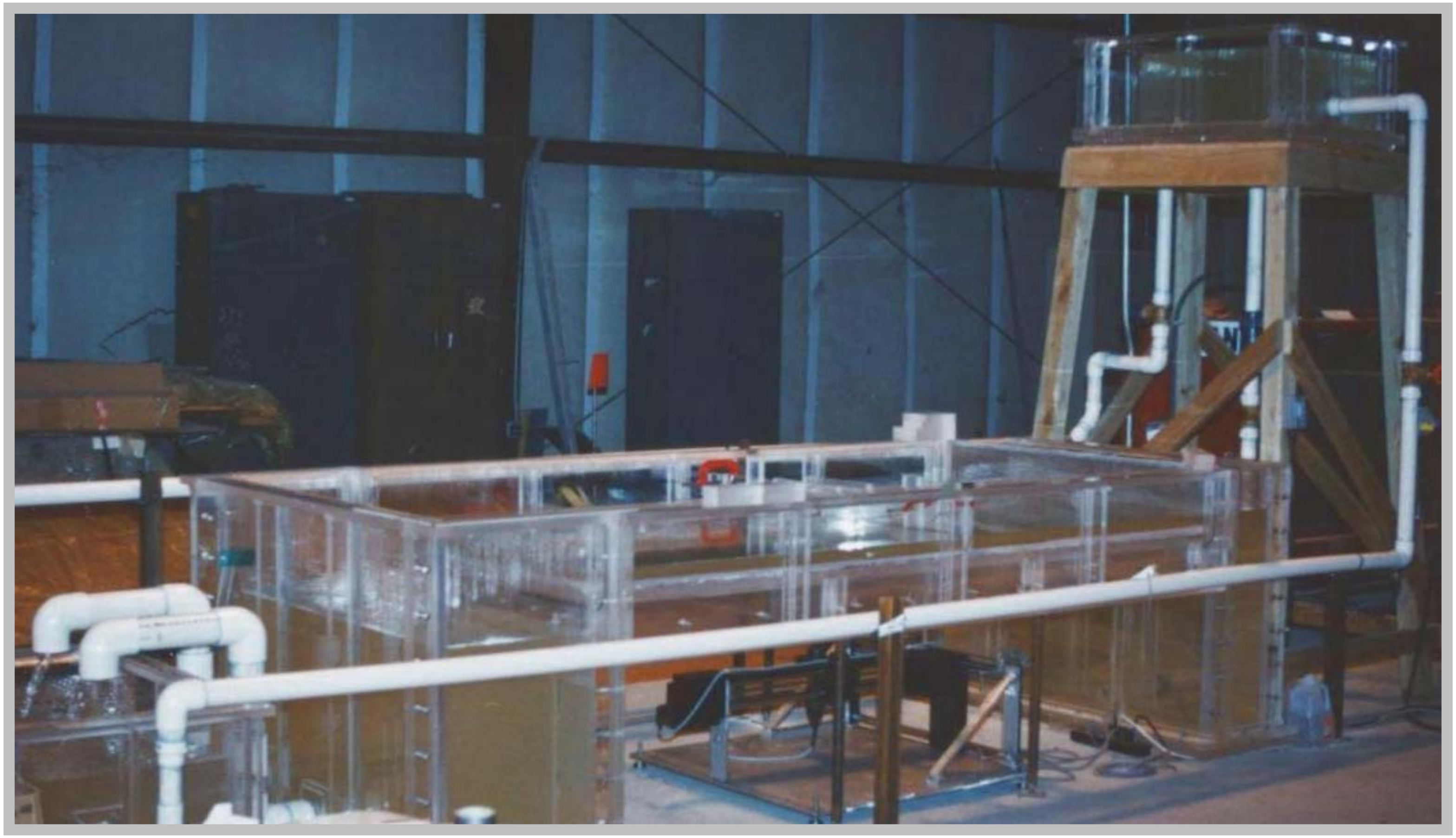
- Flow Table Studies to Support Scour Model
- Turbulent Scale Effects in Distorted Models
- Models of Opportunity w/Districts

CHL Precision Flow Table



Reference: **CETN IV-??**: (in publication)
CHL Precision Flow Table - Description and Applications

