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SURFACE DEFORMATION OF NON-COHESIVE GRANULAR MASS DUE TO LATERAL PASSIVE PRESSURE EXPERIMENT 3/2 - ROTATION OF THE STRUCTURE ABOUT THE TOP

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Summary: *The paper presents the results of physical experiment E3/0+2 both with the passive pressure and the pressure at rest of the ideally non-cohesive sand on a retaining wall rotated about the top. The experiment had two principal research objects: monitoring of the relation pressure/structure movement (rotation about the top) and visual monitoring of the granular mass displacement, both into and on the upper mass surface. The paper deals in detail with the results and methods of surface monitoring.*

1. Introduction

A long-term research of passive pressure and pressure at rest (experiment E3) has been carried out. The rotation about the toe of the physical model not only confirmed both the physical existence of the interval of pressure at rest and the residual passive pressure, but also brought about unexpected results similarly as the previous research of active pressure. The research contains among others the investigation of time (in)stability of both pressure components and the visual monitoring of displacements into the granular sample and on its upper surface. A detailed analysis of these experiment results and of the method of the surface movements and displacements forms the subject of this paper.

At the end of 2001 and during of 2002 the first part of the third experiment E3 was made, denominated E3/2. The physical 2D model consisted in a granular mass and a retaining wall, which could perform the movements of all three basic types (rotation about the toe and the top, translative motion) with an accuracy of less than 0.024 mm. The wall was 1.0 m high and perfectly stiff, without any deformations of its own. The contact surface of the retaining wall was 1.0*1.0 m. The wall movements were measured by mechanical indicators in every corner of the retaining wall. Five measuring points were situated at the granular mass/retaining wall contact surface 0.065 m, 0.265 m, 0.465 m, 0.665 m and 0.865 m deep.

The lateral sides of the stand were transparent to enable visual observation of the changes in the mass. The granular mass was 3.0 m long, 1.2 m high and 1.0 m wide and consisted of

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the same ideally non-cohesive material (loose very dry sand) as in the previous cases. The experimental equipment and tested material were described in detail earlier (Koudelka 2000a). Therefore, we shall state merely that the sand had the following basic parameters: $\gamma = 16.14$ kN/m^3 (unit weight), w = 0.04 % (water content), $\phi_{ef}' = 48.7^o$ (angle of the top shearing resistance for low stresses), $\phi_r' = 37.7^o$ (angle of the residual shearing resistance), $c_{ef}' = 11.3$ kPa (illusory cohesion), $c_r' = 0$.

The notation of the described phase is taken from previous experiments in which rotation about the top was called “phase 2”. This (first) phase of the experiment was preceded by, the experiment with the active pressure at rest, made by a small rotation about the top of 0.27 mm and back to 0 mm (6th Sept.2001 – E3/2-0, see Fig.1). Then the mass was left to consolidate for 32 days and the passive part of the experiment began (8th Oct. 2001); the initial part of E3/2 terminated on 10th Oct. 2001. The final part of E3/2 began on 18th June 2002 and the final toe movement towards the passive side attained about 159 mm on 3rd Dec. 2002.

Figure 1 The state of the mass and the first glass plate before the wall movement (rotation about the top - the moved wall is left) on 6th Sept. 2002.

The state inside the mass was characterized by the slightly curved major slip surface separating the active and the passive parts of the mass. The active part was heavily deformed and further divided into a system of others slip surfaces. The pressure near the rotated wall toe (maximally over 150 kPa) destroyed both nearest glass plates.

The retaining wall was not moved continuously, but step by step with the periods of reconsolidation between individual steps. These periods without any movement completed the experiment on time behaviour. The data of sensors were read and recorded also during the periods of reconsolidation.

2. Application of optical methods

In comparison with other methods optical methods of mechanical properties measurement can be attributed several advantages. Their number includes e.g. their non-contact, non-invasive nature, their applicability to instant acquisition of the whole 2D field of data and their suitability for immediate computer assisted data processing and evaluation using image analysis methods (Rastogi 2000). Optical methods are especially useful in the study of granular material behaviour, if the necessity to exclude any disruption of the mass, the unpredictability of slip surface location in the mass and the requirement to combine the whole area measurement and detail analysis at the same time are to be considered. That is why in the course of experimental work performed in the ITAM on granular mass, the whole range of optical methods to study deformations of lateral and top surfaces of the mass was employed. The principal idea behind the study of granular mass surface state was to correlate the evolution of inner slip surfaces to the evolution of surface discontinuities to extend experimental result analysis to the locations not observable from the sides (see Fig. 2). Displacements in lateral surface, observable through transparent walls, were investigated taking advantage of natural and/or artificial marks identification and tracking methods (Koudelka et al. 2003, Valach 2003). The top surface displacements, the subject of this contribution, by means of shadow moiré. The shadow moiré is a well known optical method used for evaluation of surface features of studied body (Asundi 2000, Huntley 1998). Its relative simplicity and reliable results in case of relatively flat surfaces make the shadow moiré an ideal candidate for investigation of surface deformation.

