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Local scour around two pipelines in tandem in steady current

Ming Zhao [a,b,*], Shailesh Vaidya [a], Qin Zhang [c], Liang Cheng [c,d]

[a] School of Computing, Engineering and Mathematics, University of Western Sydney, Penrith 2751, NSW, Australia
[b] Institute for Infrastructure Engineering, University of Western Sydney, Penrith 2751, NSW, Australia
[c] School of Civil, Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[d] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

In this study, local scour around two identical pipelines in a tandem arrangement are investigated numerically. The two-dimensional Reynolds-averaged Navier–Stokes (RANS) equations, together with the conservation equation of the sediment mass are solved to simulate the flow around two pipelines and the evolution of the local scour profile below the pipelines. The gap ratios between the two pipelines (G/D) range from 0.5 to 5 with an interval of 0.5, where G is the gap between the two pipelines and D is the diameter of the pipelines. The focus of the study is to investigate the effects of the gap ratio on the scour depth and scour time scale. It is found that the scour depth below the downstream pipeline is greater than that below the upstream pipeline under both clear water and live bed conditions because of the effect of the vortex shedding from the upstream pipeline. The maximum scour depth below the downstream pipeline occurs at $G/D = 2.5$ under both clear water and live bed conditions, which is about the critical gap ratio beyond which vortex shedding from the upstream pipeline occurs. As the gap ratio exceeds 2.5, the scour depth below the downstream pipeline decreases with increasing gap ratio due to the weakening effect of the vortex shedding from the upstream pipeline on the scour. The scour under the clear water condition is simulated at a velocity 25% lower than the critical velocity for live bed scour. The variations of the scour depths below the two pipelines in the clear water and live bed conditions are found to be similar to each other. Strong positive mean lift coefficient on the downstream pipeline was observed during the scour process, which is believed to have a negative effect on the stability of downstream pipeline. The RMS lift coefficient on the downstream pipeline increases significantly when the vortex shedding from the upstream pipeline occurs.

1. Introduction

Local scour around subsea pipelines has been studied extensively in the past decades due to its significance in the offshore oil and gas industry. Mao (1986) conducted a series of laboratory tests about scour around subsea pipelines and found that the scour process includes two stages: the tunnel scour and lee wake scour in the early and late stages of scour development, respectively. Chiew (1990) found that the onset of scour is mainly caused by the piping and the stagnation eddy in front of the pipeline. The piping is induced by the pressure drop between the upstream and the downstream of the pipeline. Sumer et al. (2001) studied the onset condition of scour experimentally and found that the piping induced by the seepage flow below the pipeline is the mechanism for the onset of tunnel scour. Dey and Singh (2007) studied scour depth below underwater pipelines and the effects of an armor layer on the scour under clear water conditions. Some experimental studies were focused on the progressing of the three-dimensional scour pit along the spanwise direction of the pipelines. Cheng et al. (2009, 2014) conducted extensive experimental studies on the three-dimensional scour and proposed the empirical formula for predicting the scour propagation speed along the spanwise direction of the pipeline.

A number of numerical models have also been developed for predicting the scour process. Zang et al. (2009) predicted the onset condition numerically and derived empirical formulae for predicting the onset condition. Some numerical models were developed to predict the scour depth at the equilibrium stage (Li and Cheng, 1999; Lu et al., 2005). These models are efficient for predicting the final scour depth but not able to predict the temporal development of the seabed profile. Many recent numerical models are based on the transport equations of the sediment mass and able to simulate the time history of the scour. In the numerical models by Brørs (1999); Liang et al (2005) and Zhao and Cheng (2008), both the bed load and suspended load sediment transport rates were considered and the evolution of the seabed profile was predicted by solving the conservation equation of the sediment mass. Scour below pipelines was also predicted by the linear Genetic Programming (LGP) method (Azamathulla et al., 2011), which is a

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[*] Corresponding author at: School of Computing, Engineering and Mathematics, University of Western Sydney, Penrith 2751, NSW, Australia. Tel.: +61 2 4736 0085.
E-mail address: m.zhao@uws.edu.au (M. Zhao).

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method of predicting scour depth from the laboratory measurements. Kazeminezhad et al. (2012) used a two-phase flow model to predict scour below pipelines.

Studies of scour below pipelines have been extended to some more complex cases. Sumer et al. (2001) studied self-burial of pipeline experimentally. Cheng and Li (2003) simulated scour below a sagging pipeline numerically and found that the ultimate scour depth exceeds one diameter of the pipeline. Sumer and Fredsøe (1995); Gao et al. (2006); Yang et al. (2008) and Zhao and Cheng (2010) investigated the interaction between the vibration of a pipeline and the seabed. It was found that the vibration of the pipeline enhances the scour depth significantly. Because spoilers can be used to control the scour below pipelines, the effects of spoilers attached to a pipeline are studied in a number of studies (Chiew, 1992, 1993; Yang et al., 2012; Zhu et al., 2013). It was found that the spoiler enhances the scour depth below a pipeline in both waves and steady currents. Kiziloz et al. (2013) studied scour below pipelines in irregular waves under the shoaling condition and proposed empirical formula for predicting the scour depth.

