Scour and Scour Protection

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Scour and Scour Protection

Contents

- Scour Problems in Coastal Engineering
- Prediction of Scour
- Design of Scour Protection
- Design of Scour Blankets

CEM Chapters VI-5-3-f And VI-5-6 (Author: Steven A. Hughes)
Scour Problems

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

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 cause 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.
**Scour Problems**

**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 forward 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.
Scour Problems

Impacts 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
Scour Problems

Physical Processes

Scour occurs whenever...

Hydrodynamic \textbf{bottom shear stresses} \ greater than 
Sediment \textbf{critical shear stress}

\textit{Clear Water Scour} : Sediment motion is localized

\textit{Live Bed Scour} : Entire bottom is mobilized with locally higher stresses
Scour Problems

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

- Scour at Pier
- Bridge Pier Scour
- Scour at Inlet Structures
- Pipeline Scour
- Scour at Seawall
- Scour at Detached Breakwater
- Scour at Vertical Pilings

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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
Scour Problems

Example of Inlet Scour

Shinnecock Inlet
Long Island, New York

Scour caused by flood and ebb jet flow separations
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Prediction of Scour

Scour at Vertical Walls

Nonbreaking Waves

(a) UNDER REGULAR WAVES

(b) UNDER IRREGULAR WAVES

(AFTER XIE 1981)
Prediction of Scour

Scour at Vertical Walls

Nonbreaking Waves

\[
\frac{S_m}{(u_{rms})_m T_p} = \frac{0.05}{[\sinh(k_p h)]^{0.35}}
\]

where

\[
\frac{(u_{rms})_m}{g k_p T_p H_{mo}} = \frac{\sqrt{2}}{4\pi \cosh(k_p h)} \left[ 0.54 \cosh \left( \frac{1.5 - k_p h}{2.8} \right) \right]
\]

and

- \(S_m\) – Maximum scour depth at node \((L/2)\)
- \(h\) – Water depth
- \(T_p\) – Peak spectral wave period
- \((u_{rms})_m\) – Root-mean-square of horizontal velocity
- \(k_p\) – Wave number associated with \(T_p\)
- \(g\) – Gravity
- \(H_{mo}\) – Significant wave height

From Xie's Regular Wave Tests

Proposed For Irregular Waves
Prediction of Scour

Scour at Vertical Walls

Nonbreaking Waves

Round, Vertical Breakwater Head

\[ \frac{S_m}{B} = 0.5 \left[ 1 - e^{-0.175(KC - 1)} \right] \]

Square, Vertical Breakwater Head

\[ \frac{S_m}{B} = -0.09 + 0.123 \, KC \]

Where

\[ KC = \frac{U_m \, T_p}{B} \]

and

- \( S_m \) – Maximum scour depth from bed level
- \( B \) – Diameter of circular head
- \( T \) – Regular wave period
- \( U_m \) – Maximum wave orbital velocity at bed
- \( KC \) – Keulegan-Carpenter number
Prediction of Scour

Scour at Vertical Walls

Breaking Waves

Rules of Thumb:

• Maximum scour depth: $S_m = H_{max}$ or $S_m = h$
• Maximum scour when wall is at breaking wave plunge point
• Reduction in reflection reduces scour
• Currents will increase reflection
Prediction of Scour

Scour at Vertical Walls

Breaking Waves

\[
\frac{S_m}{(H_{mo})_o} = \sqrt{22.72 \frac{h}{(L_p)_o} + 0.25}
\]

Where
- \( S_m \) – Maximum scour depth from bed level
- \((H_{mo})_o\) – Deepwater significant wave height
- \( h \) – Pre-scour water depth at wall
- \((L_p)_o\) – Deepwater wavelength associated with \( T_p \)

Range of Validity

\[0.011 < \frac{h}{(L_p)_o} < 0.045 \quad \text{and} \quad 0.015 < \frac{(H_{mo})_o}{(L_p)_o} < 0.04\]
Prediction of Scour

Scour at Sloping Structures

Rules of Thumb

- Generally, analytical methods are lacking
- Nonbreaking wave-induced scour is not significant
- Maximum breaking wave scour will be less than a vertical wall
- Scour depth decreases with structure reflection coefficient
- Along-structure currents can greatly increase scour depth
- Obliquely-incident waves will increase scour because of Mach-stem and generation of along-structure currents
Scour at Sloping Structures

