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# Tsunami-induced scour around monopile foundations

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ABSTRACT

A fully-coupled (hydrodynamic and morphologic) numerical model is presented, and utilized for the simulation of tsunami-induced scour around a monopile structure, representative of those commonly utilized as offshore wind turbine foundations at moderate depths i.e. for depths less than 30 m. The model is based on solutions to Reynolds-averaged Navier-Stokes equations, coupled with two-equation $k - \omega$ turbulence closure, with additional bed and suspended load descriptions forming the basis for sea bed morphology. The model is first validated for flow, bed shear stresses, and scour within a steady current, where a generally excellent match with experimentally-based results is found. A methodology for maintaining and assessing hydrodynamic and morphologic similarity between field and (laboratory) model-scale tsunami events is then presented, combining diameter-based Froude number similarity with that based on the dimensionless wave boundary layer thickness-to-monopile diameter ratio. This methodology is utilized directly in the selection of governing tsunami wave parameters (i.e. velocity magnitude and period) used for subsequent simulation within the numerical model, with the tsunami-induced flow modelled as a long sinusoidally-varying current. The flow, sediment transport, and scour processes beneath up to ten tsunami waves are simulated in succession. These illustrate a generally accumulative scour process i.e. a relatively rapid scour induced by the leading wave, with an additional build-up of the scour depth during additional trailing waves. The resulting scour seems to approach an equilibrium value after sufficient time duration, which corresponds reasonably to that predicted by existing steady-current scour depth expressions, after accounting for the finite boundary layer thickness induced by the unsteady tsunami wave, i.e. it is important to incorporate both current-like, as well as wave-like aspects of the long tsunami event. Based on the simulated results, a simple methodology for predicting the tsunami-induced scour depth in engineering practice is finally developed. This methodology is demonstrated to match the predicted scour development for all of the simulated flows considered, ranging from the series of transient tsunami waves to the steady-current limit.

## 1. Introduction

Tsunamis are long waves, typically having periods the order of minutes to hours, that are generated by sudden motions of the sea bed e.g. due to undersea earthquakes or landslides. When such waves approach and/or reach the shoreline, they are potentially catastrophic, as has been well documented e.g. in the recent tsunami event that occurred in the Indian Ocean (2004), as well as in the Tohoku tsunami off the coast of Japan (2011).

While the run-up, inundation, and destructive potential of tsunami events has received considerable attention in the literature, the associated interaction with the sea bed i.e. boundary layer dynamics, induced sediment transport, and resultant sea bed morphology, have received relatively little specific attention. Such issues and processes are important, however, both in assessing potential larger scale deposition and erosion in affected coastal regions, as well as in understanding smaller scale erosion, such as tsunami-induced local scour around coastal and offshore structures (e.g. monopiles, piers, pipelines, and breakwaters), which can potentially contribute to their failure. (Williams and Fuhrman, 2016) simulated a series of tsunami-scale boundary layers, emphasizing that they may be both current-like due to their long durations, but also wave-like, in the sense that they are unsteady and that the boundary layer may not span the entire water depth. This assertion is likewise consistent with field measurements of (Lacy et al., 2012). Studies investigating tsunami-induced scouring around coastal and offshore structures in any context are few, but include e.g. (Wilson et al., 2012), who studied

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sediment scour and deposition within harbors; (Chen et al., 2013), who studied tsunami-induced scour at coastal roadways; and (Bricker et al., 2012), who conducted a field study of scour depths measured on the landward side of seawalls and floodwalls, as well as beside a building foundation footing, from the 2011 Tohoku tsunami. Experimental investigations on the tsunami-induced scour specifically around monopiles are seemingly limited to that of (Tonkin et al., 2003), who studied the scour promoted by incident solitary waves around a cylinder on a sloping beach, where the cylinder was mounted near the shoreline and to (Nakamura et al., 2008) who studied scour around a square pile induced by solitary and long waves. The experiments by (Tonkin et al., 2003) were also simulated numerically using a nonlinear shallow water model by (Pan and Huang, 2012), with the intent of simulating tsunami-induced scour around bridge piers. At this point it is worth emphasizing that studying tsunamis as solitary waves does not allow for their effective period and wave amplitude to be determined independently, and as a result the solitary wave duration is likely too short to represent geophysical tsunami events (see e.g. the discussion of (Madsen et al., 2008)).

As seen from the above, most of the works considering the general topic of tsunami-induced scour have only recently been published i.e. in the past few years. Hence, a detailed understanding of the underlying processes, as well as general structure vulnerability, is presently lacking. The present study aims to further the understanding of tsunami-induced scour, by numerically investigating tsunami-induced flow and scour processes around a monopile structure, representative of those commonly utilized as offshore wind turbine foundations.

