Influence of precipitation and soil conditions on the Krbavčići Landslide reactivation (Istria Peninsula, Croatia)

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Abstract The Krbavčići landslide occurred at the end of January 1979 near the City of Buzet, Croatia, after prolonged heavy rainfall. The landslide damaged the local road and the retaining wall at the landslide foot, and a new stable landslide position was taken after major sliding. The Krbavčići landslide is located in an area built of flysch rock mass, which is susceptible to sliding and where many different types of mass movements have been recorded in the past. The determined dimensions of the landslide are 370 m in length, 30 m in width in the upper part and 150 m in the lower part, with an estimated landslide volume of 3 x 10^5 m^3. The field investigation indicated that the sliding surface is located within the weathered bedrock zone at the contact between the weathered and fresh flysch rock mass at the depth of 13 m. Weathering of the flysch rock mass changes the geotechnical properties and shear strength, and potentially unstable deposits are formed. This paper presents the available information about the Krbavčići landslide occurrence, precipitation conditions for landslide reactivation, and laboratory testing of flysch deposit samples from the landslide body. Among the basic laboratory tests, ring shear test on the disturbed samples from the landslide body will be performed to determine the residual shear strength. Due to the specific shape of soil samples, the ring shear apparatus is commonly used to test disturbed soil samples. Therefore, a new sampling cutter was designed and a procedure developed to enable the collection, installation, and testing of the undisturbed soil samples. The precipitation and soil conditions that lead to the reactivation of the Krbavčići landslide are analysed and discussed.

Keywords landslide, precipitation, ring shear apparatus, sample cutter

Introduction

Climate change affects the stability of natural and engineered slopes and has consequences on landslides and similar phenomena. Landslides are mainly triggered by rainfalls and earthquakes. Rainfall-triggered shallow and deep landslides in flysch deposits are a common natural hazard on the Istria Peninsula and in the Rječina River Valley in Croatia. The Krbavčići landslide is located on the Istria Peninsula in an area built of flysch rock mass that are susceptible to sliding and where many different types of mass movements have been recorded in the past. The Krbavčići landslide occurred on 31st January 1979 after prolonged heavy rainfall (Vivoda Prodan & Arbanas, 2020). The landslide damaged the local Buzet–railway station road and the retaining wall at the foot of the landslide, and after major sliding a new stable landslide position was taken. Based on the field investigations, the dimensions of the landslide were determined: 370 m in length, 30 m in width in the upper part and 150 m in the lower part, the depth of the sliding surface is 13 m at the contact between the weathered and fresh flysch rock mass (WP/WLI & Glossary, 1993). According to Skempton & Hutchinson, 1969, it is classified as a translational landslide, and as a rock planar slide according to Hungr et al., 2014, while according to Cruden & Varnes, 1996 the style was moderately moving. The landslide is now dormant as no movement was visible on the local road or the remains of the retaining wall after the initial sliding.

The assessment of landslide stability requires the determination of the geotechnical properties of the material, which usually requires the use of various laboratory devices. This paper describes the laboratory testing of flysch deposit samples from the Krbavčići landslide body (Figure 1) to obtain data of their geotechnical properties. Details of the testing methodology used are described in the following sections. Shear strength is an important parameter for estimating slope stability and dynamics during mass movements and generally depends on the shear rate and drainage conditions in a slope. A better understanding of soil behaviour during the initiation and propagation phase of a landslide using ring shear apparatus is very important. Ring shear tests (RST) have been used to investigate residual strength properties and analyse geological hazards (Liao et al., 2011; Lin et al., 2018; Li et al., 2022; Sassa et al., 2004; Setiawan et al., 2016; Tika & Hutchinson, 1999; Tiwari & Marui, 2004; Wang et al., 2002). In addition, a dynamic RST with possibility to apply seismic loads has been developed to investigate the sliding mechanisms of earthquake triggered slopes (Liao et al., 2011; Sassa et al., 2010, 2014; Setiawan et al., 2016). Although extensive research has been conducted on coarse-grained soils, less work has been conducted on clay-like soil materials(Carrubba & Colonna, 2006; Duong et al., 2018; Tiwari & Marui, 2005). RSTs that enable the measurement of pore water pressure (PWP) are quite rare and only performed by a few authors (Lin et al., 2018; Sassa et al., 2004). Rate effects on residual strength play an important role in predicting and evaluating the behaviour of reactivated landslides. Although the rate dependence of residual strength has been extensively studied, there is a lack of consistency in test results (Li et al., 2022). RSTs on undisturbed samples are rare (Jeong, 2022; Tiwari et al., 2005), and not clearly investigated. The investigation of the weathering influence on the residual strength of the flysch rock mass on remoulded samples for Valići and Krbavčići landslide reactivation analysis was performed in the RSA (Vivoda Prodan et al., 2016; Vivoda Prodan & Arbanas, 2017, 2020).

