Ocean Engineering 38 (2011) 1225–1236

Contents lists available at ScienceDirect

Ocean Engineering

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

Numerical simulation of a partially buried pipeline in a permeable seabed subject to combined oscillatory flow and steady current

Hongwei An*, Liang Cheng, Ming Zhao

School of Civil and Resource Engineering, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia

ARTICLE INFO

Article history:
Received 28 July 2009
Accepted 15 May 2011
Editor-in-Chief: A.I. Incecik
Available online 12 June 2011

Keywords:
Finite element method
Hydrodynamic forces
Pipeline
Seepage flow
Combined oscillatory flow and steady current

ABSTRACT

Hydrodynamic forces exerting on a pipeline partially buried in a permeable seabed subjected to combined oscillatory flow and steady current are investigated numerically. Two-dimensional Reynolds-Averaged Navier–Stokes equations with a $k-\omega$ turbulent model closure are solved to simulate the flow around the pipeline. The Laplace equation is solved to calculate the pore pressure below the seabed with the simulated seabed hydrodynamic pressure as boundary conditions. The numerical model is validated against the experimental data of a fully exposed pipeline resting on a plane boundary under various flow conditions. Then the flow with different embedment depths, steady current ratios and *KC* numbers is simulated. The amplitude of seepage velocity is much smaller than the amplitude of free stream velocity as expected. The normalized Morison inertia, drag and lift coefficients based on the corresponding force coefficients of a fully exposed pipeline are investigated. The normalized Morison force coefficients reduce almost linearly with the increase of embedment depth and that the *KC* only has minor effect on the normalized Morison coefficients. It is also found that the permeable seabed condition causes a slight increase on the inline force and has a little effect on the lift force, compared with corresponding conditions in an impermeable bed.

1. Introduction

Most of pipelines laid on erodible seabeds are found partially buried in the seabed after a period of time. Partial burial of a pipeline can be attributed either to installation stresses or to sediment transport processes around pipelines after installation. Pipeline embedment is beneficial to the stability of a pipeline as it reduces hydrodynamic forces acting on the pipeline and provides increased soil lateral resistance to the pipeline. Understanding of hydrodynamic force variation with pipeline embedment depth under different flow conditions is important for pipeline design.

Extensive research works on hydrodynamic forces and flow mechanisms around a pipeline (or a circular cylinder) subject to steady currents, waves and combined steady currents and waves have been published. A comprehensive summary and review of the works were given by Sumer and Fredsøe (1997). In many of the works conducted so far wave-induced flows were often approximated by sinusoidal oscillatory flow and flows induced by the combination of currents and waves are simplified as linear addition of steady current U_c and sinusoidal oscillatory flow $U_m\sin(2\pi t/T)$, where U_m is the velocity amplitude of oscillatory flow, U_c is the steady current velocity and T is the period of oscillatory flow. It is found that the hydrodynamic forces on the pipeline are governed by a number of non-dimensional parameters such as Keulegan–Carpenter number (*KC*), Reynolds number (*Re*) or alternatively frequency number (β) and ratio of U_c and U_m, defined as $m=U_c/U_m$, in addition to other common parameters such as pipeline roughness and proximity to the seabed. *KC*, *Re* and β are defined as

$$KC=U_mT/D \quad (1)$$

$$Re=U_mD/\nu \quad (2)$$

$$\beta=Re/KC=D^2/\nu T \quad (3)$$

where D is the diameter of the pipeline and ν is the kinematic viscosity of fluid.

So far, limited work has been done on hydrodynamic forces on a partially buried pipeline. Parker and Herbich (1978) carried out a series of laboratory tests to measure wave forces on a partially buried pipeline, while the experimental data showed strong degree of scatter. Ismail et al. (1986) derived a relationship between wave force coefficients and embedment depth based on existing data of fully exposed pipelines, potential flow solutions and a few assumptions. DHI (1986), Jacobsen (1988) and Jacobsen et al. (1989) measured hydrodynamic forces on pipelines partially buried in impermeable soil and exposed to combined waves and currents. It was found that hydrodynamic forces

* Corresponding author.
E-mail address: anhw@civil.uwa.edu.au (H. An).

0029-8018/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2011.05.010

acting on a partially buried pipeline were reduced substantially with the increase of embedment depth. For instance, for a pipeline with 40% embedment, drag and inertia coefficients were reduced by 60% and the lift coefficient was reduced by 30% (Jacobsen et al., 1989). The reduction of inline force was attributed to the reduction of exposure height and reduction of flow velocity above the pipeline, while the reduction of the lift was attributed only to the reduction of velocity above the pipeline (Jacobsen et al., 1989). Chiew (1990), Sumer et al. (2001) and Zang et al. (2009) investigated the mechanism of scour around partially embedded pipelines. It was demonstrated that the seepage flow through the seabed below a partially buried pipeline has a significant effect on the onset of scour.

Confusions exist in pipeline design practice on a recommendation in Det Norske Veritas (DNV) recent Recommend Practice DNV-RP-F109 (2007). DNV-RP-F109 (2007) recommends a 30% vertical load reduction due to permeable seabed condition if the vertical load used in an analysis is based on load coefficients derived from the assumption of a non-permeable seabed. It was argued (DNV-RP-F109, 2007) that "a permeable seabed will allow flow in the seabed underneath the pipe and thus reduces the vertical load". Skepticism about the validity of the recommendation exists because no reference was provided on this particular recommendation. It is speculated that the effect of flow through the seabed might have been overestimated, since the flow velocity in the seabed is often an order of magnitude smaller than the flow velocity above the seabed.

