Coastal Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Numerical modeling of local scour and forces for submarine pipeline under surface waves

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form 21 April 2016
Accepted 5 May 2016
Available online xxxx

Keywords:
Water wave
Free surface
Local scour
Pipeline
Viscous numerical model

ABSTRACT

A two-dimensional numerical model is developed to predict local scour around submarine pipelines induced by the orbital fluid motion under surface water waves. Instead of being simplified to oscillatory flow, the wave motion is modeled using a fully nonlinear wave model. The numerical model is based on the two-dimensional Reynolds-Averaged Navier–Stokes (RANS) equations with a Shear-Stress Transport (SST) k-ω turbulence closure. Both suspended load and bed load sediment transportations are considered. The moving boundaries of free surface and the evolution of seabed due to local scour are tracked using the Arbitrary Lagrangian–Eulerian (ALE) method. The Streamline Upwind Petrov–Galerkin Finite Element Method (SUPG-FEM) is used to discretize the governing equations. The numerical model is validated against the benchmarks of linear and nonlinear wave propagations and their interactions with submerged structures as well as local scour around submarine pipeline in steady current. Comparisons between the numerical results and available theoretical, numerical and experimental data show satisfactory agreements. The proposed numerical model is then used to investigate the nonlinear wave-induced local scour around pipelines placed flat and sloping seabed. The effects of wave height and wave period on local scour and wave forces on the pipelines are examined. The numerical investigations suggest the necessity of utilizing the free surface wave model rather than the simplified oscillatory flow model for the problem of local scour around submarine pipelines in case of large amplitude nonlinear waves and pipelines over uneven seabed.

1. Introduction

When submarine pipelines are laid on erodible seabed, the resultant large-scale free spans due to local scour can lead to undesirable on-bottom instability and severe vortex-induced vibration, which threat the safety of the pipelines. Local scour can be induced by ocean currents, water waves as well as the combination of wave and current.

Researchers have paid much attention on the problem of local scour around submarine pipelines. Most early research has been focused on the local scour induced by steady current. Mao (1986) studied experimentally the critical condition of the onset of local scour as a pipeline model is directly placed on sand bed. The roles of the vortices formed at the upstream and downstream sides of the pipeline were discussed. Chiew (1990) found that the piping phenomenon is the dominant cause for the initiation of local scour. In addition to laboratory tests, various numerical models have also been developed to study the local scour around pipelines. Hansen (1986) proposed a potential flow model for predicting the local scour below subsea pipelines in steady current, and found that the potential flow model is able to predict the maximum scour depth, while it fails to simulate the exact scour profile. Li and Cheng (1999) attributed this inaccuracy to the fact that the potential flow model is not able to predict the vortex shedding, which plays an important role in shaping the equilibrium scour profile. In order to overcome the weakness of the potential flow model, a viscous flow model based on the Navier–Stokes equations was proposed by Li and Cheng (2001), in which the equilibrium scour profile is calculated by means of an iterative strategy based on a seabed shear stress balance criterion. Cheng and Li (2003) later on developed a time-dependent scour model based on the large eddy simulation. The local scour around submarine pipelines was also successfully simulated by using a renormalized group turbulence model based on a finite element solver (Lu et al., 2005). Brørs (1999), Liang et al. (2005) and Zhao and Cheng (2008) developed scour models based on the RANS equations, where both bed load and suspended load sediment are considered.

A large number of experimental investigations have also been conducted to investigate the local scour around subsea pipelines under water waves, including Bijker and Leeuwestein (1984), Gokce and Gunbak (1991), Mao and Sumer (1986), among others. The experiments by Sumer and Fredsøe (1990) revealed the dependence of the scour depth on the Keulegan–Carpenter number ($KC = U_h T / D$, where U_h represents the amplitude of undisturbed horizontal velocity

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http://dx.doi.org/10.1016/j.coastaleng.2016.05.003
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Please cite this article as: Liu, M., et al., Numerical modeling of local scour and forces for submarine pipeline under surface waves, Coast. Eng. (2015), http://dx.doi.org/10.1016/j.coastaleng.2016.05.003

at the position of pipeline center, T is the wave period and D is the diameter of pipeline. Sumer and Fredsøe (1991) further found that the onset of the scour under waves is highly dependent on the KC number and the initial embedment-to-diameter ratio (e/D with e the embedment depth). Cevik and Yuksel (1999) experimentally investigated the shoaling wave-induced local scour under submarine pipeline laid on a slope. Based on their experimental observations, an empirical formula relating the maximum equilibrium scour depth to the modified Ursell number was proposed. Sumer et al. (2001) examined the self-burial of pipelines in waves, and reported that the self-burial depth is mainly dependent on the KC number, while its time scale is jointly controlled by the KC number and the Shields parameter.

So far, few numerical investigations have been carried out to study the evolution of local scour around subsea pipelines under surface waves, perhaps due to the complexity of numerical treatments of the free surface. The fluid motion due to surface waves was alternatively modeled by oscillatory flows in the numerical model in Liang and Cheng (2005). Avoiding simulating the wave free surface increases the efficiency of the numerical modeling of wave-induced local scour around pipelines. The numerical simulations by Liang and Cheng (2005) suggested that the oscillatory flow model is able to produce good predictions compared with available experimental data. The validity of oscillatory flow model in the sand backfill problems was also confirmed by Fuhrman et al. (2014). Although the simplified oscillatory flow models have been proved to predict local scour satisfactorily, it is expected that the accuracy of such simplification may decrease with the increase in the wave nonlinearity. It may not be suitable for uneven bed also, where the wave surface deforms while the waves are propagating. Therefore, it is necessary to develop a more general viscous numerical model that considers the effect of wave surface on the local scour around submarine pipelines.

