WETTING COLLAPSE AND FAILURE OF AN SLOPE TESTED IN CENTRIFUGE MACHINE

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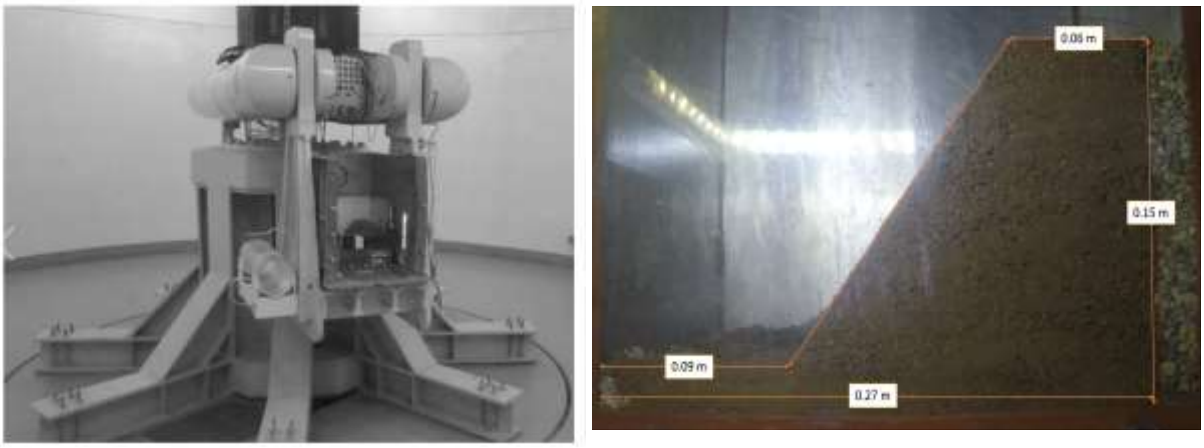
This paper presents a centrifuge model of a silty clay slope. The increase of the gravity acceleration is applied to the slope under unsaturated conditions. The slope is wetted in flight by means of water injection from the bottom. The deformation of the slope and the subsequent failure is analyzed. In order to avoid difficulties in the installation of sensors in the prototype, the model was built in a box of transparent walls and the slope behavior during the flight was recorded using a digital camera. The images were analyzed using the PIV method (Particle Image Velocimetry) and processed by means of the methodology called PIV-NP with the aim of obtaining accumulated displacements and strains. This methodology is able to provide the strains from PIV measurements following an Eulerian scheme even in case of large deformations. The experimental results indicate that the wetting-induced volumetric strains (collapse) occurred in the wetting front and the soil located above settled as a rigid block. The slope failure was observed at a certain time before the wetting front reached the slope surface and the failure surface was located close to the wetting front.

TEST DESCRIPTION AND PIV ANALYSIS

The slope model was carried out in the centrifuge of the geotechnical laboratory of the Universidad de los Andes in Bogotá (Colombia) (Fig. 1a). The prototype of the slope was built in the transparent box shown in Figure 1b. Dimensions of the slope are indicated in the figure. The slope inclination is 50º. The tested soil was a silty clay of low plasticity (w_L=33%, IP=18%) used in the construction of a dam core (Albagés dam, Spain). Initially, the soil exhibited an average water content of 10% and an average dry density of 1.5 kg/m^3 (e = 0.8). A column of gravel was built on the right side of the slope in the contact between the soil and the lateral wall of the box to facilitate the lateral inflow of water towards the slope.

After slope construction, the centrifuge flight started by increasing the gravity until 50g which corresponds to an increase of the scale of the prototype equal to 50 times. Therefore, the 15 cm high of the slope are equivalent to 7.5 m. During the centrifuge flight water injection from the box base was imposed.

The entire experiment was recorded by capturing images at 60 frames per second (fps) with a digital camera GoPro with 1440 pixels of resolution. The images were analyzed using the particle image velocimetry technique (PIV) (Adrian, 1991). This technique allows the non-invasive measurement of displacements occurred in the time elapsed between captured images. The digital images taken before and after the deformation of the object are compared at the scale of regions of pixels (called subsets) and the displacements are defined as the difference between the position of the reference subset centre and the corresponding subset centre in the deformed image.



(a) (b)

Fig. 1 (a) Centrifuge machine; (b) Silty clay slope after construction in the transparent box.

In this paper, the images were analyzed by means of the free software PIVLab (Thielicke et al., 2014). This program follows a Eulerian approach and the displacements occurred between subsequent images are measured in points fixed in the space. Consequently, the track of the particles located at different subsets during the motion is not directly provided by the method. The methodology called PIV-NP proposed by Pinyol and Alvarado (2017) was used in the analysis of the centrifuge experiment to postprocess the PIV measurements. Starting from measurements of displacement following Eulerian approach, PIV-NP provides the accumulated displacements and the strains associated with points (Numerical Particles) representing physical particles of the deformable soil. The methodology is specially well suited to interpret large strains. In the analysis performed here, interrogation areas of 100x100 pixels were selected and 9 numerical particles per element were used.

