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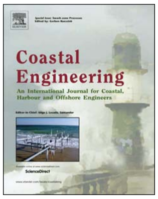

Numerical simulation of scour and backfilling processes around a circular pile in waves

C. Baykal[a,*,1], B.M. Sumer[a], D.R. Fuhrman[a], N.G. Jacobsen[b], J. Fredsøe[a]

[a] *Technical University of Denmark, Department of Mechanical Engineering, Section for Fluid Mechanics, Coastal and Maritime Engineering, Nils Koppels Alle 403, DK-2800 Kgs. Lyngby, Denmark*

[b] *Deltares, Department of Coastal Structures and Waves, Boussinesqweg 1, 2629HV Delft, The Netherlands*

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ABSTRACT

This study continues the investigation of flow and scour around a vertical pile, reported by Roulund et al. (2005). Flow and scour/backfilling around a vertical pile exposed to waves are investigated by using a three-dimensional numerical model based on incompressible Reynolds averaged Navier–Stokes equations. The model incorporates (1) k-ω turbulence closure, (2) vortex shedding processes, (3) sediment transport (both bed and suspended load), as well as (4) bed morphology. The numerical simulations are carried out for a selected set of test conditions of the laboratory experiments of Sumer et al. (1997, 2013a), and the numerical results are compared with those of the latter experiments. The simulations are carried out for two kinds of beds: rigid bed, and sediment bed. The rigid-bed simulations indicate that the vortex shedding for waves around the pile occurs in a "one-cell" fashion with a uniform shedding frequency over the height of the cylinder, unlike the case for steady current where a two-cell structure prevails. The rigid-bed simulations further show that the horseshoe vortex flow also undergoes substantial changes in waves. The amplification of the bed shear stress around the pile (including the areas under the horseshoe vortex and the lee wake region) is obtained for various values of the Keulegan-Carpenter number, the principal parameter governing the flow around the pile in waves. The present model incorporated with the morphology component is applied to several scenarios of scour and backfilling around a pile exposed to waves. In the backfilling simulations, the initial scour hole is generated either by a steady current or by waves. The present simulations indicate that the scour and backfilling in waves are solely governed by the lee-wake flow, in agreement with observations. The numerical model has proven successful in predicting the backfilling of scour holes exposed to waves. The results of the numerical tests indicate that the equilibrium depth of scour holes is the same for both the scour and the backfilling for a given Keulegan-Carpenter number, in full agreement with observations.

1. Introduction

Monopile foundations are commonly used in marine environments by the offshore wind industry. WindEurope (formerly known as European Wind Energy Association, EWEA) reports annual market share of monopile type substructure for offshore wind turbines as 88% of installed in 2016, more than 81%, the overall share of monopiles among all installed substructures in Europe [74]. Considering the fact that up-to 35% of the installation cost is attributable to the foundation works of such structures [6], predicting the time variation of the scour-hole geometry around these structures in ever changing flow conditions of marine environments stands out as an important engineering challenge for the design of these structures. The forces acting on the structure, scour protection, natural frequency and fatigue conditions of the structure, stability of energy transfer cables, maintenance and repair costs and economic lifetime of the structure – essential elements of this design exercise – are all affected by the scour geometry around these structures.

When a pile is placed on the bed in a steady current or in waves, the flow will experience substantial changes (Fig. 1): (1) a horseshoe vortex is formed in front of the pile; (2) a vortex flow pattern (usually in the form of vortex shedding) is formed at the lee-side of the pile; (3) the streamlines contract at the sides of the pile (e.g., [57], for a detailed account of these effects); and (4) a pair of counter-rotating vortices is formed at the lee wake further downstream of the pile [33,34,3]. If the bed is erodible, the end effect of these changes is mainly to increase the

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[*] Corresponding author.
E-mail address: cbaykal@metu.edu.tr (C. Baykal).

[1] Present address: METU, Department of Civil Engineering, Ocean Engineering Research Center, Dumlupinar Blvd. 06800, Cankaya, Ankara, Turkey.

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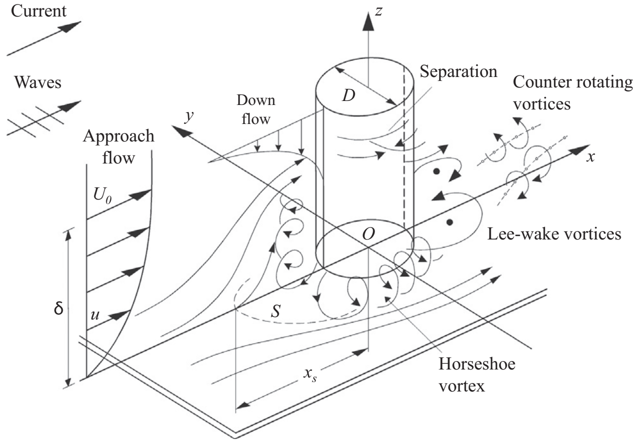

Fig. 1. Definition sketch. S: separation line. δ is the boundary layer thickness. x_s is the length characterizing the size of the horseshoe vortex.

sediment transport, resulting in local *scour* around the pile (see. e.g., [70,57]). By contrast, when a scoured bed around a pile (generated by currents, or by large waves) is exposed to relatively smaller waves, the scour hole will be *backfilled* [64].

