Physical Modelling in Geotechnics

Sequential submarine landslides: A study on a centrifuge planar setup

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ABSTRACT: Submarine landslides are gravity driven processes which can occur at the transition from the continental shelf to the continental slope. Clearly, these mass flow processes are in close range of interaction with many types of offshore infrastructure. In the southern Caribbean of Colombia's margin, submarine landslides are identified as consecutive mass failures which start near the shelf edge and intraslope at a relatively fixed location. A sequence of submarine landslides is often interpreted from the amalgamated discontinuities in the seafloor topography, identified from bathymetry and seismic profiles. The mechanisms behind these discontinuities are still unclear, demanding a simple model that differentiates between potential slide folds or sediment accumulation. In this work, we study the mobility of a sequence of immersed granular collapses over scaled-longitudinal-height-profiles. Experiments are performed in a planar model box, consisting of a thin channel, holding and releasing a granular wedge of ceramic beads. The planar model is tested in a 1g condition and in a centrifugal acceleration field, allowing the direct monitoring of the collapse kinematics and the deposit geometry and runout. The planar model adjustment to the centrifuge basket allows for an extension on the model dimensions, providing a novel opportunity for mid-rage centrifuge machines. Overall, the experimental setup allows a clear identification of the collapse sequence and its coupled motion with the surrounding fluid. The sequence of deposits shows parallel bedding, with no disruption of previous deposit profiles. This works provides a unique opportunity for the validation of numerical tools on the simulation of submarine mass movements.

Keywords: immersed flows, granular flows, physical modelling, submarine landslide.

1 INTRODUCTION

In the last decades, the offshore energy industry (e.g., oil, wind, gas) has driven a continuous growth and development of its infrastructure, demanding innovative foundation designs and facing previously unattended geotechnical hazards, like submarine landslides (Randolph et al., 2005; Randolph & Gouvernec, 2017). Submarine landslides occur at the transition from the continental shelf to the continental slope. These mass flow events can be triggered by three main sources: earthquakes, sedimentation, and release of gas-shale hydrates (Masson et al., 2006). Among the main uncertainties in the study of submarine landslides are the prediction of its runout distance and the characterization of its depositional patterns (Hampton et al., 1996), both in a potential interaction with the offshore infrastructure.

In the southern Caribbean of Colombia's margin, submarine landslides are identified as consecutive mass failures which start near the shelf edge at a relatively fixed location (see Fig. 1). A sequence of submarine landslides is often interpreted from the amalgamated discontinuities in the seafloor topography, identified from bathymetry and seismic profiles (see inset in Fig. 1). The bathymetric profiles show mean slopes between 2º and 11º, over a distance of about 1 km. The mechanisms behind these discontinuities are still unclear, demanding a simple model that differentiates between potential slide folds or sediment accumulation. In this work, we study the mobility of a sequence of immersed granular collapses over a scaled longitudinal-height-profile, by developing a novel large planar setup for centrifuge modeling. The novelty of this setup is twofold, it allows direct visualization of the collapse kinematics and extends the allowable dimensions of model containers in mid-rage centrifuge machines. The following sections focus on the characteristics of the large planar setup, the 1*g* and centrifuge tests observations, and finishes with the main remarks and recommendations for future works.

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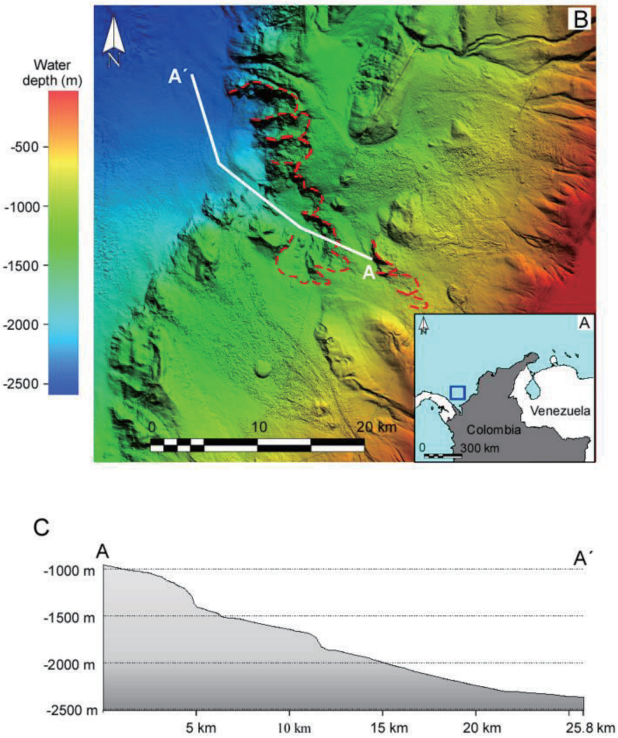

Fig. 1. (A) Colombian Southern Caribbean coast and the Sinú-offshore area. Bottom-right inset shows the location of panel B. (B) Bathymetric map showing the location of the topographic profile analyzed in this study. Red dashed lines are mass failures crowns. (C) Topographic profile across consecutive mass failures starting at the continental slope.