Sloping Structure Roundheads

Scour by Steady Streaming

\[
\frac{S_m}{B} = 0.04 \left[ 1 - e^{-4.0 (KC - 0.05)} \right]
\]

Scour by Plunging Waves

\[
\frac{S_m}{H_s} = 0.01 \left( \frac{T_p \sqrt{g H_s}}{h} \right)^{3/2}
\]

Where

\[ KC = \frac{U_m T_p}{B} \]

and

- \( S_m \) – Maximum scour depth from bed level
- \( B \) – Diameter of circular head at bed
- \( T \) – Regular wave period
- \( U_m \) – Maximum wave orbital velocity at bed
- \( H_s \) – Significant wave height
- \( KC \) – Keulegan-Carpenter number
Prediction of Scour

Scour at Vertical Piles
Small Diameter Piles - \((D < L/10)\)

Physical Processes
- Horseshoe vortex forms
- Vortex shedding in lee of pile
- Local flow accelerations

Key Parameters
- Current magnitude
- Orbital wave velocity
- Pile diameter

(Sediment size and pile shape less important)
Prediction of Scour

Scour at Vertical Piles

Small Diameter Piles

Rule of Thumb (somewhat conservative)

Maximum scour depth is equal to about twice the pile diameter
Prediction of Scour

Scour at Vertical Piles

Scour by Currents - Small Diameter Piles

\[ \frac{S_m}{h} = 2.0 \ K_1 \ K_2 \left( \frac{b}{h} \right)^{0.65} \ Fr^{0.43} \]

Where

- \( S_m \) – Maximum scour depth below average bed level
- \( h \) – Water depth upstream of pile
- \( b \) – Pile width
- \( Fr \) – Flow Froude number [\( Fr = \frac{U}{\sqrt{(gh)}} \)]
- \( U \) – Mean current velocity magnitude
- \( K_1 \) – Pile shape factor
- \( K_2 \) – Pile orientation factor
- \( \theta \) – Angle of pile orientation
- \( L \) – Pile length

\[ K_2 = (\cos \theta + \frac{L}{b} \sin \theta)^{0.62} \]
Prediction of Scour

Scour at Vertical Piles

Scour by Waves - Small Diameter Piles

- Cylindrical Pile

\[ \frac{S_m}{D} = 1.3 \left[ 1 - e^{-0.03(KC-6)} \right] \quad \text{for } KC \geq 6 \]

- Square Pile 90 deg. to Flow

\[ \frac{S_m}{D} = 2.0 \left[ 1 - e^{-0.015(KC-11)} \right] \quad \text{for } KC \geq 11 \]

- Square Pile 45 deg. to Flow

\[ \frac{S_m}{D} = 2.0 \left[ 1 - e^{-0.019(KC-3)} \right] \quad \text{for } KC \geq 3 \]

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Prediction of Scour

Scour at Vertical Piles
Scour by Waves and Currents

- No analytical methods available
- Scour depth increases when even a small current is added to waves
- Breaking waves increase scour over scour caused by currents alone
- Inverted cone shape is similar for both cases

Rule of Thumb

Estimate maximum scour depth using formula for currents alone
Prediction of Scour

Scour at Vertical Piles

Large Diameter Piles - \((D > L/10)\)

- Coincident waves and currents
- Wave diffraction occurs
- Maximum scour occurs at corners of square piles
- Scour extent used to design scour protection

<table>
<thead>
<tr>
<th>Current</th>
<th>Orientation</th>
<th>Equivalent Diameter</th>
<th>Scour Depth</th>
<th>Scour Extent</th>
</tr>
</thead>
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<tr>
<td></td>
<td>(D)</td>
<td>(D_e = D)</td>
<td>(S_m = 0.06D_e)</td>
<td>(L_s = 0.75D_e)</td>
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<td>(S)</td>
<td>(D_e = 1.82S)</td>
<td>(S_m = 0.04D_e)</td>
<td>(L_s = 1.00D_e)</td>
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<tr>
<td></td>
<td>(S)</td>
<td>(D_e = 1.82S)</td>
<td>(S_m = 0.07D_e)</td>
<td>(L_s = 1.00D_e)</td>
</tr>
</tbody>
</table>
Prediction of Scour

