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

doi: 10.32075/17ECSMGE-2019-0878

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

The role of unsaturated condition and suction in the weathering mechanisms in flysch marls

Le rôle de l'état non saturé et de la succion dans les mécanismes de vieillissement dans les marnes de flysch

G. Vlastelica
Faculty of Civil Engineering, Architecture and Geodesy/University of Split, Split, Croatia

N. Štambuk Cvitanović, P. Miščević, M. Nikolić, A. Raič
Faculty of Civil Engineering, Architecture and Geodesy/University of Split, Split, Croatia

ABSTRACT: The weathering of marls from Dalmatia (Croatia) is approached from the aspect of unsaturated conditions and suction through the first findings of a new scientific project dealing with experimental and numerical investigations of mechanisms in unsaturated geomaterials. This is done by connecting the reliable previous own research results obtained on flysch marls (database with approximately 1500 samples) and findings from the research concerning unsaturated materials of similar behavior and composition. The expected suction ranges and soil water characteristic curve (SWCC) shape parameters were determined and described, as well as role of matric suction and SWCC in the engineering behaviour of marl, types of degradation and parameters of significance for further research program. The results of analyzes conducted, data collected, and an overview of experimental and numerical methods suitable for further research were also given.

RÉSUMÉ: Dans cet article, l'altération des marnes de Dalmatie (Croatie) est abordée sous l'angle des conditions non saturées et de l'aspiration, à travers les premiers résultats d'un nouveau projet scientifique traitant des investigations expérimentales et numériques des mécanismes dans les géomatériaux non saturés. Pour ce faire, on associe les résultats de recherches antérieures fiables obtenus sur des marnes de flysch (base de données contenant environ 1 500 échantillons), les résultats des recherches concernant des matériaux non saturés de comportement et de composition similaires. Les plages de succion attendues et les paramètres de forme de la courbe caractéristique de l'eau du sol (SWCC) ont été déterminés et décrits, ainsi que le rôle de la succion matricielle et de la SWCC dans le comportement technique des marnes, les types de dégradation et les paramètres importants pour la poursuite du programme de recherche. Les résultats des analyses effectuées, les données collectées et un aperçu des méthodes expérimentales et numériques appropriées pour des recherches ultérieures ont également été présentés.

Keywords: Suction; SWCC; flysch marls; testing; numerical modelling

1 INTRODUCTION

Successful construction in soft rocks depends on correctly predictioning the behaviour of these materials. These rocks with „clay-like" behaviour (marl, siltstone, claystone or mudstone, shale, clay-shale), typically exhibit moderate to high plasticity, high water adsorption capacity, low to moderate strength, high deformability and swelling and shrinkage characteristics. During wetting they may swell or collapse and during drying they shrink.

The physical weathering of flysch marls is manifested in the breakup of material (fracturing, fragmentation) as a result of interconnected processes: wetting and drying, slaking, suction, insolation, freeze and thaw, crystallization, stress release, swelling. Slaking is a process associated with wetting and drying. The sudden absorption of water inside dry joints results in development of pressure inside rock joints which lead to the extension (deepening) of joints. Slaking is in close relation with process of suction. Significant contribution to weathering is brought by differential suction and corresponding differential swelling in unsaturated conditions (Alonso et al., 2010; Cardoso and Alonso, 2007). The differential suction influences tensile and shear stresses due to suction gradient leading to material degradation.

In the last ten years investigations have been focused on the influence of matric suction and soil water characteristic curve SWCC (or soil water retention curve SWRC) to the engineering behaviour of expansive soil. It was found that the SWCC could be a valuable tool for better prediction of the volume change behaviour of expansive soils/rocks prone to swelling/collapse.

This study analyzes data from the rich fund of own test results of flysch marl properties in Dalmatia, Croatia (Figure 1), which are relevant for the evaluation of their weathering tendency and behavior in time, and also connected to the suction and SWCC. Based on these input values, we derive the parameters relevant to the SWCC test method selection and expected suction behavior, as well as the range and limitations of future suction measurements and SWCC shape, to allow suction and SWCC measurements to become part of laboratory, field and related numerical investigations. The aim is to gradually collect new data and correlate the data in order to clarify the behavior of the natural environment of the flysch.

