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Numerical investigation of local scour at two adjacent cylinders

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ABSTRACT

Local scour around cylinders in a side-by-side or tandem arrangement under clear-water conditions is investigated numerically. Large eddy simulations with a Smagorinsky subgrid model are combined with a ghost-cell immersed boundary method, and details of the bed scouring are realized with sophisticated sediment and morphodynamic models. The scour patterns and depths in the two-cylinder cases are shown to be significantly influenced by the cylinder spacing. The features of the scour evolution, depth, and flow fields for a range of cylinder spacings are discussed. The maximum scour depth in the side-by-side cylinder cases increases as the distance between the cylinders decreases, whereas in the tandem cases, it tends to initially increase with increasing distance between the cylinders, after which it gradually decreases beyond the peak point. The maximum scour depths and trends computed using the present model show good agreement with the measured data in the literature.

1. Introduction

Three-dimensional flows around vertical obstructions in natural rivers and streams are extremely complex because of the generation of flow separation and turbulence structures in a wide range of scales [1,2]. These complex flows interact with sediment on the bed and drive local scour processes around the obstructions, which results in an unstable streambed and weakens the structural safety [3]. Local scour is a main cause of bridge pier and abutment failure, and thus the prediction of the local scour depth around vertical obstructions such as spur dikes, bridge piers, and rigid vegetation is necessary for safe design and river-training works. Several experimental studies have been conducted to estimate the scour depth, mainly around piers, and semi-empirical equations for the maximum scour depth have been presented [4–6]. However, these equations typically yielded an overestimation of the scour depth because the similitude of large-scale turbulence structures formed by cylinders was not accounted for explicitly [2,7,8].

Several three-dimensional numerical studies have been conducted to examine the scour process and estimate the scour depth around a single vertical circular cylinder. Olsen and Melaaen [9] and Olsen and Kjellesvig [10], who considered a circular pier and a non-cohesive sediment bed, used a three-dimensional steady Reynolds-averaged Navier–Stokes (RANS) model with k-ε turbulence closure combined with a sediment transport model. The results were compared with experimentally observed bed-elevation data, and reasonable agreement was obtained. Roulund et al. [11], in contrast, applied an unsteady RANS (URANS) model with k-ω turbulence closure to a study of the flow and scour around a circular pile, with the flow above the threshold of sediment motion, and showed that the simulated scour process agreed fairly well with the experimental results. However, the scour depth was underestimated by 15% because the URANS model cannot account for the fluctuating components of the horseshoe vortices at the junction of the pile. Zhao et al. [12], who developed a three-dimensional finite-element model for simulating flow and scour around submerged vertical cylinders, solved the URANS equations with k-ω turbulence closure and employed an empirical formula to calculate the bed-load transport. They found that the computed scour depth underestimated the actual sour depth by 10% to 20%. Khosronejad et al. [3] investigated the predictive capabilities of a URANS model for various bridge pier geometries (cylindrical, square, and diamond) and numerically solved the governing equations with k-ω turbulence closure in combination with a curvilinear immersed boundary method to deal with the deformations of the sand bed. The results they presented for a diamond pier showed reasonable agreement with measured scour depth and process, but differences between measured and simulated scour pattern and depth appeared in the case of the square and cylindrical piers. They concluded that this was due to deficiencies in the URANS or morphodynamic models.

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To accurately reproduce vortical structures in turbulent flow and directly consider the effects of the instantaneous flow field on sediment transport, Escauriaza and Sotiropoulos [13] developed a detached-eddy simulation (DES) model coupled with a bed-load transport model in which the sediment motion is solved in a Lagrangian framework by assuming the sediment consists of spherical particles. They simulated the erosion and bed morphodynamics around a cylindrical pier and demonstrated that the ripple dynamics, which evolve from the interactions between turbulent horseshoe vortices and a mobile bed, are captured by the numerical model. As their focus was on describing the details of the bedform phenomena around the cylindrical pier, such as the initial stages of the bed formation within and around the scour hole, they did not investigate the growth of scour or the equilibrium scour depth.

Pile groups are increasingly preferred for constructing bridge piers in rivers because the construction costs are lower than those of spread footing piers, and a number of experimental studies of the local scour around pile groups have been conducted [1,14,15]. Most studies focused on predicting the equilibrium scour depth and were carried out to investigate the effects of the longitudinal and transverse cylindrical obstruction spacings on the scouring depth. The scour mechanisms in the presence of multiple obstructions are much more complex than those of a single obstruction because of flow interference and sediment transport around the obstructions.

