Proceedings of the 24th European Young Geotechnical Engineers Conference (EYGEC), Durham, UK
Osman, A.S. & Toll, D.G. (Eds.) 2015
ISBN 978-0-9933836-01

Testing of landslide triggering mechanism by pore pressure inflation with back pressure shear box

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ABSTRACT
This study examines the slopes stability problems and landslide triggering mechanisms in colluvial soil on the deep river valley slopes. Most of the landslides in Latvia evolve in deep river valleys after heavy consecutive rainfall in Autumn or rapid snowmelt in Spring (Latvian Geological Survey, 2003). The groundwater flow and groundwater (GW) level changes affect the stress state in the soil, as well as GW flow creates seepage pressure. Soil is divided into saturated and unsaturated zone. Unsaturated part after water infiltration or exfiltration, intense rainfall or melting snow can become saturated. In this way the pore pressure will increase and the effective normal stress will be reduced, which consequently will reduce the shear resistance. However, it is important not only to evaluate groundwater fluctuations and pore pressure changes in time and space, but also other factors such as slope topography, soil stratigraphy and geomorphology. Slope stability problems desire particularly expert geologists and engineers collaboration.
Special soil testing equipment is introduced to test effective shear strength parameters and pore pressure inflation. Back pressure shear box apparatus is armed with pore water pressure measurement and back-pressure transducers, so chartering to determine effective soil strength parameters and test pore water pressure inflation mechanism.

1 INTRODUCTION

Slope stability problems in Latvia are relevant mostly in deep river valleys (Gauja, Abava, Daugava) and along steep coastal areas. Detailed investigation of slope processes in Latvia has been carried out since the second half of the 20th century. Mostly slope processes were investigated in the Gauja (Āboltiņš 1971; Āboltiņš & Eniņš 1979; Saltupe 1982; Venska 1982; Āboltiņš et al. 2011), Daugava (Eberhards 1972; Soms 2006) and Abava (Veinbergs 1975) River valleys. In recent years detailed investigations of gullies have been carried out in Southeast Latvia (Soms 2006). Nonetheless, there are many insufficiently investigated questions including the development time (Soms 2006) and conditions of landslides and gullies. In the Gauja River valley only one gully has been absolutely dated (Saltupe 1982). No absolute dating of landslides are available (Kukemilks & Saks, 2013).

All landslide events result from gravitational forces that cause the materials to fail and move downslope from an unstable to a more stable position. This movement is resisted by the shear strength of slope materials expressed by Mohr-Coulomb theory in terms of effective stresses as (Abramson, Lee, Sharma, & Boyce, 2002):

$$\tau_f = c`+(\sigma_n - u)\cdot\tan(\varphi`),$$

where

τ_f - drained shear strength of the soil;

$c`$ - effective cohesion;

$\varphi`$ - angle of internal friction in terms of effective stress;

σ_n - normal stress;

u - pore water pressure.

For natural slopes in deep river valleys, where the top part of slope is partly saturated colluvium and additional loads are not applied, exactly the effective stress analysis is most appropriate design approach. The pore water pressure in this case is variable, which defines shear resistance of soil on the shear plain.

Varying depth colluvium in natural deep river valley's slopes has deposited by different exodynamic processes in past. Normally, this is the top layer in slopes, which exhibits changes in in pore pressures. These changes are related to infiltration from atmosphere or exfiltration from lower soil layers ground water aquafers. In case of heavy consecutive rainfall or rapid snowmelt there can rise groundwater lever or ever appear temporary perched water lever, in case of relatively impermeable lower soil layer. Consequently, the pore pressures will rise reducing effective normal stress and shear resistance. This is the main triggering landslide mechanism in colluvium (Robert, Fleming, & Arvid, 1994).

The effect of suction would not be estimated in this study, because of equipment limitations; however, suction is also reduced in unsaturated zone in colluvium in case of rising ground water level, so even more reducing the shear strength.

The seepage pressure is developed in case of ground water flow, which acts also as a driving force to trigger the landslide.

2 MATERIAL AND METHODS

Along the State Regional motorway P130 Līgas-Kandava-Veģi section between Sabile and Kandava (13.95-14.25km) in September-October 2014 after consecutive rainfall the landslide developed in the upper part of Abava river valley above the road during road construction works (Fig.1).

Figure 1. Site location (Free Baltic States Maps) (GIS Latvija 10.2).

The study site is located in the Abava-Slocene valley, which span between the town of Tukums and the village of Renda, known also as the Abava-Slocene ancient valley or Abava- Slocene spillway (Veinbergs 1975), is more than 60 km long. Its width ranges from 0.7 to 2.5 km. The valley has a depth of 30-35 m at Tukums, 40-45 m in the vicinity of Kandava and up to 30 m at the village Renda. The cross-section of the valley is asymmetrical with mainly erosional terraces present. The valley slopes are dissected by numerous gullies and valleys of tributaries, particularly in the section between the towns Kandava and Sabile. The deepest, even U-shaped valleys are formed by the rivers of Amula and Imula. On the steeper slopes of the Abava-Slocene valley landslides occur (Āboltiņš 2004).

