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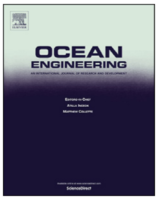

Investigation of impact forces on pipeline by submarine landslide using material point method

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ABSTRACT

Quantitative assessment of impact forces by submarine landslide is significant for the safe operation of pipelines that must cross potential runout paths. In this paper, the transient process of a submarine landslide impacting a pipeline is modelled using the material point method (MPM) with an enhanced contact algorithm. For simplicity, the partially-embedded pipeline is assumed to be fixed in space. The Herschel-Bulkley rheological model is incorporated to reflect the dependence of the undrained shear strength of the sliding mass on the shear strain rate. The behaviour of the mass flowing over the pipe was reproduced by allowing separation between the pipe and the sliding mass. The horizontal impact forces predicted by the MPM are verified by comparison with those estimated using a computational fluid dynamics approach. The impact forces are interpreted with a hybrid model considering the combined effects due to the soil's inertia, its shear strength, and also the asymmetric static pressure of the sliding material. The coefficients for the three terms are retrieved by a best-fit to the results of an extensive parametric study. The effect of the projected height of the pipe above the seabed is also investigated.

1. Introduction

Transportation of offshore oil and gas through pipelines requires consideration of the risks from submarine landslides emanating from the continental margins and slopes in the vicinity of pipeline routes. Submarine landslides, which may be triggered by phenomena such as seismic activity, dissociation of hydrate methane, diapirism etc., can lead to runout of debris comprising a mixture of soft sediments and water at speeds of up to 20 m/s (Jakob et al., 2012). The impact force from the sliding material may be substantial with respect to the integrity and functionality of the pipeline.

The magnitude of the impact force will be affected by the 'consistency' or strength of the debris, the velocity and height of the flowing material. Typically, the runout of submarine slides has been simulated through depth-averaged approaches, with the debris flow material modelled as some form of non-Newtonian fluid (Imran et al., 2001; Iverson, 2003). This practice has led naturally to the use of computational fluid dynamics (CFD) approaches to assess potential impact forces on seabed infrastructure, and in particular pipelines (Zakeri et al., 2009; Liu et al., 2015). However, such approaches fail to capture either the geometry of the debris flow (such as the height, relative to the diameter of a pipeline), or to distinguish between different contributions to the impact force, such as arising from inertial drag and what may be referred to as 'geotechnical' resistance. Published studies have also tended to focus on conditions where the pipe has been engulfed fully by the slide material, rather than initial conditions where the pipe is partially embedded in the seabed. The present study will help to determine whether pipelines will remain stable (partially buried) during slide impact.

In this paper, the impact forces of submarine slides on partially-buried pipes are investigated using the material point method (MPM) in geotechnical engineering. The pipelines are simplified as planar, since the effort of three-dimensional simulations would prove unacceptable given that a fine mesh and large sliding domain are needed. The slide material is characterised using a form of Herschel-Bulkley (H-B) model (Deglo de Besses et al., 2003), hence exhibiting strain rate dependency of strength. Attention is focused on the pipe-slide interaction during the early stage of impact under low or medium sliding velocities. A wide range of conditions have been explored in respect of the slide height and velocity, pipeline exposure above the seabed and different rheological

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properties for the slide material. Eventually the steady force, following an initial peak impact force, is then quantified with a hybrid model considering the combined effects due to the inertia, shear strength and static pressure of the sliding material.

2. Design frameworks

Estimation of impact forces on pipelines has generally focused on pipelines that are fully engulfed by (i.e. suspended within) slide material. Computational fluid dynamics (CFD) approaches, in which the sliding mass is regarded as an incompressible viscous fluid, have been used to quantify steady state forces, or average pressure, on elements of a pipe suspended within a moving fluid (Zakeri, 2009; Zakeri et al., 2009; Liu et al., 2015). The average pressure p, the horizontal force divided by the projected area of the pipe, is then expressed in terms of a drag coefficient C_D as

$$p = 0.5C_{D,Re}\rho v^2 \tag{1}$$

where ρ and v are the density and horizontal (free-field) velocity of the sliding mass, respectively. The drag coefficient, $C_{D,Re}$, is then expressed as a function of the non-Newtonian Reynolds number, $R_e = \rho v^2/s_u$ (Zakeri, 2009; Liu et al., 2015), where s_u is the mobilised shear stress (or strength).

For non-Newtonian fluids, the rate-dependent shear strength may be characterised by the Herschel-Bulkley (H-B) rheological model, expressed in its original form as (Deglo de Besses et al., 2003)

$$s_u = s_{u0} + K\dot{\gamma}^n \tag{2}$$

where s_{u0} is the yield strength at negligible strain rate, K a ‘consistency’ parameter, n the ‘shear-thinning’ index and $\dot{\gamma}$ the shear strain rate. In geotechnical applications, a normalised form of the H-B model has tended to be adopted, expressed as (Boukpeti et al., 2012a)

$$s_u = s_{u0}\left(1 + \mu\left(\frac{\dot{\gamma}}{\dot{\gamma}_{ref}}\right)^n\right) \tag{3}$$

where $\dot{\gamma}_{ref}$ is the reference shear strain rate and μ the viscosity coefficient. H-B fitting of rate-dependent penetrometer data presented by Boukpeti et al. (2012b) gave ranges of μ and n of 0.3–0.7 and 0.1 to 0.4 respectively, with $\dot{\gamma}_{ref}$ as 0.06 s^{-1}.

