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An overview of geotechnical aspects of materials involved in slope instabilities along flysch-karst contact in Croatia

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Abstract The narrowed flysch zone, in the area of central Istria and Kvarner hinterland, surrounded by carbonate rock mass (limestone, dolomitic limestone) is characterized by frequent landslides. Instabilities are caused by specific position of the flysch and carbonate rock mass, specific material properties, present geomorphological, chemical and physical processes which are influencing some physical, mechanical and hydraulic properties of involved materials. Sliding surface is mostly formed on the contact of the superficial deposits and impermeable flysch bedrock. In the zones of the chemically and physically weathered flysch rock mass, during longer and continuous rainy periods, pore pressures increase, due to which gradual loss of strength and eventual failure occurs. Many researches were carried out in the mentioned research area during landslide remediation works, doctoral thesis investigations and within different research projects. This paper provides an overview of basic geotechnical properties of materials present in different locations of the investigated area, which show significant dissipation in investigated values, but also some common material characteristics, crucial for instability occurrence.

Keywords flysch, material properties, instabilities, weathering

Introduction

The key improvement toward the effective landslide risk management lies in continuous research and collaboration on international and interdisciplinary level in the field of landslide investigation. Past and present landslide evidences, the considerable understanding of present conditions, and low level of effective landslide risk management, providing high motivation for extension of existing research on the karst-flysch contact along northern Adriatic coast in Croatia (Fig 1). Existing research results are related to geotechnical properties of the flysch rock mass, their combined relations, influence of processes such as weathering on the rock mass behaviour, landslide initiation and run off modelling, landslide susceptibility, hazard and risk assessment, landslide monitoring and climate change influence on landslide appearance. One of the future research goals is to develop advanced level of understanding the materials and processes through laboratory testing and advanced modelling of landslides in this zone, giving particular attention to landslide triggering conditions.

Many instability phenomena have been recorded on flysch slopes around the karst-flysch contact in the area of central Istrian Peninsula (Arbanas et al. 2011, Mihalić et al. 2011, Dugonjić Jovančević and Arbanas 2012, Dugonjić Jovančević 2013), Rječina River Valley (Benac et al. 2005a and 2009, Benac et al. 2011, Vivoda et al. 2012, Arbanas et al. 2017), Draga Valley (Benac et al.2009, Arbanas and Dugonjić 2010), Bakarac Valley (Dugonjić et al. 2008, Dugonjić Jovančević et al. 2012) and Vinodol Valley (Benac et al. 2005b, Đomlija et al. 2014, Đomlija et al. 2017, Đomlija 2018). Mentioned area describes research range (Fig. 1), and is part of a large Adriatic flysch basin spreading from Gorizia in Italy to Albania (Marinčić 1981).

Numerous instability processes on slopes in investigated area often occur due to weathering process of flysch rock mass that causes rapid disintegration and loss of shear strength (Arbanas et al. 2013, Benac et al. 2005, Bernat et al. 2014, Dugonjić Jovančević and Arbanas 2012, Vivoda et al. 2012). When it is exposed to water and air, flysch rock mass is strongly affected by chemical weathering and decomposition, physical disintegration and as a result of these processes, the volume of the rock mass increases and residual shear strength decreases (Vivoda Prodan et al. 2017, Vivoda Prodan and Arbanas 2016). Landslide geological profile mainly consist of flysch bedrock covered by clayey colluvium and/or residual soil, sporadically containing a larger portion of rocky fragments, mostly sandstones and siltstones originating from the bedrock. Existing documentation and past research show that instabilities in the research area include mostly translational and rotational sliding, rockfalls and rarely debris flows. Landslide volumes vary between 10^2 and $>10^6$ m^3, with estimated landslide depths from 3- 20m. Distribution of the instabilities evidenced through different researches, landslide remediation works, and smaller instabilities along the roads can be seen in Fig. 1. However, the map does not present landslide inventoryThe landslide inventory map in the research area was prepared in scale 1:10 000 only for Vinodol Valley (Đomlija 2018) and includes 633 landslide phenomena. This fact, together with the indication of instabilities, shown on Fig. 1, implies on the need to perform extensive analysis and detail landslide inventory map for the whole research area.

