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3D numerical simulation of turbulence and sediment transport within a tidal inlet

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ABSTRACT

Turbulence and sediment transport models are incorporated into a three-dimensional hydrodynamics model to investigate the mechanisms of morphologic evolution of scour holes within the Indian River Inlet, Delaware, USA. The inlet bed had eroded slightly since stabilizing the channel walls in late 1930s through 1976. The mean rate of bed erosion roughly doubled as a response to anthropogenic activities within the inlet such as the removal of ~80 piles remaining from an old bridge. Severe erosion near the in-water bridge supports and cofferdams for the replacement bridge necessitated channel bed stabilization that along with the remained debris from the removal of old bridge piles enhanced the growth of two deep scour holes on the bayside and oceanside of the bridge cofferdams. Scour hole and channel bed evolution has decreased drastically since 1994. The present investigation suggests that, initially, flow concentration through the cofferdams of the replacement bridge was the main reason for scour hole development. Bed shear stress over the forward-facing slope of the scour hole entrains sediment from the bed and extends the scour hole along the inlet and in the vertical direction. Flow separation within the developed scour holes after channel bed stabilization enhances turbulence and appears to be the dominant mechanism for further scour hole development.

1. Introduction

Tidal inlets play a major role in flushing of bay waters and in nearshore circulation. The water exchange between the ocean and bay helps maintain water quality and salinity levels for aquatic life (e.g. Blanton et al., 2003). Natural tidal inlets may meander, migrate or even close depending on temporal variability in tidal flux, alongshore currents, wave conditions and sediment supply (Hayes, 1980). The tidal inlet channel may be stabilized to maintain a fixed location and provide secure navigation (Kraus, 2005). There may be an adverse effect on nearby morphology due to channel stabilization or hardening of the inlet walls. The most obvious consequence of stabilization is the interruption of alongshore sediment transport causing updrift and downdrift inlet-adjacent beach accretion and erosion, respectively (Bruun, 1995; Clausner et al., 1992; Dean and Work, 1993; Dyson et al., 2002; Fenster and Dolan, 1996; Galgano, 2009; Gebert et al., 1992; Hughes and Kraus, 2006; Keshtpoor et al., 2013; Keshtpoor et al., 2014a; Keshtpoor et al., 2014b).

Another impact of inlet stabilization is on the hydrodynamics and morphodynamics within the inlet channel. The pressure gradient along the tidal channel drives tidal currents through the inlet (van de Kreeke, 1988; Dean and Dalrymple, 2002; Keulegan, 1967) that result in channel bed erosion if the flow velocity and turbulence are sufficient to mobilize sediment. The study of morphological evolution of tidal inlets is important since severe erosion can threaten in-water structures such as bridge piers or undermine the stabilization measure. Knowledge of the changing channel morphodynamics can improve prediction of the current velocity through the channel that subsequently impacts the morphodynamics of the channel, ebb shoal, flood shoal, and surrounding beaches.

The cross-sectional area of an inlet helps control the tidal prism (O'Brien, 1931; O'Brien, 1969; Jarrett, 1974) and, consequently, the maximum flow velocity. Thus, one of the critical values in designing a fixed channel is the channel width. A narrower channel may cause an increase in the current velocity for a certain tide-induced pressure gradient within the channel. If the current velocity exceeds the critical entrainment velocity, then sediments are mobilized from the bed causing erosion (van Rijn, 1993). Within a local geometric or bathymetric

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contraction streamlines become closer and flow velocity increases locally. Local flow concentration within the channel and around in-water structures may enhance local erosion and form scour holes or pits (Breusers et al., 1977; Chreties et al., 2013; Dey and Raikar, 2005; Hughes, 2000; Kothyari et al., 2007; Melville, 1984; Sumer and Fredsoe, 2002). Scour holes alter the flow field and can increase turbulence, mixing, and change the pattern of scouring itself (Dargahi, 1990; Graf and Istiarto, 2002; Richardson and Panchang, 1998). Elevation changes may continue to evolve until a sediment layer that cannot be mobilized is reached (e.g. large gravels) or the bed shear stress falls below the critical bed shear stress.

