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Centrifuge modeling of hydroplaning in submarine slopes

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ABSTRACT

A study of landslides on gentle submarine slopes with varied water content levels is presented here. The simulations were carried out in a beam geotechnical centrifuge submitting the model to an acceleration of 40 times earth's gravity. The simulations aim to determine which parameters influence the occurrence of the hydroplaning phenomenon and if these can be properly simulated in centrifuge physical modeling, since most studies described in the literature have been carried out in an environment of normal earth's gravity. The analyses presented here are based on measurements of total stresses and pore pressure in different points in the model. Besides, video images and parameters such as the densimetric Froude number are also used to assess whether the hydroplaning phenomenon has effectively occurred any of the tests performed.

1. Introduction

The occurrence of landslides can be a serious threat to offshore installations such as wells, rigs, pipelines and communications cables, among others underwater structures. Therefore, in order to assure safety operation conditions for structures resting on seabed, it is mister not only to find the trigger mechanisms, but also the running path of the debris, which is generally associated with hydroplaning phenomena.

Submarine landslide initiates when sliding material mixes with the water and becomes debris flow. This mixture of water and clay finely ground in an aqueous environment gradually develops to a turbidity current, which is characterized by turbulent flow. Submarine landslides and debris flows are highly mobile and can travel distances of hundreds of kilometers down gentle slopes (Locat, 2002; De Blasio et al., 2004). These great distances seem to be facilitated by the presence of a thin layer of slurry, which significantly increases debris mobility.

Naturally stable slopes may become unstable due to the action of one or more different mechanisms, such as earthquakes and tectonic activities, gas hydrates, ocean waves and human activities (Lee et al., 2004; Feeley, 2007), earthquakes being considered the main cause (Hance, 2003). Many experimental and numerical studies suggest that hydroplaning is the main cause of high mobility in landslides on gentle slopes (Mohrig et al., 1998; Harbitz et al., 2003; Barker, 1998; Zhao, 2014). Hu (2007) has developed a numerical model to simulate submarine sliding using a "block model" principle in order to study the mechanisms of hydroplaning, taking into account complex interaction between sliding block and the surrounding fluid. The author has numerically simulated small scale tests and an actual slide (Storegga Slide), with excellent results for both.

It is important to note that most previous experimental studies have been carried out in 1g models (Marr et al., 2001), thus they may not be representative of real landslides as the stress-strain behavior and gravity effects are better modeled using the principles of centrifuge modeling (Taylor, 1995; Madabhushi, 2015; Boylan et al., 2010; Chi, 2011); Gue et al. (2010) performed a series of submarine slope landslides tests in centrifuge, and concluded, also based on numerical modeling, that the correct scaling law for flow distance is determined by

$$d_p = N^3 * d_m \tag{1}$$

where d_m is the traveling distance of the model and N is the acceleration level.

The main aim of this study is to reveal, by means of centrifuge tests performed at an acceleration of 40g, which mechanisms and parameters, are involved in the generation of hydroplaning during the mobility of debris flow in such gentle slopes. In order to achieve these goals, sliding materials of different compositions and water content were tested.

2. Hydroplaning in submarine slopes

When a submarine flow moves through a water body, the movement of the water body in front of the sliding mass induces a fluid

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Nomenclature

p_f	fluid stagnation pressure
ρ_w	water mass density
v_f	frontal velocity of the flow
ρ	soil density
h_a	average sliding thickness
β	slope angle
g	acceleration of gravity
F_{rd}	densimetric Froude number
w	slurry water content level
wL	liquid limit
wP:	plasticity limit
IP	plasticity Index
N	acceleration level

pressure higher than the hydrostatic pressure. Under these conditions, fluid stagnation pressure is defined as hydrodynamic pressure which acts in the nose of the sliding mass$p_f$and may be expressed by Mohrig et al. (1999):

$$p_f = \frac{\rho_w v_f^2}{2} \tag{2}$$

where ρ_w is the water mass density and v_f is the frontal velocity of the sliding mass.

The excess of pore water pressure which takes place during the mass movement develops from the stagnation point "s" to the sliding surface in point A, as shown in Fig. 1. The point where hydroplaning begins is represented by "A".

