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Numerical simulation of wave-induced scour and backfilling processes beneath submarine pipelines

David R. Fuhrman [a,*], Cüneyt Baykal [a], B. Mutlu Sumer [a], Niels G. Jacobsen [b], Jørgen Fredsøe [a]

[a] Technical University of Denmark, Department of Mechanical Engineering, DK-2800 Kgs. Lyngby, Denmark
[b] Deltares, Department of Coastal Structures and Waves, Rotterdamseweg 185, 2629 HD Delft, The Netherlands

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ABSTRACT

A fully-coupled hydrodynamic/morphodynamic numerical model is presented and utilized for the simulation of wave-induced scour and backfilling processes beneath submarine pipelines. The model is based on solutions to Reynolds-averaged Navier–Stokes equations, coupled with $k-\omega$ turbulence closure, with additional bed and suspended load descriptions forming the basis for sea bed morphology. The morphological evolution is updated continuously, rather than being based *e.g.* on period- or other time-averaging techniques. Simulations involving wave-induced scour over the range of Keulegan–Carpenter number $5.6 \leq KC \leq 30$ demonstrate reasonable match with previous experiments, both in terms of the equilibrium scour depth as well as the scour time scale. Wave-induced backfilling processes are additionally studied by subjecting initial conditions taken from scour simulations with larger KC to new wave climates characterized by lower KC values. The simulations considered demonstrate the ability of the model to predict backfilling toward expected equilibrium scour depths based on the new wave climate, in line with experimental expectations. The simulated backfilling process is characterized by two stages: (1) An initial re-distribution phase involving re-organization of sediments in the immediate vicinity of the pipeline, potentially followed by (2) a more lengthy backfilling evolution toward equilibrium scour depth. The simulated backfilling time scales are of the same order of magnitude as in experiments, though the multi-stage process complicates a more systematic characterization. The simulated sequences of scour and backfilling achieved within the present work are estimated to represent temporal durations of up to approximately 12 h at full practical scales.

1. Introduction

Submarine pipelines are commonly used to transport water, waste water, oil, and other hydrocarbons across marine environments. An important aspect in their design and maintenance is the local scour which develops due to the action of waves and/or currents. This scour creates free-spanning regions, which in turn can increase stress and structural fatigue. To improve the understanding of these processes, significant research efforts have been devoted to studying the scour processes beneath pipelines over the past few decades. Such efforts have primarily focused on laboratory experimentation (*e.g.* Sumer et al., 1988; Sumer and Fredsøe, 1990; Çevik and Yüksel, 1999; Kızılöz et al., 2013; Cheng et al., 2014), the development of stochastic engineering approaches for scour prediction (*e.g.* Myrhaug et al., 2009), as well as the development of sophisticated numerical modeling tools for predicting the scour evolution beneath pipelines induced by currents (*e.g.* Brørs, 1999; Zanganeh et al., 2012) or waves (*e.g.* Liang and Cheng, 2005b; Kazeminezhad et al., 2012). For general treatises on scour the interested reader is referred to *e.g.* Hoffmans and Verheij (1997), Whitehouse (1998), and Sumer and Fredsøe (2002).

Most studies investigating wave-induced scour processes beneath pipelines have focused on the use of fixed wave climates, typically starting from a zero-scour initial bed profile (or small initial scour, in the case of numerical models). In engineering practice, however, it is likewise of interest to understand the scour profile development induced by changes in wave climate, as local weather and wave conditions will inevitably vary over time *e.g.* during the transition from storm to calmer conditions. The bed profile response beneath pipelines, and associated backfilling time scales, under such changes in wave climate have been investigated experimentally by Fredsøe et al. (1992). While the number of tests was limited, they found that when an initially large scour hole was subject to less violent wave conditions, a new equilibrium would develop which was predominantly governed by the new wave climate alone. The recent experiments of Sumer et al. (2013) have confirmed similar findings for backfilling around monopiles. The ability of numerical models to simulate such backfilling processes induced by changes in wave climate has yet to be established, however. This is the motivation of the present work, which will demonstrate simulation of both wave-induced scour, as well as backfilling, processes beneath

* Corresponding author.
E-mail address: drf@mek.dtu.dk (D.R. Fuhrman).

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submarine pipelines using an advanced fully-coupled hydrodynamic and morphodynamic CFD model.

The present paper is organized as follows: The hydrodynamic and turbulence models utilized are described in Section 2, which drive the sediment transport and morphological models described in Section 3. Simulations involving scour beneath pipelines are described and discussed in Section 4. These will serve to both validate the model, as well as to establish equilibrium scour configurations for a given set of wave conditions. Selected simulations involving backfilling processes, induced by changes in wave climate, are subsequently presented and discussed in Section 5. Discussion on the practical relevance of the simulations at full scales is provided in Section 6, with conclusions finally drawn in Section 7.