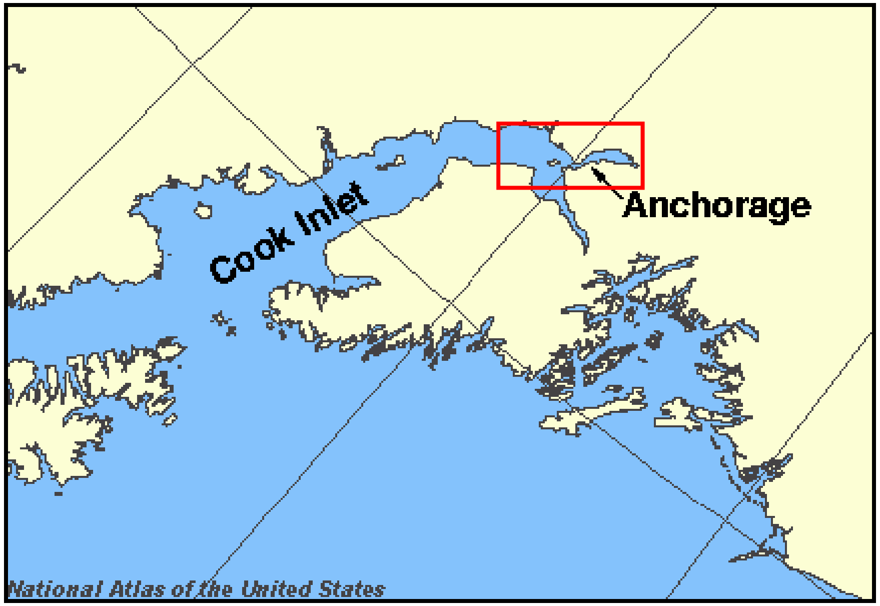
CHL Precision Flow Table



Port of Anchorage, Cook Inlet, Alaska

Situation...

- Port of Anchorage
  - High annual shoaling rate (200,000 - 400,000 yd^3)
  - Emergency dredging at times (800,000 - 1,000,000 yd^3)
- Proposed channel deepening
- Huge tidal range (+30 ft)
- Flow turbulence significant



Port of Anchorage, Cook Inlet, Alaska

Proposed Physical Model:

- Distorted physical model
- Cover 7 mi X 4 mi Area
- Scales: 1:400 horiz ; 1:100 vert.
- Model cost: near $800,000

Potential Problem:

- Turbulence/separation is important
- What is turbulence scale effect ?
- Results may be false in separation areas
- Can adjustments be made?

Flow Table Study of Cook Inlet, Alaska

Idealized and 3-D models of inlet to examine flow patterns
Goal: Determine why silt deposits in harbor region and mechanisms that generate observed flow gyres.

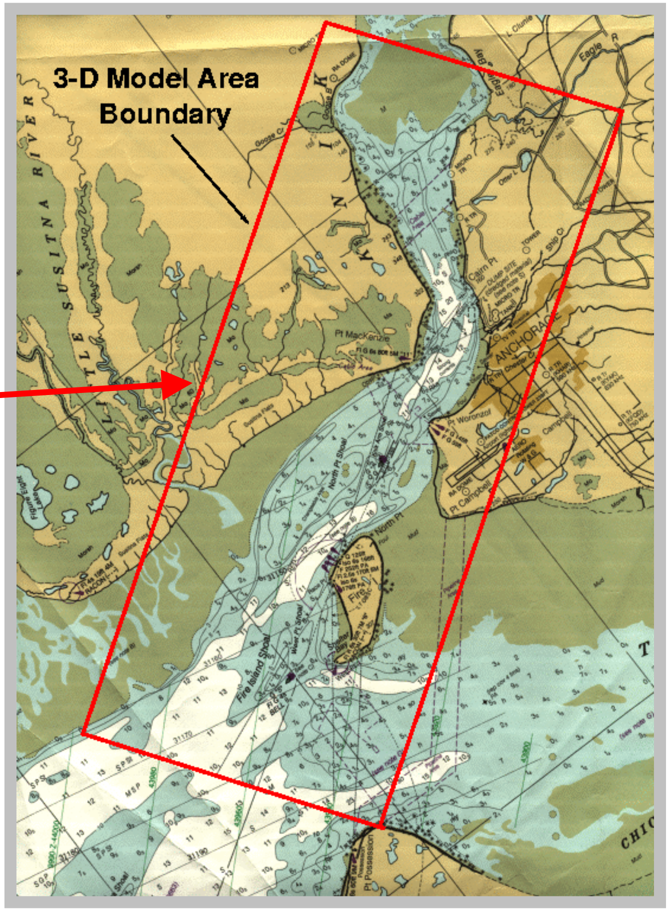
Measurements of flow near ends of dredging area
Goal: Examine if sloped transitions will increase flow velocity in harbor region to help alleviate silt deposition.

