STRAIN VERIFICATION OF NON-COHESIVE MASSES OWING TO PASSIVE ROTATION OF RETAINING WALL ABOUT THE TOE

Petr Koudelka*, Jan Bryscejn*

A basic physical experimental research of lateral passive pressure is in progress at the Institute of Theoretical and Applied Mechanics. The research is composed of three doubles of the same experiments with three basic retaining wall movements: rotations about the toe or top and translative motion. A double of the same experiments E5/0,1 and E6/0,1 with passive pressure and pressure at rest during wall rotation about the toe was carried out in 1st half 2012 and the 2nd one (E6/0,1) was finished in the early 2013. Both experiments together should prove a real behaviour of non-cohesive mass acting on moving wall. The behaviour appears distinct from a theory of EUROCODE 7-1 contemporaneously used. Each of experiments has brought a huge data quantity. The paper shows strains of both masses, i.e. deformations and slip surfaces of the experimental sandy masses.

Keywords : *lateral earth passive pressure, physical experiments, ideally non-cohesive sand, mass deformation, slip surface, behaviour verification*

1. Introduction

A basic research of earth/lateral pressure based on physical and numerical experiments has begun in 1998 at the institute of the authors and it has continued. The physical research should prove behaviour of ideally non-cohesive granular mass during three basic types of structure movement towards active and passive directions The first research period in 1998–2000 aimed on active pressure and in 2001–2002 on the first long/term experiment with passive pressure (E3/0.2) but during this the nearest glass sides cracked. Despite it the experiment went off successfully to finish but the equipment had to be reconstructed. In the course of the second period was developed experimental equipment on an advanced contemporary level. The first experiment with passive pressure E3/0,2 (2001–2) during wall *rotation about the top* was repeated like experiment E5/0,2 (2010) such as a long-term operation test of the new experimental equipment. It brought similar results to E3/0,2 however, with lower pressure values. The experiment E5/0,2 had to be repeated (2011) and a new one was denoted E6/0,2. The second experimental double (E5/0,1 and E6/0,1) searching *rotation about the toe* followed in 2012 and early 2013. Results of a visual mass monitoring of the experiments E5/0,1 and E6/0,1 are presented in the paper to be a proof of a strain behaviour of non-cohesive masses due to rotation of retaining wall/structure towards passive direction.

* P. Koudelka, DrSc., CEng., J. Bryscejn, EEng, Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences, Prosecká 76, 190 00 Prague 9, CZ

2. Experimental equipment

The actual advanced equipment was described in detail formerly [5], [6], [7]. The equipment has the same sample size (length of 3.0 m, width of 1.0 m, height of 1.2 m) and it is fully controlled by two computers (the first for front wall movement and data monitoring and registration, the second for visual monitoring and photo registration) and reaches up very suitable characterizations: max. active wall movement of 300 mm, max. passive wall movement of 242 mm, front wall movement of velocity from of 3.684 to of > 0 mm/min. i.e. arbitrarily slow movement, max. pressing force cca 2870 kN, 5 bi-component pressure sensors in front moved wall, 1 three-component sensor and 5 bi-component pressure sensors in back solid wall, 2 potential movement sensors, 2 optoelectronic movement sensors, 1 impulse summer, max. record frequency of 1000 Hz. The equipment can afford a huge quantity of data of 803 MB/day.

Deformation of the sample and displacements into it are monitored visually. Slip surfaces and uplifts of the sample mass are monitored through the right transparent side by means of red strips into the mass (see Fig. 1a). Locations of the strips are registered by a stable photo camera through the transparent right side about per day during the front wall movement. Also, the locations of the strips are measured manually in the time intervals. Displacements of black little balls (left side) located in front sample part in net of 50/50 mm are monitored by camera through the transparent left side. Upper surface of the sample is monitored by two cameras located above both front walls (moved and solid). Visual registration data of cameras are stored separately in the second separate computer.

3. Experiments E5/0,1 and E6/0,1

The experiments belong to the second passive double of the set of basic physical long-term experiments which should verify, eventually repair and prove a correct lateral/earth pressure theory. The complete set contains:

- *active pressure*: three repeated experiments with pressure at rest and active pressure (structure rotations about the toe and top and translative motion – carried out in 1998–2000,
- *passive pressure*: three repeated experiments with pressure at rest and passive pressure (structure rotations about the toe and top – carried out in 2010–2013 – and translative motion – running in 2013).