Scour at Pipelines

Pipelines Outside the Surf Zone

Scour Problem

- Scour can lead to partial burial
- Problem is differential scour due to different soil types
- Pipeline is left spanning a gap

Scour Process

- Begins with seepage increasing beneath pipeline
- Rapid scour phase (*tunnel erosion*)
- Final scour by *lee-wake erosion*
Prediction of Scour

Scour at Pipelines
Pipelines Outside the Surf Zone

Scour by Currents

For $U/U_c > 1$ (Live-bed scour)

$$\frac{S_m}{D} = 0.6 \pm 0.1$$

Scour by Waves

$$\frac{S_m}{D} = 0.1\sqrt{KC} \left(1 - 1.4 \frac{e}{D}\right) + \frac{e}{D}$$

Valid for $e/D < 0.5$
Prediction of Scour

Scour at Pipelines

Pipelines Through the Surf Zone

- Pipelines will be damaged if uncovered and exposed to strong waves and longshore currents
- Once exposed, additional scour occurs
- No design guidance is available

Rule of Thumb

*Burial depth should exceed expected profile lowering at all places*
Prediction of Scour

Other Scour Problems

• Scour downstream of sills and stone blankets due to currents
• Scour downstream of hard bottoms due to currents
• Scour at control structures due to plunging jets
• Scour at two- and three-dimensional culverts
• Scour at abutments and spur dikes
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Design of Scour Protection

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)
Sheetpile Retaining Walls

Geotechnical Considerations

\[ W = 2.0 \, d_e \]

Hydrodynamic Considerations

\[ W = 2.0 \, H_i \quad \text{or} \quad W = 0.4 \, d_s \]

Where

- \( W \) – Width of scour apron
- \( d_e \) – Depth of sheetpile penetration
- \( H_i \) – Incident wave height
- \( d_s \) – Water depth at wall
Sheepile Retaining Walls

Apron Stone Size:

- **WAVES**: For heavy wave action, use toe protection guidance \( (VI-5-3-d) \)
- **CURRENTS**: For strong currents use scour blanket criterion \( (VI-5-3-f) \)
- **WAVES AND CURRENTS**: Estimate individually, then increase largest by factor of 1.5
Sloping-Front Structures

• Adequate scour protection usually provided by toe protection design
• Additional protection might be needed for strong lateral currents
• Inlet structures are a special case
Design of Scour Protection

Vertical Piles

**Currents**
Size stone according to scour blanket guidance

**Waves**
Rule of Thumb:
Blanket width about twice maximum scour depth
Design of Scour Protection

Submerged Pipelines

Outside Surf Zone:
- Burial
- Partial covering
- Complete covering

Inside Surf Zone:
- Burial is only option

(a) Scour Protection by Partial Covering

(b) Scour Protection by Complete Coverage
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Design of Scour Blankets

Stability in Current Field

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

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)
- \( \theta \) – Bottom slope angle
- \( \phi \) – Blanket stone angle of repose (≈ 40°)
Design of Scour Blankets

**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)
  
  \[
  r = 3.8 \left( \frac{W_{30}}{w_a} \right)^{1/3}
  \]
Design of Scour Blankets

Example

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

Blanket Thickness

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

Use \( r = 0.5 \text{ m} = 1.6 \text{ ft} \)

Riprap Gradation

\[
\begin{align*}
W_{30} &= 1.9 \text{ lb} \\
W_{100_{\text{max}}} &= 16.4 \text{ lb} \\
W_{100_{\text{min}}} &= 6.6 \text{ lb} \\
W_{50_{\text{max}}} &= 5.0 \text{ lb} \\
W_{50_{\text{min}}} &= 3.3 \text{ lb} \\
W_{15_{\text{max}}} &= 2.5 \text{ lb} \\
W_{15_{\text{min}}} &= 1.0 \text{ lb}
\end{align*}
\]
Scour and Scour Protection

Scour 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
- Design of scour protection is based largely on past experience
- Knowledge about scour of cohesive sediments is virtually nonexistent