Flowslide Impact Modelling (FIM) project: centrifuge tests

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ABSTRACT: The paper deals with the interaction mechanisms that develop when a flow-like mass movement hits a protection barrier. Propagation-impact experiments were conducted in the Geo-Centrifuge of Deltares (Delft, Netherlands) at 40 *g*-level and they consisted of releasing a saturated soil mass that propagated along an instrumented slope and finally impacted against a barrier. Different protection structures, rigid and fixed to the ground as a reinforced concrete wall or deformable and free sliding as a geosynthetics-reinforced barrier were tested. The structure's height relative to flow depth was varied also. A natural Vesuvian volcanic soil, prone to static liquefaction upon shearing, was used for the first time. This is a major novelty compared to uniform particle size material previously used in the literature. As benchmark cases, solely water and a well-documented Baskarp sand from Sweden were also used. The impact pressure, total stresses and pore water pressure during the flow and the impact were measured. Insights on the role of fine content were obtained for updating the design criteria of the protection barriers. The first analysis of the tests showed that the magnitude of the peak impact pressure and its time dissipation is apparently influenced by granulometry of flow and type of barrier. The particle size regulates the flow dynamics and landslide-structure interaction, and finally results in different impact mechanisms, and type of landslide-structure interaction such as dead zone formation, run-up and/or overtopping.

1 INTRODUCTION

Flowslides occur during intense rainfall events where the saturated soil has low strength. Fluid-like behavior is predominant during propagation and impact against structures (Cuomo et al., 2020a,b), but solid-fluid interaction in the flow plays a role and soil mechanics needs for quantitative assessment (Cuomo et al., 2021,2022; Di Perna et al., 2022, 2023).

Centrifuge modelling is a valuable experimental tool to investigate complex geotechnical problems like understanding flowslide mechanisms. Indeed, centrifuge is one of the few options when full-scale testing in the field is very expensive or unfeasible like for flow-like landslide propagation and impact on protection structures.

This tests series builds upon the work of Song et al. (2017). The novelty relates to the use of natural soil instead of uniform particle size material. The particle size regulates the flow dynamics (Jiang et al., 2015; Cui et al., 2018). On the other hand, the modification of the falling height and distance of the barrier is expected to cause different impact mechanisms (Choi et al., 2015). The results consisted of: time trends of total and pore water pressure for different impact mechanisms, insights on the role of fine content and suggestions for design.

2 MATERIALS AND METHODS

The research project named FIM (Flowslide Impact Modelling), in the EU-funded GEOLAB, intended to explore five slope configurations, with a fixed barrier at two different locations, with a deformable movable barrier at two different locations, and without any barrier. The experiments involved three different materials - pure water, a saturated fine-medium sand, and a natural volcanic silty sand - in two different volumes, one 1.5 times larger than the other.

The basic idea of the centrifuge tests was to span over the combinations of the previous factors with the twofold goals to investigate the landslide-structure interaction mechanisms, and to use numerical back-analysis to assess key mechanical parameters of the fast-moving flowing materials, that are impossible to obtain with standard geotechnical tests.

In the paper we will illustrate and compare a first selection of the test results, showing the novelty of the research and the potential future improvements.

2.1 GeoCentrifuge at Deltares

The centrifuge model can accurately reproduce the fast movement of the sliding mass with realistic total stresses, pore water pressures, and the interaction between the constituents (drag forces) at prototype scale. Contrary to other devices (such as flume tests) used to model similar problems, these dominant factors are not scaled down in the centrifuge. Moreover, the centrifuge is the optimal experimental device to reproduce the field conditions of a dynamic impact loading problem experienced by a protection structure impacted by a flowslide.

The Deltares Geo-Centrifuge (Figure 1) is a C72-3 beam type centrifuge. It has a 260 g-ton capacity and a platform radius of 5.0 m. The platform can house a large strongbox (87.2×20×40cm) with one transparent wall to host the model.