This study aims to establish a two-dimensional viscous numerical model to simulate the free surface of water waves and seabed evolution due to the surface waves. The numerical model is an extension of the previous model proposed by Zhao and Cheng (2010), which was initially developed for the simulation of vortex-induced vibration of submarine pipeline in steady current. The rest of this paper is organized as follows. The details of the numerical model will be described in Section 2, followed by necessary numerical validations in Section 3. Numerical results of local scour in nonlinear waves on flat/sloping seabed will be presented in Section 4. Finally, conclusions will be drawn in Section 5.

2. Numerical model

2.1. Flow model

The two-dimensional incompressible Reynolds-Averaged Navier–Stokes (RANS) equations are adopted to describe the turbulent flow of incompressible viscous fluid. To account for the moving wave surface and seabed surface, the RANS equations are solved in the Arbitrary Lagrangian–Eulerian (ALE) frame. Accordingly, the governing equations can be written as

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \left(u_j - u_j^m\right)\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[2\upsilon S_{ij} - \overline{u_i' u_j'}\right] + g_i \tag{2}$$

where $x_1 = x$, $x_2 = y$ are the horizontal and vertical coordinates, respectively, u_i is the fluid velocity in the x_i-direction, u_j^m is the velocity of moving grid in the x_j-direction, t is the time, p is the pressure, ρ is the fluid density, υ is the kinematic viscosity of the fluid, g_i denotes the gravitational acceleration, and S_{ij} is the mean strain rate tensor with $S_{ij} = (\partial u_i / \partial x_j + \partial u_j / \partial x_i) / 2$. The Reynolds stress term in Eq. (2) reads $\overline{u_i' u_j'} = \upsilon_t(\partial u_i/\partial x_j + \partial u_j/\partial x_i) + 2k\delta_{ij}/3$, where υ_t is the turbulent eddy viscosity, k the turbulence kinetic energy and δ_{ij} is the Kronecker operator.

To close the governing equations, the Shear Stress Transport (SST) k-ω two-equation turbulence model (Menter, 1994; Menter et al., 2003) is adopted, which has shown good performance in simulating the boundary layer flows with significant adverse pressure gradient. The advection–diffusion equations for the turbulence kinetic energy k and its specific dissipation rates ω are

$$\frac{\partial k}{\partial t} + \left(u_j - u_j^m\right)\frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\upsilon + \sigma_k \upsilon_t\right)\frac{\partial k}{\partial x_j}\right] + P_k - \beta^* \omega k \tag{3}$$

$$\frac{\partial \omega}{\partial t} + \left(u_j - u_j^m\right)\frac{\partial \omega}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\upsilon + \sigma_\omega \upsilon_t\right)\frac{\partial \omega}{\partial x_j}\right] + \alpha S^2 - \beta \omega^2 + 2(1 - F1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{4}$$

where P_k is the production of turbulent kinetic energy and the related parameters in Eqs. (3) and (4) are calculated as follows

$$\upsilon_t = \frac{\alpha_1 k}{\max(\alpha_1 \omega, \quad \Omega F_2)} \tag{5}$$

$$P_k = \min\left[\upsilon_t \frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right), \quad 10\beta^* k\omega\right] \tag{6}$$

$$F_1 = \tanh\left\{\left\{\min\left[\max\left(\frac{\sqrt{k}}{\beta^* \omega y^*}, \frac{500\upsilon}{y^{*2}\omega}\right), \quad \frac{4\rho\sigma_{\omega 2} k}{D_{k\omega} y^{*2}}\right]\right\}^4\right\} \tag{7}$$

where Ω is the absolute value of vorticity, y^* is the distance to the nearest solid wall, and the parameters F_2 and $D_{k\omega}$ are

$$D_{k\omega} = \max\left(2\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, \quad 10^{-10}\right), \qquad F_2 = \tanh\left\{\left[\max\left(\frac{2\sqrt{k}}{\beta^* \omega y^*}; \frac{500\upsilon}{y^{*2}\omega}\right)\right]^2\right\}. \tag{8}$$

By using the blending function F_1, the following parameters can be calculated, i.e.,

$$\sigma_k = F_1\sigma_{k1} + (1 - F_1)\sigma_{k2}; \quad \sigma_\omega = F_1\sigma_{\omega 1} + (1 - F_1)\sigma_{\omega 2}; \quad \alpha = F_1\alpha_1 + (1 - F_1)\alpha_2; \quad \beta = F_1\beta_1 + (1 - F_1)\beta_2. \tag{9}$$

The model constants in the SST k-ω model are listed in Table 1.

2.2. Sediment transportation model

Both bed load and suspended load sediment transports are considered for the local scour process. The advection and diffusion of the suspended sediments can be described by

$$\frac{\partial c}{\partial t} + \left(u_j - u_j^m - w_{sj}\right)\frac{\partial c}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\upsilon_t}{\sigma_c}\frac{\partial c}{\partial x_j}\right) \tag{10}$$

Table 1
Constants of SST k-ω turbulent model.

β^*	α_1	β_1	σ_{k1}	$\sigma_{\omega 1}$	α_2	β_2	σ_{k2}	$\sigma_{\omega 2}$
0.09	5/9	3/40	0.85	0.5	0.44	0.0828	1.0	0.856

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