Thus, the actual research contains altogether six doubles of experiments except of the former experiment E3/0.2 that was performed using the original simple equipment of which results appear to be not fully comparable to results of the experiments E5/0,2 and E6/0,2 using the new advanced equipment.

All experiments with passive pressure in progress vary a motional phase by a following reconsolidation phase, altogether of 3 motional phases and 4 reconsolidation phases in an area of *pressure at rest* (i.e. very little movements both active and passive in order 0.1 mm). Then 3 motional phases and 3 reconsolidation phases follow in an area of passive pressure according to movement values supposed by EUROCODE 7-1 (Annex C): for mobilization of a half of top passive pressure (4^{th} phase – p1a), for mobilization of top passive pressure (5^{th} phase – p1b) and the last 6^{th} phase (p2) with movement of the maximal possible wall movement cca of 150–220 mm. The first three motional phases of pressure at rest do not evoke visible changes of the sample and due to it the changes are not measured.

The experiments with passive pressure (all) have begun using a velocity of wall movement of 0.0049 mm/min (near to slow natural processes – 50 times faster than finger nail growth or 53 times faster than continental drift). The velocity is approximately similar to that manual velocity of the former simple equipment for the active pressure experiments used. The presented experiments E5/0,1 and E6/0,1 with passive pressure during rotation about the toe was entered 28. 2. 2012, resp. 23. 8. 2012 on and finished successfully on 26. 6. 2012, resp. 17. 1. 2013. The equipment attained the maximal top movement at the experiment end of 152.00 mm, resp. 161.22 mm (wall height 1.0 m).

3.1. Sample

The same material (quartz sand) under the same compaction is used for samples of all experiments. The material is ideally non-cohesive and flowing due to extremely low moisture. Principal physical properties of the sample were found as follows: unit weight $\gamma = 15.70\,\mathrm{kN/m^3}$, resp. $15.40\,\mathrm{kN/m^3}$, effective angle of shearing resistance $\phi_{\mathrm{ef}} = 38.5°$, effective cohesion $c_{\mathrm{ef}} = 0$, residual angle of shearing resistance $\phi_{\mathrm{r}} = 31°$, structure-ground interface friction angle $\delta = 12.8°$, moisture $w = 0.3\,\%$.

3.2. Hardware and software

The entire system is equipped with electronics and computers to enable controlling experiments and also proper data collection. It has single power plug 220 V which leads to UPS which is backing up the crucial low-consumption devices and also the main computer. A stepper motor control unit is supplied from DC power source (40 V/5 A). Two kinds of software run on the main computer. InMotion program works with the stepper motor unit in two modes – program mode is used when the experiment is in progress and realizes slow steady motion of the front wall; the second mode is used for controlling the motor on demand for various purposes, e.g. during the setup of experiment. Program NextView is software which collects data from all sensors and saves it for later processing at desired sampling rate. It shows also actual data in both numerical and graphical manners. Signals of the

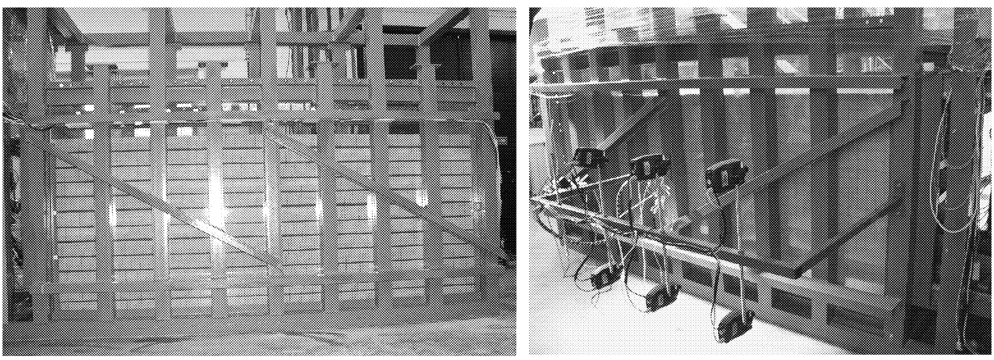

Fig.1: Experimental equipment and the sample before experiment E5/0,1 prepared; a) right transparent glass side and the sample with red strips on Febr. 28, 2012 (left); moved front wall is left; strips of the experiment E6/0,1were laid out equally; b) left transparent glass side and the sample with little black balls and camera system registering ball locations of the experiment E5/0,1 on March 20, 2012 (right); moved front wall is right; black balls of the experiment E5/0,1 were observed by a scan camera