All the tests were conducted under 40 *g* acceleration (N=40), meaning that in the prototype the lengths and the dynamic time are amplified by N, the forces are multiplied by N^2, while stresses, density and velocity are unchanged and directly measured inside the centrifuge equipment.

Figure 1. View of the GeoCentrifuge of Deltares, Netherlands (image courtesy of Deltares).

2.2 Experimental set-up

The tests aimed to simulate a real case of a piedmont area where a flowslide propagate and interact with different protection barriers. The model has a steel support structure, the slope is 330 mm long, the base slope is 20° steep. The mass falls from 342 mm and the friction at the interface between the flowing mass and the steel structure is assured through a grip tape (friction coefficient of about 0.8) glued on the support structure and on the barrier surfaces.

Five configurations were employed: 0) no barrier; 1-2) with a rigid barrier (resembling a reinforced concrete wall anchored to the ground) at two different locations and 3-4) with a free-sliding barrier (to mimic a greened geosynthetics-reinforced embankment) at two different positions. The configurations 0, 2 and 4 are shown in Figure 2. The rigid barrier is made of steel, while the free-sliding barrier consists of hard stone with a nominal compressive strength of about 65 MPa, enveloped with the grid tape glued on the slope. In the configuration b and c, the barriers can be in position 1, close to the toe of the slope, or in position 2 (see d in Table 1). The integrity of the barriers is ensured since the expected impact pressure are in the order of a few hundred of kPa for this type of flows, as estimated from previous studies (Cuomo et al. 2021, Di Perna, 2022). This value is much lower than the ultimate resistance of the steel and hard stone used.

In each configuration, pore pressure transducers (PPTs) and load cells (LCs) were used, as shown in Figure 2.

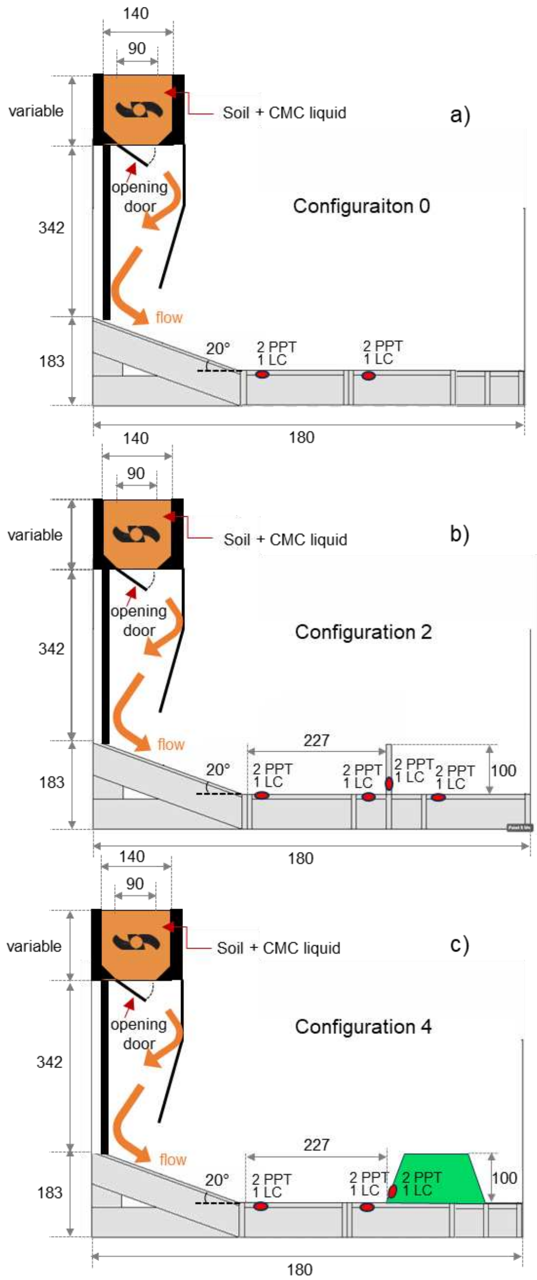

Figure 2. Some set-up configurations: a) no barrier; b) fixed rigid barrier at distal position; c) free-slide deformable barrier at distal position.