In addition, stream and river restoration works are becoming more common, and vegetation is often advocated as part for the restoration to improve the ecology; vegetation can remove nutrients and provide ideal aquatic habitats. A few experimental and field studies have been carried out to investigate the effects of patches of vegetation in open channel flows. Rominger et al. [16] have observed the effects of vegetation removal on the sand bars in a meandering channel, and in field monitoring studies of a tidal flat, Bouma et al. [17] observed local erosion at the leading edge of circular high-vegetation-density patches, whereas there was no local scour in sparse patches of vegetation. Kim et al. [18] conducted laboratory experiments to investigate the influence of the vegetation-patch density on the local scour and showed that the local scour depth at the leading edge of the vegetation patch increased with increasing vegetation-patch density. Thus, the vegetation-patch density and stem spacing are important factors in determining the local scour around vegetation patches, and the phenomenon is similar to the local scouring and patterns around circular pile groups [16,18].

However, in spite of these experimental studies, there have been no numerical investigations of the scour depth, scouring phenomena, and process in the presence of multiple circular cylinders. Understanding the scour mechanism and transport processes around cylindrical objects requires a numerical model capable of simulating the detailed hydrodynamics and morphodynamics in complex geometries, and this is still a challenging task.

The objective of the present paper is twofold: (1) to extend a recently developed morphodynamic model [19] to flows and bed morphodynamics past cylinders in a sand bed; and (2) to numerically investigate the effects of the longitudinal and transverse cylinder spacing on the flow structure, scour evolution, bed topography and maximum scour depth. We achieve these goals computationally using large eddy simulations (LES) of the flow coupled with a sediment transport model in a Lagrangian framework and a morphodynamic model. Simple side-by-side and tandem arrangements were chosen to simulate the growth of the scour holes and scouring phenomena around cylindrical objects. For the turbulent channel flow past the cylinders, the LES are carried out with a ghost-cell immersed boundary method for the boundaries of the cylinders and the bed surface. For the sediment motion, we employed a model in which the sediment is considered to consist of spherical particles and the sediment motion stages such as pick up, transport, and deposition are solved in a Lagrangian framework. To validate the LES incorporating the sediment transport and morphodynamic models, the time-averaged velocity and turbulence intensity are compared with the data presented by Liu et al. [20]. The scour evolution and bed topography in the equilibrium state around a single cylinder are compared with the laboratory data of [3]. To investigate the effects of the cylinder spacing, a range of distances between the two cylinders in the side-by-side and tandem arrangements are considered, and the scour and deposition patterns and evolution of the local scour in each case are simulated. In addition, the computed maximum scour depth is compared with the experimental data reported by Hannah [14] and Ataie-Ashtiani and Beheshti [1].

2. The hydrodynamic model

2.1. Governing equations of the flow

We employ LES to simulate instantaneous unsteady three-dimensional turbulent flow around complex geometries [21]. The governing equations of the flow are the unsteady, incompressible, filtered Navier–Stokes equations:

$$\frac{\partial \overline{u}_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[2\nu \overline{S}_{ij} - \tau_{ij}^{SG}\right] \tag{2}$$

where the x_i's are the coordinates, t is the time, $\overline{P}$ is the modified pressure, ρ is the density of the fluid, $\overline{u}_i$ and $\overline{u}_j$ (i,j = 1, 2, 3) are the resolved velocity vectors, ν is the molecular viscosity, and S_{ij} is the filtered strain-rate tensor, defined as

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{3}$$

The subgrid-scale (SGS) stresses $\tau_{ij}^{SG} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j$ in Eq. (2) result from the eddies unresolved by the computational grid and are modeled using the Smagorinsky subgrid model [22]:

$$\tau_{ij}^{SG} = -2\nu_t S_{ij} + \frac{1}{3}\tau_{kk}\delta_{ij} \tag{4}$$

$$\nu_t = (C_s \overline{\Delta})^2 |\overline{S}| \tag{5}$$

where C_s is the Smagorinsky constant (approximately 0.16), $|\overline{S}| = \sqrt{2\overline{S}_{ij}\overline{S}_{ij}}$, and Δ

is the filter size given as follows.

$$\Delta = (\Delta x \cdot \Delta y \cdot \Delta z)^{1/3} \tag{6}$$

2.2. Numerical methods

As the details of the numerical method have been documented by Nabi et al. [21], we provide only a brief explanation of the primary methods in this section.

Eqs. (1) and (2) are solved with a two-step fractional step. The advection and diffusion terms in the momentum equations are discretized in space on a staggered grid with a second-order finite-volume method. A second-order Adams–Bashforth scheme is used for the time integration of the advection term, while the Crank–Nicolson method is applied for the diffusion term.

A ghost-cell immersed boundary method based on a Cartesian grid is used for the bed surface and solid object boundaries. This