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Numerical and experimental investigation of flow and scour around a half-buried sphere

Martin Dixen [1], B. Mutlu Sumer *, Jørgen Fredsøe

Technical University of Denmark, DTU Mekanik, Section of Coastal, Maritime and Structural Engineering, Building 403, 2800 Kgs. Lyngby, Denmark

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ABSTRACT

The paper describes the results of a numerical and experimental investigation of flow and scour around a half-buried sphere exposed to a steady current. Hot-film bed shear stress and Laser Doppler Anemometer measurements were made with a half sphere mounted on the smooth bed in an open channel. The hydrodynamic model is a 3-D general purpose N–S flow solver. The k-omega SST turbulence model was used for closure. The flow model was used to study the horseshoe vortex and lee-wake vortex flow processes around the sphere. The flow model was coupled with a morphologic model to calculate scour around the half-buried sphere in currents. The morphologic model includes a sediment-transport description, and a description of surface-layer sand slides for bed slopes exceeding the angle of repose. The sediment transport description includes, for the first time, the effect of externally-generated turbulence (induced by the horseshoe-vortex flow and the lee-wake flow processes) on sediment transport. The results show that the scour depth increases and time scale decreases when the effect of externally-generated turbulence is incorporated in the calculations. Empirical expressions representing the numerically obtained data on the equilibrium scour depth and the time scale are presented. The results show that the equilibrium maximum scour depth in the live-bed regime can be approximated by 0.5 D in which D is the sphere diameter.

1. Introduction

When a spherical-shaped body is placed on a sediment bed, and exposed to a current, a scour hole will be formed in front of it, and the sphere will eventually roll into this self-generated scour hole. Observations show that, with the backfilling of the scour hole, the sphere will eventually be self buried, with a burial depth of $O(D/2)$ in which D being the sphere diameter (Truelsen et al., 2005). This process may be considered to represent an idealized case of the self-burial of stones in the upstream edge of a stone protection layer subject to currents in hydraulic and marine environment.

The half sphere or half-buried sphere configurations may be encountered in other fields as well, such as (1) sea mines on the ocean bottom, those types other than cylindrical ones, known as Gumdrop, Manta and Rockan types, Chu et al. (2006); and (2) half-spherical-shaped habitat structures installed on river bottoms to offset fish habitat losses, Shamloo et al. (2001).

The present study investigates the flow and scour around such a structure experimentally and numerically. Fig. 1 illustrates schematically the flow around the structure (e.g., Hunt et al., 1978; Paola et al., 1986). With the presence of the structure, the flow undergoes substantial changes: (1) a horseshoe vortex is formed in front of the sphere; (2) a vortex flow pattern in the form of arch vortices is formed at the lee-side of the sphere; and (3) the flow contract at the sides of the sphere. If the bed is erodible, the end effect of these changes is to increase the sediment transport, resulting in the scour around the structure.

Of particular interest is the numerical modeling of the scour process. Numerical modeling of scour around hydraulic and marine structures has been a topic of recent interest. Numerical models have been developed, from simple models (such as, e.g., Dey, 1999; Miller and Sheppard, 2002; Tsujimoto, 1986; for scour around piers/piles; and Hansen et al., 1986; Li and Cheng, 1999a, for scour below pipelines) to advanced ones (e.g., Constantinescu et al., 2004; Gothel, 2008; Liu and Garcia, 2008; Kirkil and Constantinescu, 2005; Kirkil et al., 2005; Olsen and Melaaen, 1993; Olsen and Kjellesvig, 1998; Richardson and Panchang, 1998; Roulund et al., 2005 for scour around piers/piles; Brørs, 1999; Li and Cheng, 1999b, 2001, 2002; Liang and Cheng, 2005a, 2005b; Liang et al., 2005; Smith and Foster, 2002, 2005, for scour below pipelines; Smith and Foster, 2006, 2007; Hatton et al., 2007, for scour around sea mines; Gislason et al., 2009, for scour in front of breakwaters, to give but some examples). Recent reviews by Sumer (2007a, 2008) give an extensive account of the existing work on the subject.

The general approach in the aforementioned advanced models is that the scour calculations involve a morphologic model that couples the flow solution (from a hydrodynamic model) with a sediment transport description, and routines for updating the computational mesh based on the mass balance of sediment. However, the sediment transport description so far has been essentially based on the classic

* Corresponding author. Tel.: +45 45 25 14 23; fax: +45 45 88 43 25.
E-mail address: bms@mek.dtu.dk (B.M. Sumer).
[1] Present address: DHI, Agern Alle 5, 2970 Hørsholm, Denmark.