Figure 2 Lateral view on experimental stand filled with sand. The sand stratification is visualized using strips of red colored sand. The broken strips indicate presence of slip surface in the mass and location where the slip surface reaches the sand mass surface. Appearance of the slip surface at the top sand mass surface depicts inset image.

3. Experimental set up and data processing

A rectangular frame of approximate size 0.8 x 1.2 m was used for shadow moiré investigation of body top surface. Approximately one millimetre thick black wire was used in the frame to create the mesh; the spacing of parallel wires was 2 mm, i.e. the wires and the gaps between them were of the same size. The frame was hanged about 5 cm above the surface of the granular mass. Lateral illumination was used to illuminate the surface through the frame, casting wire shadows on the surface. Digital camera placed symmetrically above the frame was used to capture moiré fringes. The dark fringes appeared at places where wire shadow filled the gap between wires in the camera view.

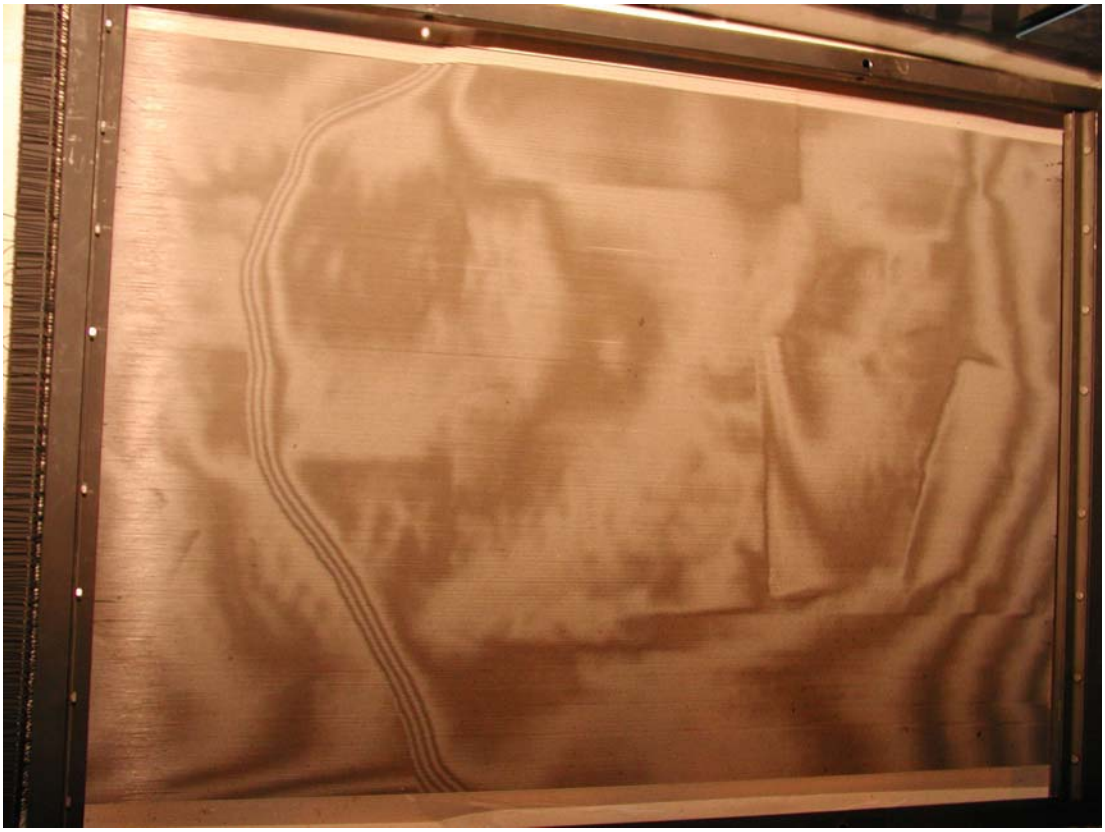

Figure 3 Shadow moiré fringes depicting the state of slip surface in the final loading stage of experiment E3.

