Scour Assessment and Design for Scour

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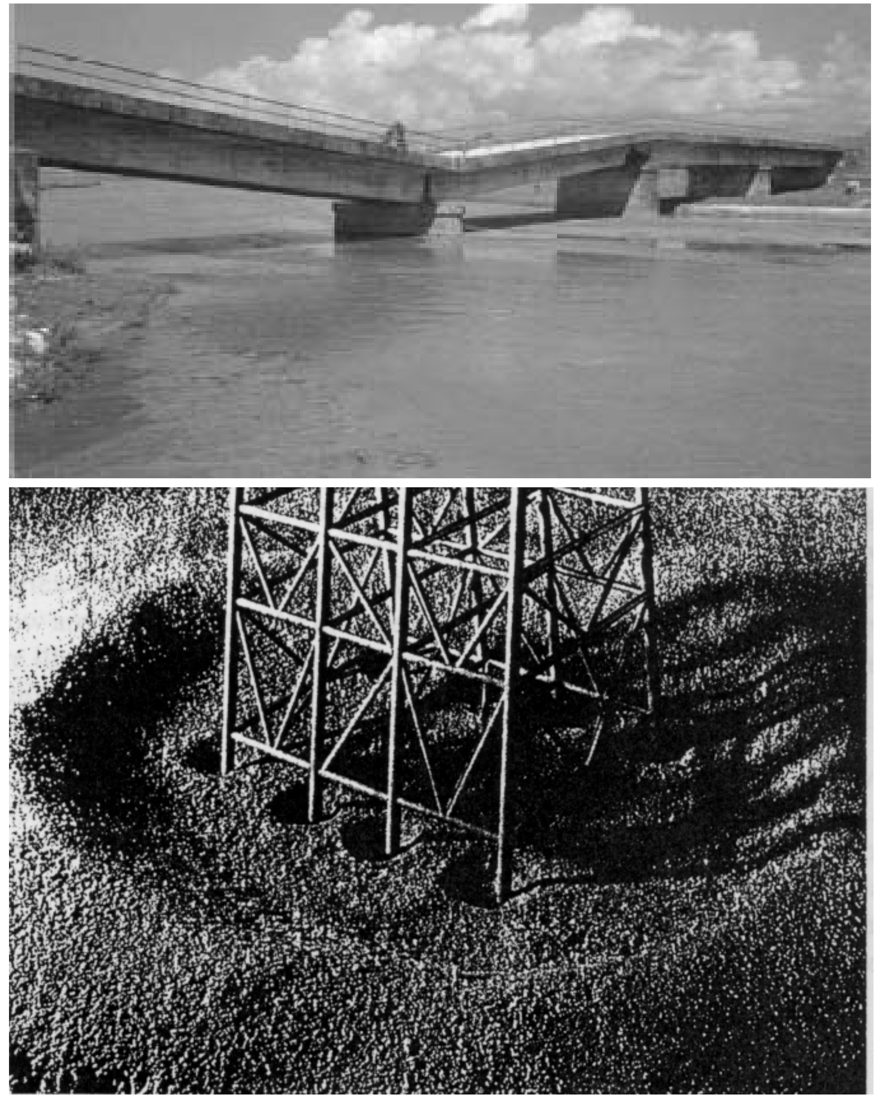
Motivation and topics

- Scour around offshore wind turbines may affect:
  - Structural integrity
  - Structural stability
  - Eigen frequency
  - Structural loads
  - Construction costs
- Scour risk around offshore wind turbines must be:
  - Assessed and
  - Accounted for

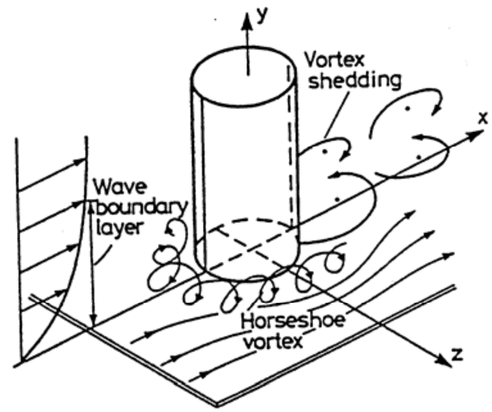
- Topics for presentation
  - Comparing methods for predicting scour to full scale measurements
  - Proposal for scour adaptive design approach