Examine scale effects in distorted physical models
Goal: Determine if a distorted physical model of Cook Inlet would be valid and appropriate for this problem (before investing ~$800,000).

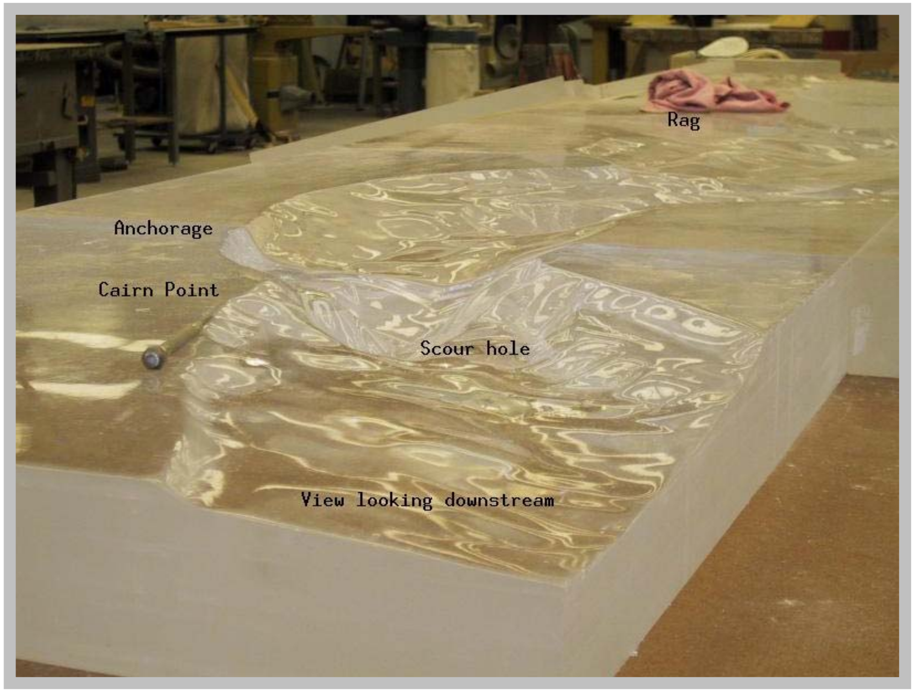
Flow Table Study of Cook Inlet, Alaska

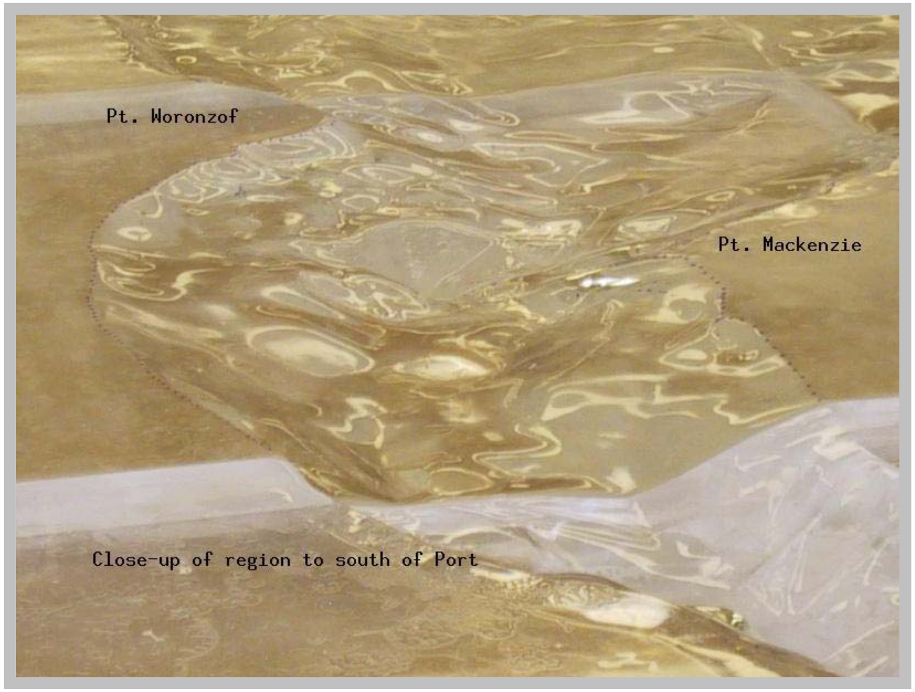
3-D Model Parameters:

