Scour around Vertical Pile Foundations for Offshore Wind Turbines due to Long-Crested and Short-Crested Nonlinear Random Waves plus a Current

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Overview of Presentation

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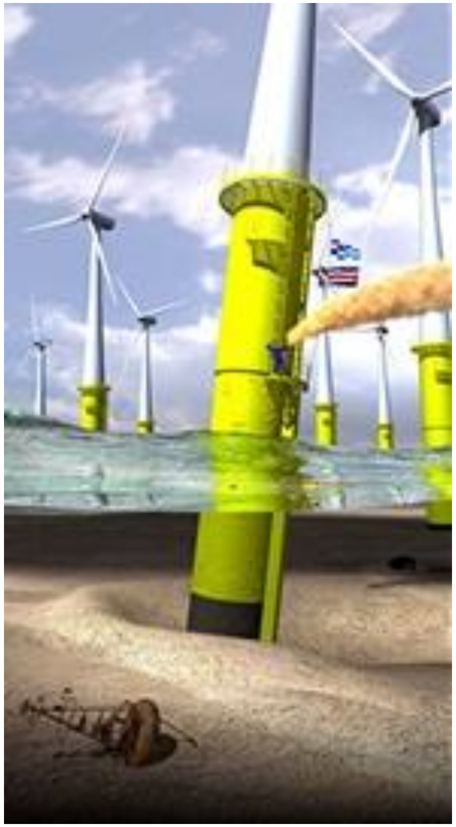
Introduction and Motivations

- Offshore wind energy appears to be promising for alternative energy.
- The design of offshore wind turbine foundations is a challenge for the engineering community.
- A scour hole gives considerable effect on the dynamic behaviour and the stability of the wind turbine.



Wind turbine foundation

Objectives

- To provide a practical approach by which the scour depth around a vertical pile exposed to long-crested (2D) and short-crested (3D) nonlinear random waves plus a current can be derived.

This is achieved by using

- the scour depth formula presented by Sumer and Fredsøe (2002)

combined with

- the wave crest height distribution based on second order theory by Forristall (2000)

Scour in Regular Waves plus a Current

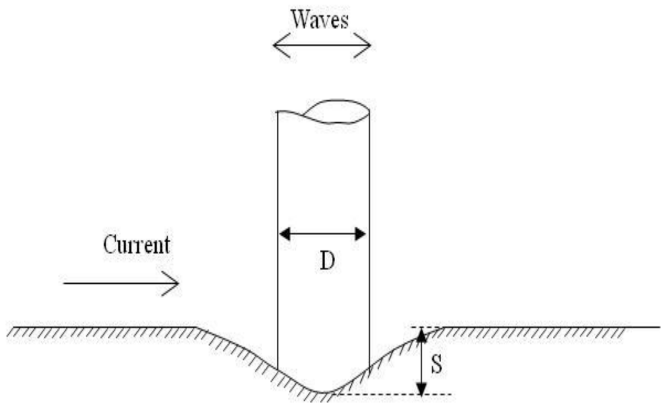
Scour depth formula (Sumer and Fredsøe, 2002) for random waves plus current

$$\frac{S}{D} = C(1-\exp[-q(KC_{rms}-r)]) \quad \text{for} \quad KC_{rms} \geq r$$

$$q = 0.03 + 0.75U_{cwrms}^{2.6} \qquad r = 6\exp\left(-4.7U_{cwrms}\right) \qquad U_{cwrms} = U_c / \left(U_c + U_{rms}\right)$$

$$KC_{rms} = U_{rms}T_p / D$$

T_p : the spectral peak period
U_{rms} : RMS value of the undisturbed near-bed orbital velocity amplitude.
U_c : the current velocity



Assuming that the equations above are also valid for regular waves if KC_{rms} and U_{rms} are replaced by KC and U.

Scour in Non-linear Random Waves

- For Stokes second-order waves, the nonlinearity is primarily caused by the larger velocity under the wave crest (crest velocity).

Assumptions

- The wave motion is a stationary narrow-band random process.
- The scour depth formula for regular waves is valid for irregular waves.
- The sea-state has lasted long enough to develop the equilibrium scour depth.
- The highest wave crests are responsible for the scour process.