For the slide-pipeline impact problem, a convenient shear strain rate may be expressed as $\dot{\gamma} = v/D$. The non-Newtonian Reynolds number then becomes

$$R_e = \frac{\rho v^2}{s_u} = \frac{\rho v^2}{s_{u0}\left(1 + \mu\left(\frac{v/D}{\dot{\gamma}_{ref}}\right)^n\right)} \tag{4}$$

Relationships between drag coefficient and non-Newtonian Reynolds number have been proposed on the basis of laboratory flume experiments (Zakeri et al., 2008) and CFD analyses (Zakeri et al., 2009; Liu et al., 2015). Although these relationships work reasonably at moderate to high velocities of the slide, Equation (1) is not appropriate to estimate interaction forces accurately at low velocities. In general the force exerted on a pipe engulfed within slide material is influenced by two components: a drag force resulting from inertial effects, and a geotechnical resistance related to the shear strength (Randolph and White, 2012). The latter contribution becomes more significant at low slide velocities (Georgiadis, 1991; Zakeri et al., 2011; Sahdi et al., 2014).

Randolph and White (2012) suggested that for planar pipes fully engulfed by slides, the impact pressure may be expressed as

$$p = 0.5C_D\rho v^2 + N_c s_u \tag{5}$$

where N_c is a conventional geotechnical resistance factor and s_u is the undrained shear strength at the relevant shear strain rate (or v/D). Since the effect of viscosity is captured within the value of s_u, both C_D and N_c may be taken as constants, independent of the slide velocity. Equation (5) was proposed on the basis of pipes fully engulfed within the sliding mass, i.e. with no gap between the pipe and the slide. A modified form of this relationship is proposed later for the conditions considered here, with slide material breaking over a partially embedded pipeline, allowing a gap to be sustained at the rear side of the pipe.

3. Methodology

3.1. Material point method

The material point method (MPM), originated from the particle-in-cell method in CFD (Harlow, 1964). It can be regarded as a combination of finite element and meshfree methods, providing an acceptable balance between computational cost and accuracy for large deformation analysis. The MPM has an inherent advantage for large deformation problems such as run-out of landslides (Andersen and Andersen, 2010) and large-amplitude displacement of structural elements through soil (Phuong et al., 2016), since it discretises the soil as Lagrangian particles. The material mechanical and kinematic properties (mass, volume, velocities, deformation gradients and stresses) are recorded and updated at the particles, while a fixed rectilinear background mesh is used just for the calculation of each incremental step. Since the mesh is fixed in space, mesh entanglement that can occur in conventional finite element methods is avoided. The MPM analyses presented here, for slides impact on a fixed pipeline, were undertaken using an in-house program that stems from the open-source package Uintah (Guilkey et al., 2012). The Uintah package was enhanced with a contact algorithm ‘Geo-contact’ (Ma et al., 2014) and a GPU parallel computing strategy (Dong et al., 2015). The GPU parallelisation strategy allows for two-dimensional simulations with up to 20 million particles. The explicit updated Lagrangian calculation is based on the generalised interpolation material point method presented by Bardenhagen and Kober (2004).

3.2. Contact algorithm

The contact between the pipe and the sliding mass was implemented with an algorithm termed ‘Geo-contact’ (Ma et al., 2014). Compared with the contact algorithms presented in Bardenhagen et al. (2000, 2001), the Geo-contact reduces numerical oscillation in the quantitative contact forces effectively. The pipe was simplified as a rigid body due to its much higher stiffness than the sliding mass. According to the Geo-contact algorithm, the pipe and the sliding mass may be in contact at element nodes if non-zero particle masses from the two bodies are projected onto a given node. For a specific node i of the sliding mass in contact, the relative normal velocity to the pipe is $\Delta v_i = (v_i - v_0)n_i$, where v_i is the velocity at node i of the sliding mass, v_0 is the velocity of the pipe and n_i is the unit vector from node i to the centre of the pipe. Node i can be distinguished as approaching ($\Delta v_i > 0$) or departing from ($\Delta v_i < 0$) the pipe according to the sign of the relative normal velocity.

In Geo-contact, the relative normal velocities for the nodes may be reduced to close to zero in order to eliminate (or minimise) inter-penetration or, if required, separation. Alternatively, if separation is allowed, no adjustment of negative relative normal velocities is necessary, leaving the sliding mass free to flow away from the pipe. When the sliding mass comes in contact with the pipe, the value of Δv_i is reducing using

$$\Delta v_i' = f_i\Delta v_i \quad \text{where } f_i = 1 - \left(\frac{\min(s_i, h)}{h}\right)^k \tag{6}$$

where h represents the square element size, s_i is the distance from the node i in the contact region to the surface of the pipe and k is a penalty power. Introduction of the penalty function f_i permits slight