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Time-dependant stability of slopes excavated in marl

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Preliminary note

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Time-dependant stability of slopes excavated in marl

The soft rock weathering is considered on the basis of criteria used in various fields such as geology, engineering geology, mineralogy, soil and rock mechanics, and geomorphology. The problem of stability over time should be considered for slopes excavated in marl, in case they are not protected against weathering processes. In addition to disintegration of material on slope surface, the weathering also results in shear strength reduction in the interior of the slope. Principal processes leading to weathering are explained on the example of marl originating from flysch formations near Split.

Key words:
marl, slope stability, durability, weathering

Prethodno priopćenje

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Stabilnost u vremenu kosine iskopane u laporu

U radu se analizira rastrošba (eng."weathering") mekih stijena koja se proučava i u okviru područja kao što su geologija, inženjerska geologija, mineralogija, mehanika tla i stijena te geomorfologija. Problem stabilnosti u vremenu treba razmatrati kod kosina koje su iskopane u laporu, a nisu zaštićene od razvoja procesa rastrošbe. Posljedica rastrošbe je, osim dezintegracije materijala na površinama pokosa, i degradacija posmične čvrstoće u dubini kosine. Na primjeru lapora iz naslage fliša u okolici Splita objašnjeni su osnovni procesi koji dovode do pojave rastrošbe.

Ključne riječi:
lapor, stabilnost kosine, trajnost, rastrošba

Vorherige Mitteilung

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Stabilität von ausgegrabenen Mergelhängen

In der Arbeit wird die Verwitterung (auf Englisch: "weathering") von weichen Felsen im Rahmen verschiedener Bereiche, wie zum Beispiel Geologie, Ingenieurgeologie, Mineralogie, Boden- und Felsmechanik sowie Geomorphologie analysiert. Das Problem der Stabilität muss bei Hängen in Betracht gezogen werden, die in Mergel ausgegrabenen wurden, aber nicht von der Entwicklung des Verwitterungsprozesses geschützt sind. Folgen des Felsverbrauchs sind, neben Desintegration des Materials auf den Böschungsflächen auch die Degradierung der Schubstärke in der Hangtiefe. Am Beispiel von Mergel aus Flyschschichten in der Umgebung der Stadt Split wurden die grundlegenden Prozesse erklärt, die zu einer Verwitterungserscheinung führen.

Schlüsselwörter:
Mergel, Hangstabilität, Dauerhaftigkeit, Verwitterung

1. Introduction

The weathering of weak rocks has been studied in various fields including geology, engineering geology, mineralogy, soil and rock mechanics, and geomorphology. However, the relationship between the weathering and the landslide and material fall is still not well understood.
Surface degradation processes and local landslides are quite frequent on slopes excavated in soft rocks. These processes affect safety and increase maintenance cost of facilities situated at the bottom of these slopes, while also lowering stability of facilities located at the top of such slopes. The excavation work in these mostly clayey rocks (marls, siltstones, mudstones, shales, claystones, etc.) must be conducted either by blasting or by means of heavy jack hammers. However, newly excavated slopes are susceptible to rapid weathering and, within several months to several years, i.e. within the engineering period of time, the rock deterioration process starts both on the slope surface and within the interior of the slope mass. These processes can be observed on many natural slopes and on slopes excavated in flysch formations, mainly formed of marls, in the region of Dalmatia. An example of a natural slope situated on the Adriatic Coastal Road near Podstrana is presented in Figure 1. Here we can see a developed process of marl degradation on the slope surface, with accumulation of detached fragments at the bottom of the slope. The understanding of the degradation process affecting these materials is of great interest to many engineers, as these processes lead to reduced stability of such slopes, and hence to higher maintenance costs.

Figure 1. Marl degradation on the cut slope surface at the Adriatic Coastal Road (at Podstrana)

Examples of impact of weathering processes on slope stability at unprotected side cuts can be found on many locations in engineering practice. For instance, such situations are quite frequent in the vicinity of Split when excavations are made in flysch material. In the foundation pit, made for a medical school in Split (location: Trstenik), the landslide formed several months after excavations is shown in Figure 2. Fortunately, the landslide occurred during the night time and so lives of workers at the foundation pit bottom were not put to danger.
An example of landslides that are quite frequent near Split at natural cliffs in flysch formations along the coast is shown in Figure 3. The sliding process is continuous. The material deposited at the bottom of the slope is carried away by the sea and thus the space is liberated for the next "sliding phase".
A formation of greater sandstone blocks at a natural side cut in flysch formations, which is also caused by marl weathering, is shown in Figure 4. The weathering rate of sandstone layers within the flysch structure is not the same as the weathering rate of marl formations. By marl layer weathering above and below sandstone layers, the marl disintegrates and is gradually removed by the action of gravity and precipitation [1-2], i.e. we witness here the process of differential weathering. Sandstone layer outcrops remain on slopes as a kind of an "cantilever" and, when the length of this overhang becomes sufficient, the blocks detach due to bending action and the resulting rockfall poses a serious threat to the zone at the bottom of the slope.
These situations are at the same time examples of damage resulting from weathering processes. This damage is reflected in threats to human lives, extension of construction times, impossibility of using beaches, closedown of vital roadways, etc.