Stochastic Method

The expected (mean) scour characteristics for the (1/n)th highest wave crests:

$$E\left[Y\left(w_c\right)\middle| w_c > w_{c1/n}\right] = n\int_0^\infty Y\left(w_c\right) p\left(w_c\right) H\left(w_c - w_{c1/n}\right) dw_c$$

Y represents the scour variable, S and $p(w_c)$ is the probability density function (*pdf*) of the non-dimensional non-linear crest height (w_c).

$$Y = 1 - \exp[-q(KC_{rms} w_c - r)] \;;\; w_c \geq w_{c1} = \frac{r}{KC_{rms}}$$

Forristall (2000) Parametric Crest Height Distribution

$$p(w_c) = dP(w_c)/dw_c \quad ; \quad P(w_c) = \frac{\exp\left[-\left(\frac{w_{c1}}{\sqrt{8}\alpha}\right)^\beta\right] - \exp\left[-\left(\frac{w_c}{\sqrt{8}\alpha}\right)^\beta\right]}{\exp\left[-\left(\frac{w_{c1}}{\sqrt{8}\alpha}\right)^\beta\right]} \;;\; w_c \geq w_{c1}$$

$$w_{c1/n} = \sqrt{8}\alpha\left[\ell n\, n + \left(\frac{w_{c1}}{\sqrt{8}\alpha}\right)^\beta\right]^{1/\beta}$$

Example Calculation

Flow Conditions

Significant wave height, H_s = 3m

Mean wave period, T_p = 7.9s, corresponding to ω_p = 0.795rad/s

Water depth, h = 10 m

Current speed, U_c = 0.2m/s

Median grain diameter (coarse sand according to Soulsby, 1997, Fig. 4), d_{50} = 1mm

s = 2.65 (as for quartz sand)

Pile diameter, D = 1.0 m

$$U_{cwrms} = U_c / (U_c + U_{rms}) = 0.196$$

Scour depth (waves alone) (m)	
S_{linear}	0.250
S_{2D}	0.303
S_{3D}	0.322
Scour depth (waves plus current) (m)	
S_{linear}	0.335
S_{2D}	0.377
S_{3D}	0.393

- The effect of the current is to increase the scour depth.
- For waves alone and for waves plus current the effect of nonlinearity is to increase the scour depth
- For the waves plus current, the nonlinear to linear ratios for 2D and 3D waves are 1.13 and 1.17, respectively.
- Short-crested waves (3D) give slightly larger values than long-crested waves (2D) due to the smaller wave setdown effects for 3D than for 2D waves in finite water depth.