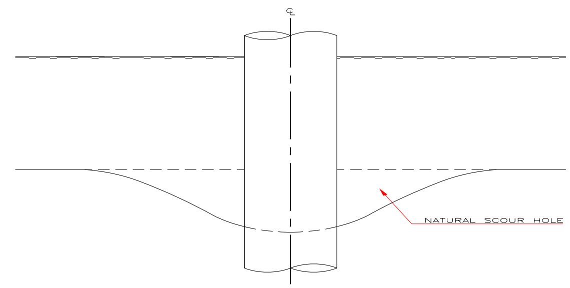


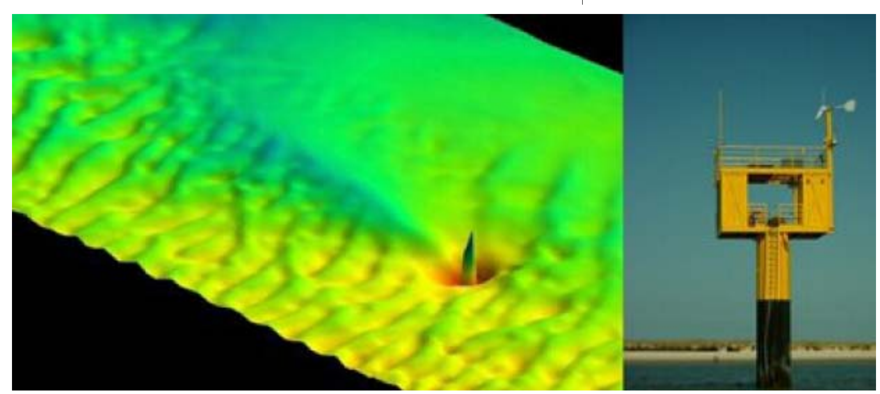
Example of global and local scour around structures

Local scour around a cylinder

- Flow around cylinder
  - Increased speed
  - Horseshoe vortex
  - Vortex shedding in wake
  - Increased bed shear by α
- Scour in non-cohesive bed occurs when $\alpha\tau_{cw} > \tau_{cr}$
  - Clear water:
    $\tau_{cw} < \tau_{cr}$ outside vicinity
    $\alpha\tau_{cw} > \tau_{cr}$ in vicinity
  - Live bed:
    $\tau_{cw} > \tau_{cr}$ in everywhere
- Scour in current only
  - $S/D = f(h, d, U_c)$
- Scour in waves only
  - $S/D = f(h, d, KC)$, $KC>6$
- Scour in current and waves
  - $S/D = f(h, d, U_c, KC)$