Figure 2. Collapse of slope in foundation pit excavated in marl (Split, location: Trstenik)

Figure 3. Landslide along the sea coast on the natural cliff in flysch formations (Split, location: Duilovo)

Figure 4. "Cantilever" formed of harder sandstone layer on the slope (differential weathering along the slope)

2. Weathering

Causes of weathering have been studied by many authors [3-8]. Properties of clayey rocks, and their behaviour during exposure to external influences on completed side cuts, are dominantly controlled by their mineralogical composition, preconsolidation history, composition of binding material in their structure, level of cementation, and rock texture.

The mineralogical composition of marl samples from flysch formations located near Split was tested so as to enable better understanding of the weathering process in marl formations. The mineralogical composition was tested using the x-ray diffraction method (University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering). Results obtained for a number of randomly selected marl samples are shown in Figure 1. Samples with the carbonate component content of up to 80 percent were selected, as it was established by observation that the weathering process develops much faster in these materials than in materials with higher carbonate component content. The following average mineral content was obtained for samples subjected to this testing: calcite 42-79 %, dolomite 2-7 %, quartz 3-11 %, plagioclase 1-9 %, chlorite 0-9%, smectite 6-20 %, vermiculite 0-6 %, micaceous minerals 3-12 %. The name "micaceous materials" was used for mixtures that probably contain illite or an interstratified illite-smectite with a small proportion of smectite layers, and perhaps with some muscovite. This mineralogical composition points to processes which, when combined, result in weathering. Smectite is a mineral susceptible to swelling, and it has been found in all samples. Although swelling causes pressure that can disintegrate the rock, it can develop in the presence of water only.

In addition to the standard form of swelling, gypsum also forms at joint walls due to mineralogical composition of the

Table 1. Mineralogical composition of marl samples from Split peninsula flysch formations

Sample designation	Carbonate minerals [%]		Vermiculite [%]	Smectite [%]	Quartz [%]	Plagioclase [%]	Micaceous materials [%]	Chlorite [%]
	Kalcit	Dolomit						
32	42	6	-	11	10	7	12	9
33	42	7	-	9	11	9	10	8
25	45	7	-	9	11	8	8	7
12	46	-	5	20	9	4	10	-
24	47	6	-	11	10	5	9	8
13	52	-	-	16	7	5	10	4
16	53	-	T	16	7	4	10	4
30	55	-	6	12	7	3	11	-
31	55	-	5	12	7	4	11	-
17	56	-	T	14	7	3	9	6
18	56	3	-	12	6	4	9	7
11	57	-	-	16	7	5	9	-
14	60	-	T	11	6	3	10	6
15	63	-	T	8	7	3	9	7
23	69	-	5	10	4	1	7	-
01	72	-	-	10	4	2	5	5
36	73	2	-	7	3	1	5	5
05	77	-	-	8	3	1	3	-
29	79	-	T	6	3	1	5	-
38	79	-	T	7	3	2	3	T

T – in traces
Micaceous material: probably contains illite and interstratified illite-smectite, with a small proportion of smectite layers, and perhaps with muscovite

marl [8]. The volume of gypsum is by 98 % greater than that of input components exuded from marl, and so the pressure is created in joints in which the gypsum forming process is under way. This pressure enlarges the existing joints and initiates formation of new ones. Here also the water is required for the process to take place. By separating a material from the marl structure in the gypsum forming process, the porosity of this 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. Gypsum, as a product of this process on marl, can be noticed as a white film that is exuded on the rock surface. Depending on chemical composition of water, and on mineralogical composition of the rock, some other forms of chemical weathering are also likely to develop on the rock surface. In such cases, the material is exuded from the rock structure through chemical reaction with water.

It can be concluded from the above description that water plays a crucial role in the change of properties of these dominantly clayey rocks. This is conducted through the processes of drying and wetting, freezing and thawing, and also through various chemical processes. This influence is manifested in the decomposition of binding material from the clayey rock structure, and in disintegration of material into smaller fragments. In other words, this material is simultaneously affected by both physical and chemical weathering processes.