2 METHODS

In this work, we simplify a submarine landslide as a granular wedge, with a vertical face and a flat top, extending over a given bathymetric profile (Grilli et al., 2017). In slopes of less than 45º, the granular wedge extends a couple of times its height (H_0) at the vertical face. The wedge geometric characteristic demands for long experimental setups, providing enough space for its formation, collapse and runout. Moreover, the model domain needs to grant additional space for the formation of new wedges with the purpose of studying a sequence of submarine landslides. In consequence, the required model dimensions become challenging for most model containers in mid-range geotechnical centrifuges. As a result, we use a planar configuration, similar as that employed for the study of submerged mass flows by Pinzon & Cabrera (2018) and Cabrera et al. (2020), and extend on the alternative configuration for centrifuge model containers presented in Estrada et al. (2006) for the study of mass flows.

The runout of a granular wedge is expected to be mainly controlled by H_0 and not by the wedge size, extending on the observations on granular column collapses (Cabrera & Estrada, 2019; 2021). Therefore, the use of centrifuge modelling is intended to account for the upscaling of the coupled particle-fluid interactions during collapse, and shed light on the depositional patterns after a sequence of submerged collapses. More details on the scaling principles of granular flows in a centrifugal acceleration field are presented in the accompanying paper of Cabrera & Leonardi (2022).

2.1 Planar setup for centrifuge modelling

The experimental model consists of a large planar setup, of two PMMA plates of 1.5 m long, 1.1 m high, and 10 mm thick, and an aluminum sheet, of 1.5 mm thick, lying between the PMMA plates (see Fig. 2). The bathymetric profile shown in Fig. 1 is reproduced by laser cutting the aluminum sheet at a scale of 1:5000. In addition, two fommy layers, of 3mm thick and covered with petroleum-jelly, are placed and compressed at the interface between the aluminum sheet and the PMMA plates, reducing the fluid volume and preventing fluid leaks at the model perimeter. The effective width between the PMMA plates is of approximately 2.5 mm. The PMMA plates and aluminum sheet are hold in place by a steel frame, secured by M8 bolts on its perimeter. The steel frame is connected to a centrifuge container by means of a U-shaped structure (see Fig. 2(b)), providing an alternative for extending the container model capacity in centrifuge modelling. Moreover, the model is backlighted by a high-intensity LED panel and recorded by using a high-speed camera at a frame rate of 500 Hz and with a resolution of 1280 px by 1024 px, centered at the wedge vertical face.

The granular wedge consists of a frustrated packing of ceramic beads, of 2 mm in diameter and with a particle density of 6000 kg/m^3, manufactured by Sigmund Lindner GmbH. The ambient fluid used in the experiments is tap water. The granular wedge is constrained by an aluminum needle of 2 mm diameter. The needle is pulled-up by a pneumatic actuator at a pressure of 8 bars. The pneumatic actuator is fixed on top of the steel frame and is connected to the needle by a nylon monofilament. The wedge release occurs in about 20 to 50 ms, ensuring a rapid release and minimal drag on the grains in contact with the needle.

The experimental protocol starts by placing the needle at a marked position on the bathymetric profile. The model saturation is performed by fluid injection in a side-top entry, until reaching a fluid height of 1 m from the model base. The granular wedge is then built behind the needle, up to the desired initial height, and shuddered to assure a flat top. The LED panel and the high-speed camera are activated and the pneumatic actuator releases the granular wedge. The runout distance reached by the wedge collapse sets the new location of the needle. A new granular wedge is then built in the free-space between the previous collapse and the needle, maintaining the same flat top. At this point, the wedge release is activated and a new collapse is observed. This

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experimental protocol is repeated until reaching three consecutive wedge collapses, allowing the visualization of the collapse kinematics over pre-existent deposits.

