Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0906

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Rainfall infiltration and stability analysis of an unsaturated slope in residual soil from flysch rock mass

Infiltration pluviale et analyse de la stabilité d'une pente non saturée dans le sol résiduel de la masse rocheuse du flysch

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ABSTRACT: Weathering process in the flysch rock mass results with a geotechnical profile consisting of residual soil, weathered flysch rock mass and fresh flysch bedrock. Back-analysis of landslides occurred in flysch slopes often indicated high values of pore water pressures that should exist on the sliding surface decreasing the soil strength and causing a slide. Associated high groundwater levels (often close to the terrain surface) have an important role in landslide occurrence but the upper unsaturated part of the geotechnical cross-section and developed negative pore pressures caused by suction may have a critical contribution in keeping a slope stable. Due to the very low hydraulic conductivity of residual soils from flysch rock mass, rainfall infiltration is very slow and necessary conditions for saturation of the unsaturated zone are long-term rainfall events. The Valići Landslide, Croatia, occurred on flysch slope in February 2014 after few months of heavy, mostly uninterrupted rainfall. To identify the impact of negative pore pressures in unsaturated zone on slope stability and landslide activation, comprehensive soil laboratory testing and numerical analysis were conducted. Undisturbed samples of residual soil were collected from the superficial part of the landslide body and advanced laboratory measurements were performed to obtain hydro-mechanical properties of soil in unsaturated conditions. Obtained soil parameters were used to assess the influence of negative pore water pressures existing in the unsaturated zone of residual soil on rainfall infiltration process and slope stability in time. In this paper, the results of carried out laboratory tests and numerical analysis will be presented. Based on these results the behavior and landslide activation in slopes built in residual soil from flysch rock mass will be explained.

RÉSUMÉ: Le processus d'altération dans la masse de roche flysch résulte avec un profil géotechnique composé de sol résiduel, de masse rocheuse de flysch altérée et de substrat rocheux de flysch frais. Une analyse en retour des glissements de terrain survenus sur les pentes du flysch a souvent indiqué des valeurs élevées de pressions interstitielles qui devraient exister sur la surface de glissement, diminuant la résistance du sol et provoquant un glissement. Les hauts niveaux d'eaux souterraines associés (très souvent très proches de la surface du terrain) jouent un rôle important dans l'occurrence des glissements de terrain, mais la partie non saturée supérieure de la section transversale géotechnique et les pressions interstitielles développées causées par la succion peuvent avoir une contribution essentielle à la stabilité de la pente. En raison de la très faible conductivité hydraulique des sols résiduels de la masse de flysch, l'infiltration des précipitations est très lente et les conditions nécessaires à la saturation de la zone non saturée sont des événements pluviométriques à long terme. Le glissement de terrain de Valići, en Croatie, s'est produit sur la piste de flysch en février 2014, après quelques mois de fortes précipitations, la plupart du temps sans interruption; événement pluvieux. Pour identifier l'impact des pressions interstitielles négatives dans la zone non saturée sur la stabilité des pentes et l'activation des glissements de terrain, des tests complets en laboratoire et une analyse numérique des sols ont été réalisés. Des échantillons non perturbés de sol résiduel ont été recueillis dans la partie superficielle du corps du glissement de terrain et des mesures de laboratoire avancées ont été effectuées pour obtenir les propriétés hydromécaniques du sol dans des conditions non saturées. Les paramètres de sol obtenus ont été utilisés pour évaluer l'influence des pressions interstitielles négatives existant dans la zone non saturée de sol résiduel sur le processus d'infiltration des pluies et la stabilité de la pente dans le temps. Cet article présente les résultats des tests de laboratoire et des analyses numériques effectués. Sur la base de ces résultats, le comportement et l'activation des glissements de terrain dans les pentes construites dans le sol résiduel à partir de la masse rocheuse du flysch seront expliqués.