The physical weathering is manifested in the breakup of material due to development of cracks, and in surface dissolution in contact with water. By excavation in thin formations, bedding joints are exposed to external influences. These are the weakened surfaces in which the detachment of fragments is most likely to occur, and are at the same time most susceptible to external influences, i.e. to the action of water which penetrates into the rock. This sudden absorption of water results in development of pressure in rock joints which leads to slaking, and hence to the extension (deepening) of joints. 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. A significant influence of freezing on the speed of disintegration process has been analyzed in detail on some weak rock examples in Spain [7] and Turkey [9].

The above assertions are also confirmed by typical landslide behaviour at cut slopes realized in flysch, i.e. the sliding/material fall most often occurs after a period of abundant precipitation, especially if during this period temperatures at soil surface fall below freezing point. The distribution of precipitation and air temperatures in Split area in the period in which the landslide occurred during construction of the Medical School in Split is presented in Figure 5. This landslide is shown as an example in Figure 2. As the date on which the landslide actually occurred was noted, it can be observed that the landslide was preceded by significant rainfall. This example shows that water has a dominant influence on the occurrence of such landslides. In addition to the influence of water on the weathering process (and hence on the reduction in strength), the following water related effects can also be observed: soft rocks affected by weathering process have the lowest strength in wet condition; due to weathering of the material the water penetrates the joints and the pressure builds up within such joints. For that reason, the effect of weathering was simulated in laboratory (as presented below) through drying and wetting, while the strength was measured on wet samples. In addition, the behaviour observed in nature shows that the influence of water pressure on shear strength along joints/surfaces should be taken into account in stability analyses.

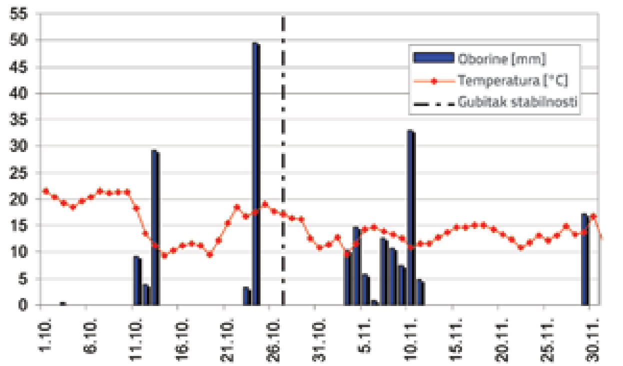

Figure 5. Quantity of precipitation and air temperatures in Split area (in period of sliding occurance during medical school construction)

3. Change in marl strength

The shear strength of marls, with natural moisture immediately after excavation, corresponds to values that are applied, according to classifications, to soft rocks. Results obtained by testing marl samples from the wider area of Split (flysch formations at Split peninsula) are presented in Table 2, so that a better insight into the order of magnitude of shear strength values can be gained. The testing was conducted on naturally moist samples using a portable direct shear apparatus. Tests were made on samples taken from the ground surface, which were previously treated by sawing without the use of water. In fact, if water is used (as is normally done in core drilling) then undisturbed samples can not be obtained simply because the wearing process starts as soon as the sample comes into contact with water.

Compact samples without visible bedding joints (samples without visible joints taken between two bedding joints), and samples containing bedding joints (shear along the bedding joint and perpendicular to it) were tested. For the sake of analysis, the samples were classified according to their carbonate content and slake durability index I_{d2} after the second cycle of testing. The shear strength is presented according to the Mohr-Coulomb criterion with the values of cohesion (c) and angle of internal friction (j). The results are presented by the increase in carbonate content, which is the dominant, but not the only value influencing the strength of this material. This is

Table 2. Examples of measured shear strength values for marl samples taken in Split area

Carbonate content [%]	Moisture at testing [%]	I_{d2} [%]	c [MPa]	φ [°]	Normal stress at testing [MPa]	Note
44,44	5,48	89,7	1,36	29,7	0,5-5,0	compact sample taken in between the bedding joints
51,35	2,41	73,4	1,24	20,1	0,5-5,0	(=) shearing along the bedding joint
51,35	2,41	73,4	1,00	35,4	0,5-5,0	(‖) shearing perpendicular to bedding joints
54,63	5,05	76,0	3,89	29,6	1,0-7,5	compact sample taken in between the bedding joints
59,68	1,82	84,4	1,48	44,1	0,5-3,5	(=) shearing along the bedding joint
59,68	1,91	87,8	1,45	30,9	0,5-3,5	(‖) shearing perpendicular to bedding joints
58,12	6,25	96,4	1,93	31,9	0,5-6,0	(=) shearing along the bedding joint
58,12	6,25	96,4	1,72	41,9	0,5-3,5	(‖) shearing perpendicular to bedding joints
69,87	4,25	98,6	7,33	26,9	1,5-9,5	compact sample taken in between the bedding joints
71,59	5,71	98,7	5,85	35,1	1,5-7,5	compact sample taken in between the bedding joints
45,02	saturated	n/a	0,014	25,9	0,1-0,8	Marly clay (testing conducted on saturated sample in the direct shear apparatus)