Different numerical and experimental techniques have been undertaken to simulate the flow and bed deformation through a channel contraction (e.g. Dey and Raikar, 2005; Straub, 1934; Gill, 1981; Komura, 1966; Lim, 1993). Dargahi (1990) conducted an experimental study to investigate the vortex structures and local scouring around an in-water circular cylinder. Small eddy structures in front of the cylinder initiate the scouring process that interacts with hydrodynamics and changes the flow pattern around the cylinder. The vorticity field is altered and in turn changes the pattern of scouring. Roulund et al. (2005) investigated the turbulence and sediment transport around a circular pile numerically and experimentally. The maximum depth discrepancy (30%) was observed at the downstream scour hole in the model/experiment comparison. The numerical results showed that the size of horseshoe vortex and the resulting bed shear stress increase with increasing boundary layer thickness to pile diameter ratio. Also, the bed shear stress around the pile decreases as the scour hole evolves from the initial stage (plane bed) to the equilibrium state. Sumer et al. (1992) found that wave-induced scour evolution around a pile is governed by both the lee-wake vortices and the horseshoe vortex. Raikar and Dey (2006) conducted a laboratory flume experiment to evaluate the scouring due to the presence of a single pier within a long contraction and found that the minimum equilibrium scour elevation is the summation of the individual equilibrium scour elevations for a long contraction and at a pier.

In this study, three dimensional (3D) turbulence and sediment transport models are incorporated into a 3D hydrodynamic model (NHWAVE; Ma et al., 2012) to study scour hole evolution within a tidal channel containing a contraction and in-water bridge pier cofferdams. A 3D model is needed to resolve horizontal and vertical flow structures (vorticity) and momentum exchange over complex bathymetry with deep scour holes having side slopes exceeding 30°. Modeling simulations are conducted for Indian River Inlet (IRI), Delaware, USA where the elevation of scour holes reached -30 m with a background channel elevation of -6 to -7 m at the time of inlet stabilization. The scour holes have evolved near in-water cofferdams over the course of 50–60 years. Channel hardening and sediment class variation within the inlet have altered the rates of scour hole evolution. The interest is to determine the potential causes of scour hole evolution within IRI. The hydrodynamic and morphodynamic interaction is addressed by analyzing the turbulence and vorticity fields at different stages of the scour evolution process.

In Section 2 NHWAVE is described and an overview of the mathematical formulation of the turbulence and sediment transport models is presented (details are provided in Appendix A). The numerical approaches used to solve the equations are given in Section 3. Details of the approaches described in this section are also provided in Appendix A. The numerical model is validated in Section 4 by comparing the modeling results with experimental measurements over a trench. Section 5 presents the history of IRI, hydrodynamic conditions, the scour hole morphology, and sediment size variability within the channel. Section 6 describes the computational domain, and initial and boundary conditions. Results of model simulations from 1976 to 1994 are provided in Section 7 with the focus being on the flow field and bed deformation over time. Discussion regarding the causes of erosion and the rate of scour hole evolution is given in Section 8. Section 9 concludes.

2. Mathematical formulation

NHWAVE solves the 3D incompressible Navier–Stokes equations in sigma (σ) coordinates (Ma et al., 2012). The governing equations of the flow field in σ-coordinates are

$$\frac{\partial D}{\partial t}+\frac{\partial Du}{\partial x}+\frac{\partial Dv}{\partial y}+\frac{\partial \omega}{\partial \sigma}=0, \tag{1}$$