In particular, the LCs are along the center line of the channel and the PPTs are placed 1 cm to the right and 1 cm to the left of the LC. The PPTs were EPB-PW_7BS-/Z0/PC0.5/L5M (700 kPa), which is a PPT specifically designed for pore water applications in either centrifuge or laboratory equipment. Such a PPT has a small size (6.4×11.4mm) and a Porous Ceramic stone with air entry at 0.5 bar. The Coriolis effect was not investigated in these experiments since the Coriolis acceleration diminishes rapidly once the flow impacts the barrier because the flow velocity rapidly attenuates through grain contact stresses and viscous shearing, as demonstrated from previous centrifuge works (Choi et al 2015., Song et al. 2017).

The total stress transducers (LCs) were Kyowa type BED-A-1MP (1 MPa), i.e. a small-sized soil pressure transducer with an outer diameter of 30 mm and a pressure-sensing surface diameter of 23 mm.

Other details of the set-up are shown in Figure 3. The soil is mixed during the flight in the top container. The opening system of this container is a gate that opens clockwise, away from the nearby wall. A fixed inclined slider directs the saturated mixture towards the top of slope, from where the soil mass propagates downslope.

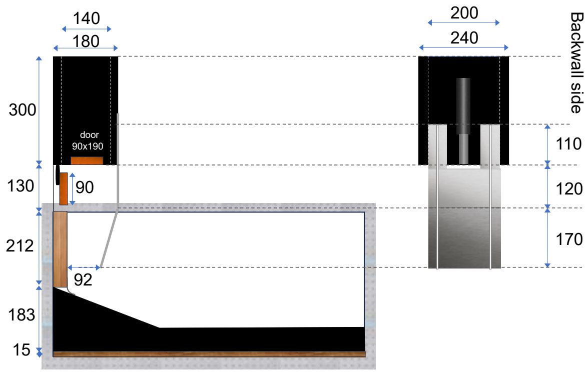

Figure 3. Details of the opening gate and slider.

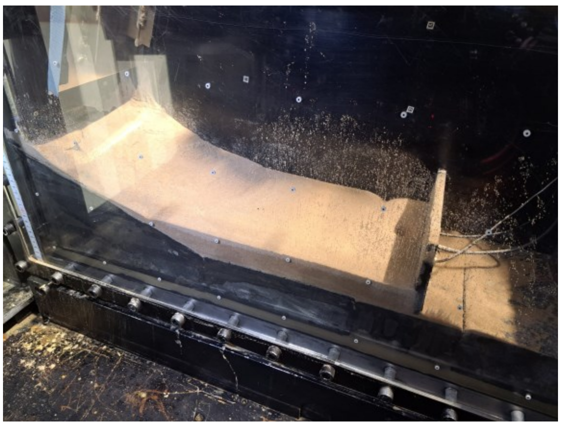

Figure 4. View of the centrifuge model at the end of a trial test with uniform sand.

Non-contact measurements were performed using two high-speed cameras with a maximum resolution of 1,920×1,800 pixels and an acquisition of 2,500 frames per second. A picture of the set-up at the end of a trial test with uniform sand is shown in Figure 4. Image analysis was carried out through particle image velocimetry (PIV) technique, which is a non-contact, non-intrusive optical flow measurement technique, very well suited to trace the path of particles in a flow (Hain and Kähler, 2007).

2.3 Materials and tests

The tests were performed on a saturated natural soil and compared to a saturated Baskarp sand and to pure water used as benchmark tests.

The natural soil is a Vesuvian volcanic silty-sand soil characterized by low specific gravity (2.3 – 2.80) with D_{10}= 0.0127 mm, D_{50}= 0.1613 mm and D_{80}= 1.9296 mm, labelled as ITA soil hereafter. On the other hand, the so-called Baskarp (B25) is a silica sand (specific gravity 2.65) with D_{10} = 0.144 mm, D_{50} = 0.222 mm and D_{90} = 0.331 mm.