also confirmed by shear strength values, which do not increase in accordance with an increase in carbonate component. During the testing, the range of vertical pressures exerted on samples was adjusted to the sample strength, so as to obtain the widest possible range of applicability of shear strength values.

If the presented results are analysed with regard to strength values obtained for shearing perpendicular to and parallel with bedding joints, the expected results that the strength along joints is lower than the strength perpendicular to layers are in fact not obtained. It was established by inspection of samples after fracture that in such situations the fracture occurs along the secondary system of joints which are often almost perpendicular to layers, and which are characterized by a darker brown film on the surface of these joints (Figure 12). Measurement results for marl samples with carbonate content of up to about 70 percent are presented. As a rule, in these materials the strength increases with an increase in carbonate content, while the susceptibility to weathering diminishes. According to the principle of the weakest link in the chain, the test results with smaller carbonate content were presented. They are more relevant for stability analysis of cut slopes excavated in flysch formations in which marls are in most cases the dominant component.

The shear result for marly clay that occurs as a cover above flysch formations, and is a fully weathered basic material, is also presented in Table 2. The result is presented as a reference value indicating the smallest strength the material has at the end of the weathering process. The testing was conducted in the direct shear apparatus for soil with fully saturated samples.

If the back analysis of a stable slope built of marly clay is conducted using shear strength parameters measured for marly clay, then the obtained slopes have the values that correspond to field measurements of inclination of deposited weathered material. It was established by field measurements that the inclination of the weathered marl deposited at the bottom of the slope amounts to α = 31°-38°, [10] (example shown in Figure 6). The weathered material at the bottom of the slope indicate a material with marly clay properties.

Figure 6. Measured inclination of weathered marl material deposited at the bottom of the slope (arrow), inclination range: α = 31° do 38°

According to values presented in Table 2, the strength of clayey rock (soft rock) immediately after the excavation is such that even relatively high cuts can be excavated with a sufficient stability and with almost vertical inclinations.

However, the experience has shown that the sliding and material fall occur during subsequent use of such cut slopes. The sliding occurs because of strength reduction caused by external influences, such as the propagation of weathering from the surface towards the slope inside, and the progress of weathering through bedding joints and other joints. In this paper, this change in strength is presented on the example of marls contained in flysch formations found in the wider area of Split (Split peninsula).

It can be concluded from processes leading to weathering, as described in Section 2, that water has the dominant (but not the only) influence on the development of processes that result in weathering. For that reason, the strength reduction analysis was conducted for the influence of the drying and wetting processes [11 – 16].

The basic problem in this analysis is that the tested sample disintegrates very rapidly during the weathering process, due to intense changes in moisture [17]. To enable this testing, the decision was made to use the testing procedure that is in fact a modification of the standard procedure for testing shear strength by means of a portable direct shear apparatus for rocks. Test samples were taken from the freshly excavated zones and sawn without water, so as to prevent disintegration prior to the testing. Samples were cut to dimensions of about 10 x 10 x 8 cm. Before installation in the testing plaster, the samples were wrapped in metallic mesh that can easily be fitted around the sample (Figure 7a). The mesh 2 mm in aperture was selected. It was determined during the testing that the testing plaster can reach the sample through this aperture and, at the same time, the aperture is small enough to prevent a significant loss of sample during simulation of the drying and wetting process. This mesh is cut immediately before the testing according the shearing surface defined in advance (Figure 7b) so as to eliminate the influence of mesh strength on test results.

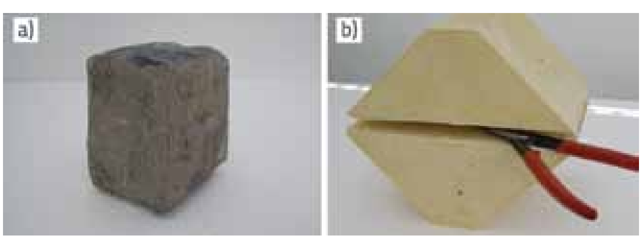

Figure 7. Preparation of test samples: a) sample wrapped in mesh before it is placed into the testing plaster; b) example of mesh cutting once the sample is placed into the testing plaster

The weathering process was simulated in laboratory by means of drying and wetting cycles composed of the following phases:

- sample drying at 105 °C for 24 hours,
- sample cooling at ambient temperature in laboratory for 24 hours, and
- immersion of sample in distilled water for 24 hours.