The Ring shear apparatus (RSA) ICL-1 in the Geotechnical Laboratory of the Faculty of Civil Engineering, University of Rijeka was obtained as a part of the Croatian-Japanese project „"Risk identification and land-use planning for disaster mitigation of landslides and floods in Croatia". The main advantages of the RSA are the possibility of testing under high normal stress (up to 1 MPa) and high PWP (up to 1 MPa) (Oštrić et al., 2014; Sassa et al., 2004). For this reason, it is most often used to investigate deep-seated, rapid landslides. So far, the device has been used to investigate the shear strength properties of remoulded soil samples originating from flysch rock mass by performing strain-controlled tests under drained and undrained conditions, and PWP controlled tests under static conditions, which are crucial for investigation of landslide reactivation (Vivoda Prodan, 2016; Vivoda Prodan & Arbanas, 2017, 2020). RSTs under dynamic conditions in the described device have not yet been performed. Due to the specific shape of soil samples, RSA is commonly used for testing of remoulded soil samples. A sample cutter was developed that enables collection, installation and testing of undisturbed soil samples.

Numerical 2D slope stability and 3D landslide simulations were performed by Vivoda Prodan & Arbanas, 2020, based on the input parameters obtained by ring shear and direct shear tests on disturbed siltstone samples from flysch rock mass of different weathering grades from nearby location. Further research is needed to provide relevant soil properties from landslide location for the validation and calibration of landslide numerical models.

Defining the duration of the precipitation during which cumulative precipitation should be considered is essential for predicting the landslide occurrence. Arbanas et al., 2014; Dugonjić Jovančević & Arbanas, 2012 have shown that the cumulative twelve-month values as well as the maximum monthly, weekly or daily precipitation preceding the landslide have no significant influence on the triggering of a landslide initiation in the North Istria. Their analyses show that the precipitation from approximately three months before a landslide initiation has the primary influence on the rising infiltration and ground water level as the main triggering factor for the activation of landslides on flysch slopes in North Istria. In the last 10 years, many shallow landslides triggered by short intensity rainfalls have occurred on flysch slopes in the North Istria and they were. Prolonged rainfall events are critical for triggering deep-seated landslides, while short and intense rainfall events play a greater role in triggering shallow landslides and erosion process.

This paper describes the performance of laboratory tests on flysch deposit samples to determine basic physical properties and to investigate shear strength and pore water pressure conditions during shear deformation on disturbed samples using RSA, as well as the development of a procedure for installing and testing undisturbed soil samples using RSA. The results of the precipitation analysis and laboratory tests would provide a better insight into the soil properties, which will be valuable input data for conducting numerical analysis of slope stability and landslide propagation in such materials. The results obtained will be valuable for future research as they will provide insights into the response of the soil under different shear conditions as well as input parameters for different numerical models.

