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Impact of weathering on slope stability in soft rock mass

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ABSTRACT

Weathering of soft rocks is usually considered as an important factor 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 soft rocks, 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 in association with weathering are discussed with the examples of marl hosted on flysch formations near Split, Croatia.

1. Introduction

Weathering of soft rocks has been studied in various fields including geology, engineering geology, mineralogy, soil and rock mechanics, and geomorphology. However, the relationship between influence of weathering and slope instability (i.e. landslides, rockfalls, and surface erosion) is still not well understood.

Surface degradation processes and local landslides occur frequently on slopes excavated in soft rocks. As a result, safety of facilities at the bottom of these slopes is threatened and the cost of maintenance and/or supporting is usually significantly high. At the same time, the stability of facilities located at the top of such slopes is also submitted to increasing risk. The excavation work in these geomaterials (mostly clayey rocks, such as marl, siltstone, mudstone, shale, claystone, etc.) can be performed only with use of heavy machinery (rock breaker) or explosives, as well as in other types of rocks. However, in a relatively short time after excavation, the excavated slope in marl is exposed to influence of atmospheric agents during that period, e.g. a couple of months, then rock deterioration process starts both on the slope surface and the rocks inside. These processes can be observed on many natural slopes and on cuts excavated in flysch formations in the region of Dalmatia, Croatia, which were formed in the Eocene epoch and usually consisted of marl as the main soft rock component.

Information about marl strength at all phases of slope exploitation is of utmost importance for any stability analysis of cuts and slopes in this geomaterial. To provide data for analysing the strength deterioration of rocks, there should be a possibility to test degraded materials. Weathering processes fragmented marl samples into smaller pieces, thus the fragmented sample is very difficult to be operated with and to be installed into a testing device. For the solution of this problem, additions to the standard test procedure were used (Miščević and Vlastelica, 2009). Additions refer to the standard procedure of a direct shear test method (ISRM suggested methods for determining shear strength in 1974) enabling the tests of deteriorated samples. Results of this procedure will be presented and discussed.

The main scope of the presented study is to identify the main influences of weathering on slope stability in marl formation, present some basic engineering observations or previous experiences on known examples of observed slopes in this material, and propose solutions associated with those observations for future projects and studies. Also, it is important to emphasise the necessity of proper engineering solutions that prevent the development of the weathering process, which can lower the potential of slope instability and the maintenance cost.

2. Weathering

An example of surface deterioration induced by weathering of a natural slope, situated on the Adriatic Highway in the Podstrana municipality, is presented in Fig. 1. Here we can see a developed

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Fig. 1. Marl degradation on the surface of a cut slope on the Adriatic Highway (Podstrana municipality).

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 such as that in this example is of great interest to many engineers, as these processes lead to reduced stability of such slopes and hence to higher maintenance costs.

Examples of impact of weathering processes on stability of unprotected cuts can be found on many locations in these geomaterials. For instance, such situations are quite frequently reported in the vicinity of Split when excavations are made in flysch rock mass. The landslide formed several months after excavation at the building site of the Medical School in Trstenik, Split is shown in Fig. 2. Fortunately, the landslide occurred during the night, therefore the lives of workers at the bottom of the foundation pit were not endangered.

An example of landslide at natural cliff in flysch formation along the coast is shown in Fig. 3. The sliding process is usually continuous if it is not interrupted by remediation works, a kind of instability that is quite frequent along the coastline near the town of Split. 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 cut in flysch formation, caused by weathering of marl, is shown in Fig. 4. The weathering rate of sandstone layers within the flysch formation is not the same as that of marl. It could be stated that the sandstone is almost unchanged in the engineered time scale. Because marl is significantly influenced by weathering around the sandstone layer, it disintegrates quickly and is gradually removed by the action of gravity and precipitation (Neiman, 2009; Admassu et al., 2012), i.e. we can witness here the process of differential weathering. Sandstone layer outcrops remain on the slope as a kind of “cantilever” and when the length of this overhang becomes sufficient, the blocks detach due to bending action. Resultant rockfall poses a serious threat to the zone at the bottom of the slope.

Fig. 2. Collapse of slope in foundation pit excavated in marl (Trstenik, Split).

Fig. 3. Landslide along the coastal cliff in flysch formation (Duilovo, Split).

Fig. 4. “Cantilever” of harder sandstone layer on the slope (differential weathering along the slope).

Previously described situations are just some typical 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.