A usual trigger of landslides in the area is raising of the groundwater caused by heavy and continuous rainfall in a few months' period. Landslides are thus occurring mostly in the late winter and spring period (from November to May), when the number of rainy days in the three-month period is high and evapotranspiration is low. Due to relatively low permeability of the cover, the infiltration is generally slow and the runout coefficient is high (Peranić 2019, Peranić et al. 2019). The analyses of the daily, monthly and annual precipitation data have shown that the cumulative precipitation in three months (70–100 days), prior sliding, may have a great influence on water infiltration and groundwater levels rising (Dugonjić Jovančević and Arbanas 2012, 2017; Dugonjić Jovančević 2013). Material characteristics relevant for instability occurrence, investigated trough landslide remediation works, scientific research projects, student terrain investigations, doctoral thesis, etc. are presented in this paper. Laboratory testing was mostly performed in the Geotechnical laboratory, at the Civil Engineering Faculty, University of Rijeka. The aim of this research is to define some of the basic geotechnical aspect of materials involved in slope instabilities.

Grain size distribution, plasticity limits and strength parameters were tested on the flysch samples of different weathering grades: in Grey Istria (Žufić 2011, Gulam 2012, Dugonjić Jovančević 2013, Vivoda Prodan 2016, Maček et al. 2017), Rječina River Valley (Benac et al. 2014, Vivoda Prodan 2016, Peranić 2019), Vinodol Valley (Vivoda Prodan 2016, Pajalić et al 2017). Mineralogical composition in the research area has been investigated by Gulam (2012), Benac et al (2014) and Vivoda Prodan (2016). Hydraulic properties (soil-water retention curves and permeability) were investigated by Maček et al. (2017) and Peranić et al. (2018), while Peranić (2019) and Peranić and Arbanas (in press) have investigated shear strength properties in unsaturated conditions. Žufić (2011) and Vivoda Prodan (2016) and Vivoda Prodan and Arbanas (2016) investigated slaking behaviour of siltstone samples from Istria Peninsula. Some laboratory testing was performed during this research (durability characteristics and uniaxial compression strength on fresh siltstones).

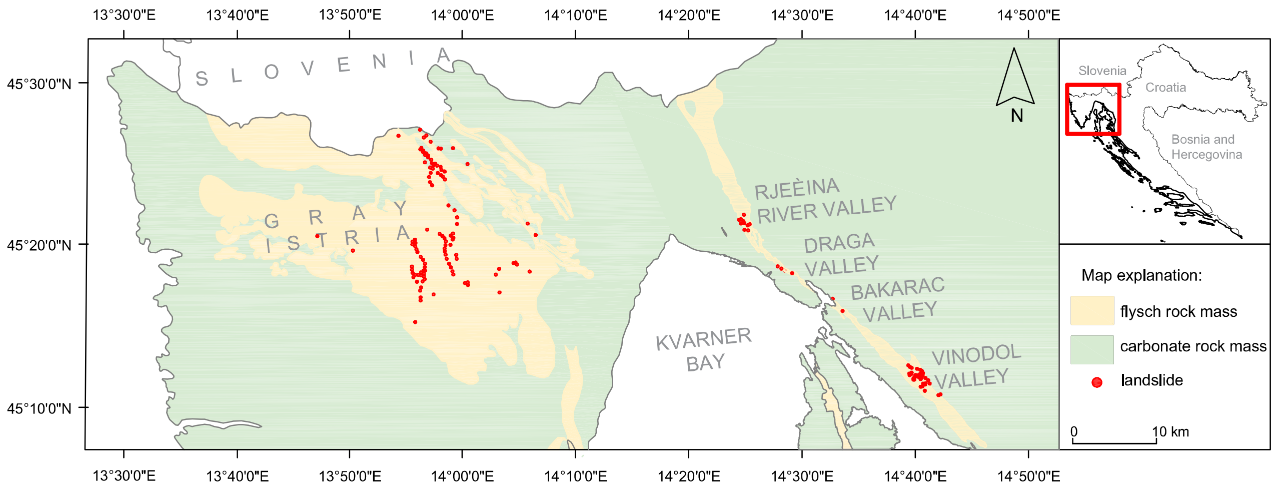

Figure 1 Study area along the coastal area of large Adriatic flysch basin

Index and strength materials properties

The study area (Fig. 1) is composed of two types of rock mass: (a) the prevailing Cretaceous and Paleogene carbonate rock mass, with karstified limestone and dolomites; and (b) Paleogene flysch rock mass. Tectonic movements from the Paleogene period, together with the after movements, have caused formation of the folding and faulting zones generally striking in the NW-SE direction. These tectonic movements caused sporadically narrowing of the flysch sediment basin in the Adriatic belt and reduced appearance of the flysch deposits on the surface, as well as rising of the surrounding karstic terrain.