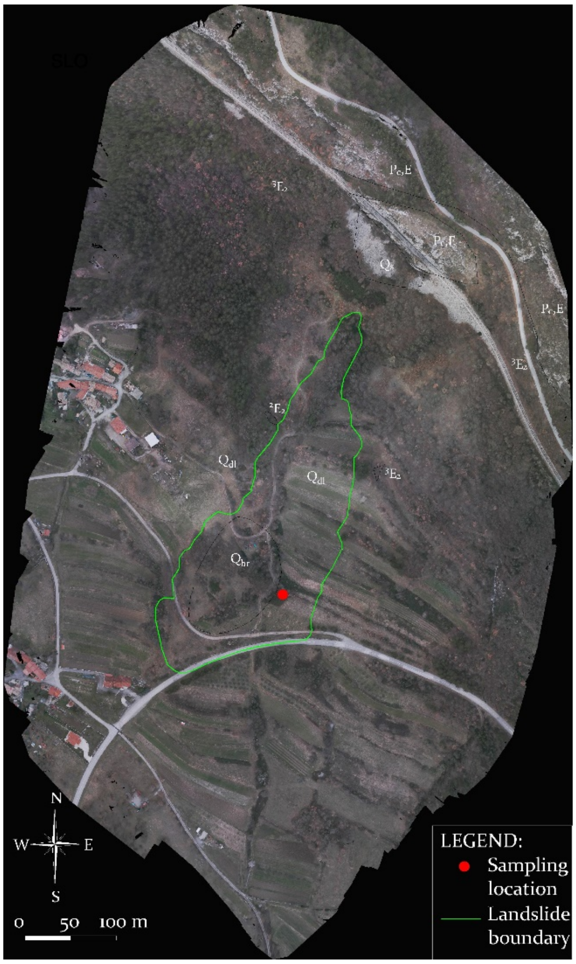

Figure 1 Krbavčići landslide on a detailed orthophoto map from 2016 with sampling location and landslide boundary ($Q_{(br,dl)}$-cover deposits, $^{3(2)}E_2$-marl and siltstone outcrops, Pc,E-limestone).

Precipitation conditions

Based on the precipitation data for the last 57 years (from 1966 to 2022) obtained from the Lupoglav rain gauge (390 m a.s.l.), about 10 km from the Krbavčići landslide, the daily and monthly precipitation amounts were observed.

The crucial cumulative three-month precipitation amount that triggered the Krbavčići landslide on 31st January 1979, was 509.2 mm. The amount of precipitation in January 1979 reached 327.2 mm, which was almost three times higher than the average amount of precipitation in January in the period 1966-2022. Figure 2 shows that all monthly precipitation within one year before the Krbavčići landslide occurrence was above the average monthly precipitation value, with the exception of the months of September and November 1978: the wet and dry period before the landslide occurrence was rainy with amounts above the average values.

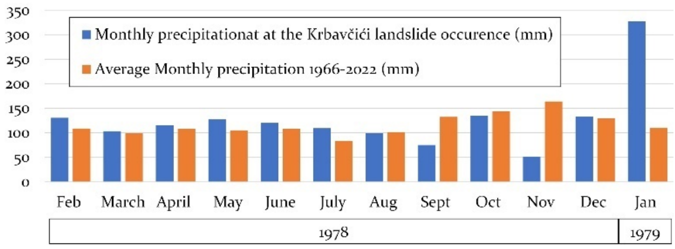

Figure 2 Monthly precipitation within a year before the Krbavčići landslide occurrence.

Laboratory testing

Soil properties

Disturbed and undisturbed residual soil samples originating from flysch rock mass were taken from the sample pit in the central part of the Krbavčići landslide (Figure 1). Sampling was carried out from the surface at a depth of 0.5 m. A series of tests were performed to determine the basic physical properties of the soil samples: specific gravity of soil solids (ASTM D854-14, 2014), saturated unit weight, particle size distribution (ASTM D422-63, 2007), liquid limit (*LL*), plastic limit (*PL*), plasticity index (*PI*) (ASTM D4318-10e1, 2010), classification of the material according to the USCS (ASTM D2487-17e1, 2020) and saturated coefficient of permeability using the falling head method (ASTM D5084-03, 2010). In addition to determining the basic physical properties, disturbed and undisturbed samples were taken to investigate the shear strength in the RSA.

Sample cutter design

Due to the specific shape of soil samples, RSA is commonly used to test remoulded soil samples. Here is described the development of a sample cutter (Figure 3) that makes it possible for the first time to obtain and analyse undisturbed samples of residual soil from a flysch rock mass from landslides which occur frequently on the Istria Peninsula and in other areas prone to sliding.

The sample cutter was designed together with the extruder in January 2024. The sample extruder was printed using a 3D printer with PLA material in the Hydrotechnical Laboratory of the Faculty of Civil Engineering, University of Rijeka. The two rings are connected with a threaded rod and M5 nuts (Figure 3b). Sampling was carried out from the surface at a depth of 0.5 m using a newly developed sample cutter for ring shear tests (Figure 3a). After the cutter was pushed into the soil, it was excavated and sealed to prevent evaporation, and the sample was prepared (Figure 3c) and extruded into the ring shear box in the Geotechnical laboratory (Figure 4).