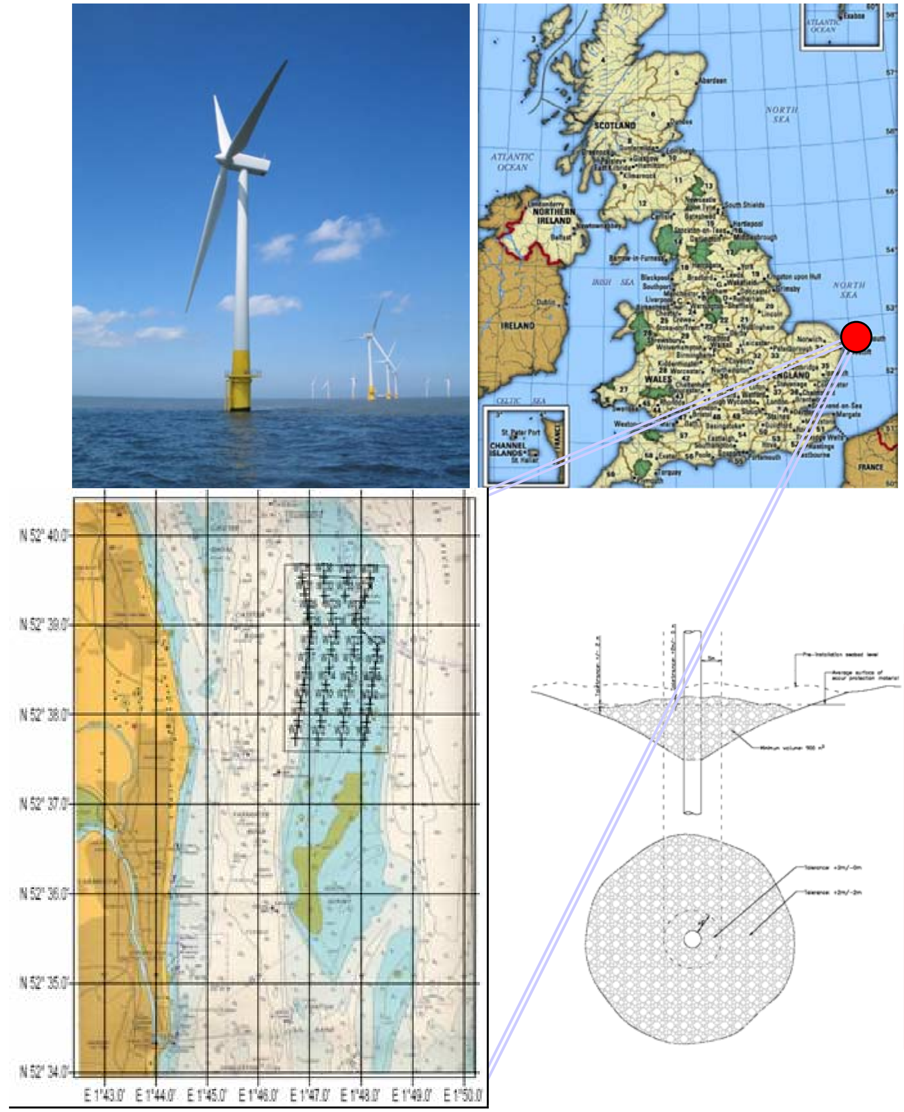




Scour around a cylinder in waves and current

Scroby Sands Offshore Windfarm

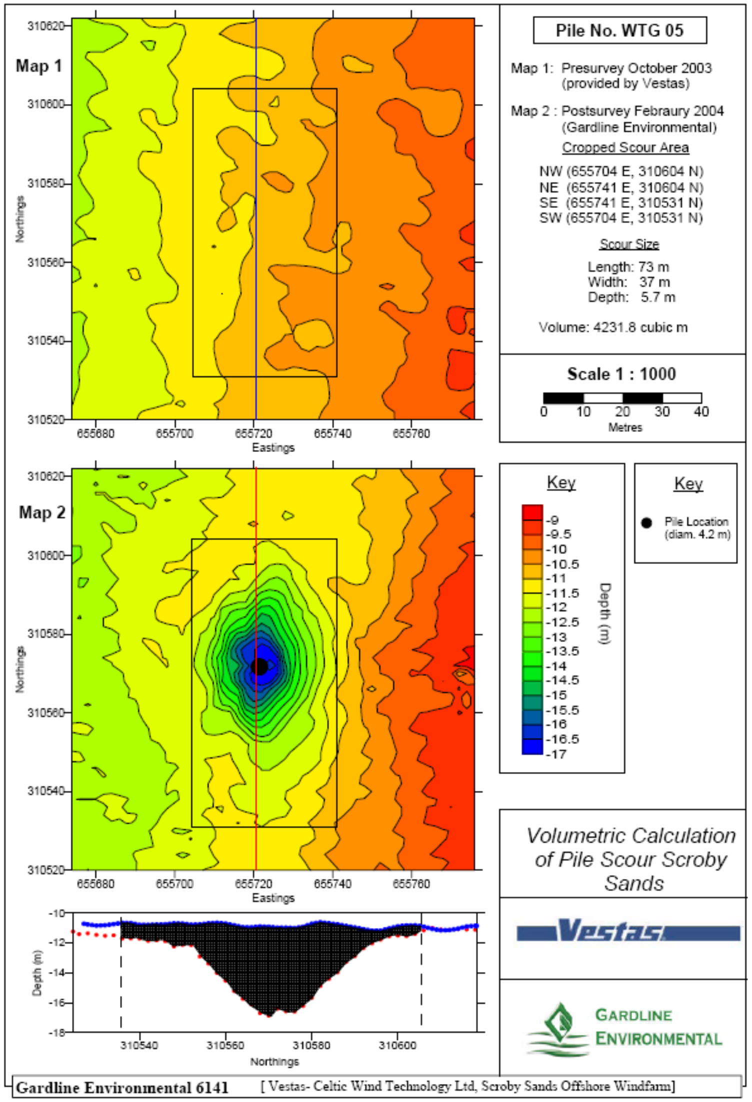
- Sand bank 3 km off shore
- Completed 2004
- 30 2MW Vestas V80 WTG
- Monopile foundation
  (D = 4.2 m)
- Water depth
  ($1 < h < 11$ m LAT)
- Tidal current
  ($U_{max,tide}$=1.3 m/s)
- Wave induced current
  ($U_{max,wave}$=1.2 m/s)
- Depth limited wave climate
  (H_{max}= 5.7 m, T_{ass}= 8.1 s)
- Fine non-cohesive seabed
  ($0.2 < d_{50} < 0.4$ mm)
- Post installed dynamic scour protection: 60 – 240 mm



Location of the Scroby Sands Offshore Wind Farm

Scroby Sands Offshore Windfarm

- Surveys
  - 10/2003 Pre survey
  - *Mono piles installed*
  - 02/2004 Post survey
  - *Scour protection installed*
  - 6/2004 Out survey
- Scour assessment by Gardline Environmental based on interim survey:
  - Maximum scour depth
  - Extent of scour pit
  - Volume of eroded material