After each cycle, samples were weighed and masses obtained were compared with sample masses noted at the start of the procedure so as to check whether or not a significant portion of sample was lost due to fallout of fragments through the mesh enveloping the sample. The same material was used to form sample sets each made up of five samples. The sets were subjected to simulated weathering by means of an appropriate number of cycles.

Typical test results are presented as marl sample A (carbonate component content: 54.6 % and slake durability index I_{d2} = 76.0 %), and marl sample B (carbonate component content: 44.4 % and slake durability index I_{d2} = 89.7 %). Samples with smaller carbonate content were selected as experience has shown that in such materials the weathering process is more pronounced.

The strength was tested after immersion in water (in wet condition). Shear strength results expressed according to the Mohr-Coulomb strength criterion are presented in Tables 3 and 4. Parameters were determined on the straight line interpolated according to the least-squares method and this through measured values of shear strength at failure of samples from the set. The selection of the maximum number of drying-wetting cycles depended on the moment in which the samples started to fully disintegrate, i.e. on the moment in which their compactness could not be preserved even by means of meshes surrounding them.

Table 3. Shear strength parameters for the sample "A"

Number of simulated weathering cycles	c [MPa]	φ [°]	Normal stress during the testing [MPa]
0 (natural moisture)	3,89	29,6	1,0-7,2
2	0,09	29,7	1,0-6,0
4	0,24	29,7	2,0-6,0
8	0,16	31,2	1,0-4,0
Note: Carbonate content of 54.6 %, after the simulated weathering cycles 2, 4 and 8			

Table 4. Shear strength parameters for the sample "B"

Number of simulated weathering cycles	c [MPa]	φ [°]	Normal stress during the testing [MPa]
0 (natural moisture)	1,36	29,7	1,0-5,5
1	0,18	37,2	0,5-0,35
2	0,43	28,4	0,8-2,7
4	0,13	25,9	0,3-2,0
Note: Carbonate content of 44.4%, after the simulated weathering cycles 1, 2 and 4			

In the results for the sample "A" the angle of internal friction remains practically unchanged during the drying-wetting cycles, and that the value obtained corresponds to the values obtained by testing other marl samples with approximately the same carbonate content ($\varphi \cong 30°$). The cohesion component changes significantly after the first several drying-wetting cycles and, after that, it does not change greatly regardless of the number of cycles. The change in cohesion, which is not consistent with the number of testing cycles, is due to the accuracy of the measuring instrument used, accuracy of the interpolation procedure applied, and the fact that the samples, although taken from the same layer, were not completely the same.

The sample "B" is an example of sample behaviour showing inconsistent results during the testing, i.e. the expected fall in strength was not obtained with an increase in the number of drying and wetting cycles. It can be seen by visual inspection of disintegrated sample after the testing that individual samples contain greater or smaller quantity of secondary joints (cf. Figure 12), which could not have been noticed on sample surface prior to the testing. Depending on the way of sampling, individual samples from the same series can (but do not need to) contain such joints, and so the differences occur in strength results within the same series. This deficiency can be removed only by testing series with great number of samples where several samples will be tested using the same normal load.

An increase in the value of angle of friction after the first drying and wetting cycles is also typical for these samples. Visual inspection of such samples, conducted after the testing, shows that the sample is divided into a number of coarse fragments, but the degradation does not reach the material in the deeper zone (Figure 8b). A part of fragment from the surface of the presented sample has detached due to shearing and separation of the pieces of sample, and a continuous failure surface can not be noticed. During shearing, the sample behaves as a well graded compacted gravel, which may be the cause of apparent increase in the angle of friction.