A viscous liquid fluid was used to avoid discrepancy between the time scales for pore fluid diffusion processes and inertia processes, when translating from prototype to model. The viscous fluid consisted of a solution of water and carboxy methyl cellulose (CMC) in such a proportion that the liquid viscosity equalled 0.04 Pa·s (corresponding to 0.001 Pa·s in prototype, which is the dynamic viscosity of water). The density of this viscous liquid is close to water (1,000 kg/m^3), thus the granulometric structure of the sample was not changed.

The test procedure can be summarized as: i) sample preparation, ii) spinning, and iii) release.

The mixture of CMC-saturated soil was created at least 12 hours before the test, to ensure the saturation of sample. For each test, the mixture was put in the mixing container.

Then the strongbox was spined up to 40 g increasing the g level with 5 g/min. The 5 g/min was chosen to prevent the drying of the PPTs. During the flight, a tailored-designed mixer prevented solid–liquid segregation. The stabilization of the sensors at 40g was ensured by waiting a few seconds before the release. Then, the hinged door of the mixing container was released in-flight, using a hydraulic actuator.

Once the container door was released, the saturated soil mass fell and was guided along the slide towards the top of the slope and propagated downwards, along the slope.

Table 1. Set up combinations: M= release mass, H = barrier height, d = barrier distance from the toe of slope.

Conf.	Details	Main parameters prototype scale			Main parameters model scale		
		M (ton)	**H (m)**	**d (m)**	**M (kg)**	**H (mm)**	**d (mm)**
0	no barrier	455 or 672	-	-	7 or 10.5	-	-
1	Rigid barrier in position 1	455 or 672	4	2.4	7 or 10.5	100	6
2	Rigid barrier in position 2	455 or 672	4	9	7 or 10.5	100	227
3	Free-sliding barrier in position 1	455 or 672	4	2.4	7 or 10.5	100	6
4	Free-sliding barrier in position 2	455 or 672	4	9	7 or 10.5	100	227

3 SELECTED RESULTS

3.1 Images and global behaviour

The flow velocity was estimated through the images of two high-speed camera, elaborated via PIVlab, a MATLAB tool (Thielicke and Sonntag, 2014, 2021), which adopts PIV technology.

An example of the high-resolution images acquired is provided in figure 5a, while examples of the maps created with PIV are showed in figure 5b-c, from where estimates of flow velocity along the barrier were also obtained (Figure 6).

The velocity vector map (Figure 5 b) shows the velocity as a vector with direction of the velocity, which also allow defining the direction and the angle of flow impact on the barrier. The velocity magnitude map (Figure 5 c) shows the zones close to the barrier where the velocity reaches the maximum values.

