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Impact forces of submarine landslides on offshore pipelines

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A B S T R A C T

Impact forces induced by submarine landslides on pipelines are estimated using a computational fluid dynamics (CFD) approach. It is found that the predicted forces using the CFD approach are consistent with those predicted using the conventional geotechnical approach. It is also found that the impact angle of the debris flow induced by landslides affects the normal drag factor but hardly has any effect on the longitudinal drag factor. Empirical formulae for estimating normal and axial impact forces on a free spanned pipeline induced by an oblique debris flow are developed based on numerical test results. A new failure envelope that can be used in conventional geotechnical approaches is also obtained based on the numerical test results.

1. Introduction

Submarine landslides and debris flows frequently occur on both active and inactive continental margins and slopes. The released sediment volumes through landslides may travel hundreds of kilometers on gentle slopes (0.5–3°) over the course of less than an hour to several days (Bryn et al., 2005; Ilstad et al., 2004; Hühnerbach and Masson, 2004; Masson et al., 2006). They may seriously damage fixed platforms, submarine pipelines, cables and other subsea facilities and have severe negative economic impact (Nadim and Locat, 2005; Locat and Lee, 2002; Locat and Lee, 2005; Mosher et al., 2010). Pipelines, particularly export trunklines that carry hydrocarbon products from offshore production areas to onshore processing facilities, are the most exposed to impact risk from submarine slides because of their excessive length and varied terrain conditions they often encounter. To ensure the safe operation of submarine pipelines, it is important to assess the impact forces from submarine slides on pipelines (Jeanjean et al., 2005).

Generally speaking, submarine mass movements can be described using a fluid mechanics approach or a soil mechanics (geotechnical) approach. The fluid mechanics approach assumes that the submarine mass is fully fluidized, and the submarine debris flows behave like Bingham, Herschel–Bulkley or other non-Newtonian fluids. Therefore, fluid mechanics principles can be applied (O'Brien and Julien, 1988; Jiang and Le Blond 1993; Locat, 1997; Imran et al., 2001; Zakeri et al., 2008, 2009; Boukpeti et al., 2012a). However, a conventional geotechnical approach treats the submarine mass as soils. The soil drag forces on the installations are directly linked to the soil shear strength either linearly or through a power-law relationship, which involves the rate of shear (Leroueil et al., 1996; Locat, 2001; Zakeri, 2009a; Randolph et al., 2010; Zhu and Randolph, 2011; Boukpeti et al., 2012b; Randolph and White, 2012). Zakeri (2009a) reviewed the available methods for drag force prediction that were developed between the late 1970s and mid-1980s, which included both geotechnical and fluid mechanics approaches.

Submarine mass movements go through various stages: initiation, transition into debris flow, subsequent formation of a turbidity current and its movement on the sea floor until the final deposition (Locat and Lee, 2002). In the early stages of submarine landslides, the geotechnical approach is appropriate. However, in the later stages, the fluid mechanics approach may be more appropriate (Zhu and Randolph, 2011). Boukpeti et al. (2012b) continuously extended the geotechnical characterization of fine-grained sediments into the liquid range and proposed a combined model that could simulate the full process of submarine landslides. Sahdi et al. (2014) proposed a hybrid approach that combined geotechnical and fluid-mechanics-based components of the horizontal drag resistance. This approach provided an improved method to link the density and strength of the landslide material to the force applied on the pipe. In addition, this approach yielded a notably wide range of Reynolds number (0.00001–1000).

Zakeri et al. (2008, 2009) performed physical laboratory experiments and CFD analyses to estimate the drag force on a free-span or laid-on seafloor pipeline when it was impacted by a submarine debris flow normal to its axis. Zakeri (2009b) extended the investigation into oblique debris flow to the pipeline. Five angles of impact were selected for the CFD analysis: 0°, 30°, 45°, 60° and 90°. Most debris flow velocities were larger than 1.0 m/s in the numerical simulation. Based on these numerical results,

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Zakeri (2009b) proposed two empirical formulae to estimate the normal and longitudinal drag forces on a free-span pipeline at any attack angle.

Based on a re-analysis of the numerical results from Zakeri (2009b), Randolph and White (2012) proposed a failure envelope following a more geotechnical approach to estimate the axial and normal interaction forces for any attack angle of the debris flow. Although the envelope provided a reasonable fit to the data points for 45° and 60°, the data point for 30° lay well within the envelope and implied some concavity in the envelope. Randolph and White (2012) suggested that further detailed numerical simulation for flow angles between 0° and 45° are needed to resolve this issue. This somewhat motivated the present study.

To resolve the issue encountered by Randolph and White (2012), all the cases investigated by Zakeri (2009b), together with some additional cases with different flow oblique angles (7°, 15° and 75°) and low flow velocities, were re-simulated using a commercial CFD package on a refined mesh over that used in Zakeri (2009b). The effect of the debris material composition, attack angle and flow velocity on the impact force is discussed in details. The Reynolds number investigated in this study ranges from 1 to 350. Based on the simulation results, it is found that the impact angle strongly affects the normal drag factor but hardly has any effect on the longitudinal drag factor. Based on the numerical results, empirical formulae are developed to estimate the normal and axial impact forces on free-span pipelines at any attack angle. The CFD results were also re-analyzed following the geotechnical approach, and a new failure envelope was obtained to provide a reasonable fit to all data points, including the data point at 30°. The predicted forces based on the geotechnical approach agree reasonably well with the CFD results.