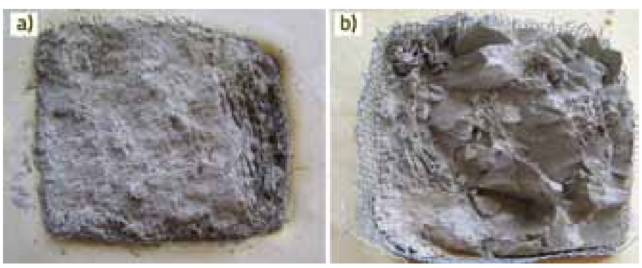

Figure 8. Examples of failure surfaces during weathering simulated in laboratory: a) failure surface after 4 drying-wetting cycles; b) failure surface for the sample that disintegrated into smaller fragments due to weathering action

Samples containing more than 50 % of clay minerals, as is the case in sample "B", consistently show full degradation at a relatively small number of drying-wetting cycles (2 to 4 cycles), cf. Figure 8a. The weathering effect can be seen throughout the depth of the sample. Samples that are still insufficiently compact for measurement after the simulated weathering reveal shear strength results that are close to the values obtained for marly clay (cf. Table 2).

4. Depth of weathering influence

Other than the fact that marl strength decreases with the time of exposure to atmospheric influences, the depth in which the layer is affected by such influences is also significant for the analysis of stability of cut slopes formed in marl. At that, it was established by observing behaviour of such cut slopes that the influence of water (drying and wetting) is operated in two ways. Firstly the process develops on the exposed surface of the rock which results in constant "ravelling" of material from the surface (Figure 1). Transported by gravitation and precipitation, the degraded material accumulates at the bottom of the slope, where it eventually disintegrates into material that can be classified as soil (clayey silt) rather than as rock. This process has a greater impact on maintenance costs than on the global stability of the cut slope. In fact, the material accumulated at the bottom of the slope must regularly be removed. The slope "moves away" from initial position, and becomes unseemly from the aesthetic point of view (Figure 1). It was established by observation of existing cut slopes and by laboratory testing on samples that the influence of weathering on the surface of the slope can spread from several centimetres to some ten centimetres in depth. The depth of this influence depends on the proportion of carbonate and clayey components in marl, orientation of bedding joints and secondary joints with respect to the slope, and slope inclination or "rate" at which the disintegrated material is removed from the surface. The total depth of the surface layer that detaches from the surface with the passage of time is also dependant on meteorological conditions, i.e. on the number of dry and rainy periods, on the quantity and intensity of precipitation, on the exposure of slope to the influence of sun, and on the change in air temperature in the area in which the slope is located.

Secondly, the weathering process also spreads deeper down into the rock mass and this through the joint system that can easily be penetrated by water. An example of cut slope on which wet zones near the joints can be seen, while the basic material is "dry", is shown in Figure 9. In this example, yellow brown deposits on the surface of the bedding joints and secondary joints point to the fact that seepage had been occurring even prior to the excavation. However, as can be seen in this example, the actual disintegration of material occurs only after the excavation and this in form of material bursting in the vicinity of joints (arrow in Figure 8). The bursting (fracturing) started some 20 days after the excavation and this despite the fact that there was no precipitation in the meantime. The depth until which the process can advance is presented in Figure 10 where pronounced moisture can be noticed in the vicinity of the joint along which the slope sliding was initiated, as shown in the example given in Figure 2.

Figure 9. Water seepage through joints formed in flysch

Figure 10. Seepage through secondary joints along which the sliding occurred

Figure 11. Slope at Žnjan district in Split in the period from 2003 to 2012

Both of the above described forms of weathering are documented with a number of pictures of the same slope in flysch formations, which were taken during the observation period of 9 years after the excavation (Figure 11). The quantity of material that detached from the slope surface can be noticed as material accumulated at the bottom of the slope. This material had been removed on several occasions during the observation period. The "depth" of the surface part of the slope that was eliminated from the surface through weathering can easily be noticed as the change in the length of the harder sandstone layers "overhanging" from the slope surface. This sandstone had been initially excavated to the same levels as the surrounding layers, but was not eliminated with weathering. It can be concluded that the weathering rate in this example is: 0.8 meters of the sandstone overhang / 8 years = 10 centimetres per year. The observations made on similar slopes have shown that the minimum depth of the material disintegrated from the surface of cut slopes in Dalmatia amounts to 1-2 cm annually.

The sliding and weathering caused by seepage through joints can be seen on the given example at the left side of the slope. Several greater blocks, formed at joints through which the water penetrated, have over time been affected by sliding. The arrow in Figure 11 shows the position of the last material fall. In 2004 and 2010, the concrete protective structure was extended in order to protect the man-built facility situated above the cut slope, as the foundations of this facility were endangered by weathering and disappearance of slope material underneath the foundations. At that, it can be seen that the excavation was conducted very favourably with respect to bedding joints, i.e. that it was made perpendicular to bedding joints.