Ring shear testing procedure

An important advantage of the RSA is possibility of measuring PWP conditions at the shear surface during shearing, obtaining both peak and residual stress envelopes through infinite deformation under static (rainfall) and dynamic (earthquake) loading.

Disturbed residual soil samples were fully saturated with deaired distilled water and tested in the RSA. The ring shear box was first filled with CO_2 and de-aired distilled water and then with the saturated sample. After checking the sample saturation and consolidation under normal effective stresses of 235 kPa, the sample was sheared under a constant shear rate of 0.01 cm/s in undrained conditions until a steady state was reached. The procedure for installing and testing undisturbed residual soil samples from a flysch rock mass is currently being developed. For both types of sampling, basic parameters (peak and residual friction angle and cohesion) as well as the steady-state normal and shear stresses can be determined.

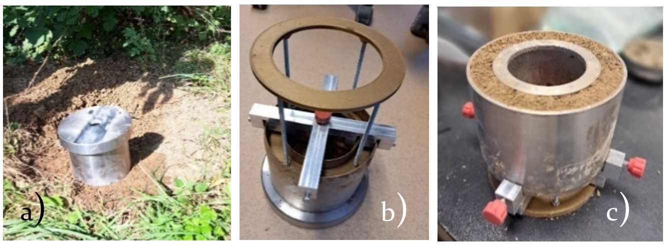

Figure 3 Collection of near-surface soil samples with the newly developed equipment for undisturbed soil sampling for RST: a) sampling in the field; b) sampling extruder; c) preparation of the sample surface.

Figure 4 Installing undisturbed sample in the ring shear box: a) during extruding procedure; b) at the beginning of RST.

Results

The silt and clay content of the residual soil originating from the flysch rock mass were 40% (Figure 5), The sample had a liquid limit of 39% and a plastic limit of 20%, while the plasticity index was 19%. The sample was classified as clay of low plasticity (CL) in the plasticity chart according to USCS soil classification (ASTM D2487-17e1, 2020). The specific gravity value was 2.7. The determined value of the saturated coefficient of permeability was 1.12e-04 cm/s. Table 1 gives an overview of the test results with the basic physical properties of the sample.

The residual shear strength was determined based on the RST. Figure 6a presents changes in shear stress, total and effective normal stress and pore water pressure in time during shearing with shear rate control while Figure 6b shows a normal/shear stress diagram for the disturbed sample from the Krbavčići landslide. In Figure 6b, the green line represents the effective stress path, the purple line is the total stress path. When the effective stress path reached the failure line, it started to decrease due to pore water pressure generation along the failure line until the steady-state shear resistance was reached. The total shear resistance measured during the sample shearing, was additionally reduced by the value of rubber friction (12.6 kPa) to obtain the actual value of the shear resistance of a tested sample. The graph on Figure 6b shows that the residual friction angle was 19.3°, the residual cohesion was 18.4 kPa and the steady-state shear resistance was 39.4kPa.

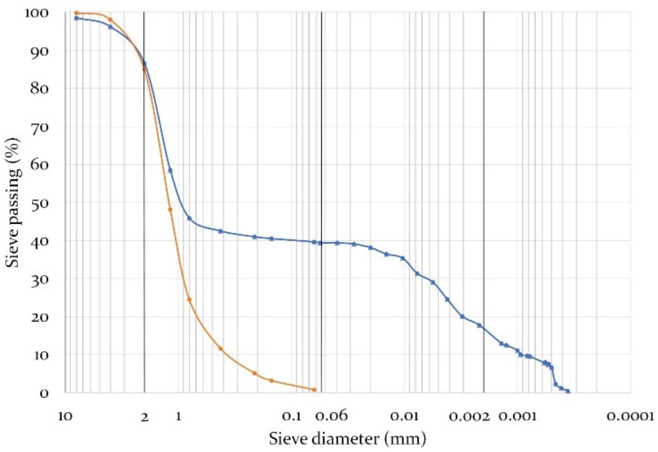

Figure 5 Grain size distribution curve of sample from Krbavčići landslide based on the dry sieving (orange line) and wet sieving + hydrometer test (blue line).