In general, weathering includes two dominant processes (Miščević and Vlastelica, 2009): physical and chemical weathering. Physical weathering results in the disaggregation of rocks without mineralogical change, and chemical weathering results in the decomposition of the constituent minerals to stable or metastable secondary mineral products. The weathering process on marl and marly materials from flysch formation can be described as mainly physical weathering, combined with chemical weathering on the surface of material and on the crack walls inside the material, suggesting all surfaces of geomaterials can be in the contact with water.

Causes of weathering have been widely studied (Miščević, 1997, 1998; Miščević and Roje-Bonacci, 2001; Martinez-Bofill et al., 2004; Števanić and Miščević, 2007). Properties of clayey rocks and their behaviours 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 formation 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 (Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb). Results obtained on a number of randomly selected marl samples are shown in Table 1. Samples with the carbonate component content of up to 80% were selected, as it was established by observation that the weathering process develops much faster in these materials than those with higher carbonate component content. The following average mineral contents were obtained for samples subjected to this test: 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 interstratified illite–smectite with a small proportion of smectite layers, and occasionally 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 rocks, 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 marl (Miščević, 1997). The volume of gypsum is approximately 98% greater than that of input components exuded from marl, and so the pressure is created in joints where the gypsum forming process is underway. 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 part of 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 clayey-dominant 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

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

Sample designation	Carbonate minerals (%)		Vermiculite (%)	Smectite (%)	Quartz (%)	Plagioclase (%)	Micaceous materials (%)	Chlorite (%)
	Calcite	Dolomite						
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

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

rock joints, leading 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 analysed in detail on some weak rock examples in Spain (Martinez-Bofill et al., 2004) and Turkey (Yavuz et al., 2006).

The above assertions are also confirmed by typical landslide behaviour at cut slopes realised 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 the period when the landslide occurred during construction of a medical school in Split is presented in Fig. 5. This landslide is shown as an example of slope instability in Fig. 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 major 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), it can also be observed that soft rocks affected by weathering process have the lowest strength in wet condition. Also, due to weathering of the material, the water penetrates the joints and the pressure builds up within such joints. For this reason, the effect of weathering was simulated in laboratory (as presented below) through drying and wetting process, 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.

3. Change in marl strength

The shear strength of marl, with natural moisture immediately after excavation, corresponds to values of a soft rock according to classifications. Results obtained in laboratory test of marl from the wider area of Split (flysch formation at Split peninsula) are presented in Table 2. Through these results a better insight into the order of magnitude of shear strength values can be gained. The test was conducted on samples with natural moisture using a portable direct shear apparatus. Tests were made on samples taken from the freshly excavated marl from shallow pits and after that they were shaped by sawing without the use of water. In fact, if water is used (as is normally done in core drilling), undisturbed samples cannot be obtained simply because the wearing process starts as soon as the sample comes into contact with water.

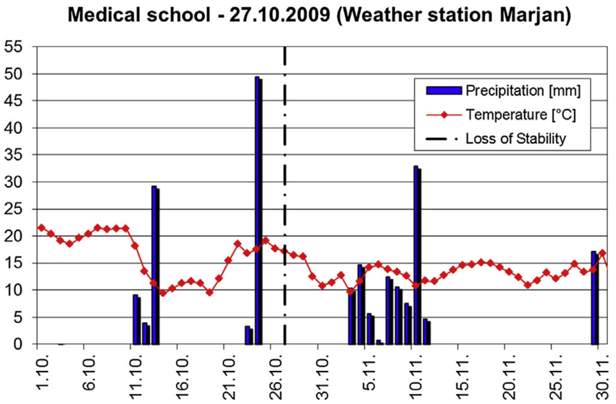


Fig. 5. Precipitation and air temperatures in Split area (in period of sliding occurrence during medical school construction).

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 purpose of this 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 (φ). The results are presented by the increase in carbonate content, which is dominant, but not the only value influencing the strength of this material. This is 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.

When the presented results are analysed with regard to strength values obtained for shearing perpendicular to and parallel with bedding joints, the expected results would be that the strength along joints is lower than the strength perpendicular to layers. These conclusions 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 are characterised by a darker brown film on the surface of these joints. Measurement results for marl samples with carbonate content up to about 70% are presented. Usually, 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 test 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, 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 $\alpha = 31°–38°$ (Roje-Bonacci, 1998) (example shown in Fig. 6). The weathered material at the bottom of the slope indicates marly clay properties.

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 marls examples contained in flysch formations that are found in the wider area of Split (Split peninsula).