Images of moiré fringes (similar to that of Fig. 3) were processed in Matlab using user written scripts for semi-automated data processing, taking advantage of Matlab's suitability to handle a large matrices calculation – the native form of digital image, as the image pixel intensity level can be directly treated as the matrix element value. The processing has involved several steps: The recognizable presence of frame wires in original image was removed from the image by the application of a smoothing Gaussian filter. The purpose of subsequent illumination intensity adjustment was to make the background intensity even and to set approximately same difference between dark and light fringe intensity using "local equalization procedures" available in Matlab's Image analysis toolbox. This step is very important due to the fact that human eye can easily discriminate the dark fringe from the light one, even when in the same image a light fringe in one place can be darker than dark fringe in other place, but for the computer this task represent a tough problem (Fig. 4). When the dark/light ratio has been adjusted roughly to the same level, the image can be binarized in the next step setting up an intensity threshold for turning all lighter pixels into white and all darker pixels into black. The binarization step has to be followed by the step in which unwanted jaggy borders and other small details are removed in order to significantly reduce the number of objects (a set of connected white or black pixels) representing the fringes in the image (Fig. 5). Having identified the fringes – the objects in the binary image a step in which the fringes are properly numbered has to be carried out. In this step assistance by the human to otherwise automated run of the script is necessary, as no general rule for automated fringe numbering can be derived. Finally, a subset of numbered pixels belonging to fringes is selected in such a manner as to achieve the relative uniform distribution of known values across the investigated area. The subset is then used as input to area interpolation procedure yielding smoothly varying fringe values for every pixel in the area. In the last step, the multiplication factor relating height to one fringe order is to be determined (Fig. 6).

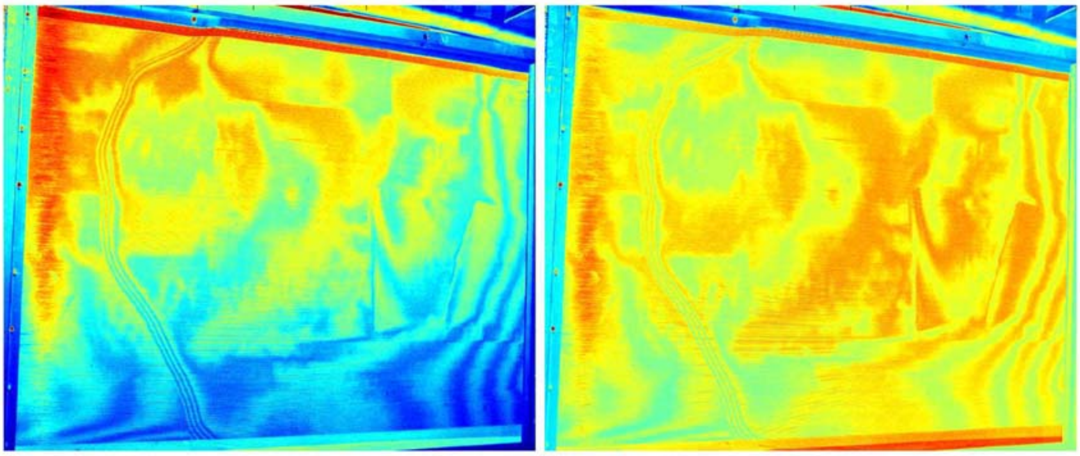

Figure 4 Fringe image before and after local intensity equalization leading to uniform intensity background level