Valley height reaches +80.0…+90.0 m.a.s.l. in the particular section. The river flows at +30.0…+35.0 m.a.s.l., so slopes relative height is 45-60m inclined at 20°-35°. The soil body of study area involves Upper Devonian sandstones, clay, and dolomite layers, while glacial till lays on the top of the slope and colluvium of varying depth (1.5m-14m) covers the sloping part of it. In places on the lower parts of the slopes, mainly along the southern slope of the valley, the bedrock (Upper Devonian sandstone, clay, dolomite or dolomicrite) also outcrops (Āboltiņš 2004).

The soil block samples were taken from at the bottom of cracks, which were developed 2m deep and 2m wide at most, assuming the shearing plane to laboratory and tested for physical soil properties and with special back pressure shear box designed by GDS Instruments for soil strength properties and pore water pressure inflation.

Simultaneously with explorations in situ and laboratory testing, the historical background of this site was explored. The very important fact about the particular section of Abava river valley was found out. In 1960ies during the new road construction the soil deformation on the slope were recorded and decisions made to stabilize the slope foot with concrete walling (Latdoravtoprojekt, 1962). This directed that not only peak shear strength parameters, but also residual strength parameters would be essential to measure at laboratory.

2.1 Physical soil tests

Soil physical tests were performed from trimmings and material left from block samples. These tests were made in order to identify and classify the soil and evaluate physical soil parameters for further landslide analysis with analytical and/or numerical methods. The following physical tests were performed:

- Moisture content according to LVS EN ISO/TS 17892-1;
- Soil density according to LVS EN ISO/TS 17892-2;
- Particle density according to LVS EN ISO/TS 17892-3;
- Particle size distribution according to LVS EN ISO/TS 17892-4;
- Determination of Atterberg limits according to LVS EN ISO/TS 17892-12.

2.2 Back pressure shear box

At Riga Technical University soil mechanics laboratories soil samples were prepared for the shear box testing according to LVS EN ISO/TS 17892-10. Soil samples were trimmed out of block samples to precisely 100x100x45mm and pushed in shear box enclosure.

Experimental testing was carried out using the unique back-pressured shear box (BPSB) apparatus developed by the University of Durham and constructed by GDS Instruments (Fig 2.).

Figure 2. BPSB apparatus (GDS Instruments).

The BPSB provides the opportunity to carry out direct shear testing on soil samples by controlling the pore water pressure of the specimen. The BPSB is based on a standard direct shear device, modified to allow the measurement of pore water pressure and control of back pressure. The apparatus can function as both a conventional direct shear and back pressured shear machine (Carey, 2011).

The testing was performed in two different setups:

- Firstly, the soil strength properties were tested according to LVS EN ISO/TS 17892-10, but measuring pore water pressure to get effective parameters. Testing was carried out in following stages:
  1. Sample saturation by applying both normal stress and back pressure, keeping the difference not higher than 10kPa, so not letting the sample consolidate;
  2. Sample consolidation at desired consolidation pressure until the process of consolidation has finished;
  3. Sample shearing was done to get both peak and residual shear strength parameters by reversal shearing.
- Secondly, the pore water inflation mechanism was tested by the following stages:

  1.-2. The same as previous setup;

  3. The shear stress was chosen in the "save" side of Mohr-Coulomb failure plain for

peak soil strength parameters, and applied to the specimen at ramp by 2kPa/h;

4. When desired normal stress and shear stress values were reached, they were kept constant. The pore water pressure was raised at ramp by 2kPa/h controlled by back pressure system. Soil sample was under pore pressure inflation and sheared at constant total normal stress and shear stress at some point.

3 RESULTS

Soil average physical properties for soil tested are shown in the Table 1.

Table 1. Soil physical parameters

Parameter	clayey SILT (clSi)
I_P	9.5
I_L	0.39
Natural water content	21.1%
Soil particle distribution:	
0-2µm (CLAY)	22.1%
2-63µm (SILT)	58.4%
63µm-2mm (SAND)	10.1%
>2mm	9.4%
Particle density	27.2kN/m^3
Bulk density	20.7 kN/m^3

Soil shear strength parameters were determined at three different consolidation pressures (normal stresses), chosen in range between 25kPa and 150kPa, assuming that shearing plane was relatively shallow- about 2m deep at most (Figure 3).