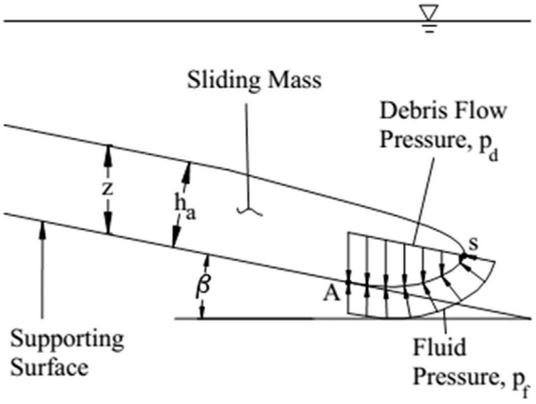

Fig. 1. Behavior of clay-rich mud flow (Ilstad et al., 2004a).

Fluid pressure is resisted by the equivalent downward normal stress p_d, also called debris flow pressure, and produced by the submerged weight of the sliding mass on the slope. Normal stress can be, therefore, calculated by:

$$p_d{=}(\rho_d{-}\rho_{w)}\,gh_a cos\beta \tag{3}$$

where ρ_d is the soil density and g is the acceleration of gravity. The term h_a represents the landslide's average thickness and β is the slope angle.

There are some conditions to hydroplaning to occur, and it is worth to mention them in a separate way for clarifying purposes.

- Condition I: Hydroplaning occurs when the hydrodynamic pressure (p_f) acting in front of the sliding mass exceeds the normal stress produced by the submerged sliding mass on the normal sliding surface (p_d).
- Condition II: As consequence of Condition I, chances of hydroplaning to occur is related to the lift of frontal head, which can be visualized from high speed images.
- Condition III: This condition is directly related to the densimetric Froude number which is defined as

$$F_{rd}{=}\sqrt{2\left(\frac{p_f}{p_d}\right)} \tag{4}$$

Mohrig et al. (1998, 1999) calculated F_{rd} for 1 g experiments in submarine slopes, and concluded that 0.30 should be the minimum value for F_{rd} in order for hydroplaning to occur.

- Condition IV. Following previous studies, Ilstad et al. (2004c) observed three main conditions in 1gtests of submarine slopes (Fig. 2): a) the grains are in direct contact with the base, thus total stresses are higher than pore pressures (Fig. 2a); b) the debris flow is

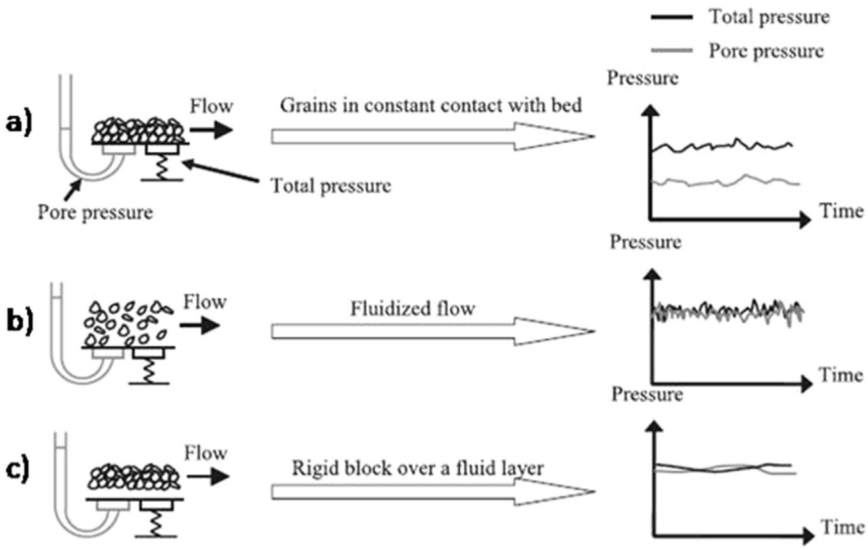

Fig. 2. Representation of stress patterns observed in 1 g mudflow tests (Ilstad et al., 2004a).