Keywords: Unsaturated residual soil; flysch; rainfall-induced landslides; infiltration; stability analysis

1 INTRODUCTION

Precipitation in the form of rainfall is the most common landslide cause. Rainfall-induced landslides occur in various geologic, climate, and topographic conditions. Factors primarily controlling rainfall-induced slope failures are both the rainfall characteristics and soil properties (e.g., Rahardjo et al. 2007; 2016). Rain falling on the slope generates a transient infiltration process within the unsaturated zone existing between terrain surface and phreatic line, increasing the soil water content and reducing the matric suction. The later directly affects hydro-mechanical features of the soil. A decrease of the matric suction causes a reduction of the effective stress and available shear strength. At the same time, increased water content increases the hydraulic permeability of the soil. Quantities such as shear strength, hydraulic permeability and water storage capacity of unsaturated soil depend on the matric suction value, which varies with the water content of soil. Thus, quantities generally considered to be constants for soil existing in saturated conditions take the form of non-linear functions in case of partial saturation. The unsaturated shear strength, water retention and hydraulic conductivity function are the most important unsaturated soil property functions (USPFs). These have to be determined when analyzing the stability of unsaturated slope exposed to transient rainfall infiltration process.

Principles of the unsaturated soil mechanics have been applied extensively for explaining the phenomena of shallow slides with the slip surface developed in partially-saturated conditions. Good praxis is presented for shallow landslides triggered by rainfall in pyroclastic soils in Italy (e.g., Casagli et al. 2006; Cascini et al. 2010) or in steep slopes in residual soils in Singapore (e.g., Rahardjo et al. 2005; Rahimi et al. 2011), Korea (e.g. Kim et al. 2012) and Hong Kong (e.g., Ng and Pang 2000; Li et al. 2005). Another one conceptual model of rainfall-induced shallow landslides pertains on conditions where the entire slip surface is developed under completely saturated and positive pore-water pressure conditions (e.g., Santo et al. 2018). Only a few studies quantitatively analyze the effect of transient rainfall infiltration on the slope stability of deep-seated landslides built of low hydraulic conductivity materials (e.g., Sun et al. 2009; Zhao et al. 2017). This kind of studies is completely absent in case of flysch material in slopes.

Previous studies of landslide occurences in flysch slopes have been mainly focused on the increase of pore-water pressure caused by long-term heavy precipitation as a landslide triggering factor (e.g., Arbanas et al. 2014, 2017; Berti et al. 2017) and the effects of the weathering process of flysch rock masses on physical and chemical changes of material (e.g., Vivoda Prodan and Arbanas 2016, Vivoda Prodan et al. 2017). Simple conceptual rainfall infiltration model and field measurements indicated the Slano Blato Earthflow in flysch deposits in Slovenia were reactivated in always-saturated conditions (Maček et al. 2016).

In this paper we present a part of the field, laboratory and numerical activities conducted to investigate the importance of the unsaturated zone for the rainfall infiltration process and landslide activation in flysch slopes.

2 STUDY AREA AND SOIL PROPERTIES

Previous studies of landslides in the Rječina River Valley, Croatia indicated that water infiltration in the unsaturated part of the slope and groundwater level (GWL) rise expand relatively slowly, with a consequently low rate of pore pressure increase. Long rainy periods have shown to be crucial for landslide initiation, and all landslide appearances occurred after long periods of heavy rainfall (Benac et al. 2011). Examples of recent landslides in flysch slopes triggered after few months of heavy rainfall are the Grohovo Landslide reactivated in December 1996, and the Valići Landslide reactivated in February 2014 (Benac et al. 2005; Arbanas et al. 2014, 2017). With the residual soil present at the slope surface, directly exposed to the atmosphere conditions, the Valići landslide was chosen as the investigation site for a comprehensive study of rainfall-induced landslides in flysch deposits with consideration of unsaturated soil mechanics principles. A novelty of this study consists in consideration of hydro-mechanical properties governing the transient process of rainfall infiltration into the slope and affecting the slope stability state through time.

According to the test results obtained for samples collected at a superficial part of the landslide body, investigated material could be classified as lean clay (CL) with prevailing silt-size particles (Peranić et al. 2018). Identification tests suggest very similar granulometric composition and consistency limits of the material covering the slope surface. Since the later have shown to reflect water retention and hydraulic conductivity features of the soil, the identification test results indicate presumably similar USPFs of the residual soil covering the sliding mass. Basic soil properties are summarized in Table 1.