2. Fluid mechanics approach

Based on the CFD numerical simulations, Zakeri (2009b) proposed two empirical formulae to estimate the drag coefficients that are normal (C_{D-90}) and parallel (C_{D-0}) to the pipe axis, respectively, as shown in Eqs. (1).

$$C_{D-90} = 1.4 + \frac{17.5}{\mathrm{Re}_{non-Newtonian}^{1.25}} \tag{1a}$$

$$C_{D-0} = 0.08 + \frac{9.2}{\mathrm{Re}_{non-Newtonian}^{1.10}} \tag{1b}$$

The non-Newtonian Reynolds number, $\mathrm{Re}_{non\text{-}Newtonian}$, is expressed in Zakeri et al. (2008) as follows:

$$\mathrm{Re}_{non-Newtonian} = \frac{\rho U_\infty^2}{\tau} \tag{2}$$

where ρ is the fluid density, U_∞ is the free upstream flow velocity, and τ is the fluid shear stress, which can be calculated based on a rheological model such as the power-law or Herschel–Bulkley models. Based on Eqs. (1) and (2), the drag forces can be expressed as

$$F_{D-90} = C_{D-90}\left(\frac{1}{2}\rho U_\infty^2\right)A_{90} \quad A_{90} = A\ \sin\ \theta \tag{3a}$$

$$F_{D-0} = C_{D-0}\left(\frac{1}{2}\rho U_\infty^2\right)A_0 \quad A_0 = A\ \cos\ \theta \tag{3b}$$

where F_{D-90} is the drag force normal to the pipe axis, and F_{D-0} is the longitudinal drag force on the unit length pipe. A is the projected frontal area of the pipeline per unit length (m^2/m) in the normal impact situation. In other words, A equals to the pipeline diameter. θ is the angle between the fluid flow direction and the pipeline axis.

2.1. CFD numerical model

ANSYS CFX 13.0 (CFX 2010a, 2010b), which is a general purpose CFD program that includes a solver based on the finite volume (FV) method for unstructured grids, was employed in this study. The inhomogeneous two-phase separated Eulerian–Eulerian multi-phase flow model was used to simulate the submarine debris flow. A general description of the theory and the associated formulations are provided in Appendix A for reference purposes.

In the present study, eight attack angles were simulated: 90°, 75°, 60°, 45°, 30°, 15°, 7° and 0°. The 90° and 0° angles of attack correspond to the impacts that are normal and parallel to the pipe axis, respectively. Two pipe sizes were used in the numerical simulations: 25.0 and 50.0 mm outside diameter (O.D.). The domain dimensions and pipe arrangements in a plan view are shown in Fig. 1. In each simulation, the total drag force on a segment of the pipe (the hatched area on the pipe as shown in Fig. 1) was calculated in three directions: x, y and z. To minimize/eliminate any effect from the side wall on the forces exerted on the pipe, Zakeri (2009b) suggested to have the far ends of the pipe segment located at least four times the pipe diameter away from the walls. Furthermore, the downstream end of the pipe was not fully extended to the left wall. The boundary conditions employed

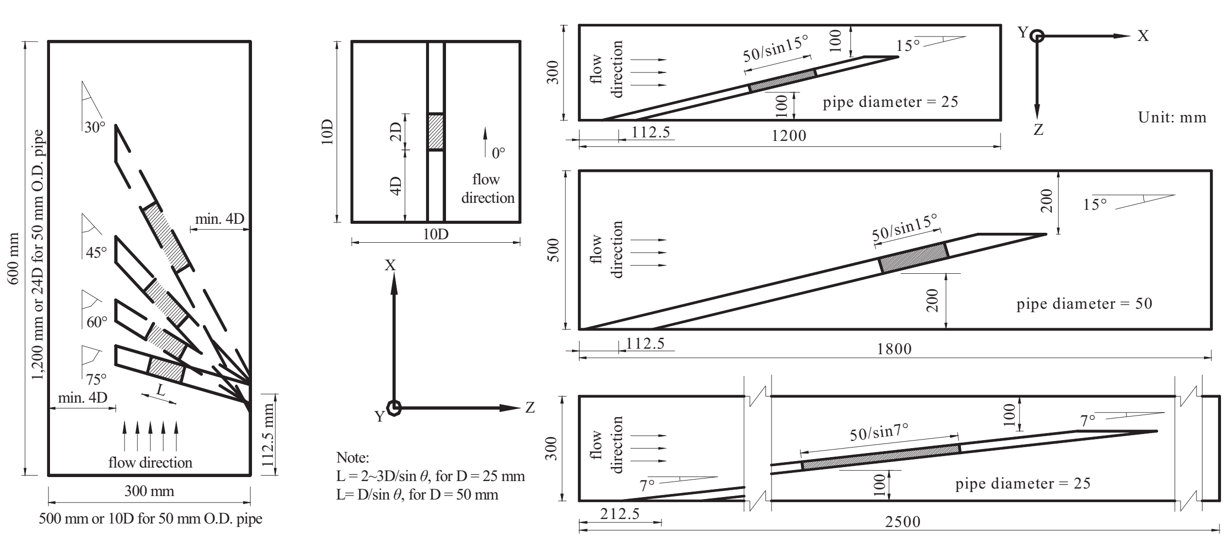

Fig. 1. Plain view of the domain dimensions.