Scour assessment for prior to Scroby Sands

Tools for predicting equilibrium scour depth in current and waves

- Sumer & Fredsøe
  - Current only
  - Waves only
  - Current and waves
- S/D = 1.3 adopted by DNV for design of offshore wind turbine foundations

$$\frac{S}{D} = 1.3 \qquad and \qquad \sigma_{S/D} = 0.7$$

$$\frac{S}{D} = 1.3\left(1 - e^{-0.03(KC-6)}\right) \qquad for \qquad KC > 6$$

$$\frac{S}{D} = \frac{S_C}{D}\left(1 - e^{-A(KC-B)}\right) \qquad for \qquad KC \geq B$$

$$A = 0.03 + \frac{3}{4}U_{cw}^{2.6}$$

$$B = e^{-4.7U_{cw}}$$

$\alpha = 1.3$

- CSU/HEC-18
  - Current only

$$\frac{S}{D} = 2.0K_1K_2K_3K_4\left(\frac{h}{D}\right)^{0.35} Fr^{0.43}$$

$$\frac{S}{D} = 2.2\left(\frac{h}{D}\right)^{0.35} Fr^{0.43}$$

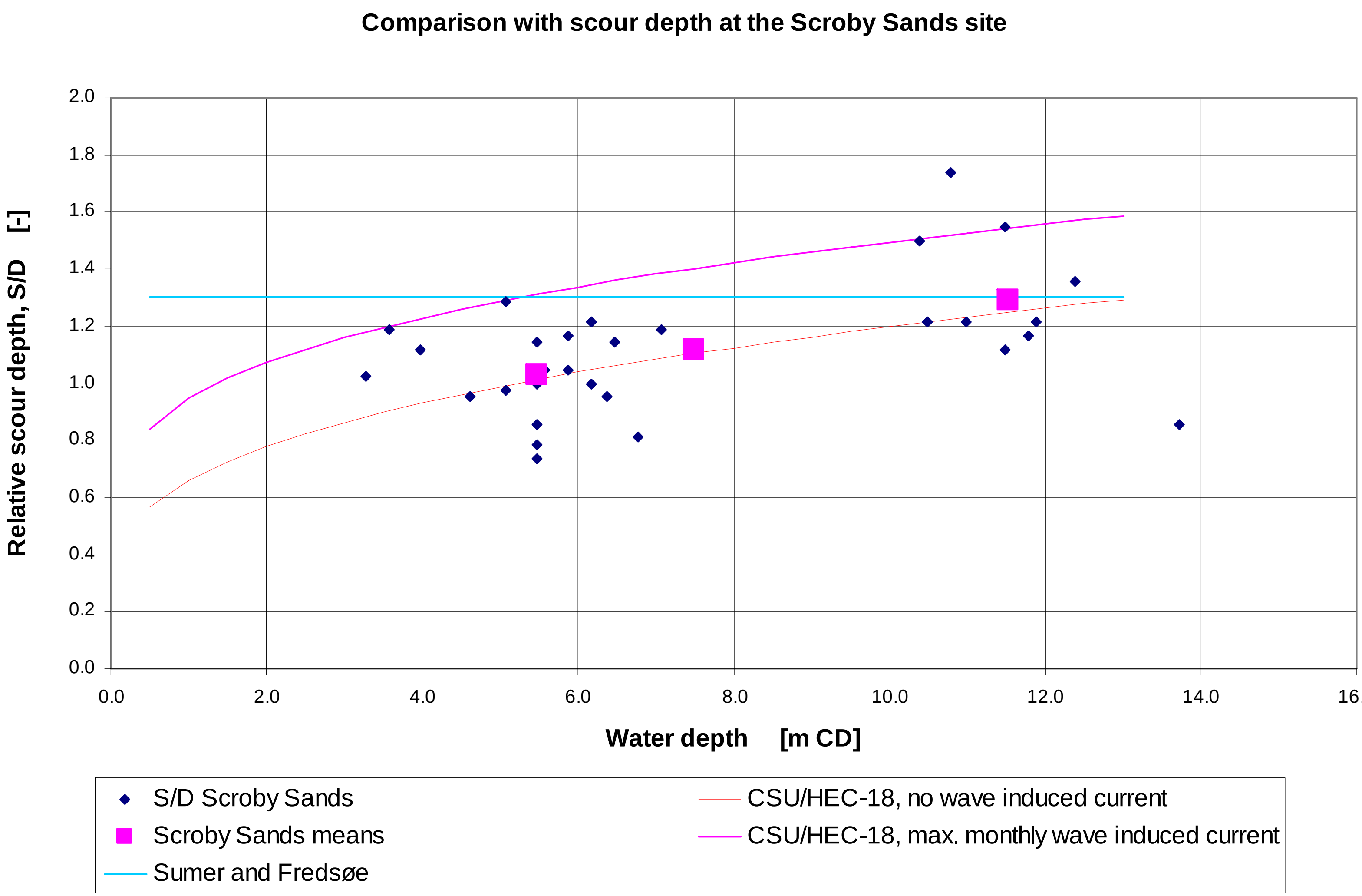
- Breusers et al.
  - Current only

$$\frac{S}{D} = \alpha \tanh\left(\frac{h}{D}\right)$$

- OptiPile
  - Current only
  - Uses Sumer & Fredsøe for waves/combined waves and current