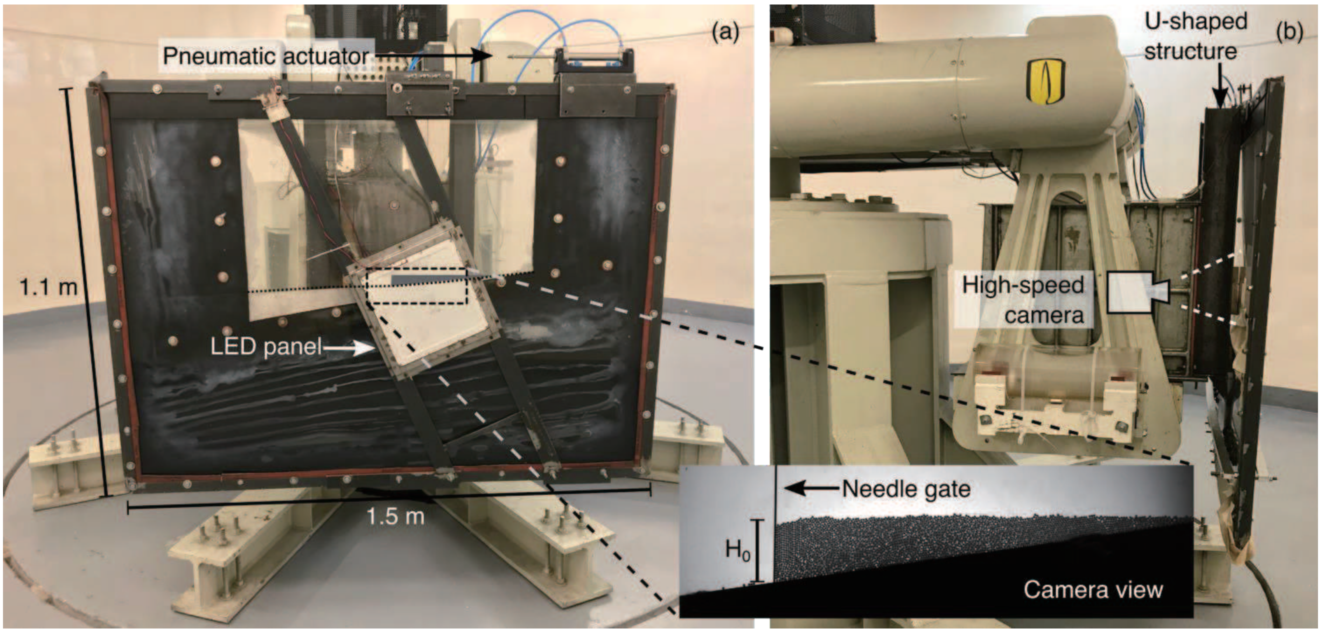

Fig. 2. Experimental setup mounted in the geotechnical centrifuge. (a, b) Front and side views and inset with camera view.

3 RESULTS AND DISCUSSION

The following results focus on two series of experiments, one conducted outside the centrifuge (termed as 1*g*) and one conducted under an effective centrifugal acceleration of 10*g*. Both experiments allow a complete visualization of the collapse kinematics. The wedge initial heights, after three consecutive collapse events, vary between $H_0 \in$ [50 to 55] mm at 1*g* and $H_0 \in$ [75 to 96] mm at 10*g*. Each collapse event transitions trough three stages (see Fig. 3). First, the vertical face accelerates, releasing a collection of grains above a well-defined sliding plane. Then, the moving grains spread laterally at a constant velocity, until reaching its final stage and coming to a halt. Overall, these stages are common for both 1*g* and 10*g* tests, with a quicker collapse in the case of 10*g* tests. Note that the packing of grains under 10g is denser than that at 1g, reducing $H_0 \in$ [32 to 57] mm after the collapse sequence. This occurs due to small deformations on the PMMA plates and the inclination of the needle, due to the centrifugal acceleration field, widening the gap between plates. Despite this variation in the initial configuration, the observed behaviors remain equivalent.

By means of digital image analysis is possible to identify the region of moving grains, the configuration of the sliding plane, the runout distance and the slope of the final deposit. Overall, the deposit of all collapse events is characterized by an approximately constant inclination and close to the value of the repose angle of ceramic beads in a planar configuration (≈ 28.1°), while the inclination of the deposit sliding surface is close to 50.5°. In consequence, the occurrence of a slide above a pre-existent deposit will not cause deformations on the former. Moreover, the profiles of different events belonging to the same landslide sequence are separated by a common thickness of ≈ 25 mm. Finally, the runout distance reached by the sequence of collapses increases proportionally to $H_0^{0.7}$, confirming previous observations on the collapse of short columns (Pinzon & Cabrera, 2019).