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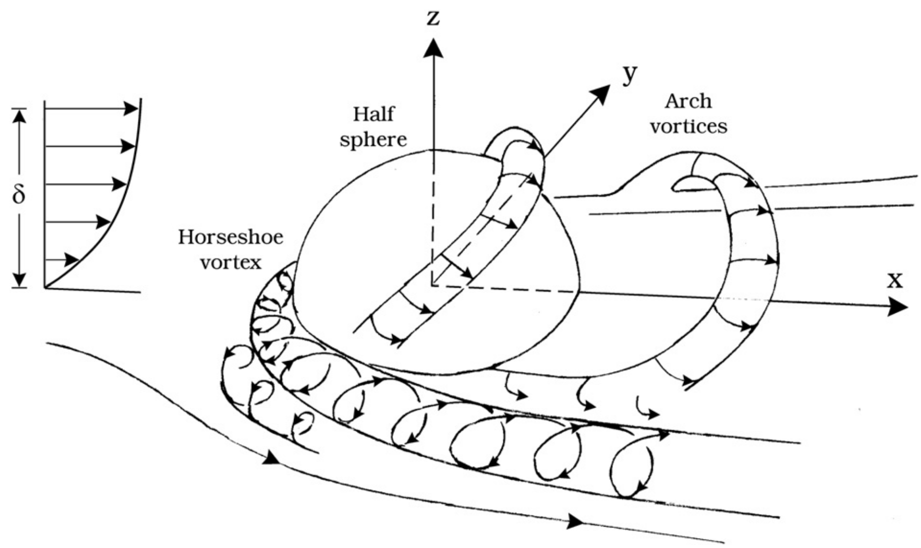

Fig. 1. Definition sketch.

sediment transport formulae such as Meyer-Peter and Muller (1948). In the present study, the sediment transport description has, for the first time, been extended to include the effect of externally-generated turbulence, caused by the horseshoe-vortex flow and the lee-wake flow processes (Fig. 1). This new approach reveals two significant features, which deserve early mention. First, the equilibrium scour depth increases by as much as 35% (in agreement with the experimental data) when the effect of externally-generated turbulence is incorporated in the scour calculations. We note that Roulund et al. (2005) reported differences between the experiment and computation as much as 15–30% in the case of a circular pile, and they attributed this to the previously mentioned externally-generated turbulence which was absent in Roulund et al. (2005) calculations. Second, the time scale of the scour process decreases by as much as a factor of 3 (in the case of live-bed regime scour) with the incorporation of the externally-generated turbulence in the computations.

2. Hydrodynamic model

2.1. Governing equations

The three-dimensional general purpose flow solver, EllipSys3D, was used to calculate the flow. It is the same flow solver as that used in Roulund et al. (2005). It is a multiblock finite-volume numerical model that solves the incompressible Reynolds-averaged N–S equations

$$\frac{\partial \rho U_i}{\partial t}+\frac{\partial \rho U_i U_j}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[(\mu+\mu_T)\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right] \tag{1}$$

in which U_i is the ith component of velocity; t is the time; x_i are the Cartesian coordinates; ρ is the fluid density; p is the dynamic pressure; μ is the viscosity; and μ_T is the eddy viscosity, calculated by a two-equation eddy-viscosity type turbulence model, namely the $k-\omega$ SST (Shear Stress Transport) model, as detailed in Roulund et al. (2005). The $k-$ and $\omega-$ equations of the $k-\omega$ model are, respectively

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho U_j k}{\partial x_j}-\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_T)\frac{\partial k}{\partial x_j}\right]=\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta^*\rho k\omega, \tag{2}$$

$$\frac{\partial \rho\omega}{\partial t}+\frac{\partial \rho U_j\omega}{\partial x_j}-\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_T)\frac{\partial \omega}{\partial x_j}\right]=\frac{\gamma}{\nu_T}\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta\rho\omega^2+2\rho(1-F_1)\frac{\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{3}$$

in which k is the turbulent kinetic energy, and ω is the specific dissipation of turbulent kinetic energy, defined by, respectively:

$$k=\frac{1}{2}\overline{u_i{}'u_j{}'} \tag{4}$$

$$\omega=\frac{\varepsilon}{k\beta^*} \tag{5}$$

with ε, the dissipation of turbulent kinetic energy,

$$\varepsilon=\nu\overline{\frac{\partial u_i{}'}{\partial x_k}\frac{\partial u_i{}'}{\partial x_k}} \tag{6}$$

In the preceding equations, τ_{ij} is the Reynolds stresses

$$\tau_{ij}=\mu_T\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\frac{2}{3}\rho k\delta_{ij} \tag{7}$$

u_i' is the fluctuating components of the velocity, δ_{ij} is the Kronecker delta ($\delta_{ij}=1$ for $i=j$ and $\delta_{ij}=0$ for $i\neq j$), and $\nu_T=\mu_T/\rho$ is the kinematic eddy viscosity. The quantities σ_k, β^*, σ_ω, γ, β and $\sigma_{\omega 2}$ are the model coefficients, and F_1 is the so-called blending function. As the turbulence model is precisely the same as in Roulund et al. (2005), the reader is referred to the latter publication for further details of the model.

Two kinds of hydrodynamic calculation have been performed: (1) steady-state-flow calculations; and (2) unsteady-flow calculations. In the steady-state-flow calculations, the SIMPLE algorithm (Patankar, 1980) is used. In this algorithm, the pressure field is calculated and the velocity field is corrected so that the continuity equation,

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho U_j}{\partial x_j}=0 \tag{8}$$

is satisfied in an iterative manner. By under-relaxation of the correction to the velocity field, the unsteady components of the flow are suppressed. Although the majority of the present study involved steady-state flow calculations, some unsteady-flow calculations have also been performed.