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# Centrifuge modelling of active slide–pipeline loading in soft clay

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Submarine slides are a significant hazard to the safe operation of pipelines in the proximity of continental slopes. This paper describes the results of a centrifuge testing programme aimed at studying the impact forces exerted by a submarine slide on an offshore pipeline. This was achieved by dragging a model pipe at varying velocities through fine-grained soil at various degrees of consolidation, hence exhibiting properties spanning from the fluid to the geotechnical domains, relevant to the state of submarine slide material. To simulate the high strain rates experienced by the soil while flowing around a pipe in the path of a submarine slide, tests were conducted at pipe–soil velocities of up to 4·2 m/s. The changing density and shear strength of the samples were back-calculated from T-bar penetrometer test results. A hybrid approach combining geotechnical and fluid-mechanics-based components of horizontal drag resistance was developed. This approach provides an improved method to link the density and strength of the slide material to the force applied on the pipe. Besides fitting the present observations, the method provides an improved reinterpretation of similar data from the literature.

KEYWORDS: centrifuge modelling; clays; consolidation; offshore engineering; pipelines; shear strength

## INTRODUCTION

With the expansion of the oil and gas industry into deeper waters, there is now a greater reliance on subsea infrastructure to extract hydrocarbon resources. Export pipelines, used to convey resources to shore, may be over 500 km long. The viability of these developments relies on the pipeline having sufficient integrity against potential damage from geohazards along the pipeline route. One of the most damaging forms of geohazard is the submarine slide. Compared with subaerial slides, submarine slides have greater mobility, with run-out distances of more than 100 km (Locat & Lee, 2002), and involve larger volumes of failed material. As a result, they pose serious threats to the safety of nearby pipelines, as illustrated by Jeanjean *et al.* (2005).

Existing methods to quantify the impact forces exerted by a slide on a pipeline can be divided into the geotechnical and fluid mechanics methods. At the onset of a submarine slope failure, the failed mass travels downslope, initially at low velocity (compared with the more advanced stages of a slide), and possesses geotechnical properties close to those of the intact parent (pre-failure) soil mass. Therefore the slide horizontal drag pressure $q_H$ can be estimated from the operative undrained shear strength of the soil $s_{u\text{-op}}$ using a conventional geotechnical bearing capacity factor $N_H$, to give

$$q_H = N_H s_{u\text{-op}} \tag{1}$$

However, $q_H$ is a function of the slide velocity, owing to the effect of strain rate and thus slide velocity on $s_{u\text{-op}}$ (Zhu & Randolph, 2011). To capture this effect, previous authors have proposed modifying $N_H$ (Georgiadis, 1991; Zakeri *et al.*, 2011). A more straightforward approach is to use a single $N_H$ factor – reflecting that bearing factors are essentially a function of the problem geometry, not the soil properties – and to account for the enhanced $q_H$ imposed at high velocities by adjusting $s_{u\text{-op}}$ for strain rate by way of a shear-thinning parameter $m$ (e.g. Biscontin & Pestana, 2001; Boukpeti *et al.*, 2012)

$$s_{u\text{-op}} = s_{u\text{-ref}} \left( \frac{\dot{\gamma}}{\dot{\gamma}_{ref}} \right)^m \tag{2}$$

where $\dot{\gamma}$ is the shear strain rate, and $s_{u\text{-ref}}$ is the reference undrained shear strength at a reference strain rate $\dot{\gamma}_{ref}$. Boukpeti *et al.* (2012) showed that, for a given soil, $m$ is independent of the soil density (or void ratio). Zhu & Randolph (2011) further demonstrated that, for materials such as soil with relatively low viscosity, it is sufficient to take $\dot{\gamma}$ equal to $v/D_{pipe}$.

As the failed mass travels further downslope, remoulding of the soil and interaction with the surrounding water take place. This causes a decrease in the shear strength (or mobilised shear stress) of the slide material (now known as a debris flow) compared with the original intact pre-failure slope. Debris flows can travel at velocities of typically 7–30 m/s (Bjerrum, 1971; Imran *et al.*, 2001; Canals *et al.*, 2004; De Blasio *et al.*, 2004). Although a debris flow has low shear strength, the density of the slide material is sufficiently high to cause damage to a pipeline installation located in the path of the debris flow. Because of the reliance on the slide material operative shear strength, the geotechnical approach (equation (1)) is inadequate on its own to estimate the slide impact force on a pipeline when inertial drag forces – which arise from the density of the flow, rather than its strength – are not negligible.

A common approach to assess the impact load from a debris flow is to start from a fluid drag perspective and characterise the flow as a non-Newtonian fluid. The slide impact force is linked to the slide material inertia (combined effects of slide density $\rho$ and velocity $v$) by way of a drag coefficient $C_D$ according to

$$q_H = C_D \tfrac{1}{2} \rho v^2 \tag{3}$$

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