Three-Dimensional Scour at Submarine Pipelines under Indefinite Boundary Conditions

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Abstract

Most laboratory experiments to study the lateral propagation of the scour hole along the pipeline are performed in terms of flume tests. However, boundary conditions are restricted in all flume tests. Such limitations can be overcome in numerical model. This paper presents the results of a numerical model application to simulate three-dimensional scour development at submarine pipelines with uniform sediment under a unidirectional current in clear-water conditions. The scour development predictions are compared with measurements, for which the results are in good agreement with experimental data published in the literature. The model is then extended for larger boundary conditions, which are restricted in the laboratory. The results clearly reveal that the development of the scour hole slows down when the pipeline is extended indefinitely.

Keywords: Submarine pipeline scour, three-dimensional scour, indefinite boundary conditions.

1. Introduction

Submarine pipeline, unlike any other hydraulic structures that are vertically erected, are laid horizontally on the bed of oceans and rivers. Hence, the design of submarine pipelines associated with their stability can be rather complex. Pipeline scour is an aspect which engineers and designers cannot afford to overlook in the design process of submarine pipeline. Pipeline scour is generally caused by the very presence of the pipeline itself (Sumer and Fredsøe, 1992).

Pipeline scour is a severe problem as it causes submarine pipeline damage and failure. Overwhelming researches and extensive studies were conducted in this particular area of interest for the past decades. Most published experimental and numerical modeling studies of pipelines scour were performed with a two-dimensional model (Sumer and Fredsøe, 2002). However, the scour development in the spanwise direction of the pipeline is beyond the capacity of two-dimensional models (Cheng and Zhao, 2010). Pipeline scour is essentially three-dimensional.

Several notable publications including Hansen et al. (1991), Sumer and Fredsøe (2002), Cheng et al.

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(2009), and Wu and Chiew (2012) have attempted to study the three-dimensional pipeline scour by examining the lateral propagation of the scour hole along the pipeline. Nevertheless, most laboratory experiments to study the lateral propagation of the scour hole along the pipeline are performed in terms of flume tests. In flume test, the boundary conditions are often restricted. This condition limits any lateral propagation of the scour hole that is supposed to occur beyond that. This raises interesting engineering issues and questions of how will the lateral propagation develop in the transverse direction of the flow if the boundary condition can be extended to an indefinite length and what will the scour pattern eventually be.

Boundary limitations in physical modeling can be overcome with numerical modeling. Therefore, the objective of this study is to overcome the boundary limitation by extending the boundary condition to an indefinite length using numerical simulation and the free span development under the indefinite boundary condition is also examined. To this end, a commercially available Computational Fluid Dynamics (CFD) model, Flow-3D, has been employed to generate the numerical simulation of the three-dimensional pipeline scour.

2. Governing Equations

2.1 Hydrodynamics model

The hydrodynamics module is based on the solution of the three-dimensional Navier-Stokes equations and the continuity equation. The continuity equation and the model formulation of the Navier-Stokes equations for incompressible flows used in Flow-3D are (Flow Science Inc., 2008):

$$\frac{\partial}{\partial X_i} U_i A_i = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{1}{V_f}\left(U_j A_j \frac{\partial u_i}{\partial X_j} \right) = -\frac{1}{\rho}\left(\frac{\partial P}{\partial X_i} \right) + G_i + f_i \tag{2}$$

where U_i = mean velocity; P = pressure; A_i = fractional open area open to flow in the I direction; V_f = fractional volume open to flow; G_i represents the body accelerations; f_i represents the viscous accelerations; and ρ = density of water.