The Istrian flysch basin as small part of the large Adriatic flysch basin has an approximate width of 60-90km. The upper parts of the flysch-type rocks consist of interchanges of thinly bedded marls (15–20 cm) and carbonate-siliciclastic rocks (3– 5 cm). In the lower part, there is prevailing turbidite succession of marls and carbonate-siliciclastic sandstones randomly intercalated by several thick carbonate beds of debrite origin. The geological setting of the Rječina River Valley and Vinodol Valley is similar to the general settings of the whole 100km long morphostructural unit (Ilirska Bistrica-Novi Vinodolski), which includes Cretaceous and Paleogene limestone situated at the top of the slopes, in the form of cliffs, and Paleogene siliciclastic and flysch-type rocks situated on lower slopes (Mihalić Arbanas et al. 2017). Vinodol Valley is characterized by elongated irregular shape, with a wide range of different landforms types, where karstified carbonate rocks (Đomlija et al. 2014, 2017).

Due to different weathering grades (fresh rock to residual soil) and alteration of competent and incompetent members, flysch rock mass is characterized by significant varieties of rock mass properties. Limestone and sandstone presents stronger, competent rock mass members, inside which specific types of instabilities occur (e.g., rock falls, rock topples, rock irregular slides). Carbonate fragments, originating from the landslide occurrence in carbonate rock mass, have been mixed with the clayey soils originating from weathering of flysch, and these superficial deposits cover the flysch bedrock along the studied area in various thicknesses. Properties of the competent members and karst, however, are not of the interest for this research.

Atterberg's Limits and grain size distribution

In slope stability analyses, colluvial cover and residual soil (product of flysch rock mass weathering) are considered as materials with similar properties, forming upper layers of the geotechnical profile. It can be seen that clays of intermediate- (CI) to-high (CH) plasticity (Fig. 2) prevail in Grey Istria and Vinodol Valley, while in the Rječina River Valley low (CL) to intermediate plasticity clay (CI) prevails. Depending on the water content semisolid to plastic in consistency.

Grain size distribution analysis, including dry and wet sieving, aerometry and SediGraph methods, show that silt size particles prevail in the superficial layers (Dugonjić Jovančević 2013, Vivoda Prodan 2016, Pajalić et al. 2017, Peranić et al. 2018).

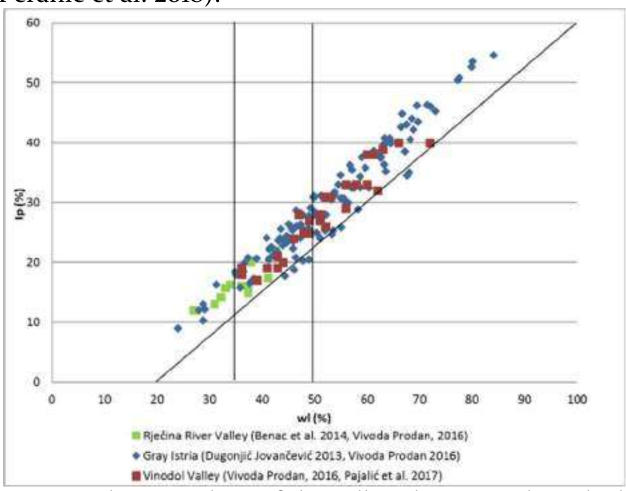

Figure 2 Plasticity chart of the colluvial cover and residual soil (product of flysch rock mass weathering).

Strength parameters

Considering the heterogeneity of materials involved in landslide occurrence in the research area, as well as their different grades of weathering (varying from soil like materials to rock), different laboratory methods were used to determine strength properties.

Mohr-Coulomb shear strength parameters were obtained from laboratory testing in direct shear and ring shear devices on the flysch surface and borehole samples (Benac et al. 2014, Vivoda Prodan 2016, Maček et al. 2017, Peranić 2019). Residual and peak shear strength parameters of flysch samples of different weathering grades show considerable variations (Table 1).

Table 1 Range of shear strength parameters of flysch samples obtained from different studies.

Research area	Test type	c'(kPa)	ϕ (°)	Source
Gray Istria	DS	3*	28*	2
	DS, RS	14-56**	20-31**	1
Rječina River Valley	DS	1-10*	24-29*	3,4
	DS, RS	4-32**	18-35**	1
Vinodol Valley	DS	5*	23*	2
		11-12**	18**	1

DS/RS – direct shear/ring shear apparatus; *- peak values **- residual values; [1] - Vivoda Prodan (2016); [2] – Maček et al. (2017); [3] – Benac et al. (2014); [4] – Peranić (2019).