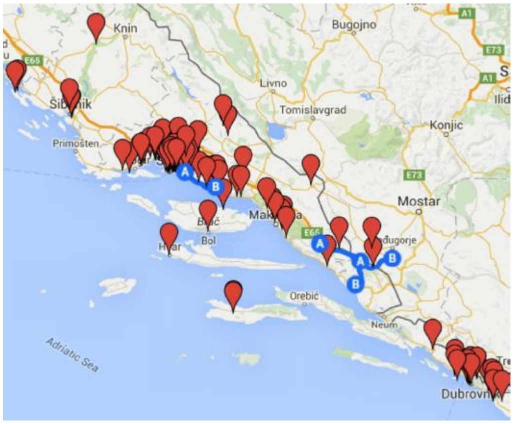

Figure 1. Location map of collected samples - the area of Central and Southern Dalmatia (Croatia)

2 RESULTS OF PREVIOUS RESEARCH

The classification approach including weathering and durability focuses on two categories of behaviour: the immediate response (strength and deformability) and the long-term behaviour of the rock mass. Marls from this study are more closely described in the work of Vlastelica et al., 2018.

2.1 Strength and deformability of marls

Most approaches used to characterise any rock are based on the uniaxial compressive strength (*UCS*). From the database of 1500 samples only data referring to the group of marly materials (marly clay, clayey marl, marl, limestone marl) were isolated and analyzed using linear and nelinear regresion, single and multiple (NCSS, 2016). Several models of correlation of properties have been obtained, in which *UCS* is dependent on porosity n, carbonate content $CaCO_3$, v_P velocity, dry unit weight γ_d, water content w_0, Young's elasticity modulus E and other properties, of which the following model is presented: $UCS = 0.5700\ CaCO_3 - 1.0251\ n$ (R^2=0.69, Figure 2, 564 groups of data).

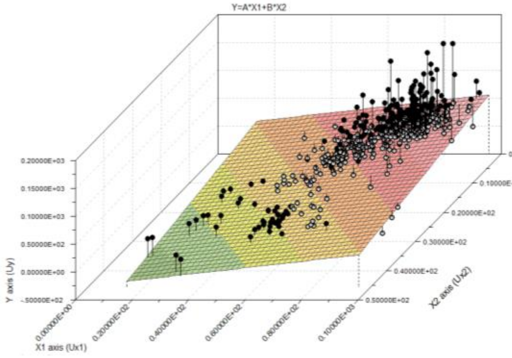

Figure 2. Response surface as a form of correlation of variables: axis X1 = $CaCO_3$ (%); axis X2 = porosity n (%); axis Y = UCS (MPa)

Taking into analysis only the marls (319 data sets) the nonlinear model of correlation *UCS - n* is obtained (R^2=0.61). Similarly, *E* is dependent on *UCS* and *n* (R^2=0.70, N=378), and numerous other correlations have been determined.

According to the engineering classification of intact rocks (Jurak and Belošević, 1999, Figure 3, 621 specimens), the observed marls fall into the areas of low *E* and *UCS* ratio (ductile rocks of very low, low and moderate strength).

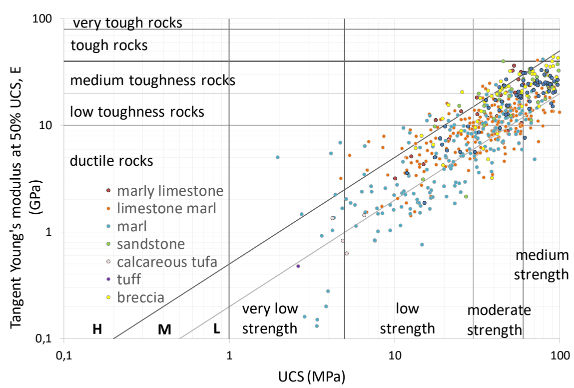

Figure 3. Engineering classification of intact rock

Typically, stress-strain curves for these marls exbit ductile behaviour with large axial strain at failure. Ductile behaviour indicate, for example, yield resulting in a plastic zone around the tunnel i.e. potential for squeeze.