$$\frac{\partial \boldsymbol{U_t}}{\partial t}+\frac{\partial \boldsymbol{U_x}}{\partial x}+\frac{\partial \boldsymbol{U_y}}{\partial y}+\frac{\partial \boldsymbol{U_\sigma}}{\partial \sigma}=\boldsymbol{S_{hp}}+\boldsymbol{S_\tau}, \tag{2}$$

where, t, x, y, and σ represent the independent temporal and spatial variables in σ-coordinates, $\boldsymbol{U_t}=(Du,Dv,Dw)$, $\boldsymbol{U_x}=(Duu+0.5gD^2, Duv,Duw)$, $\boldsymbol{U_y}=(Duv,Dvv+0.5gD^2,Dvw)$, $\boldsymbol{U_\sigma}=(u\omega,v\omega,w\omega)$, u, v, and w are the velocity components in x, y, and z directions, ω is the mean vertical velocity in σ-coordinates, D is the water depth, ρ is water density, g is gravitational acceleration, $\boldsymbol{S_{hp}}$ is the total pressure term and $\boldsymbol{S_\tau}$ is turbulent stress term (see Ma et al., 2012). NHWAVE is a non-hydrostatic wave model that has been used to model surface gravity waves (Ma et al., 2012), hydrodynamics-vegetation interaction (Ma et al., 2013b), and tsunami modeling (Ma et al., 2013a). For the current study, only hydrostatic pressure was taken into account due to the fact that flow acceleration under the impact of tidal flow is weak at the studied spatial scale. The turbulence structures affected by the non-hydrostatic processes cannot be resolved at such scale.

2.1. Turbulence model

Turbulent flow is modeled using a 3D k-ε closure (Lin and Liu, 1998) to obtain the mixing coefficient and consequently bed shear stress. Turbulent kinetic energy (k) and energy dissipation rate (ε) in every grid cell are calculated by solving the σ-transformed conservative form of k (Eq. (3)) and ε (Eq. (4)) equations.

$$\frac{\partial Dk}{\partial t}+\frac{\partial DUk}{\partial x}+\frac{\partial DVk}{\partial y}+\frac{\partial \omega k}{\partial \sigma}=\frac{\partial}{\partial x_j^*}\left[\left(\frac{\nu_t}{\lambda_k}+\nu\right)D\frac{\partial k}{\partial x_j^*}\right]+\left(-\langle u_i'u_j'\rangle\frac{\partial u_i}{\partial x_j^*}-\varepsilon\right)D, \tag{3}$$

$$\frac{\partial D\varepsilon}{\partial t}+\frac{\partial DU\varepsilon}{\partial x}+\frac{\partial DV\varepsilon}{\partial y}+\frac{\partial \omega\varepsilon}{\partial \sigma}=\frac{\partial}{\partial x_j^*}\left[\left(\frac{\nu_t}{\lambda_\varepsilon}+\nu\right)D\frac{\partial \varepsilon}{\partial x_j^*}\right]-\left\{C_{1\varepsilon}\frac{\varepsilon}{k}\langle u_i'u_j'\rangle\frac{\partial u_i}{\partial x_j^*}+C_{2e}\frac{\varepsilon^2}{k}\right\}D, \tag{4}$$

where, $(i,j)=1,2,3$, $x_1^*=x^*$, $x_2^*=y^*$ and $x_3^*=z^*$ are independent variables in Cartesian coordinates, u_i is the velocity component in Cartesian coordinates, $\nu_t=C_d\frac{k^2}{\varepsilon}$ is the turbulent eddy viscosity, U represents the mean horizontal velocity in the x-direction, V is the mean horizontal velocity in y-direction, u' represents the fluctuating part of u, υ is molecular viscosity, λ_k and λ_ε are Schmidt numbers in the k and ε equations, respectively, and recommended values by Rodi (1980) are $\lambda_k=1.0$ and $\lambda_\varepsilon=1.3$, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are empirical coefficients (1.44 and 1.92, respectively; Rodi, 1980), and the $\langle\,\rangle$ is the time-averaging operator.