To determine the uniaxial compression strength (UCS), Point Load Test (PLT) (ISRM 1985) was performed on regular and irregular samples of completely-to-moderately weathered siltstones obtained by boring. The corresponding UCS values tested in Gray Istria are researched by Vivoda Prodan (2016) 21.12-52.8 MPa; Gulam (2012) reports a wide range of UCS values 9.36-87.12 MPa; and Žufić (2011) obtained UCS 6.9-30.4 MPa. The test results of the PLT performed during this research, on irregular fresh siltstone samples from Pazin (tested 1 day after the excavation) showed that the corresponding UCS of this material ranges from 8.42 to 81.28 MPa. UCS values were also estimated using Schmidt rebound value in combination with the unit weight of flysch rock mass 25.5 kN/m^3. Testing performed in Gray Istria (Gulam 2012 and Vivoda Prodan 2016) resulted in the UCS values from 15.4 to 48 MPa. Obtaining the specimens for uniaxial compression testing in the laboratory is almost impossible (only 11 specimens were tested in Žufić (2011), and their values show considerable range of UCS value 5.3-54.03 MPa), and therefore are unreliable for engineering analyses without taking adequate precautions. In the Rječina River Valley PLT testing was performed in November 2018 and the results show UCS value ranged from 15.6 to 54MPa.

Weathering influence on durability characteristics of flysch rock mass

Weathering is the process of alteration and breakdown of rock and soil materials at or near the earth's surface by physical, chemical and biotic processes (Selby 1993). Weathering processes are particularly expressed in incompetent members, such as claystones, shales, and siltstones. The standardized slake durability index in the second cycle is not sufficient to classify the durability of weak rock masses such as siltstones (Gamble 1971, Erguler and Shakoor 2009, Miščević and Vlastelica 2011, Vivoda Prodan 2016, Vivoda Prodan and Arbanas 2016). Because greater weathering of weak rocks during testing was observed, quantification from the fragment size distribution after each of five slaking cycles and new classifications of weak rocks have been proposed by several authors (Erguler and Shakoor 2009, Cano and Tomás 2016). The slake durability index (I_{d2}) and disintegration ratio (D_{R2}) were determined to classify the tested siltstone samples of different weathering grades, and the modified disintegration ratio (D_{RP2}) was used to determine potential long term degradation of the tested samples. Highly degraded and fragmented fresh sample after each of five cycles, despite of high I_{d2} value, is visible on Fig. 3.

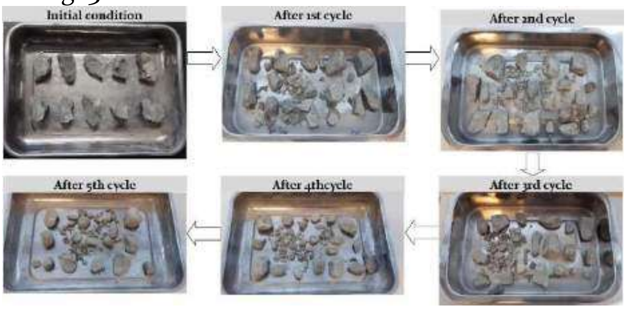

Figure 3 Highly degraded fresh siltstone from Pazin after each of five cycles of the slake durability test with I_{d2}=86.12 % and D_{RP2}=0.68.

Table 2 Results of the slake durability tests, including the slake durability index, disintegration ratio and modified disintegration ratio after second cycle, for siltstones of different weathering grades in the study area.

Sample	Slake durability index (I_{d2}) [%]	Disintegration ratio (D_{R2})	Modified disintegration ratio (D_{RP2})
FR Pazin*	86.12	0.68	0.31
FR (1)	88.31	0.65	0.35
MW (2)	89.69	0.60	0.40
FR (3)	97.03	0.81	0.19
MW (4)	95.39	0.79	0.21

* FR flysch sample tested during this research

Table 2 presents the slake durability index, disintegration ratio, and modified disintegration ratio after second cycle, for siltstones of different weathering grades in the study area from previous tests (Vivoda Prodan and Arbanas 2016) and a new fresh siltstone sample from Pazin tested for this research.

Hydraulic properties of the residual soil from flysch rock mass

Soil water retention curve (SWRC) relates the potential energy of a liquid phase (e.g. soil suction) with the variations in the water content of the soil. It has a crucial role when dealing with problems of rainfall infiltration process through the unsaturated part of the slope, as well as for determination of the effective stress in unsaturated soil, thus affecting the soil's shear strength. Hydraulic conductivity function (HCF) is another non-linear soil property function required when analysing the seepage process through unsaturated part of the slope.