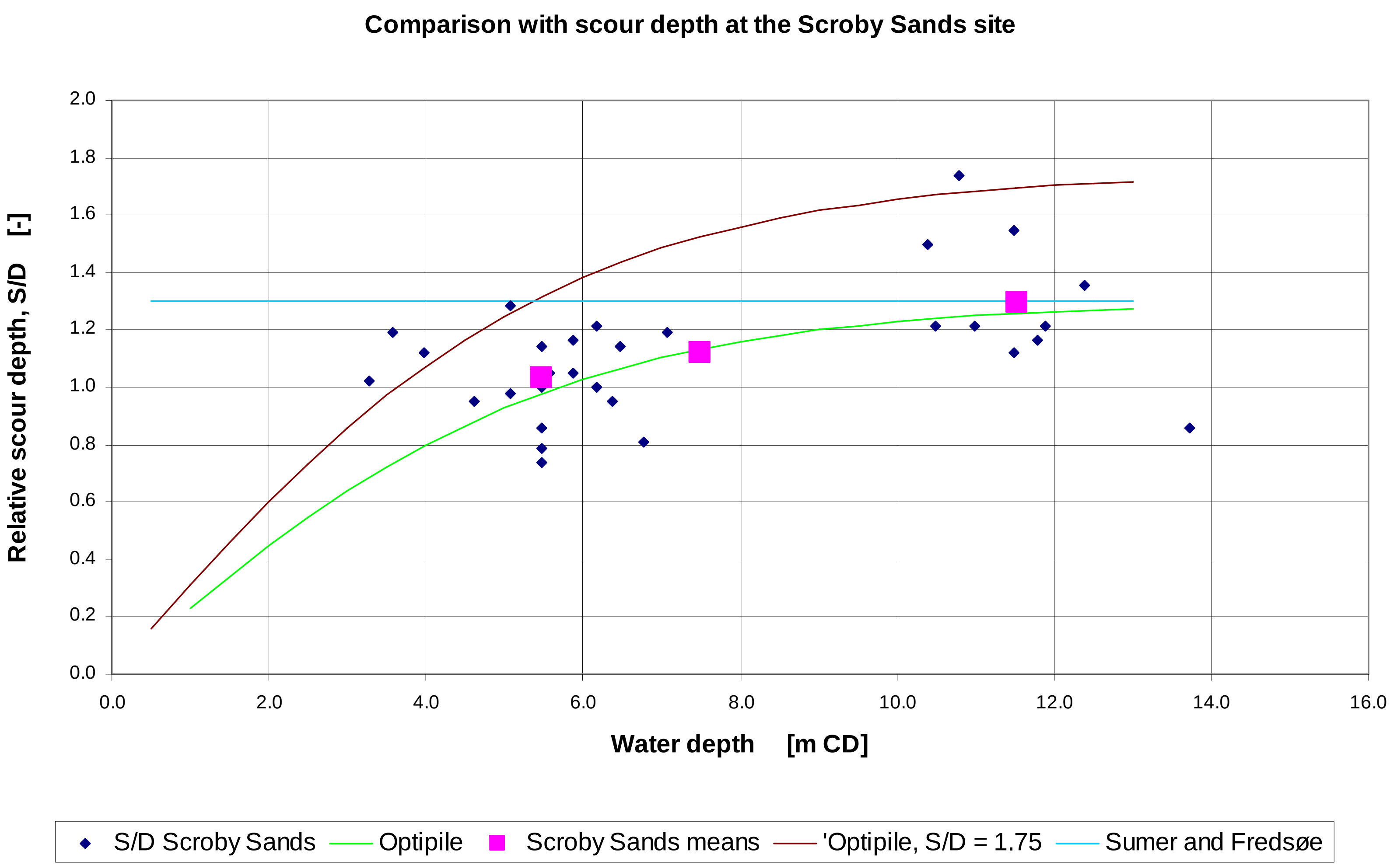
$$\frac{S}{D} = \alpha K_1 \tanh\left(K_2 \frac{h}{D}\right)$$