The RNG closure scheme is considered as the transport closure scheme in this paper. The RNG model uses equations similar to the equations for the k-ε model. Likewise, the closure equations for the turbulent kinetic energy, k and the dissipation rate, ε can be expressed by

$$\frac{\partial \kappa}{\partial t} + \frac{1}{V_f} U_i A_\xi \frac{\partial \kappa}{\partial X_i} = C_{sp} \frac{\mu}{\rho V_f} 2 A_{xi} \left(\frac{\partial U_i}{\partial X_i} \right)^2 + \left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right) \left(A_{xj} \frac{\partial U_i}{\partial X_j} + A_{xi} \frac{\partial U_j}{\partial X_i} \right)$$
$$- \frac{1}{V_f} \frac{\partial}{\partial X_j} \left[\frac{A_{xi}}{\rho} \left(\mu + \frac{\mu_T}{\sigma_\kappa} \right) \frac{\partial \kappa}{\partial X_j} \right] \tag{3}$$

where C_{sp} is the shear production coefficient.

$$\frac{\partial \epsilon}{\partial t} + \frac{1}{V_f} U_i A_{xi} \frac{\partial \epsilon}{\partial X_i} = C_{\epsilon 1} \frac{\epsilon}{\kappa} \left\{ C_{sp} \frac{\mu}{\rho V_f} \left[2 A_{xi} \left(\frac{\partial U_i}{\partial X_i} \right)^2 + \left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right) \left(A_{xj} \frac{\partial U_i}{\partial Xj} + A_{xi} \frac{\partial U_j}{\partial X_i} \right) \right] \right\}$$
$$- \frac{1}{V_f} \frac{\partial}{\partial X_j} \left[\frac{A_{xi}}{\rho} \left(\mu + \frac{\mu_T}{\sigma_\kappa} \right) \frac{\partial \kappa}{\partial X_j} \right] - C_{\epsilon 2} \frac{\epsilon^2}{\kappa} \tag{4}$$

The equation constants that are found empirically in the standard k-ε model are derived explicitly in the RNG model. The closure coefficients and auxiliary relations are $C_{\varepsilon 1}$ = 1.42, C_{μ} = 0.085 and σ_k = 1.39. $C_{\varepsilon 2}$ is computed from the turbulent kinetic energy and turbulent production terms.

2.2 Flow-3D scour model

The FLOW-3D scour module uses a bulk approximation of a conservation of mass and advection/diffusion scheme to predict the transport of sediment. The drift and settling length scale (L_{drift}) of the suspended sediment is calculated using a Stokes formulation at the hydrodynamic time step (Abdelaziz et al., 2010)

$$L_{drift} = \frac{d_{50}^2}{18\mu}\frac{\nabla P}{\rho}(\rho_s - \rho)\Delta t \qquad (5)$$

where ρ_s is the sediment density; ρ is the density of the fluid; d_{50} is the median grain size; Δt is time step. The lift length of the packed bed is calculated using an excess shear formulation

$$L_{lift} = \overline{n_s}\alpha\sqrt{\frac{\tau - \tau_{cr}}{\rho}}\Delta t \qquad (6)$$

where τ_{cr} is the critical shear stress; n_s is the unit vector normal to the bed.

2.3 Bed-load transport module

For bed-load transport, the model currently used is that of Meyer, Peter and Muller (Brethour and Burnham, 2010). This model predicts the volumetric flow rate of sediment per unit width over the surface of the packed bed. The model is expressed as

$$\Phi_i = \beta_i\left(\theta_i - \theta''_{cr,i}\right)^{1.5} \qquad (7)$$

where θ_i is the dimensionless local bed shear and Φ_i is the dimensionless bed-load transport rate.

3. Model Setup

According to the preceding introduction, Wu and Chiew (2012) conducted a series of laboratory experiments to examine the general characteristics of the lateral propagation of scour hole along the pipeline. All the experiments are conducted in a glass-sided flume that is 19-m long, 1.6-m wide and 0.45-m deep. In this paper, case no. A7 by Wu and Chiew (2012) was selected for further simulation using FLOW-3D. In this case, the bed material is uniform sand with a median grain size d_{50} = 0.56 mm, a density of 2650 kg/m^3 and a 1.6-m long PVC pipe line with a diameter of 49 mm. The flow condition for this case is as follows. The flow velocity is maintained at 0.24 m/s. The flow depth is controlled to be 0.2 m throughout the experiment. The initial embedment to pipeline diameter ratio, *e/D* is 0.2. These experimental conditions of case no. A7 are the basis of the setup of the numerical model. To this end, it is noteworthy to mention that this study has been as faithful as possible to the literature, strictly following the experimental setup without any major manipulation. Figure 1 shows the three-dimensional computational mesh of the numerical model.