4 CONCLUSIONS

This paper presented an experimental setup for the study of a sequence of submerged landslides, providing a novel insight into the deformation and displacement patterns during and after collapse. The experimental setup introduces an alternative for testing large containers in mid-range centrifuges. The triggering mechanism provides a smooth and quick release of the granular wedge. The overall collapse stages remained unchanged between single collapse events, showing that grains slide over a plane above the precedent deposit slope and the characteristics of the sliding planes and deposit slopes are fully controlled by the material frictional contacts. Finally, the effect of the centrifugal acceleration field focuses on the increase on the collapse inertia, without resulting in a change in the flow regime.

Future works could use the direct experimental observations for the validation of coupled numerical methods, aiming at developing a rational methodology for evaluating the associated hazard of submarine landslides and offshore infrastructure.

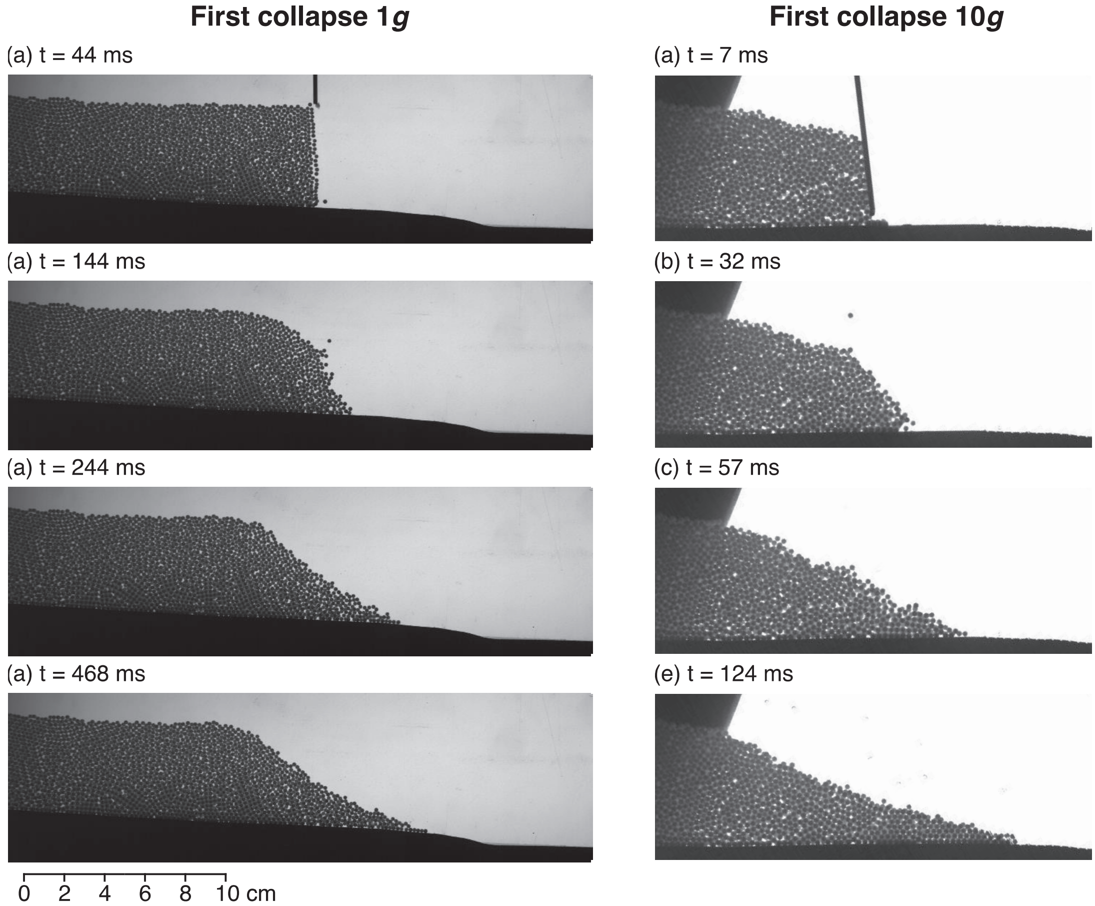

Fig. 3. First collapse event at (right) 1*g* and (left) 10*g*. Note that the gate releases simoultaneously all grains without inducing notable perturbations on the released grains.

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