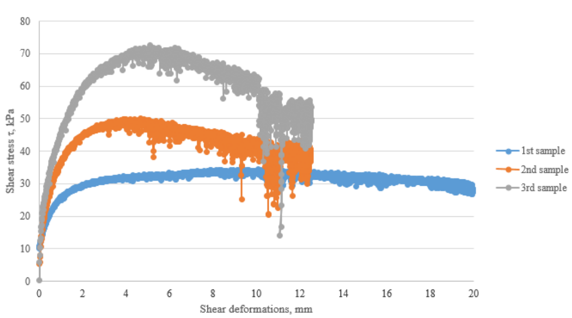

Figure 3. Shear stress (strength) as a function of shear deformations.

Mohr-Coulomb failure criteria for tested three soil samples both for peak and residual parameters are shown in Figure 4. The shear strength (peak and residual) of tested soil specimens at particular effective normal stress are as follows:

- For the 1st specimen at normal stress of 39.07 kPa: $\tau_1 = 34.38kPa$, $\tau_{residual\_1} = 20.12kPa$;
- For the 2nd specimen at normal stress of 107.61 kPa: $\tau_2 = 50.05kPa$, $\tau_{residual\_2} = 39.54kPa$;
- For the 3rd specimen at normal stress of 137.27 kPa: $\tau_3 = 72.62kPa$, $\tau_{residual\_3} = 51.08kPa$.

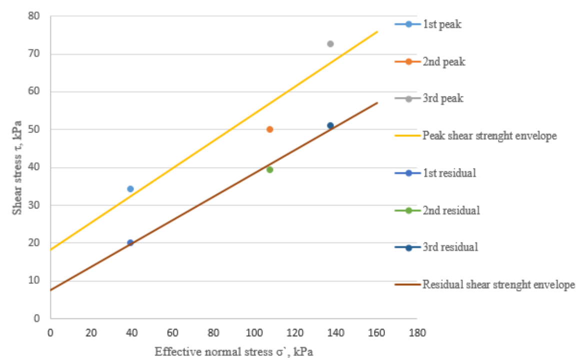

Figure 4. Shear stress (strength) as a function of effective normal stress.

The main strength parameters both peak and residual can be calculated as follows:

$$tg\varphi` = \frac{3\cdot\sum\tau_i\cdot\sum\sigma_i - \sum\tau_i\cdot\sum\sigma_i}{3\cdot\sum(\sigma_i)^2 - \left(\sum\sigma_i\right)^2};$$

$$c` = \frac{\sum\tau_i\cdot\sum\sigma_i{}^2 - \sum\sigma_i\cdot\sum\sigma_i\cdot\tau_i}{3\cdot\sum(\sigma_i)^2 - \left(\sum\sigma_i\right)^2}.$$

So the effective peak strength parameters are $\varphi` = 19.86^\circ$; $c` = 18.15kPa$ and the effective residual strength parameters are $\varphi`_{residual} = 17.20^\circ$; $c`_{residual} = 7.61kPa$.

Pore water pressure inflation mechanism was tested according to the second setup. Four separate tests were conducted assuming point at the “safe” side of the Mohr-Coulomb failure plain and raising pore water pressure at constant rate until sample shears. Three samples were tested at the same constant shear stress of 30kPa and one sample at 25kPa, therefore only two measurements shown on the Figure 5.

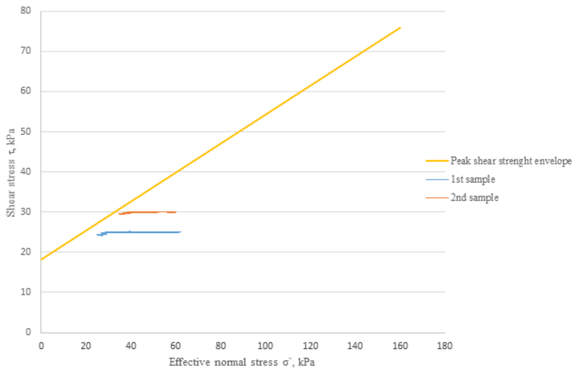

Figure 5. Shear stress as a function of effective normal stress; pore pressure inflation testing.

This setup acts as a physical model of real condition, where in slopes pore water pressure is rising due to water infiltration or exfiltration. These several tests have proved that soil will shear close to the peak shear strength envelope, as expected (Fig. 5). Therefore, knowing the stress state in situ and pore water pressure fluctuation at the same point, we can evaluate whether slope will fail or not.

4 CONCLUSION AND DISCUSSION

1. The shear strength of soil is highly dependent on pore water pressure changes. The effective stress analysis is most appropriate design approach in natural slopes where upper soil layer is colluvium and there is no additional load applied.
2. BPSB allows determining effective shear strength peak and residual parameters by measuring pore water pressure.
3. Pore water inflation testing allows to apply the stress path (Fig. 5), which pretends real case situation of pore water triggered landslide.
4. Pore water inflation testing has showed that soil will shear close to the peak shear strength envelope, so it is possible to evaluate shear strength parameters by testing different stress path starting from "safe" side of envelope, also changing effective normal stress by pore water pressure control.
5. BPSB test data can be used for further analytical and/or numerical design of slope stability in Abava river valley.

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