Natural water content measurements performed in several campaigns from October 2017 to June 2018 reveal that the absence of rainfall and excessive evaporation during dry summer months cause desiccation of the soil in the first few meters from the surface (Table 2). In the same time, short-term rainfalls of higher intensity during September and October were able to significantly increase the water content of soil in only very first 1 m, while in deeper layers degree of saturation remained unchanged.

According to the rainfall data recorded at the nearest meteorological station in the period from 1958 to 2015, the average annual rainfall was 1.567 mm, with a maximum of 2.339 mm and the minimum amount of 832 mm recorded in 1960 and 2011 respectively.

Precipitation measurements obtained in the period from September 2013 until 14 February 2014 were used to define the flux boundary condition in numerical analysis. Hourly rainfall measurements were collected with the tipping bucket rain gauge installed at the nearby the Grohovo Landslide (Arbanas et al. 2014).

Table 1. Mean values of the basic properties of the residual soil samples used in this study (Peranić et al. 2018)

C; M; S; G (%)	**LL/PL/PI** (%)	**Gs** (/)	**USCS**
30.3; 53; 10.4; 6.3	44/24/20	2.7	CL

Table 2. Natural water content (w_n), dry density (ρ_d), degree of saturation (S), and volumetric water content (θ) of the near-surface soil.

<u>*July 2017*</u>

Depth (m)	w_n (%)	ρ_d (g/cm^3)	*S* (%)	θ (cm^3/cm^3)
surface	16.5	/	/	/
0.12-0.17	15.3	1.54	54.4	0.23
0.32-0.37	16.3	1.53	57.6	0.25
0.57-0.62	13.1	1.65	56.1	0.22
0.87-0.92	11.3	1.60	44.1	0.18

Figure 1 reveals that the cumulative rainfall amount of 1.164 mm was recorded for the considered period.

3 SOIL-WATER RETENTION CURVE AND HYDRAULIC CONDUCTIVITY

The soil-water retention characteristics of the soil were investigated by Peranić et al. (2018). Measurements performed by using different devices and measurement techniques (mini-tensiometers, axis-translation technique and dew-point potentiometer) were combined to determine the complete SWRC, both for the desorption and adsorption process, and under different net vertical stress values.

A non-linear regression analysis was performed on the obtained results to define the best-fit parameters of the van Genuchten's (1980) (1) and Fredlund and Xing's (1994) (2) SWRC equations summarized in Table 3:

$$\theta = \theta_s \left[\frac{1}{1+(\alpha\psi)^n}\right]^m \tag{1}$$

$$\theta = C(\psi)\frac{\theta_s}{\left\{ln\left[e+\left(\frac{\psi}{a}\right)^n\right]\right\}^m} \tag{2}$$

where a, α, n, and m are constants, and $C(\psi)$ is a correction function defined as

$$C(\psi) = 1 - \frac{ln(1+\psi/\psi_r)}{ln(1+1{,}000{,}000/\psi_r)} \tag{3}$$

and ψ_r (MPa) a constant related to the suction at residual water content,θ_r.

Table 3. Best fit parameters and sum of the squared residuals (r^2) (Peranić et al. 2018).

VG	**SSR(r^2)**	θ_r	α	n	m
drying	0.00049	0.028	0.004	1.186	0.323
wetting	0.00021	0.011	0.005	0.973	0.348
F&X	**SSR(r^2)**	ψ_r	α	n	m
drying	0.00039	178	300	1.073	0.907
wetting	0.00022	254	284	0.859	1.053

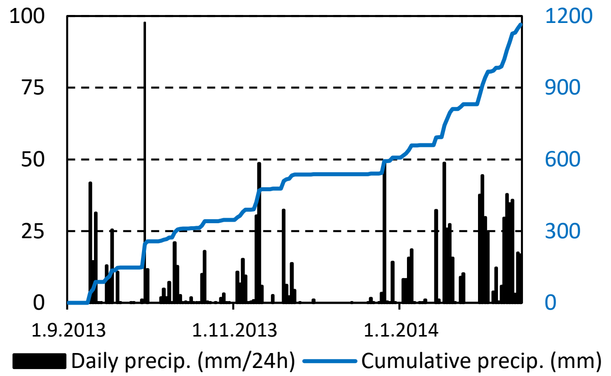

Figure 1 Daily rainfall measured from 1 September to 14 February 2014.