The experiment shows the settlement of the slope when gravity increases. During wetting, water went up through the soil and, more quickly, through the sandy column. This wetting induces the settlement of the slope due to soil collapse. At a certain time, the failure of the slope took place and the final inclination of the failed saturated slope was equal to 28º.

ANALYSIS OF EXPERIMENTAL RESULTS

Three stages of the motion of the slope were identified by the PIV analysis. Firstly, the slope settled due to the increase of gravity till 50g. Figure 2 shows the displacement and strains occurred during this first stage of loading. The incremental displacements measured by comparing two images captured at the end of the loading stage, obtained directly by PIV, are shown in Figure 2a. The accumulated displacements, obtained by means of PIV-NP, are plotted in Figure 2b. The displacements were larger in the zone where the slope is higher. A maximum displacement of 5 cm was measured. A well-defined shear zone was observed in the middle of the slope due to the different settlements between the toe and the crest. Maximum volumetric strains were measured in the deepest zone of the slope, where mean stresses reach the highest values.

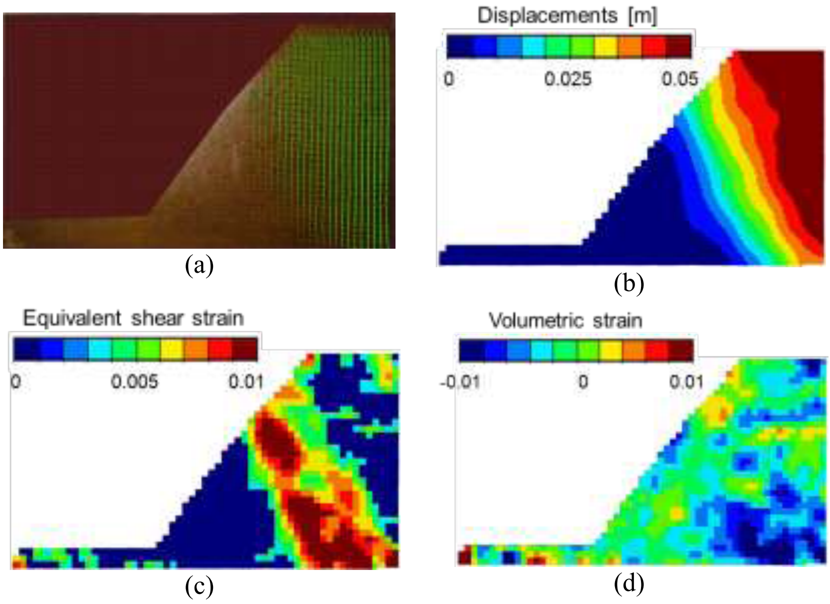


Fig. 2 Measurements at the end of the gravity increase stage (t = 10s). (a) Incremental PIV displacements vectors occurred during 2 seconds; (b) Accumulated displacement; (c) Accumulated equivalent shear strain; (d) Accumulated volumetric strain.

During the wetting process, water injected from the bottom of the slope went up through the silty soil and through the gravel column. A horizontal flow from the gravel column (quickly saturated) into the soil was observed. The evolution of the wetting front in time could be clearly distinguished because of the change in the colour of the sand between unsaturated and saturated states. The wetting-induced slope deformation is shown in Figure 3. The volumetric compression strains due to the wetting collapse were concentrated in the wetting front where the soil becomes saturated. Displacements were mainly observed above the wetting front where the soil settled as a rigid block.