These and other features in earth fill embankments or deep cuts in soft rocks/hard soils, characterised using the *UCS* or undrained shear strength c_u, are all water content/suction dependent, e.g. variation of undrained shear strength due to suction changes (Maček et al., 2014).

2.2 *Long-term performance of marls*

After the construction, the ground suction and water content change and, as a consequence, engineering properties change as well (equilibration with the surroundings). Groundwater and suction pose significant impact on the long-term behaviour due to water content changes, especially the potential for softening (significant loss of strength), slaking (leads to the desintegration of the rock) and swelling.

Properties of clayey rocks, and their behaviour during exposure to external influences are dominantly controlled by their mineralogical composition, preconsolidation, composition of binding material, level of cementation, and rock texture. For marls from the wider area of Split (Miščević and Vlastelica, 2011), mineralogical composition contents of individual minerals are in the following ranges: calcite 42-77%, dolomite 0-7%, quartz 3-11%, plagioclase 1-9%, chlorite 0-9%, smectite 6-20%, vermiculite 0-6% and micaceous minerals 3-12% (indicate a mixture which probably contains illite and smectite).

The results of the Atterberg limits (Figure 4), the clay activity (ratio of plasticity index *IP* and the percentage of particles <2 μm) and the swelling potential, indicate the content of illite and low to medium swelling potential. According to measured values (ISRM, 2007), swelling pressure is low to moderate and ranges up to 100 kPa. The properties of flysch/clayey marls with the Atterberg limits tested are shown in Table 1.

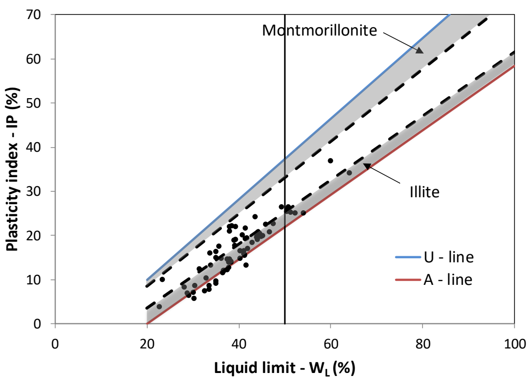

Figure 4. Casagrande-Mitchell plasticity chart, (Mitchell, 1976), with results for flysch/clayey marls

The most notable mechanical and chemical weathering processes in soft rocks are the processes of decarbonation of $CaCO_3$ component, oxidation processes and swelling. As a consequence of decarbonation, for example, gypsum forms at joint walls. The volume of gypsum is by 98% greater than that of input components exuded from marl, and so the pressure is created in joints which enlarges the existing joints and initiates formation of new ones. Here the water is required for the process to take place. In the gypsum forming process, the porosity of soft rock increases, and hence the depth of water absorption increases as well. This speeds up the process and increases the depth of its influence. It can be concluded that water/suction plays a crucial role in the change of properties of these dominantly clayey rocks through the processes of drying and wetting, freezing and thawing, and various chemical processes (manifested in the decomposition of binding material from the clayey rock structure, and in disintegration of material into smaller fragments).

The physical weathering is manifested in the breakup of material due to development of cracks, and in surface dissolution in contact with water. Sudden absorption of water results in development of pressure in rock joints which leads to process usually described as slaking, and hence to the extension (deepening) of joints. Wetting and drying cycles are also the main cause of suction changes which leads to differential swelling displacements caused by suction gradients inside the rock. In addition, release of stress provoked by removal of material during excavation (relaxation) causes development of new joints (listric joints). The development of new joints speeds up physical weathering and enables deeper penetration of chemical weathering effects.