The saturated coefficient of permeability (k_s = 4.60E-08 m/s) measured with the constant head method on undisturbed samples in the conventional triaxial apparatus 28-WF4050 (Controls S.p.A.) and the van Genuchten (1980) SWRC equation parameters obtained for the wetting process were combined to estimate the unsaturated hydraulic conductivity function (UHCF) of the soil used in numerical simulations.

4 NUMERICAL ANALYSIS

The GeoStudio (GEO-SLOPE International, Ltd.) software suite was employed to perform numerical analysis of rainfall infiltration and slope stability. Two modules of the noted software were combined to determine the influence of the rainfall infiltration and the unsaturated zone on the state of slope stability through time.

4.1 Infiltration analysis

The 2D finite element software modulus SEEP/W was used to obtain pore-water pressure distributions in geotechnical cross-section for defined material properties, initial (ICs) and boundary conditions (BCs).

Pore-water pressure distribution can be obtained from defined SWRC and UHCF, by solving the 2D transient seepage equation based on continuity considerations and Darcy‘s law:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) = m_2^w \rho_w g \frac{\partial h}{\partial t} \qquad (3)$$

where h is the total head, k_x and k_y are the coefficients of permeability respective to the water phase, and m_2^w represents the water storage modulus obtained by differentiation of the SWRC-θ (Fredlund et al. 2012).

Collected hourly rainfall data were used to define the flux BC along the slope surface, q ($m^3/s/m^2$) vs. time (days) shown in Figure 2. Generation of the positive pore water pressure on the slope surface due to an excessive rainfall intensity relative to the infiltration capacity was disabled by using the “potential seepage face review” option. The average working level of the Valići storage was considered by applying constant water total head equal to 228 m asl on the right side of the model in the toe of the slope. According to the back-analysis results shown in Figure 3, the slope becomes unstable when the sliding mass becomes fully saturated, with the GWL reaching the slope surface almost at the entire sliding mass. Arbanas et al. (2017) obtained similar results by using the shear strength reduction method. The corresponding value of 301.8 m asl was used as a constant water total head as the BC for the left side of the model.

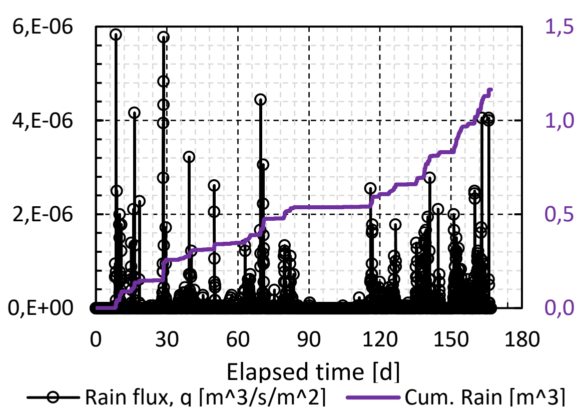

Figure 2 Flux boundary condition derived from the hourly rainfall measurements collected in-situ.

Discretization of the domain was performed with automatically generated unstructured pattern of quadrilateral and triangular elements, with an approximate global element size of 1m. Additional four regions 0.5 m high, parallel to the terrain surface were created in the near-surface zone of the numerical model to obtain finer discretization in the part of the domain where imposed BCs cause changes to occur more rapidly.