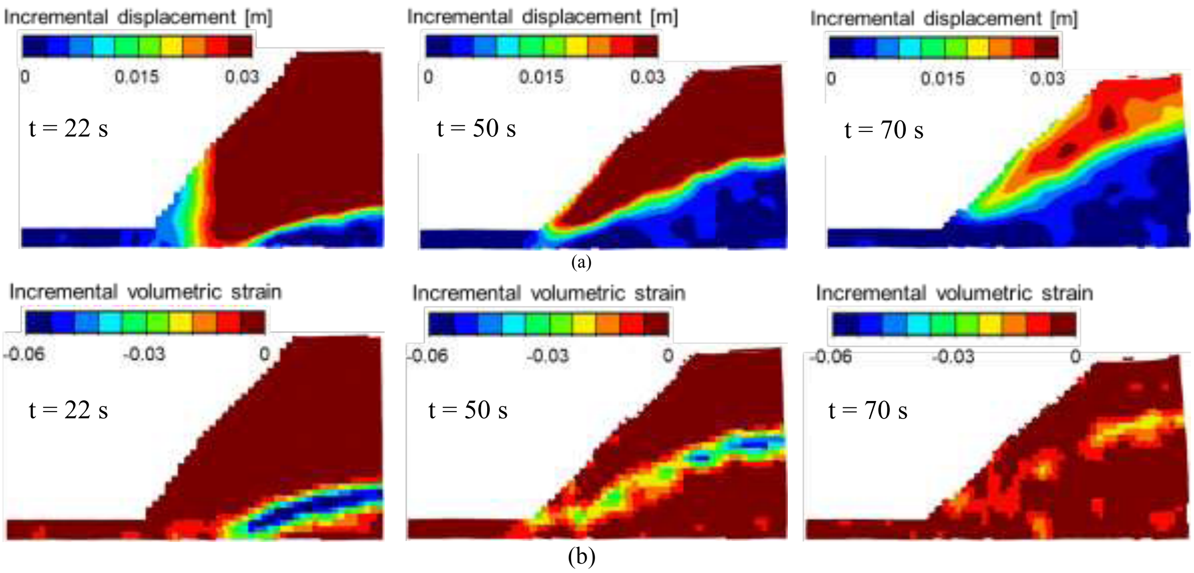


Fig. 3 Wetting stage. (a) Postprocessed incremental displacements; (b) Incremental volumetric strains.

Finally, the imposed wetting induced the failure of the slope (Fig. 4) due to the loss of suction. At this stage, collapse and shear deformation occurred at the same time. During wetting, shear strains localized in the wetting front and at certain time (t=140 s) a catastrophic shallow sliding was observed.

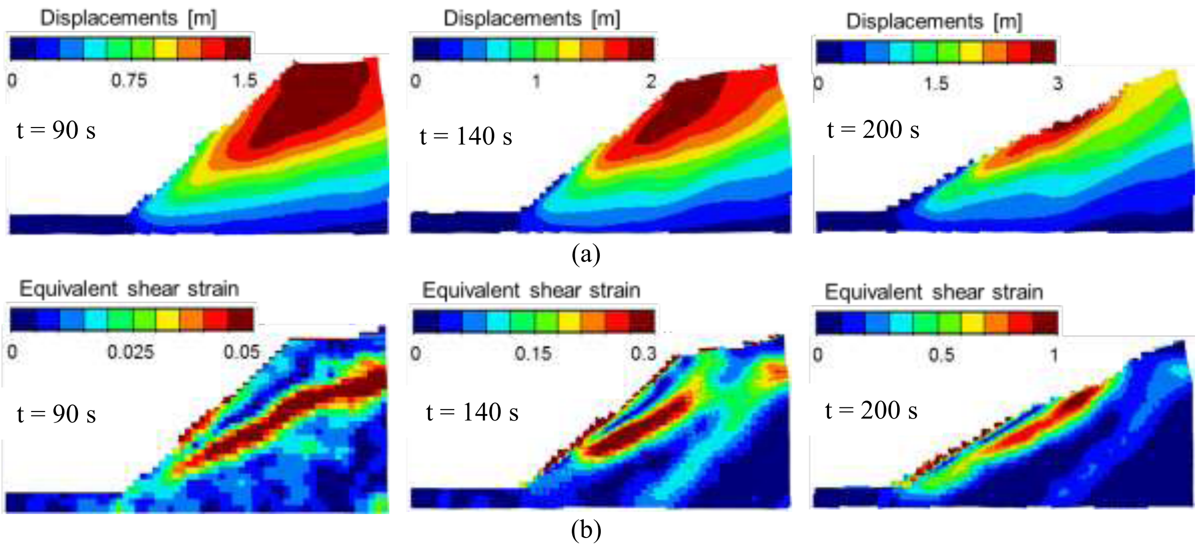


Fig. 4 Failure stage. (a) Accumulated displacements; (b) Equivalent shear strain.

CONCLUSIONS

A novel PIV interpretation technique, recently developed, provided an accurate estimation of the deformations observed in a wetted steep unsaturated slope in a low density silty soil. Initial stages of wetting from a lower boundary resulted in a progressive collapse strains of the soil, concentrated in the upward moving wetting front. This deformation mode evolved into a well-defined shallow sliding failure when the wetting front approaches the slope surface. The detailed information provided by this experiment constitutes a good benchmark to check the capabilities of available models for the analysis of slides in unsaturated soils subjected to wetting.

ACKNOWLEDGMENTS

The authors acknowledge the financial support to CIMNE via the CERCA Programme/ Generalitat de Catalunya and to the Spanish Government for the research fellowships awarded to the second and third authors.

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