In this study, combined oscillatory flow and steady current past a partially buried pipeline in sands is investigated numerically. The primary objective is to investigate hydrodynamic force coefficients of the pipeline at different flow conditions and embedment depths, and to validate the DNV-RP-F109 recommendation. The embedment depth of the pipeline is in the range of $0.0 \le e/D \le 0.5$. Simulations are carried out at five m values of 0.0, 0.25, 0.5, 0.75 and 1.0 and four KC numbers of 10, 20, 30 and 40. The Reynolds number based on U_m and the diameter of pipeline in offshore engineering is in the range of $O(10^5)$–$O(10^6)$ depending on the pipe diameter and flow velocity. In present study a fixed Re value of 3×10^5 is selected. The study about oscillatory flow past a pipeline by DHI (1986) shows that the drag and inertia coefficients of inline force increases with Reynolds number, while the lift coefficient decreases as Reynolds number is in the range of 0.5×10^5–4×10^5. The present study focuses on the influence of embedment depth and flow ratio on the forces. The dependence of numerical results on Re is beyond the scope of this study and is not discussed in the present work. Local flow structure, pressure distribution and force coefficients are examined under those conditions.

2. Governing equations and numerical method

An illustrative sketch of flow over a partially buried pipeline with an embedment depth e is shown in Fig. 1. The two-dimensional Cartesian coordinate system is fixed at the center of the pipeline. The position of a point on the surface of pipeline is identified by angle α, which starts from the positive direction of x-axis and is defined as positive in counter-clockwise direction.

The flow investigated in present work is three-dimensional and turbulent physically according to the selected Re value of 3×10^5 (Sumer and Fredsøe, 1997). However direct numerical simulation of such three-dimensional flows is still prohibitively expensive from computational facility point of view. However, Reynolds-averaged Navier–Stokes (RANS) with turbulence closures and two-dimensional assumption is a feasible tool to simulate high Re flows around pipeline. Therefore the flow is simulated by a two-dimensional numerical model, in which the flow above seabed was simulated by RANS equations with a $k-\omega$ turbulence model closure (Wilcox, 1994). The code to solve RANS equations was initially developed by Zhao et al. (2007). Liang and Cheng (2005) investigated the effect of different turbulence models ($k-\varepsilon$, $k-\omega$ and SGS) on the simulation of flow around a pipeline, and concluded that '*the Wilcox $k-\omega$ models with the no-slip boundary condition on the cylinder surface give better predictions on the shedding of vortices than their counterparts using the wall function boundary condition*'.

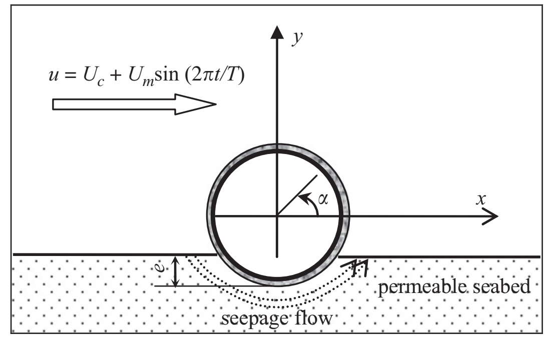

Fig. 1. An illustrative sketch of a partially buried pipeline subject to combined oscillatory flow and steady current.

The seepage flow in the seabed was simulated by the Laplace equation based on Darcy's law. This model has been used by Zang et al. (2009) to investigate the onset of scour around a partially buried pipeline. The details of the governing equations are not given in this paper but can be found in Zhao et al. (2007) and Zang et al. (2009).

The computational procedures for solving the governing equations are as follows:

(1) The flow field above the seabed and hydrodynamic pressure acting on the exposed surface of the pipeline and the seabed are determined by solving the RANS equations.
(2) The Laplace equation of pore pressure is solved by the calculated pressure from step (1) as the boundary conditions to obtain the pressure distribution on the invert of the pipeline.
(3) Hydrodynamic forces acting on the partially buried pipeline is calculated by integrating the pressure distribution around the pipeline surface and the shear stress on the exposed part of the surface.

It should be noted that the effect of seepage flow velocity streaming out of the seabed on the external flow is ignored in the present study, since the magnitude of the seepage velocity at the seabed is expected to be small.

3. validation of the numerical model

The numerical model is validated against the experimental data of steady currents, oscillatory flows and combined flows past a pipeline resting on an impermeable plane boundary. A computational domain of 80 D in length and 10 D in height is discretized by four-node quadrilateral elements as shown in Fig. 2. The distance from the center of the pipeline to the inlet boundary is 40 D. In order to maintain a good quality of computational mesh beneath the pipeline, the pipeline is deliberately placed above the plane boundary (seabed) by 0.005 D in the simulation. The gap between the pipeline and seabed is blocked computationally at the position of $x=0$. The total number of nodal points in the computational mesh is 24,036. High density of nodal points is distributed around the solid boundaries to ensure the accuracy of the solution. The pipeline perimeter is discretized by 200 nodal points and the