pressure sensors, temperature sensor and analog potentiometric sensors are conditioned, amplified and led to 16bit A/D convertors, then via interfacing USB devices (BMCM) into the measuring computer. Two digital displacement sensors (resolution 10 nm) and two potentiometric sensors, located on upper and lower wall part next to wall axis, are connected into the PC via internal card. The second computer is used for controlling of a camera system.

4. Results

The experiments bring an extreme data quantity. At all events, size of experimental results does not make it possible to transfer data in a suitable format and to analyze them in short time and of course, to present the complete results in one paper. The paper deals with strain changes of the sample both inside and outside (deformation, slip surfaces, displacements) regarding wall movement. Data of pressure sensors are not analyzed here.

The front wall rotation about the toe influences the maximal movement of the top. The wall is very rigid and it behaves like solid structure and due to it movements of other wall points depend on the top movement linearly according to their distance to the top. That is a reason that all results are regarded to a relevant top movement value.

4.1. Data

Data collected during whole experiment as well as the rest phases are saved to disk in NextView's proprietary data format (.lfx). The experiments E5/0,1 and E6/0,1 brought of basic data (.lfx) of 1.027 GB, resp. of 0.904 GB (time data and sensor data except of visual monitoring data and photos). The sampling rate of these datasets differs. In order to obtain human-understandable results, these data is exported to ASCII format first. This leads into huge amount of data in format .txt (the experiments E5/0,1 and E6/0,1 of 30.3 GB, resp. of 26.6 GB), so the decimation process takes place here. It is done via several short scripts written in Matlab language. This lessens amount of the data reasonably, so it can be put into several well-arranged Excel tables. For this purpose, a macro in Excel was developed. The original data with high sampling rates are used in subsequent evaluation process.

Very important movement of the front wall top was measured using four independent techniques: potential movement sensor, incremental optoelectronic movement sensor, impulse summator and the maximum distance of the wall top center from its original location by electronic micrometer. There were not found significant differences. A position of the front wall toe (not moved) was controlled by other potential and incremental optoelectronic movement sensors. Movement values presented in the paper are data according to the electronic micrometer. Movement data during the experiment could be calculated regarding to time for arbitrary time moment due to an absolutely equable wall movement.

4.2. Strains and slip surfaces

Amplitudes and extents of the sample deformations are shown through uplift (or stability) and failures (due to slip surfaces) of the red strips on the sample right side and also through uplift and slip surfaces openings on upper surfaces of the samples. The figures can give a good imagination on behaviour of sandy masses during retaining wall rotation about the toe. An opening state of E5/0,1 is in Figs. 1, a state of E6/0,1 was the same. States responding to supposed (EC 7-1) mobilization of full passive pressure after both top movements of

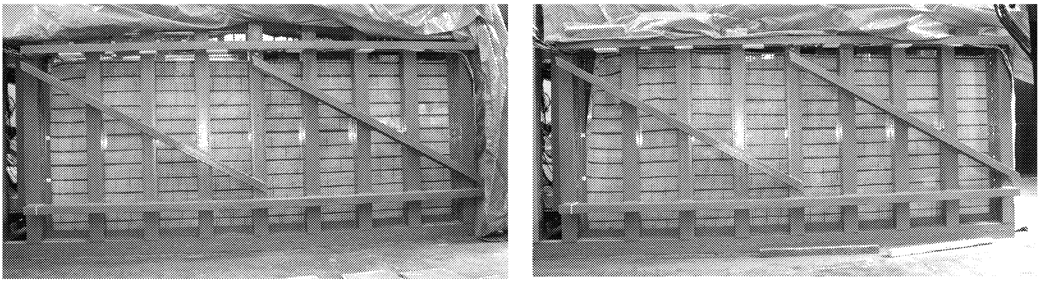

Fig.2: Views on deformation of the sample E5/0,1(especially of front part left) according to the red strips after front wall rotation about the toe; the moved wall is left and the back solid wall is right; a) deformation of the sample after top movement of 66.33 mm without any slip surface (in detail see Fig. 4a); b) deformation of the sample after the final top movement of 152.00 mm with four slip surfaces in the sample front part into depth of about 0.3 m (in detail see Fig. 4b)