Table 1. Properties of flysch/clayey marls obtained from tested 75 samples with $CaCO_3$ content 15-56%

Value	**Clay content (%)**	**ρ_d (Mg/m^3)**	**w_0 (%)**	**n (%)**	**w_L (%)**	**w_P (%)**	**IP (%)**	**UCS (MPa)**	**c' (MPa)**	**φ' (°)**
Min.	5.0	1.54	3.49	16.27	22.62	13.27	4.02	0.06	0	10.7
Max.	65.0	2.21	24.64	39.82	64.11	29.78	37.06	1.02	0.038	46.3
Main	30.6	1.86	13.69	29.67	39.76	22.87	16.89	0.39	0.017	27.3

In mechanical terms, the degradation of marl manifests itself through reduction of strength. When performing direct shear tests on marl samples for intact and laboratory weathered samples (Vlastelica et al., 2016), a variety of results in beginning phases of weathering can occur, not necessary consistent with carbonate content. After multiple cycles of weathering, shear strength results are close to the values obtained for the marly clay. Therefore it is possible that in beginning phases of degrading of the material suction has a significant role in the way in which cracking of the intact material develops, then consequently on the shear strength. Typical values of shear strength parameters of these marls are described in

Miščević and Vlastelica, 2012 and Vlastelica et al., 2016.

When assessing durability of marls (Miščević and Vlastelica, 2011), it was noted that some marls exhibit different behavior when subjected to slake durability testing, and that results are misleading. This is obvious upon visual inspection of the retained material in the drum (considerable fragmentation even though large quatnity of material is retained). This phenomena isn't yet explained in detail, just modifications of the testing procedure is usually suggested. Dozens of modifications have been suggested by multiple authors, and for Dalmatian marls one is suggested by Vlastelica et al., 2018. However, possibility that the test procedure itself has the significant influence to this kind of fragmentation is not yet investigated. Test includes drying at 105°C and immersing of the material in water in multiple phases, which can possibly lead to some suction effects (producing fragmentation).

3 ROLE OF SUCTION AND SWCC

Since the properties of marl (density, shear strength, elastic modulus, permeability...) are water content/suction dependent, it is possible to develop criteria for monitoring changes of properties and for construction on/in landslides, cuts, embankments and sustainable environment.

3.1 SWCC and suction – laboratory results

Soil water characteristic curve SWCC is defined as relationship between the water content *w* (or volumetric water content θ, or degree of saturation S_r) and soil suction, Figure 5. Before the matrix suction (the difference between pore air pressure and pore water pressures u_a-u_w) reaches the air entry value (*AEV*), soil is saturated, and changes in *w* result in volume deformations without decrease in S_r. At *AEV* the air enters into the pore space. Suction at *AEV* correspod to a water content a little higher than shrinkage limit w_S, and *AEV* is well correlated to *IP*. When the matrix suction exceeds *AEV* value, S_r decreases rapidly, and soil behaviour shows typical hysteresis between drying and wetting curve in desaturation zone, Figure 6. After reaching the residual suction s_r, in the zone of residual saturation, there's no water flow and *w* can be changed only by vapour transport (Fredlund, 2012).

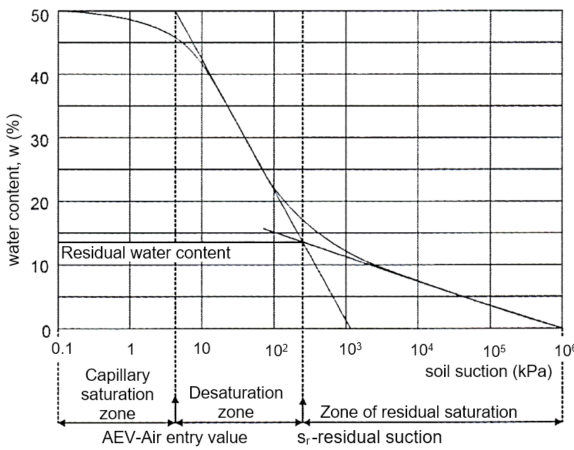

Figure 5. SWCC with characteristics zones (Sillers et al., 2001)