- Distorted physical model
- Modeled 11 mi X 31 mi Area
- Scales: 1:15,000 horiz ; 1:1,000 vert.
    - Horizontal…..1,250 ft = 1 in.
    - Vertical……...83 ft = 1 in.
    - Velocity……..1.6 m/s = 5 cm/s

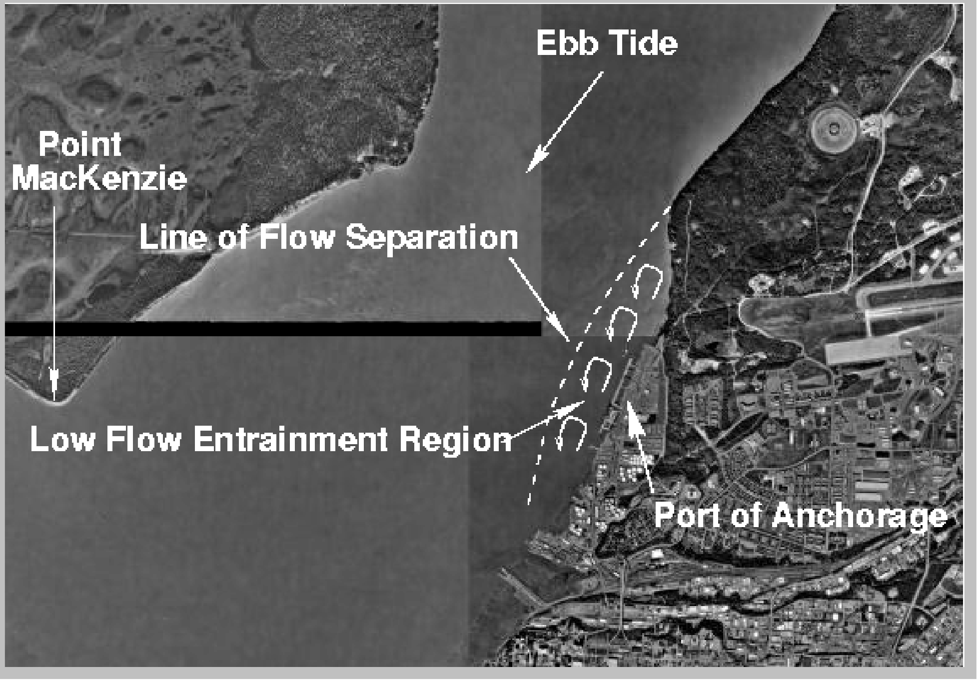


Flow Table Study of Cook Inlet, Alaska





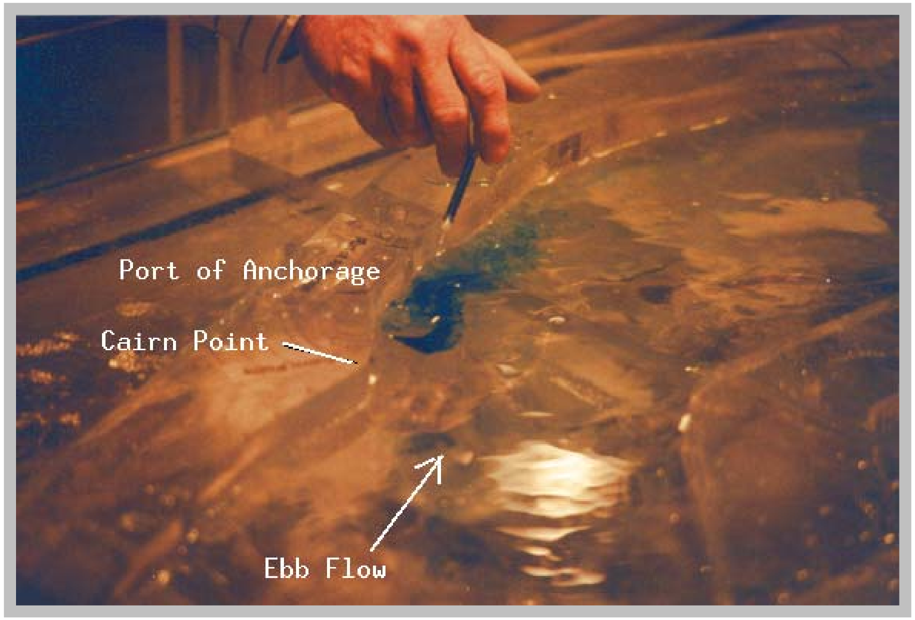
Flow Table Study of Cook Inlet, Alaska



Flow Table Study of Cook Inlet, Alaska

Study Findings...

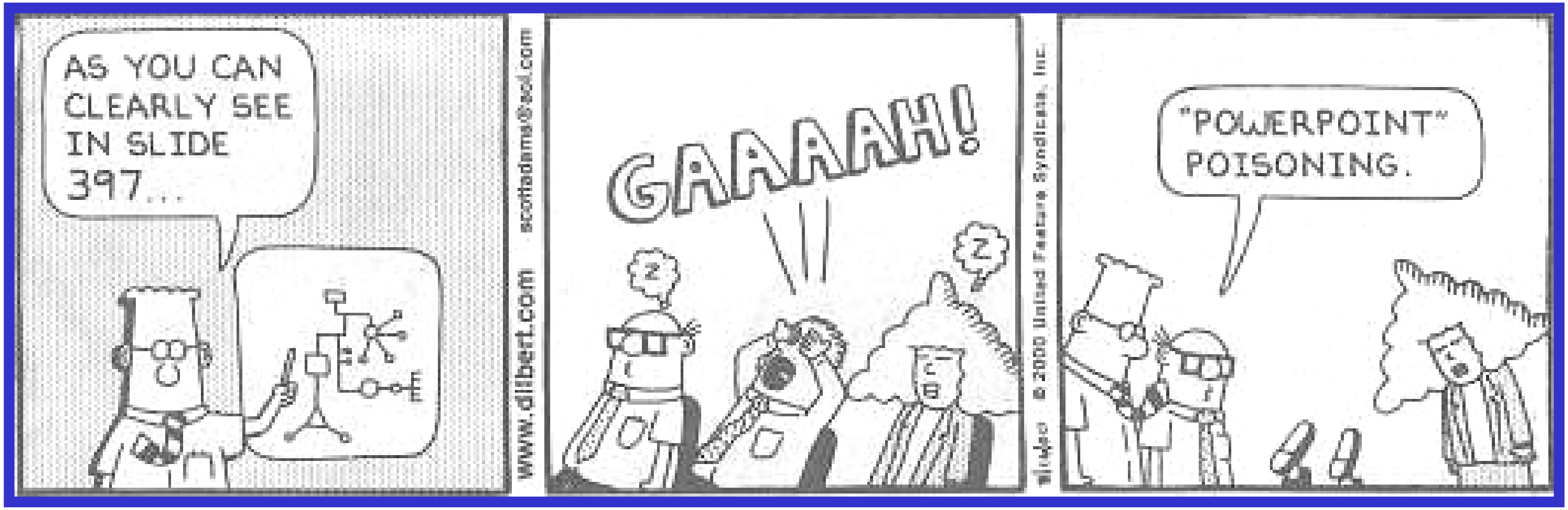
- Shoaling due to ebb flow separation at Cairn Point
- Dredge disposal practices improved
- Turbulence scale effects not severe



Conclusions

- Scour at structures can cause damage leading to reduced project functionality
- Capability to predict maximum scour depth is lacking for many situations
- Important to identify dominant scour mechanism
- Structured inlets act like jets which can cause scour near structures
- Methods are available for estimating scour due to jets
- Design of scour protection is based largely on past experience
- Knowledge about scour of cohesive sediments is virtually nonexistent

Questions?


AS YOU CAN CLEARLY SEE IN SLIDE 397...
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"POWERPOINT" POISONING.
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