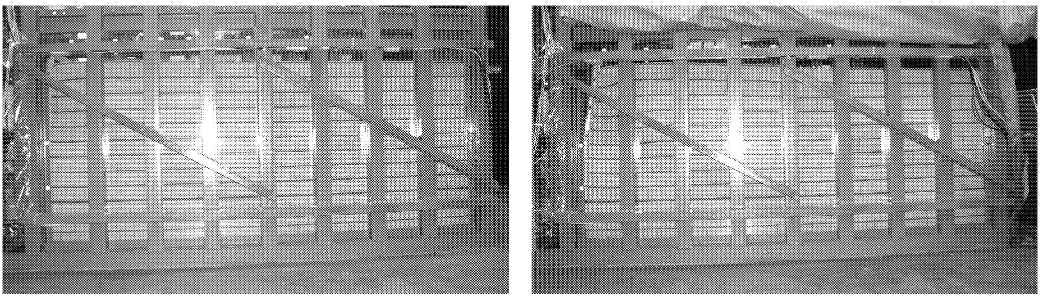

Fig.3: Views on similar deformation of the sample E6/0,1 (especially of front part left) according to the red strips after front wall rotation about the toe; the moved wall is left and the back solid wall is right; a) deformation of the sample after top movement of 64.83 mm without any slip surface (in detail see Fig. 5a); b) Deformation of the sample after the final top movement of 151.38 mm with six slip surfaces in sample front part into depth of about 0.3 m (in detail see Fig. 5b)

66.33 mm and of 64.83 mm, resp. are shown in Figs. 2a, 3a, 4a and 5a. This state did not create any visible shear slip surface. Slip surfaces began to be created after top movement more than of 75 mm near to front wall (0.5 m) and above (depth of 0–0.2 m).

The maximal final top movements were reached of 152.00 mm resp. of 151.38 mm. The actual uplifts of the red strips and four resp. six visible slip surfaces can be seen in Fig. 2b resp. Fig. 3b and in detail according measured data in Fig. 4b, resp. Fig. 5b. Not all slip surfaces of the sample E5/0,1 crosscut through adjacent strip: two slip surfaces nearer to the moved wall were continuous but the other surfaces (farer from the wall) were not continuous what is obvious in Fig. 3b. The surface did not get deep into the sample, e.g. the first two surfaces got in a depth of 0.2 m, the deepest single strip failure was registered in depth of 0.4 m. A behaviour of the sample E6/0,1 is similar but not the same. The slip surfaces are numbered from left to right independently in each figure. A slip surface creating is very furtive and sometimes a slip failure in a strip can be changed and missed due to material displacement. Due to this phenomenon the numbers of slip surfaces of both samples are different but the difference does not appear too substantial.