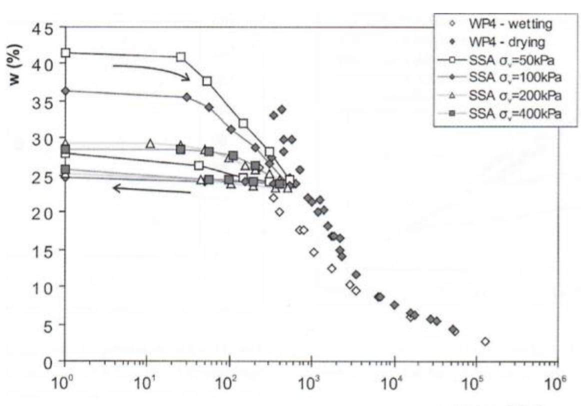

Figure 6. Suction measurements (fines from earth-flow; Maček et al., 2016). WP4-results from dew-point potentiometer; SSA-results from simple shear apparatus used as a suction controlled oedometer.

It is known that SWCC is correlated with the soil specific area *SSA* (dry end of the curve), so it can also serve for 'forensic' determination of clay minerals. Value known as w_A – water adsorption capacity of powders (Enslin-Neff test methods according to DIN standard) suits well with the initial point on SWCC.

In Figure 6 (*w* - suction), up to *AEV* there‘s no unique SWCC since there is also influence of the total stresses on the state of the soil. In that sense SWCC is better described by S_r - suction curve.

The previously described properties of flysh marls from this study have been compared and correlated with literary data and test results of the materials of similar behavior and composition. So estimated characteristic values and ranges of suction will be guidelines for further research. Namely, from the examined suction testing results of similar material (Maček et al., 2016; Peranić et al., 2018), and analysis of the real values of parameter *wPI* (samples for Table 1), some conclusions listed below can be derived. The „*wPI*“ value, as a product of the percentage of particles below 0.075 mm $p_{0.075}$ (as a decimal value) and plasticity index *IP* (%), was defined in research on SWCC variability (Figure 7; Zapata et al., 2000). On that basis it can be concluded:

- Measured *AEV* on similar materials amounts up to around 1000 kPa, even 1300 kPa.
- The general SWCC suction range is mainly up to 100 MPa, typically above 10 MPa.
- Value *wPI* is 15-25 for samples from Table 1 (where $p_{0.075}$=50-100%, mainly 60-90%).
- For SWCCs of range *wPI* =15-25 in Figure 7 the residual zone begins at s_r ≈1000, 5000 and 10000 kPa for *wPI*=5, 15 and 25 respectively.

Therefore, the characteristics of the measuring equipment should also be chosen accordingly (e.g. HAEPD-High Air Entry Porous Disc value in axis translation technique should be 1500 kPa), and different measuring techniques should be combined to cover suction measuring range. This may include but not be limited to use of HYPROP evaporation method device (up to 100 kPa, and more with preconditioning), dew-point potentiometer (above 300 kPa), axis translation technique (up to 1500 kPa), filter paper method (in the zone of residual saturation) and other indirect methods.

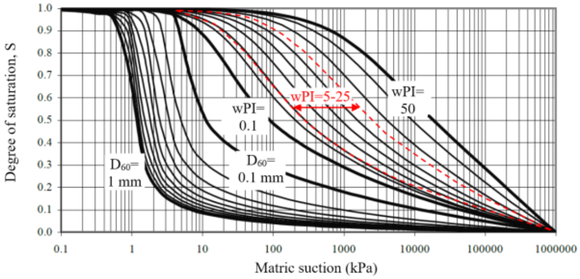

Figure 7. Family of SWCCs (Zapata et al., 2000)

3.2 Field observations

By setting measurement profiles inside the flysch marl bedrock (e.g. Watermark suction probes) it is possible to observe how the suction inside the marl changes during its degradation. Suction changes (both along the masurement profile and in depth) should be observed in parallel with precipitation to improve our understanding of the drying processes and how seasonal weather changes affect the development of suction. From variations of suction it is possible to detect delay between the lowest suction values and the start of the wet rainy periods, as well as the occurence of surface drying and shrinkage (desiccation cracks) and flow of water into the ground during rainfall.