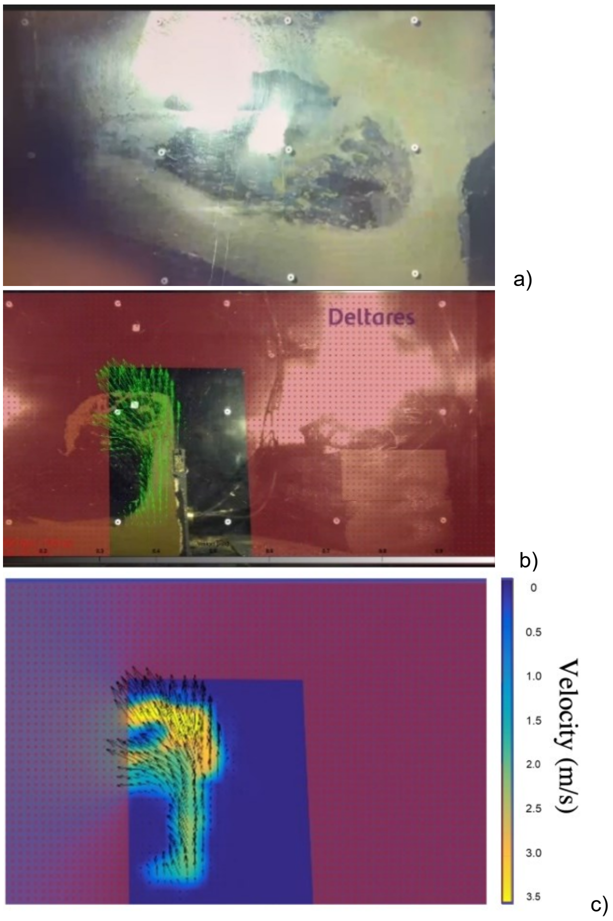

Figure 5. Examples of: a) image by high-speed camera, b)-velocity vector map, c) velocity magnitude map.

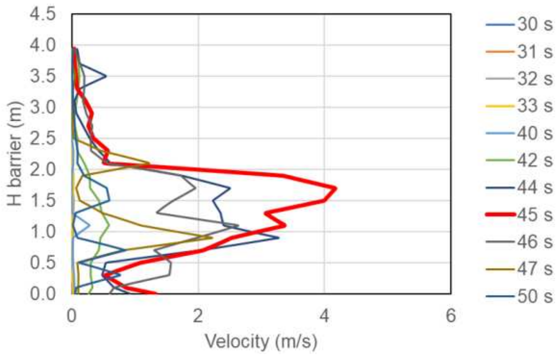

Figure 6. Flow velocity estimated along the rigid barrier at different time lapses.

3.2 Measured flow stresses

The basal flow total stress generated during the impact was measured using total load cells (LCs) located at the toe of the slope, and on the rigid and free-sliding barriers. The resulting measurements of some tests are showed in Table 2 and Figures 7 to 9.

The measured total stress at the toe of the slope appeared to be quite reproducible. For instance, it equals about 15 kPa for tests 10 and 16 (Baskarp sand B25) and equals about 50 kPa for tests 11 and 17 (Vesuvian soil ITA). The difference in total stress measured for the two materials (15 kPa instead of 50 kPa) is related to their different flow propagation patterns (Table 2).

Experimental evidence to consider for further interpretation (also based on geomechanical modelling) is that the peak impact pressure measured on the rigid barrier (independent on the configuration, namely Config. 1 or Config. 2) is higher for Baskarp sand than Vesuvian soil. This is the case for tests 14 and 15 (with approx. 70 kPa versus 60 kPa, respectively, figure 7) and for the tests 16 and 17 (with approx. 120 kPa versus 105 kPa, figure 8).
Another insight comes from the comparison of the peak impact value measured on different types of barriers positioned at the same location. Comparing tests

11 and 17 (figure 9) shows a peak impact of approximately 105 kPa on the rigid barrier (config.2) versus about 75 kPa (config.4) in the free-sliding barrier, which confirms the interest to use movable protection barriers towards traditional fixed barriers.

Table 2. Initial mass and measured stresses for some tests.

ID	Config.	Material	Initial mass (kg)	Peak total stress at the toe of the slope	Peak total stress on the barrier
10	4	B25	10.5	14.80	**<u>27.53</u>**
11	4	ITA	10.5	57.74	74.86
14	1	B25	7.0	73.17	71.47
15	1	ITA	7.0	66.74	58.238
16	2	B25	10.5	15.00	118.23
17	2	ITA	10.5	48.54	106.14

4 CONCLUSIONS

The interaction mechanisms, which develop when a flow-like mass movement hits a protection barrier, were investigated through propagation-impact experiments performed in the GeoCentrifuge of Deltares (Delft, Netherlands).

The centrifuge tests allowed estimating the magnitude of the impact pressure and time trends of total stresses and pore water pressure generated during the impact.