Evaluating CSU / HEC-18



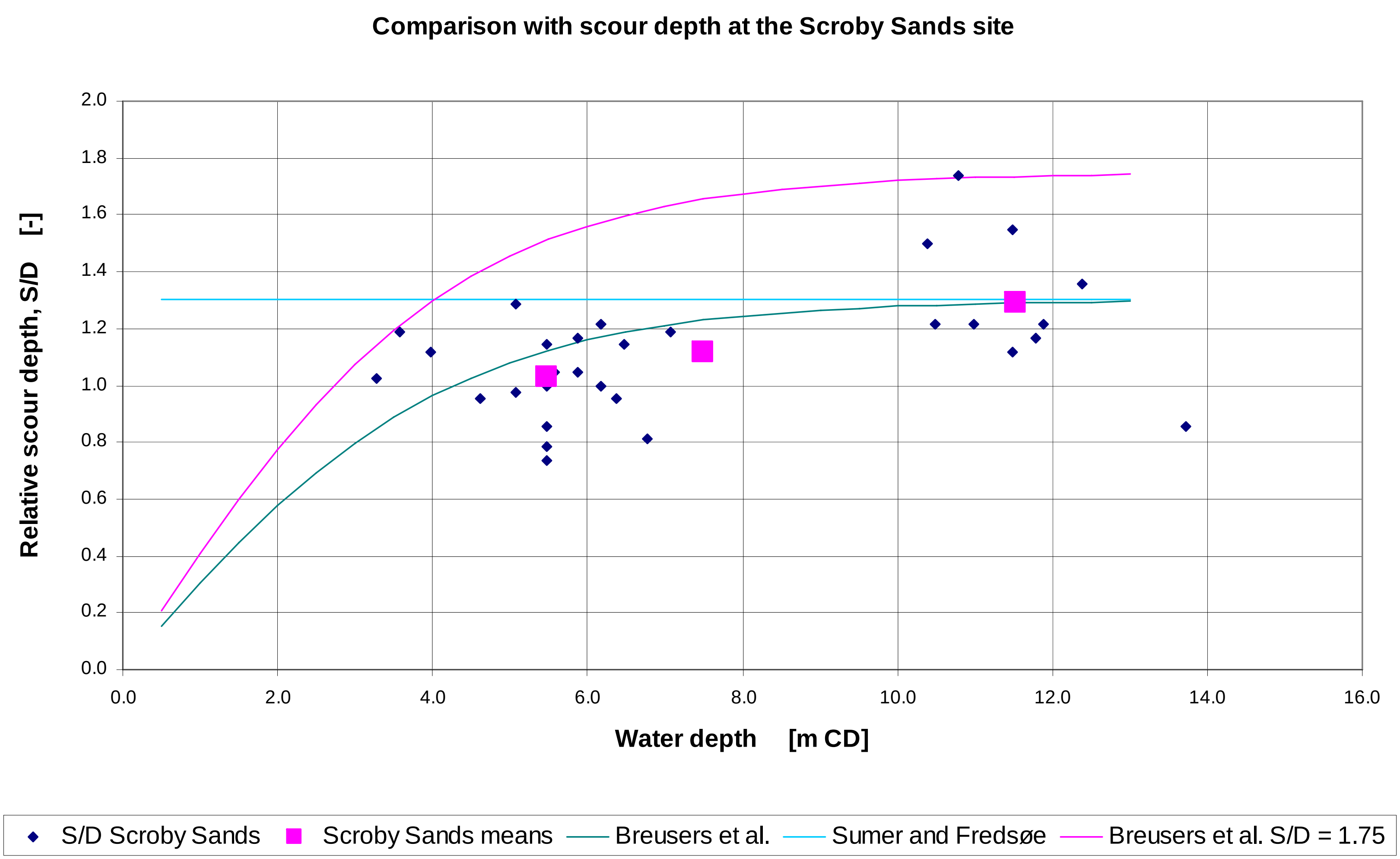
Scour prediction using the CSU/HEC-18 model on the Scroby Sands project site

Evaluating OptiPile



Scour prediction using the OptiPile tool on the Scroby Sands project site

Evaluating Breusers et al.