4. Results and Discussion

Early calculations using the default values proposed by FLOW-3D did not reproduce the scour development with any favorable quality. After a series of calculations with different model parameter sets, reasonable agreement between the numerical model and experimental results was obtained. The development of scour hole in spanwise direction qualitatively agrees with what was observed in the laboratory tests, although the predicted scour propagation speed is smaller than the experimental propagation speed. The propagation of scour at early stage when t = 100 s can be clearly observed in Figure 2.

The pipeline was then extended to a width of 5 m and 10 m in order to see the effect on the span development. Both cases exhibit nearly the same pattern. Initially, the scour propagates at high and constant rates, However, the propagation actually slowed down, almost at a constant speed when the scour propagated towards the two ends. Although there is no strong experimental evidence available on this phenomenon yet, it is reasonable that the span development does not cease. Around the two span shoulders, the flow field is fully three-dimensional and complex. Wu and Chiew (2013) claimed that the combined effect of the transverse deflection and the spiral vortex increase the sediment capacity at the span shoulders. Cheng and Zhao (2010) found that high Shield parameter and steep bed slopes at the two shoulders of the span contribute to the sediment transport and thus the consistent scour propagation. Therefore, the scouring at the span shoulders can still be intense even though the middle portion of the span has progressed into a slower development stage.

5. Conclusion

A preliminary simulation has been carried out under the same condition as in case no. A7 by Wu and Chiew (2012). The simulated scour agrees qualitatively with the observed results in the laboratory experiment. When the boundary condition was extended to overcome laboratory limitation, the lateral propagation of the scour hole did not cease, but continue to develop in a slow yet constant speed. Scour development at the shoulders can be intensive due to complex mechanisms at the span shoulder. This study has provided a preliminary insight of the three-dimensional scour at submarine pipelines under indefinite boundary conditions. The scour pattern observed in the numerical simulation can also be of interesting topic. However, further works are needed to enhance the accuracy of the model.

6. Acknowledgment

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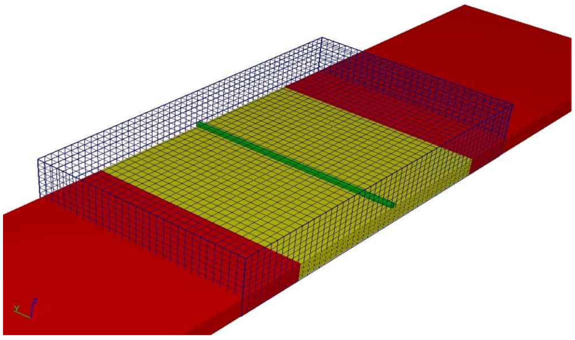

Figure 1. Three-dimensional view of computational mesh

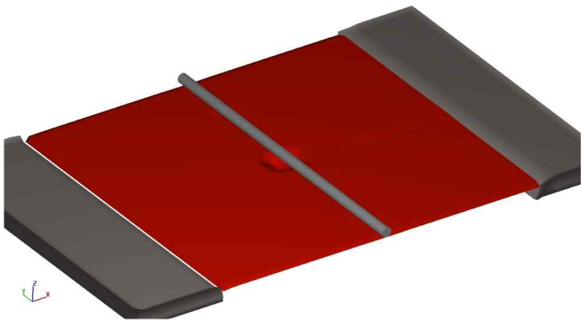

Figure 2. Three-dimensional scour development (t = 100 s)