From pore water pressure/suction distribution in depth, and suction needed for desiccation cracks, it is possible to predict the maximum depth of the desiccation cracks at the site. Knowing the *AEV* value, it is also known whether the soil is actually (un)saturated or not. Measurement data can be used for the general indication of periods when the factors of safety of the slopes might be very low.

One of the possible degradation mechanisms of marl fragments can be explained by differential swelling displacements caused by suction gradients inside the rock (Figures 8 and 9) and assumes isotropic behavior. When wetting occurs, the particle boundary is firstly wetted and a suction gradient is created inside the rock fragment. This suction gradient induces water transfer and reduces in time until it reaches a zero value when full saturation is attained. As long as there are suction gradients, differential swelling deformations will be developed inside the rock fragment. The geometry, stratification and confinement of the fragment restrain swelling displacements and lead to tensile and shear stresses, which finally result in cracking and loss of structure. A similar mechanism can be invoked to explain the degradation caused by drying (shrinkage instead of swelling).

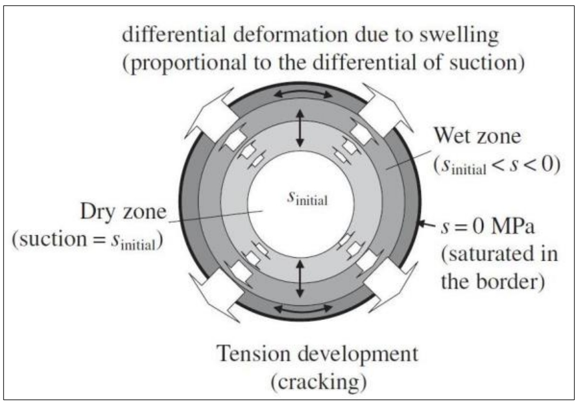

Figure 8. Degradation mechanism: differential swelling caused by suction gradients (Alonso et al., 2010)

Figure 9. An example of degradation caused on marl sample by suction

3.3 Numerical models for unsaturated soil

The proposed field and laboratory results will be used for numerical simulations which will be conducted with commercial software Plaxis and in-house code which is currently in development phase. Plaxis models for unsaturated soils can be used in pre-failure regime. However, in this project we aim to find an answer for mechanical failure response which is under the influence of unsaturated flow. For that purpose we are developing the novel hydro-mechanical model which is based on existing coupled model for failure in saturated conditions (Nikolić et al., 2016; Nikolić et al., 2018). The model is based on lattice of Timoshenko beams which act as cohesive links between the grains of material represented with Voronoi cells. Such structure allows us to capture the complex failure mechanisms in geological materials, where cracks can initiate, propagate, branch, merge and simultaneously grow. The coupled flow regime is currently implemented with Biot's theory. The future development should extend the methodology towards the unsaturated flow which is best described by Richards equation. It will be possible to consider suction, as well as drying and wetting cycles in geological materials.

4 CONCLUSIONS

A reliable data on the properties of marls from Dalmatia were established by analyzing a large number of own results. By making correlations of these results and available data on materials of similar behavior and composition, guidelines for expected values and ranges related to SWCC and suction measurement were also obtained. According to these values (e.g. *wPI*, suction range, *AEV*, s_r), the possible SWCC measurement techniques and parameters needed to select equipment in future research are determined. Since the SWCC depends on the stress history, it is necessary to include the equipment for the SDSWCC (Stress Dependent Soil Water Characteristic Curve) measurement.

The Atterberg limits (including w_S), *IP*, water adsorption capacity w_A and content of clay and fines are recognized as additional parameters of importance for further research program (indicators of the SWCC shape). Finally, it is suggested that suction measurements need to be introduced as part of laboratory and field investigation in general.