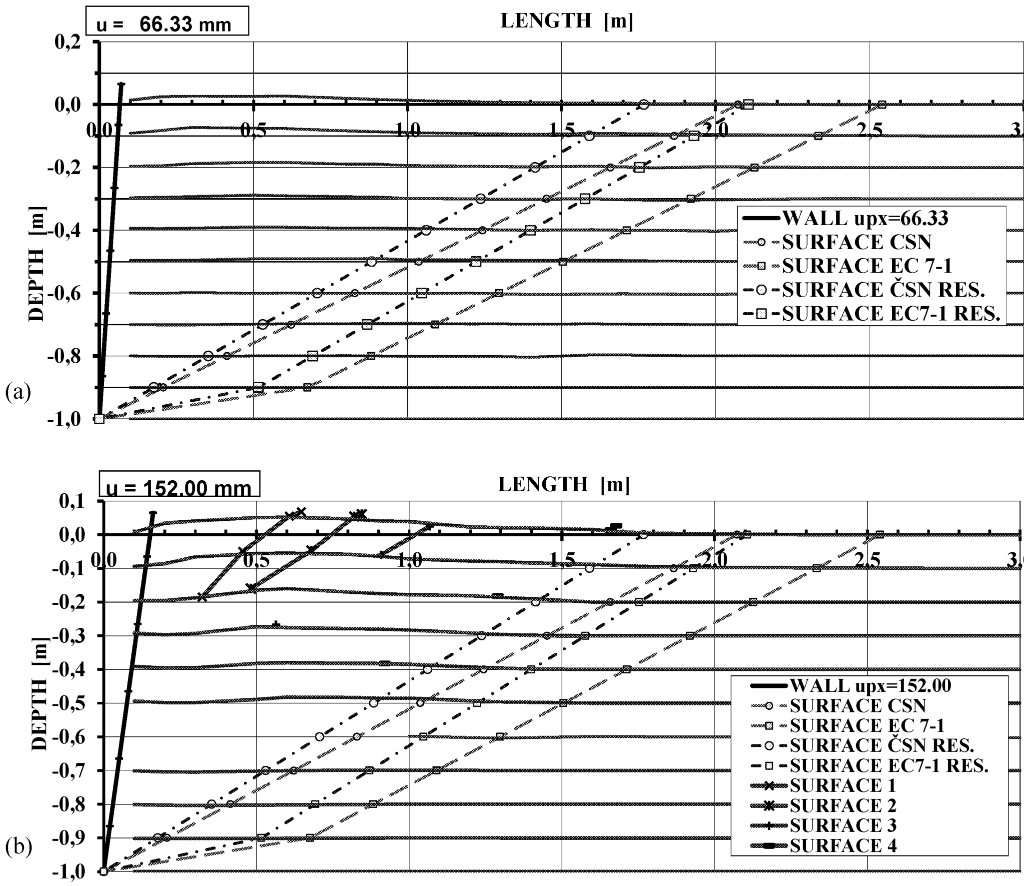

Fig.4: Measured uplifts of red strips and slip surface of the sample E5/0,1; dashed and dot-dashed lines are theoretically considered shear surfaces for analysis of passive earth pressure according to ČSN 73 0037 and EUROCODE 7-1, resp.; a) deformation of the sample after top movement of 66.33 mm without any slip surface (actual state see in Fig. 2a); b) Deformation of the sample E5/0,1 after the final top movement of 152.00 mm with four slip surfaces in sample front part into depth of about 0.3 m (actual state see in Fig. 2b)

4.3. Pressures

Pressure analyses will be performed after the data transformation to the xls format. Contemporarily, it can be stated for the sample E5/0,1 the passive pressure maximum has been found after the toe wall movement of 152 mm and its value has been 98 kPa. This value is near to maximal passive pressure values of 107.8 kPa and 102.4 kPa however which had been found before during the experiments E5/0,2 and E6/0,2 resp. during rotation about the top after toe movement of 60.0 mm and the value of 102.3 kPa had been found after toe movement of 87.1 mm.