SWRC measurement results obtained on soil samples from the Brus Landslide (Grey Istria) and Slani Potok (Vinodol Valley) were reported by Maček et al. (2017). Peranić et al. (2018) and Peranić (2019) have determined SWRC and HCF of the residual soil present at the surface of the Valići Landslide in the Rječina River Valley, which was found to play an important role for the rainfall infiltration process and time required for the slope failure (Peranić et al. 2019). Different measurement techniques (mini-tensiometers, axis-translation technique and dew-point potentiometer) and devices (suction-controlled oedometers, standard and volumetric pressure plate extractors, the HYPROP evaporation method device, and WP4-T dew point potentiometer) were successfully combined to obtain a complete SWRC of the residual soil from the Valići Landslide, both for the adsorption and desorption process. Obtained SWRC measurement results are shown in Fig. 4, while Table 3 summarizes best-fit parameters of the van Genuchten (1980) and Fredlund and Xing (1994) models obtained by a nonlinear regression analysis.

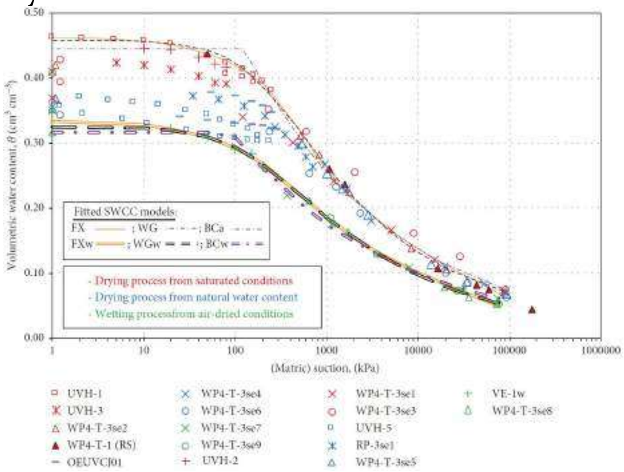

Figure 4 Measurement results and SWRC of residual soil from a flysch rock mass from the Valići Landslide (Peranić et al. 2018).

Table 1. Best fit parameters of the van Genuchten (VG) and Fredlund and Xing (F&X) models (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

The formation process of the soil covering flysch slopes in the Rječina River Valley was found to results with a complex soil structure that cannot be obtained with standard sample preparation techniques used in laboratory. Instead, undisturbed samples have to be used in order to correctly define hydraulic properties of the soil. For example, different retention properties were obtained for measurements performed on intact and remolded samples (Peranić et al. 2018), while the saturated coefficient of permeability of intact samples (k_s = 4.60E-08 m/s) was found to be around two orders of magnitude higher than was the case for completely remoulded and consolidated samples.

Discussion and Conclusions

Landslides in the research area are mostly caused by terrain condition, material properties, and present geomorphological and physical slope processes influencing the material mechanical behaviour. Presented results show significant dissipation of the investigated values, but some conclusions about the material properties correlated with the past and present instabilities can be drawn.

Clays of intermediate to high plasticity prevail in Grey Istria and Vinodol Valley, while low to intermediate plasticity clays prevail in the Rječina River Valley. Testing of the grain size distribution has shown that silt size particles prevail in the superficial layers. Further on, siltstone samples from flysch rock mass of different weathering grades investigated in this study are highly susceptible to weathering, which causes changes in the durability and geotechnical properties in a short period of time. Fresh samples disintegrate less than moderately weathered samples; therefore, fewer drying-wetting cycles are required to reach the maximum possible degradation. The standard slake durability index increases the slaking resistance of the tested siltstone samples by at least one class.

Strength parameters of flysch samples of different weathering grades show considerable variations (cohesion varies from 3-56 kPa, and friction angle is from 18-35 °). The UCS values estimated through PLT testing show a great range of values collected from different previous researches (6.9-87.12 MPa) and confirmed in testing performed during this research (8.42-81.28 MPa) in Gray Istria. Obtained UCS values in Rječina River Valley ranged from 15.6 to 54MPa. One of the limitations for correct UCS determination in the laboratory, is that cylindrical samples of the flysch rock for uniaxial compression testing are almost impossible to obtain.

Presented results highlighted the importance of the unsaturated zone existing in a flysch slope for maintaining the slope stable during prolonged periods of heavy rainfall. However, a specific position of the flysch-karst contact plays a significant role for rainfall infiltration, favouring the pore pressure rising, decrease in material strength properties and landslide triggering.

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