Table 1 Basic physical properties of the tested sample from the Krvavčići landslide.

Parameter	Symbol	Unit	Value
Specific gravity	G_s	(-)	2.7
Liquid limit	*LL*	(%)	39
Plastic limit	*PL*	(%)	20
Plasticity index	PI	(%)	19
Effective particle size			
	D_{10}	(mm)	0.001
	D_{60}	(mm)	1.2
Coefficient of permeability	k_s	(m/s)	1.12E-06

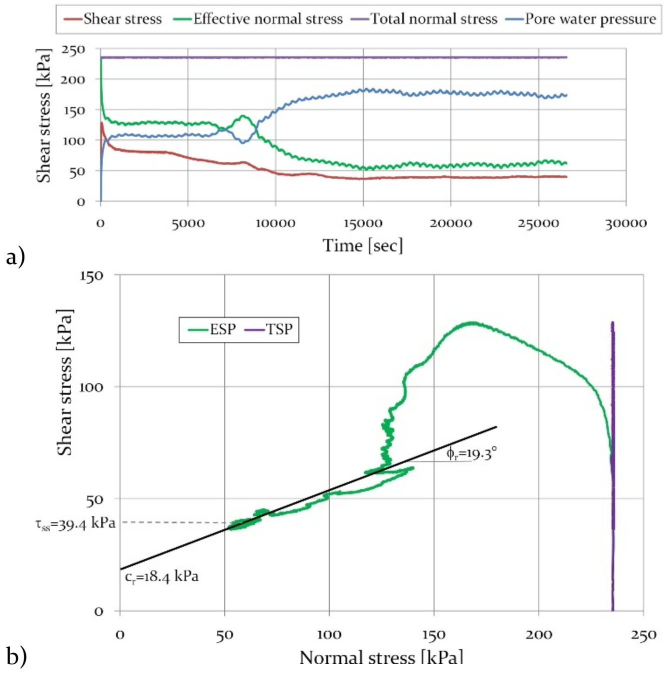

Figure 6 Undrained shear rate control test: a time series data, b stress path (green-effective stress path ESP, purple-total stress path TSP).

Summary and conclusions

In 2012, a high stress undrained ring shear apparatus, ICL-1, has been developed for the landslide research, and donated by the Japanese government for landslide analysis in Croatia. This RSA is suitable for undrained shear tests under all types of loading and enables the observation of the undrained shear behaviour of soils at high stresses up to 1 MPa at high speed movements with unlimited shear displacement.

The samples of residual soil from flysch rock mass taken from the Krbavčići landslide were tested. This paper presents experimental results of undrained speed control test until steady state condition is reached on the disturbed samples. From this test, the basic material properties, the residual friction angle, the residual cohesion and the steady state shear resistance were obtained. A newly developed sample cutter and a subsequent sample extruder will enable to obtain and test undisturbed samples in the ring shear apparatus. The results obtained on the disturbed samples must be compared with the results obtained on the undisturbed samples in the ring shear apparatus and also with the test results of other devices and further investigations are required. It should also be noted that in addition to the strength properties of the soil, other factors such as the hydraulic conductivity, the slope terrain and the initial moisture condition of the soil can also influence the triggering of landslides. The slopes in the Krbavčići area lie under deep deposits of flysch residual soils with intermediate permeability. Prolonged and low-intensity precipitation could lead to a relatively large amount of infiltration and eventually cause the slope more susceptible to failure.

The developed sample cutter is a new practical tool for research of undisturbed soil samples taken near the ground surface with the ring shear apparatus and for the subsequent research of landslides in Croatia. The future laboratory results and precipitation analysis will serve as a basis for the numerical simulation of the selected Krbavčići landslide and the analysis of a possible reactivation of the landslide in the surrounding area.

Acknowledgements

This research was funded by the University of Rijeka under the project ZIP-UNIRI-1500-1-22 and partially supported by the project uniri-mladi-tehnic-22-62. This paper has been supported by the International Consortium on Landslides under the IPL-256 project. Rainfall data received from Croatian Meteorological and Hydrological Service are also gratefully acknowledged. The authors would like to thank Duje Kalajžić for the construction of sample extruder. These supports are gratefully acknowledged.

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