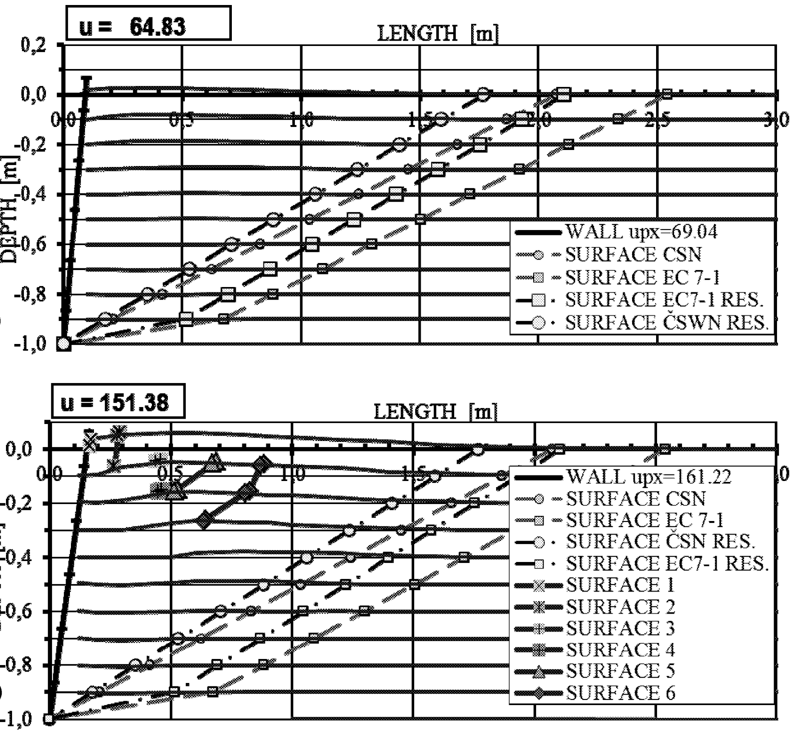

Fig.5: Measured uplifts of red strips and slip surface of the sample E6/0,1; dashed and dot-dashed lines are theoretically considered shear surfaces for analysis of passive earth pressure according to ČSN 73 0037 and EUROCODE 7-1, resp.; a) deformation of the sample after top movement of 64.83 mm without any slip surface (actual state see in Fig. 3a); b) deformation of the sample E6/0,1 after the final top movement of 151.38 mm with six slip surfaces in the sample front part into depth of about 0.3 m (actual state see in Fig. 3b)

5. Conclusion

In order to prove both results the experiment was repeated in the second half of the last year till January 2013. It can be concluded meanwhile as follows:

- behaviour of the mass and its deformation and slip surfaces during rotation about the toe are different than during rotation about the top which fact is logical due to different wall actions,
- it appears the values of mobilized passive pressure differ notably and are higher from those of former experiments (E5/0,2 and E6/0,2) owing to quite different actions (rotation about the top) of the moved wall.

The experiment E6/0,1 will provide also a scan analysis of black balls on left side of the equipment that should complete data and results. Regarding to a limited paper range it will be presented in the future.

Acknowledgement

The Grant Agency of the Czech Republic and the Grant Agency of the Czech Academy of Sciences provided financial support of the connected research (GP Nos. 103/02/0956, 103/05/2130, 103/07/0557, 103/08/1617, P105/11/1160 and A2071302 resp.). The authors would like to thank them all for support.

References

[1] ČSN 73 0037: Earth pressure acting on structures, 52 ps., Prague: Vydavatelství norem, (in Czech), 1992
[2] EUROCODE 7-1: Geotechnical design – Part 1: General rules', CEN, Bruxeles, 2004
[3] Koudelka P.: Nonlinear bicomponent lateral pressures and slip surfaces of granular mass, Proc. IC GeoEng2000, Melbourne, Technomic Publ.Co.Inc., Lancaster/Basel, p. 72 (ps. 8), 2000
[4] Koudelka P.: Granular Mass Behaviour Under Passive Pressure, Proc. 6th IC Case Histories in Geotechnical Engineering, Arlington (USA), University of Missouri-Rolla, Rolla (Missouri), Shamsher Prakash, ISBN 1-8870009-14-0, # 5.35, 2008
[5] Koudelka P., Bryscejn J.: Original Experimental equipment for Slow Processes of Lateral Pressure in Granular Masses, 48th Int. Scientific Conference on Experimental Stress Analysis, Velké Losiny, Proc. ISBN 978-80-244-2533-7, P. Šmíd, P. Horváth, M. Hrabovský, pp. 177–184, Web of Science, Thompson Reuters, 2010
[6] Koudelka P., Valach J., Bryscejn J.: 'Operation Test of a New Experimental Technology for Research of Lateral Pressure, 49th Int. Scientific Conference on Experimental Stress Analysis, Znojmo, Proc. ISBN 978-80-214-4275-7, pp. 155–160, 2011
[7] Koudelka P., Valach J., Bryscejn J.: Experiment E6/0,2 Lateral Passive Pressure – Rotation about the top, 18th IC Engineering Mechanics 2012, Svratka, May 14–17, Proc. ISBN 978-80-86246-39-0, Proc. CD ISBN 978-80-86246-40-6, J. Náprstek – C. Fischer, Prague, pp. 172–174, 2012
[8] Koudelka P., Bryscejn J.: Experiment E5/0,1 with Lateral Passive Pressure during Rotation about the toe, 19th IC Engineering Mechanics 2013, Svratka, May 13–16, Proc. ISBN 978-80-87012-46-8, Proc. CD ISBN 978-80-87012-47-5, I. Zolotarev, Prague, pp. 83–84, ps. 6, 2013

Received in editor's office: August 5, 2013
Approved for publishing: February 27, 2014