While the scour around monopiles due e.g. to waves and tidal currents has been extensively studied (see e.g. (Sumer and Fredsøe, 2002)), the potential scour around offshore wind turbine foundations induced by tsunami attack has not been previously studied, either experimentally or numerically. To ensure proper design, it is therefore important that a detailed understanding of the potential tsunami-induced scour around such structures be improved.

## 2. Hydrodynamic and turbulence model description

In this section the hydrodynamic model is presented. The flow is simulated by solving the incompressible Reynolds-averaged Navier-Stokes equations (RANS) and the continuity equation, coupled with a two-equation $k$-$\omega$ turbulence model for closure. The continuity equation and the RANS equations are, respectively, given in (1) and (2):

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left(2\nu S_{ji} + \frac{\tau_{ij}}{\rho}\right), \tag{2}$$

where $u_i$ are the mean components of the velocities, $x_i$ are the Cartesian coordinates, $p$ is the pressure, $t$ is the time, $S_{ij}$ is the mean strain rate tensor given by

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{3}$$

and $\tau_{ij}$ is the Reynolds stress tensor, which is expressed according to the Boussinesq approximation

$$\tau_{ij} = -\overline{u_i' u_j'} = 2\nu_T S_{ij} - \frac{2}{3}k\delta_{ij}. \tag{4}$$

Here the overbar signifies time (ensemble) averaging, $\nu_T$ is the eddy viscosity, $\delta_{ij}$ is the Kronecker delta, and

$$k = \frac{1}{2}\overline{u_i' u_i'} \tag{5}$$

is the turbulent kinetic energy density. In the above a prime superscript denotes turbulent (fluctuating) velocity components. To achieve closure, the $k$-$\omega$ turbulence model by (Wilcox, 2006, 2008) will be utilized. This model includes the following transport equations for the turbulent kinetic energy density $k$ and the specific dissipation rate $\omega$:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \tau_{ij}\frac{u_i}{x_j} - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma^* \frac{k}{\omega}\right)\frac{\partial k}{\partial x_j}\right], \tag{6}$$

$$\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k}\tau_{ij}\frac{\partial u_i}{\partial x_j} - \beta\omega^2 + \frac{\sigma_d}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma \frac{k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right]. \tag{7}$$

The closure coefficients are given as $\alpha = 0.52$, $\beta = 0.078$, $\beta^* = 0.09$, $\sigma = 0.5$, $\sigma^* = 0.6$, $\sigma_{do} = 0.125$, and

$$\sigma_d = H\left(\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}\right)\sigma_{do} \tag{8}$$

where $H(\cdot)$ is the Heaviside step function, which takes a value of unity if the argument is positive and zero otherwise.

In this model the eddy viscosity, which is present in the Reynolds stress tensor via the Boussinesq approximation, is given by

$$\nu_T = \frac{k}{\tilde{\omega}}, \tag{9}$$

with $\tilde{\omega}$ defined according to:

$$\tilde{\omega} = \max\left[\omega, C_{lim}\sqrt{\frac{2S_{ij}S_{ij}}{\beta^*}}\right], \tag{10}$$

where the second part of the expression is a stress limiting feature, with $C_{lim} = 7/8$.

The computational domain is discretized into finite volumes of quadrilateral blocks in varying shapes and dimensions. Fig. 1 shows an example computational mesh typical of that used for the forthcoming scour simulations, which consist of two steady current validation simulations and two tsunami scour simulations. The computational domain, unless stated otherwise, has the following dimensions: length, $l = 20D$, width, $w = 15D$, and height, $h = 2D$, in which $D$ is the monopile diameter. The total number of cells comprising the computational domains utilized is 170,496 with the near-bed cells having a height $O(d)$, in which $d$ is the grain size. The monopile is located at the center of the domain $(x, y) = (0, 0)$. It is emphasized that considerable effort has been put into optimizing the computational mesh for convergence while at the same time keeping the computational time affordable. The length of $20D$ for the tsunami simulations is justifiable as is it sufficient to simulate steady current scour, which can be viewed as the infinite period limit for waves, see the forthcoming validation in Section 5.

### 2.1. Boundary conditions

The boundary conditions for the hydrodynamic model are as follows: The friction wall boundaries, that is the monopile and the seabed, will have a no-slip condition imposed such that velocities are zero. The top boundary will be modelled as a frictionless lid meaning that vertical velocities are set to zero, and horizontal velocities and scalar hydrodynamic quantities have zero vertical gradient. This means that the top boundary does not represent the free surface of tsunami waves and the simulations are performed as single-phase simulations. As described in (Roulund et al., 2005) this is reasonable provided that the depth based Froude number $Fr_h$ is sufficiently small. In the simulated tsunami cases $Fr_h = U_m/\sqrt{gh} \leq 0.2$, where $U_m$ is the velocity magnitude beneath the tsunami waves. In the two steady current validation cases to be shown later $Fr = U/\sqrt{gh} = O(0.4)$ which is slightly larger, but not radically different, than O(0.2) where (Roulund et al., 2005) showed that there