Figure 4 presents the changes in the degree of saturation and pore-water pressure in the cross-section at sampling pit location (indicated with a black line in Figure 3) during 167 days of simulation. 0 sec refers to the starting conditions in simulation obtained by defined ICs which could have existed on 1 September 2013, according to the field observations, laboratory measurements, and previous slope stability analysis. Obtained results indicate slow dissipation of the matric suction during the first 130 days of simulation, following by the rapid increase of pore water pressure from the 150^{th} day of analysis. From the start of the simulation up to the 110^{th} day, the GWL increases for only about 1m. Rainfall infiltration causes a further rise of the GWL for 1 m in the following 20 days period and 2 meters from the 130^{th} to the 150^{th} day of simulation. During the last 17 days of analysis, the GWL increases for around 5 m, reaching almost the ground surface in the selected profile.

4.2 Stability analysis

The SLOPE/W modulus with implementing limit equilibrium method (LEM) was used to perform slope stability analysis. The SEEP/W transient infiltration analysis results saved after every 24h of simulation were used to define pore-water pressure distribution in slope stability analysis.

Total of 167 pore-water pressure distributions was introduced into the SLOPE/W modulus to calculate the factor of safety (FoS) values using the Morgenstern and Price (1965) method (Figure 5). Obtained results provide information about

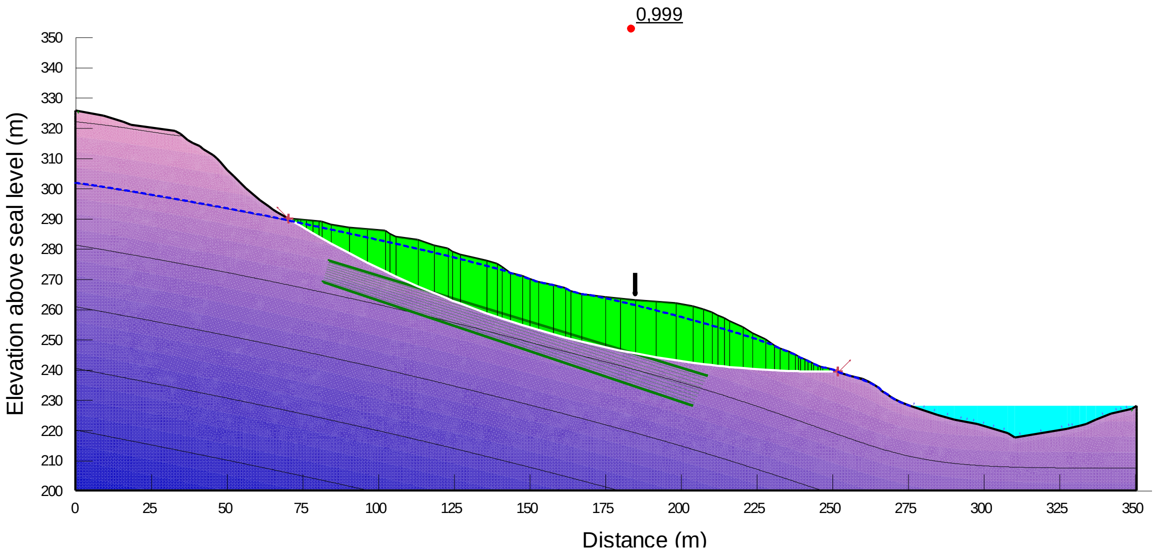

Figure 3 Critical slip surface and groundwater conditions according to the slope stability back-analysis.