5. Stability of slopes in marl

Based on data presented in previous sections, it can be concluded that the stability of slopes cut in marl should not be considered only from the standpoint material strength of material immediately after the excavation, nor only from the aspect of position of bedding joints and other joints with respect to the cut slope position [18, 19, 20]. The analysis should include the factor of time in which the strength of this material will be reduced with weathering, and the factor of weathering depth should also be taken into account. This in fact defines the issue of durability of slopes cut in marl. If the slope is not adequately protected so as to prevent the weathering, the resistance of cut slope to weathering will over time be reduced.

The weathering affecting the slope surface will mostly influence the aesthetic appearance of the zone, and will increase maintenance activities so as to ensure functionality of facilities situated at the bottom of the slope. Normally, this process does not greatly affect the global stability of the cut slope, although it can influence the local stability through formation of harder blocks, such as sandstones, which are less susceptible to weathering than marls. This difference in weathering rate is called "differential weathering". The overhang is formed by removal of marl from the area around the harder layer. Over time, when the overhang becomes long enough, and when the tensile strength of the material is exceeded due to bending (overhang), or if a joint appears in that layer, the block finally detaches from the slope (Figure 4).

A greater problem is the weathering that occurs along the joints and through the basic material (marl) in between the joints, which results from water seepage. Joints are quite numerous in flysch formations. The following joint types can be differentiated: bedding joints located at a relatively small distance from one another (thinly layered form), secondary joints resulting from layer bending caused by geological processes such as folding and heaving, and listric joints that occur most frequently as a result of material relaxation after excavation, and partly as a result of excavation method used. In addition, the weathering results in the extension of the existing joints, and in creation of new joints that penetrate into the basic material. This is why the rule that favourable excavation with respect to dominant bedding joints ensures good stability is not fully applicable in these formations. This is additionally confirmed by slope sliding examples shown in photographs presented in this paper. In practical terms, a favourable orientation of the side slope surface does not actually exist as, in addition to along bedding joints, the sliding can occur in any side slope position, and also along secondary joints (Figure 12), random joints or joints formed by weathering, and through basic material (marl). An example of landslide along secondary joints is shown in Figure 13 (enlarged detail from Figure 11g). The fact that the water seeps through these joints is proven by plant roots (marked in the Figure) which follow the spreading of such secondary joints.

Figure 12. Marl sample with three joint systems almost perpendicular to each other (first and third – secondary joints; second – bedding joints)

Figure 13. Sliding along secondary joint set

The parametric analysis of wedge sliding along the joint at an angle a (cross section in Figure 14) was conducted in the scope of analysis of shear strength at which the sliding occurs. This analysis was conducted for the side cut 10m in height. The rock mass was modelled with the unit weight of γ = 23 kN/m^3, and the cohesion and joint inclination toward the side cut (α) were varied for the constant angle of friction along joints φ_j = 30°. The value of the angle of internal friction was selected based on shear strength measurements in marl, as shown in Tables 2, 3 and 4, and for the weathered and non-weathered samples. The goal was to define the value c_j for which the limit state (F_s = 1) is obtained at different joint dip values (α). The influence of water pressure on joints is analyzed under assumption that the bottom end of the joint was still non-weathered immediately prior to fracturing i.e., that water could not have escaped toward the bottom end of the joint. Thus the hydrostatic pressure was modelled along the joints (example from Figure 10). The following expression was derived from these conditions:

$$c_j = \frac{\frac{H}{2}\cdot\gamma\cdot\cos\alpha - \left(\frac{H}{2tg\alpha}\cdot\gamma\cdot\cos\alpha - \frac{H}{2}\cdot\gamma_w\cdot\sqrt{1+\frac{1}{tg^2\alpha}}\right)\cdot tg\phi_j}{\sqrt{1+\frac{1}{tg^2\alpha}}} \quad (1)$$

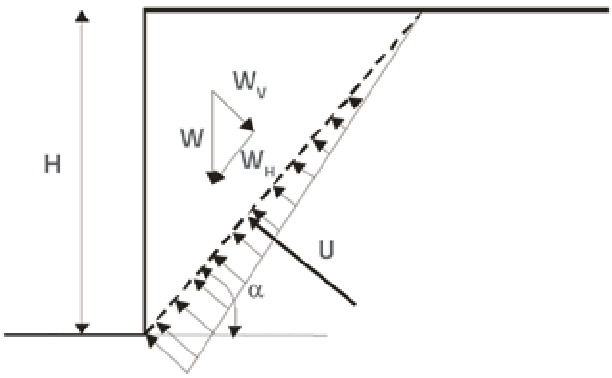

Figure 14. Model of wedge sliding along the joint, as used in parametric analysis

Parametric analysis results are presented in Table 5. If cohesion values obtained from the above analysis are considered, it can be concluded that they roughly correspond to the cohesion value measured at degraded samples treated by laboratory weathering (Tables 3 and 4). The end product of weathering is the residual material in form of marly clay, and the shear strength of fully degraded material should correspond to the strength of marly clay. However, the weathering level is not necessarily the same along the entire length of the joint, or along the material depth. For that reason, the shear strength at which the failure and sliding occur can only be taken as an average value along the failure surface.