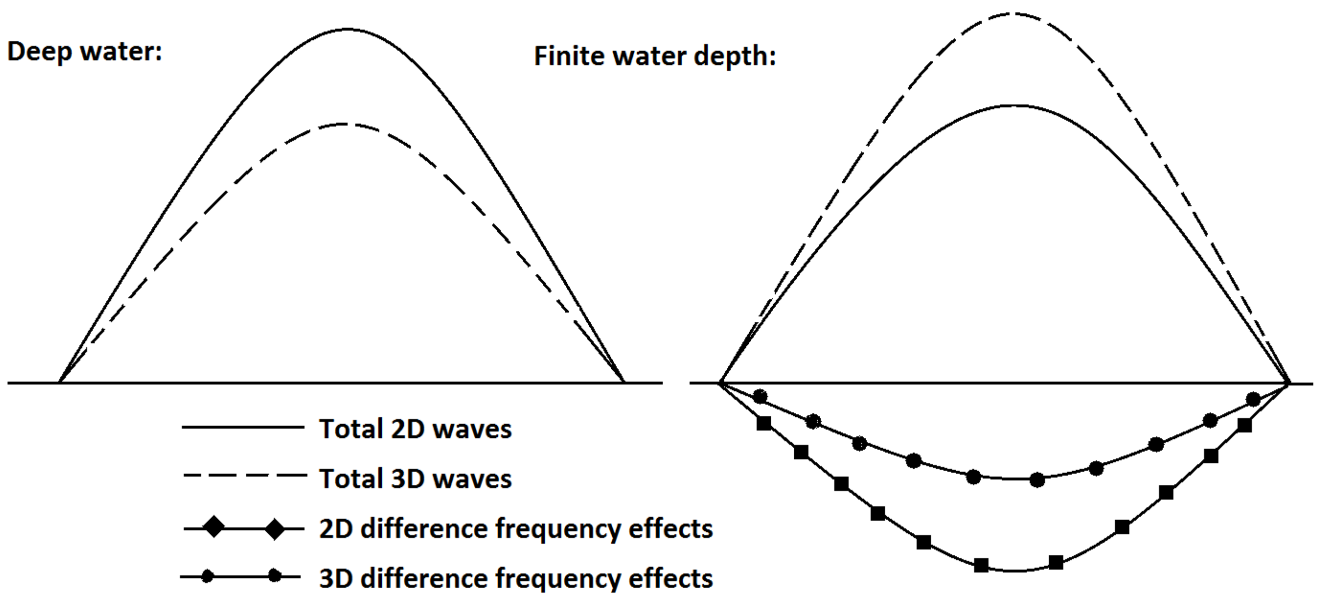
Conclusions

- A practical stochastic approach for estimating the maximum scour depth around circular vertical piles due to long-crested (2D) and short-crested (3D) nonlinear random waves plus a current has been given.

- An example of calculation demonstrates that the effects of current and wave nonlinearity are important.

- The scour depth is only slightly larger beneath 3D nonlinear waves than beneath 2D nonlinear waves due to the smaller wave setdown effects for 3D than for 2D waves in finite water depth.

- The present approach should be useful as a first approximation. Comparisons with data are required before a conclusion regarding the validity of this approach can be given.



Sketch of difference-frequency effects and total height of wave crest

Forristall (2000) Parametric Crest Height Distribution

A two-parameter Weibull distribution with the cumulative distribution function (*cdf*) of the form

$$P(w_c) = 1 - \exp\left[-\left(\frac{w_c}{\sqrt{8\alpha}} \right)^{\beta} \right] \; ; \; w_c \geq 0$$

The Weibull parameters α and β were estimated from the fit to the simulated data.

2D Waves

$$\alpha_{2D} = 0.3536 + 0.2892 S_1 + 0.1060 U_R$$
$$\beta_{2D} = 2 - 2.1597 S_1 + 0.0968 U_R^2$$

$$S_1 = \frac{2\pi}{g} \frac{H_s}{T_1^2}$$

3D Waves

$$\alpha_{3D} = 0.3536 + 0.2568 S_1 + 0.0800 U_R$$
$$\beta_{3D} = 2 - 1.7912 S_1 - 0.5302 U_R + 0.284 U_R^2$$

$$U_R = \frac{H_s}{k_1^2 h^3}$$

Shields Parameter

$$\theta_m = \frac{\tau_m}{\rho g (s-1) d_{50}} \qquad \theta_{rms} = \frac{\tau_{rms}}{\rho g \left(s-1\right) d_{50}}$$

τ_m : the maximum bottom shear stress under the wave crest for individual random waves.