Several engineering models [39,47,48,20] have been developed with the purpose of predicting the time history of scour and backfilling around monopile foundations for large times (weeks, months, or years). The existing information on scour has been successfully incorporated in these models. This is not so, however, for the backfilling because of the massive lack of knowledge although recent works [4,64,66] has shed some light onto the understanding of backfilling processes.

Numerical simulations of scour around vertical piles have been previously investigated by several researchers. Important contributions include Olsen and Melaaen [41], Olsen and Kjellesvig [40], Roulund et al. [49], Gothel and Zilke [18], Liu and Garcia [38], Zhao and Cheng [75], Gothel [19], Zhao et al. [76], Escauriaza and Sotiropoulos [12,13], Baranya et al. [2], Stahlmann and Schlurmann [51], Stahlmann [52], and Jacobsen et al. [27].

The present study is a continuation of the work of Roulund et al. [49], who studied - both numerically and experimentally - flow and scour around a circular pile exposed to a steady current. The numerical work of Roulund et al. [49] has, in the present study, been extended to cover the following two cases; (1) scour around a pile exposed to waves, and (2) backfilling of an initially scoured bed around the pile, again, exposed to waves. Two cases are both academically and practically important. As for the wave scour, the questions that remain unsettled are, among others: (1) Do the flow features, essential for the scour process, such as the horseshoe vortex and the lee-wake flow, experience significant changes when the flow environment changes from current to waves? (2) Can these changes be captured with the present-day numerical modelling practice? (3) What is the mechanism of scour in the case of waves, and can it be revealed by means of numerical simulations? Likewise, with respect to the backfilling of scour holes by waves: (1) What is the principal mechanism behind the backfilling process? (2) Can the backfilling be captured by the same morphological numerical model developed for scour? (3) Previous applications of numerical scour models have proven successful in predicting the scour properties (such as the scour depth and the time scale). Can these models prove equally successful in predicting the backfilling properties? (4) There is a long debate in the offshore community as to whether the equilibrium depth of scour hole is the same for both the scour process and the backfilling process. Although this latter question has been settled by the experimental findings of Sumer et al. [64], can this be confirmed by numerical simulations of the backfilling processes?

This study basically addresses these questions. The present numerical simulations reveal the following features, which deserve early mention. The flow structures such as the horseshoe vortex and the lee-wake flow undergo substantial changes when the flow changes from current to waves. The horseshoe vortex emerges only during a certain portion of the half period of the wave with a significantly diminished “strength”, and the lee-wake flow pattern changes from the familiar vortex shedding to multiple vortex shedding regimes governed by the Keulegan-Carpenter number. The present numerical simulations reveal (both qualitatively and quantitatively) the experimental observations (see, e.g., [57]) that the lee-wake vortex flow is the key element behind the mechanism of scour in waves, in contrast to the steady current situation. The present numerical simulations also reveal that the equilibrium depth of scour hole is the same for both the scour process and the backfilling process, confirming numerically, for the first time, the earlier experimental findings of Sumer et al. [64].

Earlier results of this study have been presented at the 34th Int. Conf. on Coastal Engineering [4]. It may also be noted that the authors have, in a previous study [3], investigated the influence of vortex shedding and that of suspended load on scour around a circular pile exposed to a steady current, using the same numerical model as that described in the present paper.

In this study, three kinds of numerical simulations are carried out: (1) rigid bed simulations to investigate the flow features (which will also serve to validate the model); (2) sediment-bed scour simulations; and (3) sediment-bed backfilling simulations. In the rigid bed simulations, the bottom of the calculation domain is kept rigid by turning off the morphological model, whereas, in both scour and backfilling simulations, the morphological model is turned on, and therefore the bed is continuously updated.

The paper is organized as follows. The hydrodynamic and turbulence models used are described in §2, and the sediment transport and morphological models are described in §3. The numerical simulations regarding the flow features around a vertical circular pile placed on a rigid bed under steady or oscillatory flow conditions are described and discussed in §4, while the results of the scour and backfilling simulations are presented in §5 and §6 respectively. The predicted time scales of scour and backfilling from numerical simulations are presented and discussed in §7. Finally, conclusions are drawn in §8.

2. Hydrodynamic model

2.1. Governing equations

The numerical model solves the incompressible Reynolds-averaged Navier-Stokes (RANS) equations

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

combined with the continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0. \tag{2}$$

Here, S_{ij} is the mean-strain-rate tensor

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

where u_i are the mean velocities (phase-resolved in the case of waves), 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. The Reynolds stress tensor is defined according to the following constitutive relation:

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

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