2. Hydrodynamic and turbulence models

2.1. Governing equations

In this section a description of the computational model used throughout the present work is provided. The numerical model solves the incompressible Reynolds-averaged Navier–Stokes equations

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[2\nu S_{ij}+\frac{\tau_{ij}}{\rho}\right] \tag{1}$$

where the mean–strain-rate tensor is

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

These are combined with the local continuity equation

$$\frac{\partial u_i}{\partial x_i}=0. \tag{3}$$

Here u_i are the mean (phase-resolved) velocities, x_i are the Cartesian coordinates, t is time, p is the pressure, ν is the fluid kinematic viscosity, ρ is the fluid density, and τ_{ij} is the Reynolds stress tensor, which accounts for additional (normal and shear) stresses due to momentum transfer from turbulent fluctuations.

Throughout the present work the Reynolds stress tensor will be defined according to the constitutive relation

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

where δ_{ij} is the Kronecker delta, ν_T is the eddy viscosity,

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

is the turbulent kinetic energy density, and the overbar denotes time averaging.

To achieve closure, the two-equation $k-\omega$ turbulence model of Wilcox (2006, 2008) is adopted. In this model the eddy viscosity is defined by

$$\nu_T=\frac{k}{\tilde{\omega}},\quad \tilde{\omega}=\max\left\{\omega, C_{lim}\sqrt{\frac{2S_{ij}S_{ij}}{\beta^*}}\right\}, \tag{6}$$

which incorporates a stress limiting feature, with $C_{lim}=7/8$. This model additionally utilizes transport equations for the turbulent kinetic energy density k

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

as well as for the specific dissipation rate ω

$$\frac{\partial \omega}{\partial t}+u_j\frac{\partial \omega}{\partial x_j}=\alpha\frac{\omega}{k}\frac{\tau_{ij}}{\rho}\frac{\partial u_i}{\partial x_j}-\beta\omega^2+\frac{\sigma_d}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}+\frac{\partial}{\partial x_j}\left[\left(\nu+\sigma\frac{k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right], \tag{8}$$

where

$$\sigma_d=\mathcal{H}\left\{\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}\right\}\sigma_{do}, \tag{9}$$

and $\mathcal{H}\{\cdot\}$ is the Heaviside step function, taking a value of zero when the argument is negative, and a value of unity otherwise. The standard model closure coefficients are used: $\alpha=13/25$, $\beta=\beta_0 f_\beta$, $\beta_0=0.0708$, $\beta^*=9/100$, $\sigma=1/2$, $\sigma^*=3/5$, and $\sigma_{do}=1/8$. Note that for two-dimensional problems, as considered throughout the present work, $f_\beta=1$ and hence $\beta=\beta_0$; For the generalization to three spatial dimensions see Wilcox (2006). It can finally be noted that the basic hydrodynamic model used herein represents a single-phase variant of the two-phase (air–water) model utilized by Jacobsen et al. (2012).

2.2. Boundary conditions

The hydrodynamic model described above is subject to the following boundary conditions: At friction wall boundaries a no-slip condition is imposed whereby velocities are set to zero. Alternatively, the top boundary is treated as a frictionless slip wall *i.e.* with vertical velocities set to zero, and horizontal velocities and scalar hydrodynamic quantities having zero gradient. It is therefore emphasized that the top boundary does not represent the free surface of real waves, the flow beneath which will be approximated by an oscillatory flow as described below.

At the bottom seabed boundary, where sediment transport processes will be modeled, a hydraulically rough-wall will be assumed. Hence, the friction velocity U_f is determined from the tangential velocity at the nearest cell center based on an assumed logarithmic velocity distribution

$$\frac{u}{U_f}=\frac{1}{\kappa}ln\frac{30y_c}{k_s}, \tag{10}$$

where $y_c=\Delta y/2$ is the normal distance from the wall to the cell center, with Δy being the cell thickness, $\kappa=0.4$ is the von Karman constant, and $k_s=2.5d$ is Nikuradse's equivalent sand roughness. The friction velocity is then utilized within standard wall functions for k and ω in the cells nearest to the wall. In dimensional, or equivalent dimensionless, forms these read:

$$k=\frac{U_f^2}{\sqrt{\beta^*}}\quad\text{or}\quad\frac{k}{U_f^2}=\frac{1}{\sqrt{\beta^*}} \tag{11}$$

$$\omega=\frac{U_f}{\sqrt{\beta^*}\kappa\Delta y}\quad\text{or}\quad\frac{\omega\nu}{U_f^2}=\frac{1}{\sqrt{\beta^*}\kappa\Delta y^+} \tag{12}$$

where $\Delta y^+=\Delta yU_f/\nu$ is the thickness of the near-wall cell in wall coordinates. It can be noted that the former yields $k/U_f^2\approx 3.33$, which is in good agreement with flume measurements of k presented by Fuhrman et al. (2010), based on all three fluctuating velocity components.

Pipeline boundaries will be modeled as smooth walls, formally employed within a generalized wall function approach. Accordingly, the friction velocity at pipeline walls is determined from the tangential