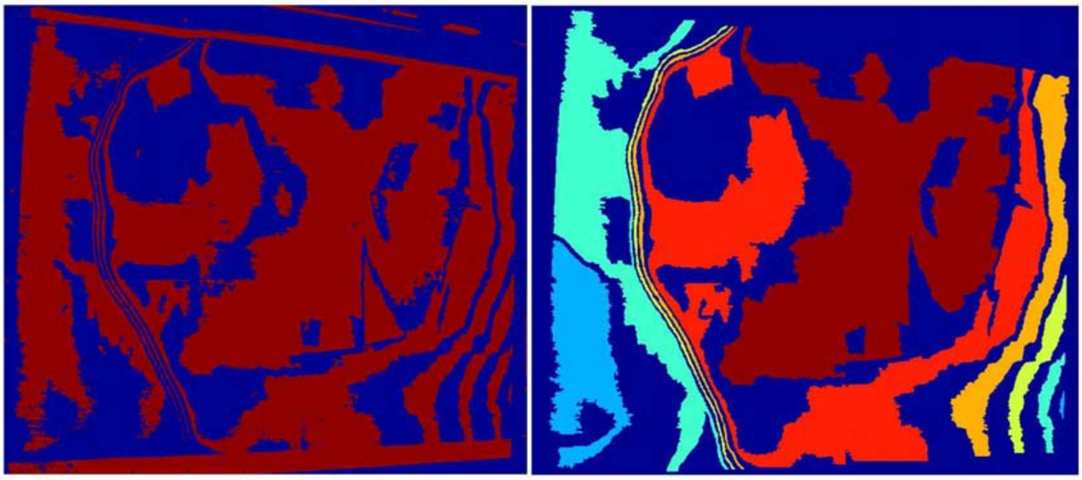

Figure 5 Binarized fringe image (left) and numbered fringes (right)

4. Discussion

Surface topography evolution reveals processes taking place in loaded granular mass. The measurements can be carried out to quantify rise/depression of specific areas of the surface and to determine the location of the slip surfaces on the sand mass surface. On the free surface there exists a limiting angle above which the slope is unstable and cannot be fixed. That is why the true thickness of the slip surface, the presence of several slip surfaces very close to each other, cannot be determined by surface profile analysis. On the other hand the slip surfaces have proved their narrow localization reaching this limiting angle of the slopes. Another interesting aspect of the observation is the curved line of the slip surface. The middle part of the line is far ahead of the endpoints of the line touching the glass wall of the stand. This may be due to the resistance of the lateral glass wall to the flow of the sand mass resembling the properties of viscous fluids. This statement is supported by observation of nearly straight lines of slip surfaces in the case of active pressure loading (Koudelka, Valach 2000).

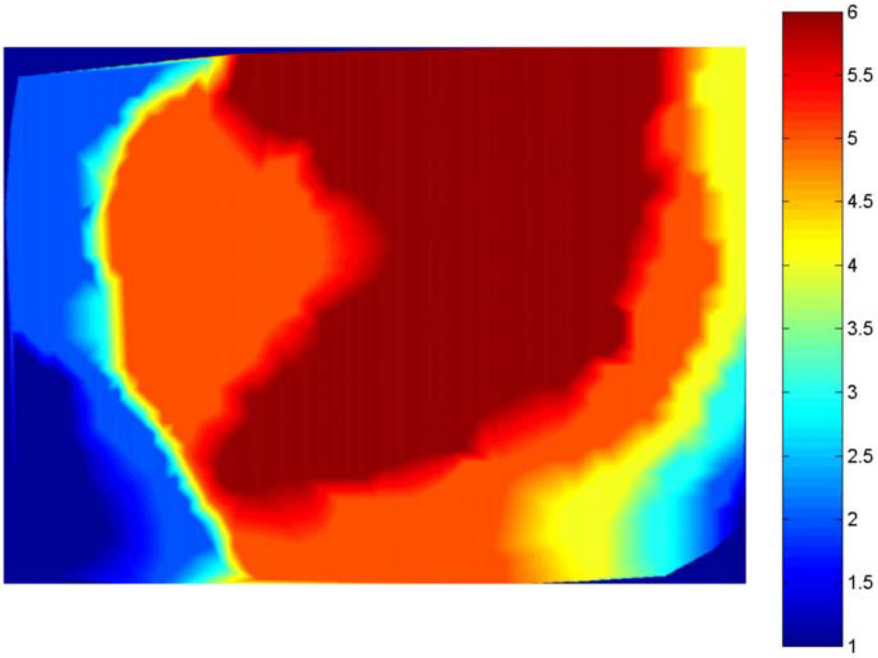

Figure 6 Final stage of image processing – colour coded height map of sand mass surface revealing steep ridge of slip surface at the left side

5. Conclusions

Optical methods are indispensable in this experiment as they yield data not available by other methods. The clear necessity of further automating image processing in the future applications and experiments become evident. Observed surface discontinuity is in relation to inner slip surface and can be easily localised, although the exact width of the slip surface cannot be accurately determined. The curved surface discontinuity indicates difference in sand condition in the bulk and on the lateral surface.

6. Acknowledgement

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