Scour prediction using the model of Breusers et al. on the Scroby Sands project site

Scour adaptive design approach

- Current practice in FLS and ULS load verifications
  - Global scour +
  - Most likely local extreme scour, i.e. a current only situation (DNV: S/D = 1.3)
- High impact on foundation costs, hence often more feasible to install a scour protection

- Maybe too conservative:
  - Extreme local scour in current only
  - Reduced local scour in waves/current & waves
  - ULS and FLS Hydrodynamic loads governed by waves

Key to table below:		
	(green)	Scour depth < 0.1P
	(orange)	Scour to depth < P
	(pink)	Scour to depth > P

Table of relative scour depths S/P

				Uc [m/s]										
Hs [m]	Tp [s]	Um [m/s]	KC	0.10	0.30	0.60	0.90	1.10	1.30	1.50	1.70	1.90	2.10	p(Um)
0.00	1.00	0.00	0.00	0.00	0.50	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	0.23
0.50	3.10	0.35	0.03	0.00	0.57	1.06	1.10	1.11	1.12	1.12	1.12	1.13	1.13	0.40
1.00	4.40	0.71	0.21	0.04	0.29	0.66	0.86	0.93	0.98	1.02	1.04	1.06	1.07	0.24
1.50	5.40	1.06	0.49	0.02	0.14	0.41	0.64	0.74	0.83	0.88	0.93	0.96	0.99	0.09
2.00	6.20	1.41	0.85	0.01	0.09	0.29	0.49	0.60	0.69	0.77	0.83	0.87	0.91	0.03
2.50	6.80	1.77	1.24	0.01	0.06	0.21	0.39	0.50	0.59	0.67	0.74	0.79	0.84	0.00
3.00	7.40	2.12	1.69	0.01	0.05	0.17	0.32	0.42	0.51	0.59	0.66	0.72	0.77	0.00
3.50	7.70	2.47	2.09	0.00	0.04	0.14	0.27	0.36	0.44	0.52	0.59	0.66	0.71	0.00
4.00	7.90	2.83	2.48	0.00	0.03	0.11	0.23	0.31	0.39	0.47	0.54	0.60	0.66	0.00
4.50	8.00	3.18	2.84	0.00	0.03	0.10	0.20	0.27	0.35	0.42	0.49	0.55	0.61	0.00
5.70	8.10	4.03	3.66	0.00	0.02	0.07	0.15	0.21	0.27	0.33	0.39	0.45	0.51	0.00
			p(Uc)	0.12	0.40	0.38	0.10	0.01	0.00	0.00	0.00	0.00	0.00	1.00

Desk Study: Relative scour depths in current and waves for Scroby Sands average test case

Scour adaptive design approach

Development of scour

- Dimensionless time scale
- Empirical expressions:
  - Current only
  - Waves only

$$S(t) = S(1 - e^{-\frac{t}{T}}) \qquad T^* = \frac{(g(s-1)d^3)^{1/2}}{D^2} T$$

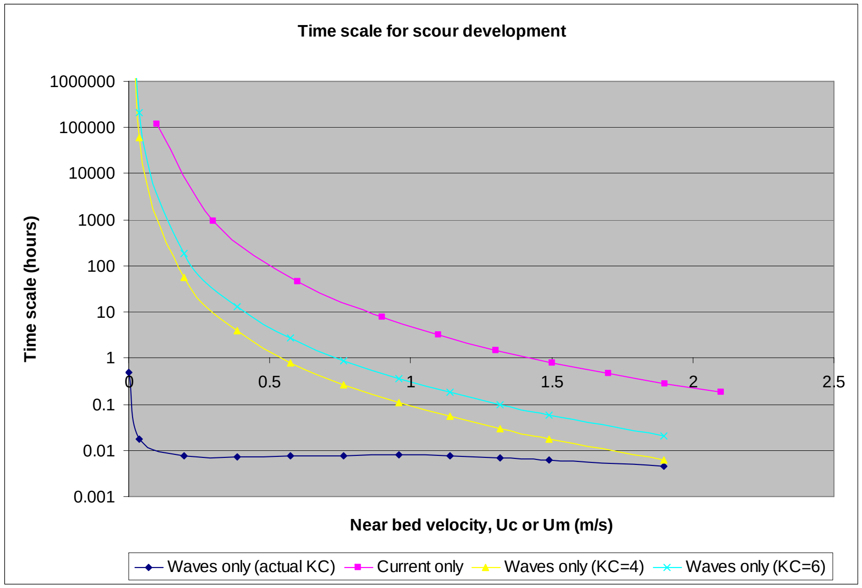
$$T_c^* = \frac{1}{2000} \frac{h}{D} \theta^{-2.2}$$

$$T_w^* = 10^{-6} \left(\frac{KC}{\theta} \right)^3$$

Desk study

- Time scale calculated for
  - current only
  - waves only (*KC*=real, 4, 6)
- $T_{waves} << T_{current}$
- $=> T_{current+waves} \cong T_{waves}$
- Statistics for scour depth ≅ joint wave-current statistics

$$p(S/D \mid U_m, U_c) = p(U_m) p(U_c)$$



Desk study: Time scale for scour development

Scour adaptive design approach

Design applications

1. Unconditional mean relative scour depth
2. Conditional mean relative scour depth
3. Weighted unconditional mean relative scour depth