Table 5. Results of parametric analysis for the cohesion value c_j

Joint inclination [α]	c_j [kPa]	Total average normal stress at the joint [kPa]
80°	46,0	67,48
70°	57,5	47,52
60°	61,5	28,75
50°	57,5	13,45
40°	46,0	3,47

The above analysis is the reflection of behaviour registered in nature. The sliding/material fall occurs in marl cut slopes when the shear strength of material is reduced through weathering along the joint/failure surface to the value at which the stable state can no longer be maintained. At that, the pore pressure occurs in joints after the period of significant precipitation.

6. Conclusion

Two basic forms of slope instability can be differentiated in flysch formations that are mainly formed of marl layers:
- surface "exfoliation" of weathered material,
- sliding along joints/zones in which the weathering process has developed.

The surface "exfoliation" of weathered material does not directly affect global stability of cut slopes in flysch. An indirect influence on stability is the change of slope geometry as a result of this process. Here the problem is the need to increase maintenance activities and the possibility that the material deposited in the foot of the slope will hinder functionality of facilities situated under the slope (such as roads or railway lines). The safety of traffic may be affected by deposition of degraded material onto a roadway/railway facility. This process may also cause functionality problems for space on top of the slope. The slope "disappears" at the rate of 2 to 8 cm per year. In twenty years, this means 40 to 160 cm, if the situation is not further aggravated by landslide. The sliding along joints/zones in which the weathering process has developed may indirectly provoke sliding of harder rock blocks in the flysch structure where an "overhang" is formed through disappearance of material around a harder layer. When this "overhang" attains a sufficient length, it detaches and slides down the slope. At unprotected cut slopes in flysch the landslides/material fall phenomena may develop in the period of several months to several years, which depends on the weathering rate along the depth of the slope. The development of the weathering process depends on: orientation of bedding joints and other joints with respect to the position of the slope surface, exposure of slope to the action of precipitation and sun, hydrological conditions in the zone in which the slope is situated, preconsolidation history, mineralogical composition of the rock, composition of binder within the structure, cementation level, and rock texture.

To prevent long-term instability of cut slopes excavated in marl, it is of utmost significance to block development of the weathering process. To this end, it is important to prevent the influence of factors that enable weathering, and this both on the slope surface and in the interior of the slope. Factors that dominantly influence development of weathering are cyclic processes of drying/wetting, heating/cooling, freezing/thawing, etc. They result in a whole array of secondary processes that contribute to the development of both physical and chemical forms of weathering (swelling, dissolution, gypsum formation, slaking, etc.). In order to block the influence of these processes, the slope surface must be "sealed". The rock can be sealed in two ways:

a) Prevent removal of degraded material from the slope surface. The degraded material kept on the surface lessens penetration of the above mentioned influences along the depth. If a vegetation cover develops on such surface, the layer will become "reinforced" by roots. This can easily be achieved by making slopes with a relatively low inclination. The natural inclination of degraded material deposited at the slope bottom ranges from 31 to 38 degrees, which means that it can not be removed by precipitation. In addition, it is certain that a vegetation cover will over time naturally develop on such material.
b) Place surface protection that will prevent development of these processes toward the interior of the slope (geosynthetics, vegetation cover, sprayed concrete, etc.).

At that, it is important to note that the surface behind the top of the slope must also be treated so as to prevent penetration of water from higher areas into the slope zone. The weathering along the joints can be generated by water seeping through joints, because of the dry and rainy seasons (drying-wetting). The weathering is usually not caused by water that does not emerge on the surface of the slope, and in cases when ground water table oscillations are not significant.

The above measures are not necessary for cut slopes that can be proven to be stable for shear strength parameters corresponding to weathered marl (marly clay, as the final product of weathering of marly materials). At that, due to occurrence of secondary joints and development of weathering along such joints, we are not able to claim with confidence that the slope that has been cut "favourably" will in fact be stable with respect to bedding joints.

Therefore, cut slopes excavated in marl layers can not be considered as permanently stable if the development of weathering is not blocked. Temporary stability on untreated slopes is possible in periods ranging from several dozens of days to several years, but it is just a question of time when the weathering process will lead to the loss of strength and ultimately to the sliding and detachment of slope material.

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