Some studies were focused on the scour process below two pipelines. Jensen et al. (1990) found that the vortex shedding from pipelines occurs after the scour reaches a certain depth. Zhao and Cheng (2008) studied scour below a piggyback pipeline (comprised of two pipelines of different diameters) in steady current and found that the existence of a small pipeline on top of the big one increases the scour depth. In the production fields of offshore oil and gas engineering, multiple pipelines are common. Two pipelines are sometimes laid in parallel due to technical and economical consideration. For two parallel pipelines close to each other, local scour process is affected by the spacing between the two pipelines. Because the distance between two parallel pipelines may change due to the movement of the pipelines (Gao et al., 2012, 2013), understanding the effects of the distance between the two pipelines on scour is important. Westerhorstmann et al. (1992) investigated scour below two and three-pipelines in tandem arrangements. It was found that the vortex shedding from the upstream pipeline and local scour below the pipelines are dependent on the gap between the pipelines.

Although many studies have been conducted to investigate scour below a single pipeline, the effects of the spacing between two pipelines on scour behavior are not properly understood. The present numerical study will focus on understanding scour behavior of two tandem pipelines under different pipeline spacing conditions. Specifically, local scour below two pipelines of an identical diameter in a tandem arrangement in steady current is simulated numerically. The flow field around the pipelines is simulated by solving the two-dimensional Reynolds-Averaged Navier–Stokes equations with a k–ω turbulence model closure. Both bed load and suspended load sediment transport are considered in the numerical model. The scour development is predicted by solving the conservation equation of the sediment mass. The numerical results are firstly compared with the experimental data. Then the effects of the spacing between the two pipelines are studied by simulating the scour under both live bed and clear water scour conditions for spacing ratios (the ratio of the distance between the two pipelines to the diameter of the pipelines) ranging from 0.5 to 5.

2. Numerical method

Fig. 1 shows an illustration sketch for scour below two tandem pipelines of an identical diameter. The diameter of the pipeline and the gap between the two pipelines are denoted by D and G, respectively. The upstream and downstream pipelines are denoted by Pipeline 1 and Pipeline 2, respectively. The scour depth below the centers of Pipeline 1 and Pipeline 2 are defined as S_1 and S_2, respectively. The numerical method used in this study is similar to that used in Zhao and Cheng (2008). The flow is simulated by RANS equations and the turbulence is simulated by the SST (shear stress transport) k–ω turbulence equation by Menter (1994). The SST k–ω model is used because of its demonstrated performance in simulating flows with adverse pressure gradients and flow separations. The RANS equations are expressed as

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

$$\frac{\partial u_i}{\partial t} + \left(u_j - \hat{u}_j\right)\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_i^2} + \frac{\partial}{\partial x_j}\left(-\overline{u'_i u'_j}\right), \tag{2}$$

$x_1 = x$ and $x_2 = y$ are the coordinates, t is the time, $u_1 = u$ and $u_2 = v$ are the fluid velocity components in the x- and y-directions, respectively, p is the pressure, $\hat{u}_j$is the velocity of the mesh movement, ρ is the density of the fluid, ν is the kinematic viscosity of the fluid. The Reynolds stress tensor $-\overline{u'_i u'_j}$ is computed by

$$-\overline{u'_i u'_j} = \nu_t\left(\partial u_i/\partial x_j + \partial u_j/\partial x_i\right) + \frac{2}{3}k\delta_{ij}, \tag{3}$$

where ν_t is the turbulent viscosity and k is the turbulent energy. The turbulent viscosity is obtained by solving the SST k–ω equations developed by Menter (1994). The SST k–ω equations has been successfully used in the numerical models for simulating local scour around subsea structures (Roulund et al., 2005; Zhao et al., 2010). The SST k–ω equations can be found in Menter (1994) and will not be represented here. In the simulation, the mesh moves according the evolution of the seabed, the speed of the mesh is considered in the momentum Eq. (2) (Zhao and Cheng, 2008).

The RANS equations and the SST k–ω equations are solved by the Pertrov-Galerkin Finite Element Method (PG-FEM) (Brooks and Hughes, 1982; Zhao et al., 2007). The detail about the PG-FEM model for the flow equations can be found in Zhao et al. (2007) and will not be presented here. Both bed load and suspended load sediment transport rates are considered in this study. The concentration of the suspended sediment is calculated by solving the following convection diffusion equation:

$$\frac{\partial c}{\partial t} + (u - \hat{u})\frac{\partial c}{\partial x} + (v - \hat{v} - w_s)\frac{\partial c}{\partial y} = \nabla\cdot\left(\frac{\nu_t}{\sigma_c}\nabla c\right) \tag{4}$$

where c is the volume concentration of the suspended sediment, w_s is the settling velicity of the sediment particles in water and the parameter

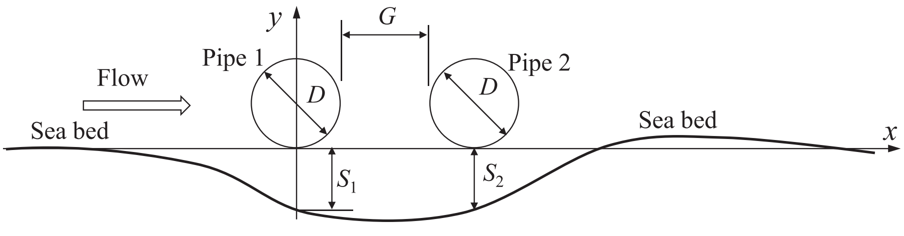

Fig. 1. Sketch for scour below two pipelines in steady flow.