$$\overline{S/D} = \sum_{Uc=0}^{\infty}\sum_{U_m=0}^{\infty} p(S/D \mid U_m, U_c) \cdot S/D(U_m, U_c)$$

$$\overline{S/D}(U_m) = \sum_{Uc=0}^{\infty} \frac{p(S/D \mid U_m, U_c) \cdot S/D(U_m, U_c)}{p(U_m)}$$

$$\overline{S/D}_{fatigue} = \left(\sqrt[m \cdot 3/2]{\sum_{Uc=0}^{\infty}\sum_{U_m=0}^{\infty} p(S/D \mid U_m, U_c) \cdot \left(L_0 + S(U_m, U_c)\right)^{m \cdot 3/2}} - L_0 \right) / D$$

Description	*S/D*	*S*
Adaptive design scour depth to be used for fatigue loads calculations [3]	0.63	2.67 m
Adaptive design scour depth to be used for extreme wave loads calculations [2]	0.05	0.21 m
Adaptive design scour depth to be used other extreme loads calculations [1]	0.61	2.56 m
OptiPile maximum scour depth	1.13	4.76 m
Current practise design scour depth for fatigue and extreme load calculations	1.3	5.46 m

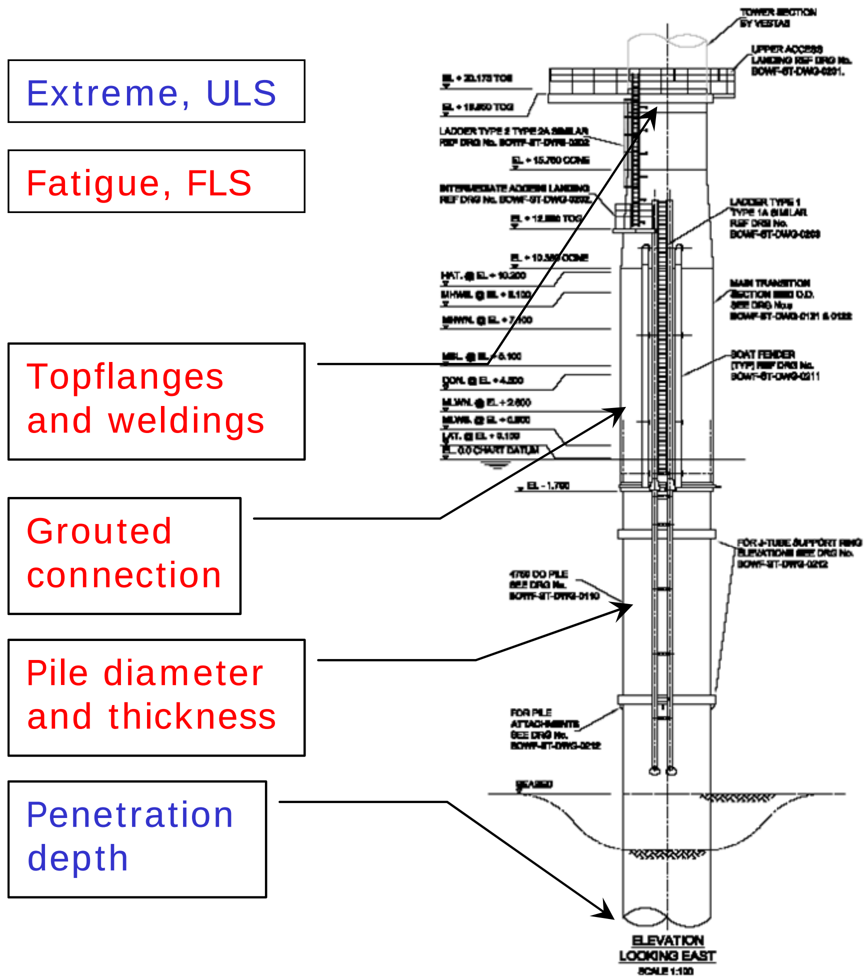
Adaptive design scour depths compared to current practice and OptiPile calculated maximum scour depth

Scour adaptive design approach

Effect of adaptive design

- Extreme loads
  - Govern penetration depth
  - Penetration depth reduced by app. 5m
  - Saving maybe 30 ton/pile
- Fatigue loads
  - Govern pile dimensions
  - Damage ~ $(L_0 + S)^{3/2m}$
  - $L_0 + S$ reduced by 3 %
  - Equivalent fatigue load reduced by 22 %
  - Saving maybe 40 ton/pile
- Significant effects

- **Request further research**



Governing design limit states for foundation parts