The paper presents a first analysis of the tests performed on Baskarp sand (B25) and Vesuvian soil (ITA) and using five different set up configurations are presented. The image analysis carried out through Particle Image Velocimetry (PIV) enables to estimate the evolution of the flow impact velocity along the barriers. The PIV also allows plotting a velocity map for each image acquired by the two high-speed cameras. The PIV furthermore estimated a map of the flow velocity direction and the direction of the flow at the impact with the barrier.

Local measurements of the basal flow total stress generated during the impact were acquired at the toe of the slope and on the barrier. The results underlie that, independent on the configuration, the peak impact pressure measured on the rigid barrier is higher for monogranular sand than natural soil. Thus, the grain size distribution apparently influences the magnitude of the impact and the time necessary to dissipate the stress. Moreover, the peak impact value is also influenced by the type of the barrier even if they are placed at the same location, e.g. the rigid barrier experienced higher peak impact than the free-sliding one.

These insights should be used as starting point to design new set-up configurations for centrifuge tests and to investigated further natural soils through centrifuge and numerical modelling.

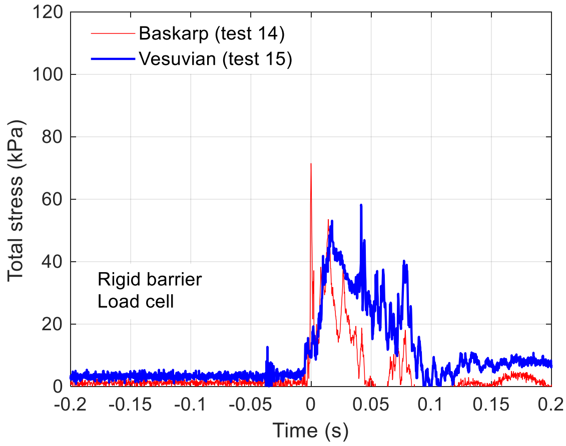

Figure 7. Total stress measured on the rigid barrier (Config. 1) for Baskarp sand (B25) vs Vesuvian soil (ITA).

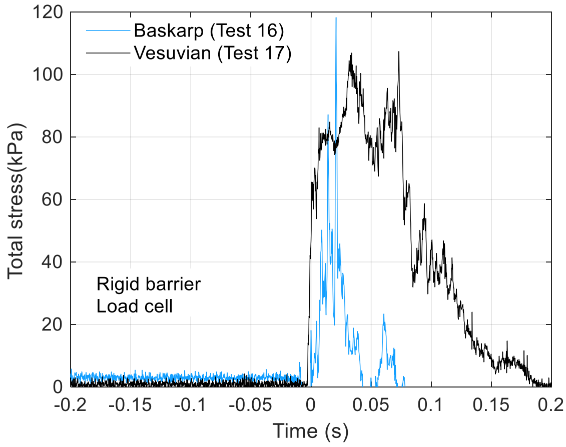

Figure 8. Total stress measured on the rigid barrier (Config. 2) for Baskarp sand (B25) vs Vesuvian soil (ITA).

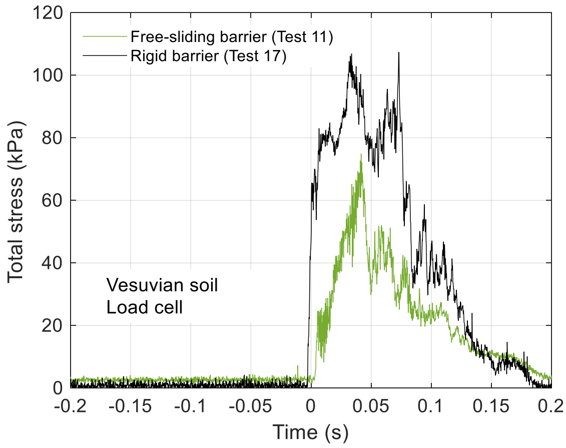

Figure 9. Total stress measured for the Vesuvian soil (ITA) for the fixed barrier (Config. 2, test 17) and free-sliding barrier (Config. 4, test 11).

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