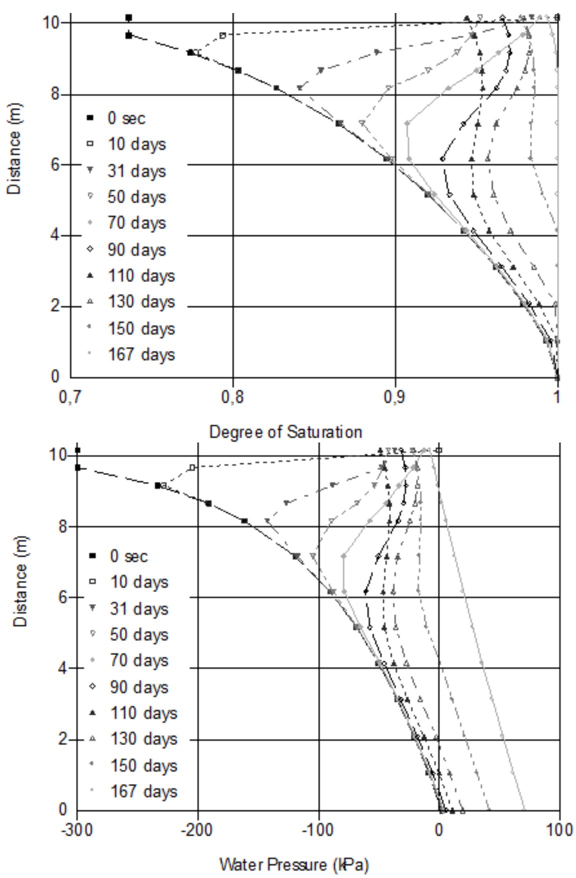

Figure 4 Degree of saturation and pore-water pressure change obtained from the numerical model.

the temporal change of the slope stability state caused by rainfall infiltration. Starting FoS value of 1.6 corresponds to the applied ICs and BCs defined in the SEEP/W analysis. Reduction of the FoS value is resulted by the infiltration process and its effects inside the unsaturated zone. It was expected that the shear strength component associated with the matric suction would affect only the starting absolute FoS value, while in the following stages of the rainfall simulation should have decreasing effects on the slope stability due to the dissipation of the matric suction in the slope cross-section.

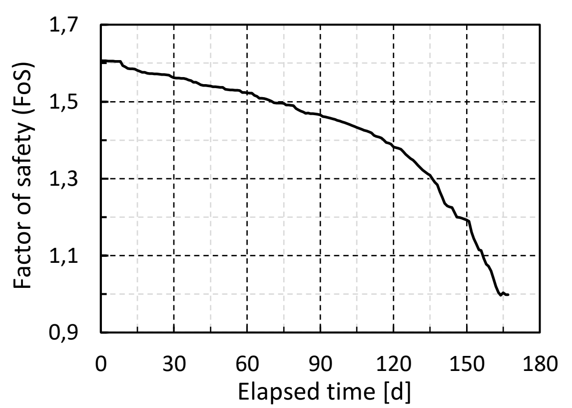

Figure 5 Change of slope stability state through 167 days of simulation.

Table 4. Material properties for slope stability analysis in SLOPE/W.

Unit weight γ (kN/m^3)	**Strength parameters**		**Failure envelope**
	c'(kPa)	$\phi' = \phi^b$(°)	
19	0	29	Mohr-Coulomb

According to previous shear strength studies and SWRC characteristics, it was assumed that $\phi' = \phi^b = 29°$. Material properties used in the slope stability analysis are summarized in Table 4. Change of the soil weight calculated from the SWRC during the rainfall infiltration was found to have negligible effects on the slope stability results. The Extended Mohr-Coulomb failure envelope was used to define the shear strength criteria.

5 CONCLUSIONS

This paper provided some basic insights on how the transient rainfall infiltration process and the unsaturated zone of the flysch slope affect the slope stability state through time. Envisioned by some previous studies, long-lasting rainfall was quantitatively confirmed as the key factor for the landslide initiation. Obtained results showed that under defined conditions and applied rainfall, the slope remained stable during the 167 days of simulation before the FoS dropped below 1.0. Although the performed simulation relies on rather simple LEM, which has its drawbacks, and the evaporation effects were assumed to be negligible for the period analyzed, the obtained results correspond closely to field observations. Although the build-up of positive pore-water pressures along the sliding surface induced the slope failure, it seems that the unsaturated zone with its storage capacity and low hydraulic conductivity has the main role in maintaining the stability of the flysch slope during long-lasting heavy rainfall periods.

6 ACKNOWLEDGEMENTS

The part of laboratory equipment used for laboratory testing was provided in the frame of the Project “Research Infrastructure for Campus-based Laboratories at the University of Rijeka”, co-funded by Ministry of Science, Education, and Sports of the Republic of Croatia and the European Fund for Regional Development (ERDF). The authors would like to thank GEO-SLOPE International Ltd. for providing the GeoStudio 2018 during the research.

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