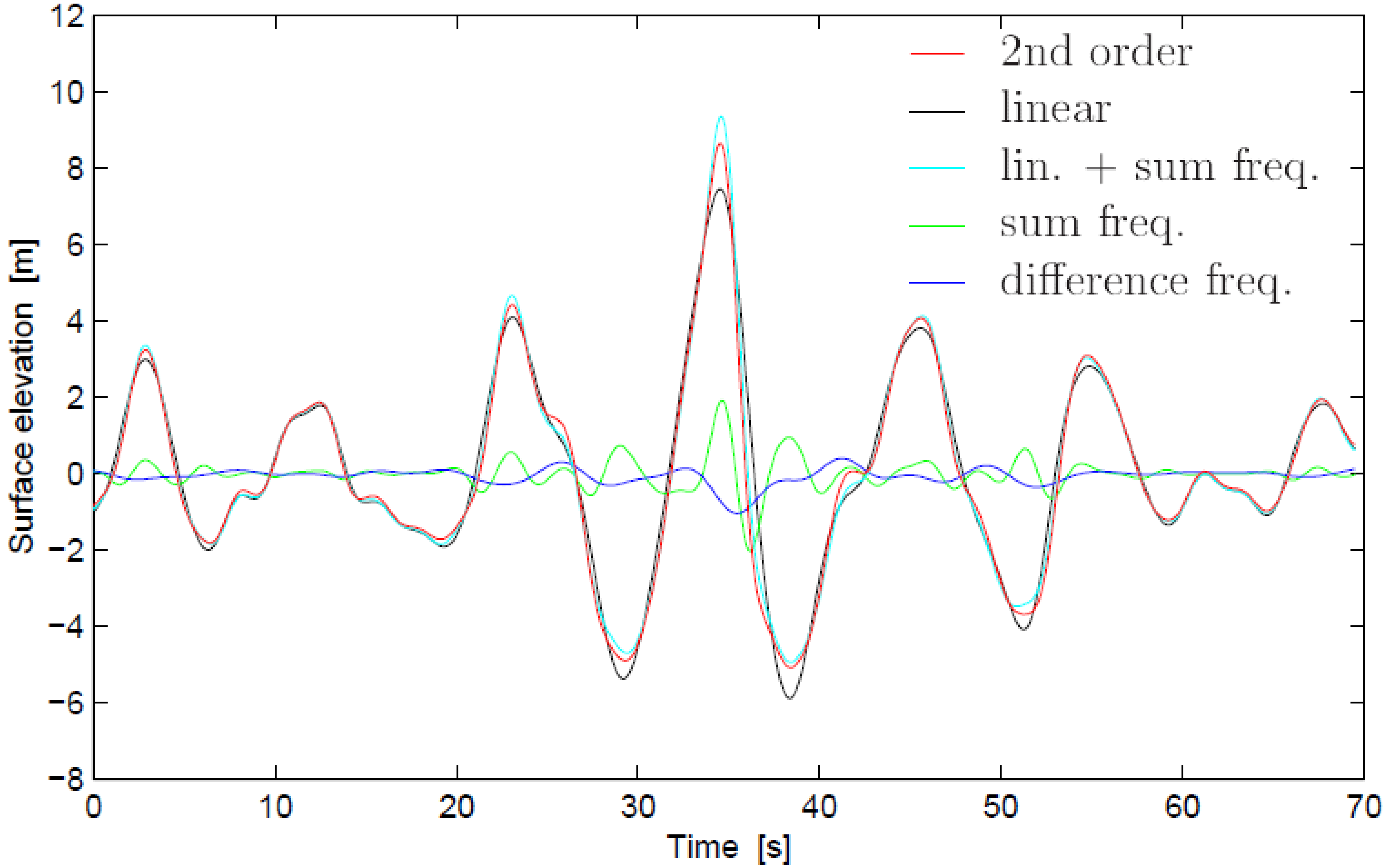
τ_{rms} : the rms value of bottom shear stress for individual random waves.

$$\theta_c = \theta_m / \theta_{rms} \quad \longrightarrow \quad \theta_c = w_c^{2-d}$$

See Myrhaug & Holmedal (2011)

Stochastic Method

$$E\left[\theta_c\left(w_c\right) | w_c > w_{c1/n}\right] = n\left(\sqrt{8}\alpha\right)^{2-d} \Gamma\left(1 + \frac{2-d}{\beta}, \ln n\right)$$



Surface elevation [m]
Time [s]
12
10
8
6
4
2
0
−2
−4
−6
−8
0
10
20
30
40
50
60
70
2nd order
linear
lin. + sum freq.
sum freq.
difference freq.

a_{rms} (m)	1.06
k_p (rad/m)	0.09
S_1	0.031
U_R	0.370
α_{2D}, β_{2D}	0.4018, 1.9468
α_{3D}, β_{3D}	0.3911, 1.7874
A_{rms}	1.033
U_{rms}	0.822
U_{cwrms}	0.196
$U_{rms}/(U_{rms}+U_c)$	0.804
A_{rms}/z_0	12399
c,d	0.112, 0.25
KC_{rms}	6.5
θ_{rms}	0.22

$\theta_{mnonlin,2D}$	0.807
$\theta_{mnonlin,3D}$	0.850