5 ACKNOWLEDGEMENTS

This work has been fully supported by the Croatian Science Foundation under the project number UIP-2017-05-3429. The authors are deeply grateful for this support.

6 REFERENCES

Alonso, E.E., Pineda, J. A., Cardoso R. 2010. Degradation of marls; two case studies from the Iberian Peninsula. *Weathering as a Predisposing Factor to Slope Movements: Engineering Geology Special Publications* (Eds: Calcaterra, D. & Parise, M.), 23, 47-75. Geological Society, London.

Cardoso, R., Alonso, E.E. 2007. Degradation of compacted marls: a microstructural investigation, *Soils and Foundations* **49** (3): 315-327.

Fredlund, D. G., Rahardjo, H., Fredlund, M. D. 2012. *Unsaturated Soil Mechanics in Engineering Practice*, John Wiley & Sons, Inc., New Jersey, Hoboken.

ISRM 2007. *The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006 („The blue book“)*, Commission on Testing Methods.

Jurak, V., Belošević, V. 1999. Durability of the „Macelj sandstone“. *Rock mechanics and tunnelling: Proceedings* (Eds: Jašarević, I., Hudec, M. & Vujec, S.), 47-52. Faculty of Civil Eng. and Faculty of Mining, Geology and Petroleum Eng., Zagreb, Croatia.

Maček, M., Smolar, J., Petkovšek, A. 2014. Variation of undrained shear strength due to suction changes. *XV Danube-European Conference on Geotechnical Engineering: Proceedings* (Eds. Brandl, H. & Adam, D.), Paper No. 236. Vienna, Austria.

Maček, M., Majes, B., Petkovšek, A. 2016. Lessons learned from 6 years of suction monitoring of the Slano blato landslide, *Rivista Italiana di Geotecnica* **1/2016**, 21-33.

Miščević, P., Vlastelica, G. 2011. Durability characterization of marls from the region of Dalmatia, Croatia, *Geotech. Geol. Eng.* **29** (5), 771–781.

Miščević, P., Vlastelica, G. 2012. Time-dependant stability of slopes excavated in marl, *Građevinar* **64** (6), 451-461.

Mitchell, J.K. 1976. *Fundamentals of Soil Behavior*, John Wiley&Sons.

Nikolić, M, Karavelić, E, Ibrahimbegović, A, Miščević, P. 2018. Lattice element models and their peculiarities, *Archives of Computational Methods in Engineering* **25** (3), 753-784.

Nikolić, M, Ibrahimbegović, A, Miščević P. 2016. Discrete element model for the analysis of fluid-saturated fractured poro-plastic medium based on sharp crack representation with embedded strong discontinuities, *Computer Methods in Applied Mechanics and Engineering* **298**, 407-427.

NCSS 11 Statistical Software 2016. NCSS LLC, Kaysville, Utah. www.ncss.com/software/ncss

Peranić, J., Arbanas, Ž., Cuomo, S., Maček, M. 2018. Soil-Water Characteristic Curve of Residual Soil from a Flysch Rock Mass, *Geofluids* **2018**: article ID 6297819, 15 pages.

Sillers, W. S., Fredlund, D. G., Zakerzadeh, N. 2001. Mathematical attributes of some soil-water characteristic curve models, *Geotechnical and Geological Engineering* **19** (3-4), 243-283.

Vlastelica, G., Miščević, P., Štambuk Cvitanović, N. 2018. Durability of soft rocks in Eocene flysch formation (Dalmatia, Croatia), *Engineering. Geology* **245**, 207-217.

Vlastelica, G., Miščević, P., Pavić, N. 2016. Testing the shear strength of soft rock at different stages of laboratory simulated weathering, *Građevinar* **68** (12), 955-966.

Zapata, C.E., Houston, W.N., Houston, S.L., Walsh, K.D. 2000. Soil–Water Characteristic Curve Variability. *Geo-Denver 2000: Proceedings* (in Geotechnical Special Publication), 84-124. ASCE.