It can be concluded from processes associated with weathering, as described in Section 2, that water has a dominant (but not the only) influence on the development of processes that result in

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 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 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 between the bedding joints
71.59	5.71	98.7	5.85	35.1	1.5–7.5	Compact sample taken 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)

weathering. For that reason, the strength reduction analysis was conducted considering the influence of the drying and wetting processes (Maekawa and Miyakita, 1991; Gokceoglu and Aksoy, 2000; Gökçeoğlu et al., 2000; Duperret et al., 2005; Erguer and Ulusay, 2009; Miščević and Vlastelica, 2011).

The basic problem in this analysis is that the tested sample disintegrates very rapidly during the weathering process, due to drastic changes in moisture (Miščević and Vlastelica, 2009). 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.

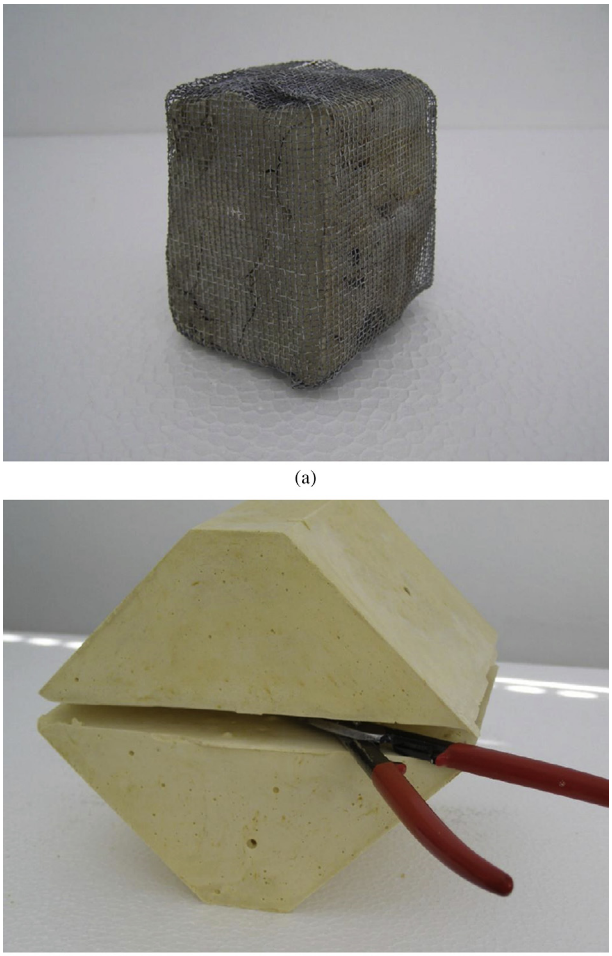
Test samples were taken from the freshly excavated zones and sawn without water, so as to prevent disintegration prior to the testing. Samples were cut to dimensions of about 10 cm × 10 cm × 8 cm. Before installation in the testing plaster, the samples were wrapped in metallic mesh that can easily be fitted around the sample (Fig. 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 to the shearing surface defined in advance (Fig. 7b) so as to eliminate the influence of mesh strength on test results.

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

(1) Sample drying at 105 °C for 24 h.
(2) Sample cooling at ambient temperature in laboratory for 24 h.
(3) Immersion of sample in distilled water for 24 h.

After each cycle, samples were weighed and masses obtained were compared with the sample masses noted at the start of the procedure so as to check whether or not a significant portion of

Fig. 6. Measured inclination of weathered marl deposited at the bottom of the slope (arrow), inclination range $\alpha = 31°–38°$.


(a)

(b)

Fig. 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.

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 in order to know that in such materials the weathering process is more pronounced.

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

It is interesting to note in the results for the sample A that the angle of internal friction remains practically unchanged during the drying–wetting cycles, and that the obtained values correspond to the ones obtained by testing other marl samples with approximately the same carbonate content ($\varphi = 30°$). 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–wetting cycles. It can be seen by visual inspection of disintegrated sample after the testing that individual samples contain greater or smaller quantities of secondary joints, 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–wetting cycle 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 (Fig. 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 cannot 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.

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 (2–4 cycles), as shown in Fig. 8a. The weathering effect can be seen throughout the depth of the sample. Samples that are still insufficiently compacted for measurement after the simulated weathering reveal that shear strength results are close to the values obtained for marly clay (see Table 2).

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	0.5–3.5
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.

(a)

(b)

Fig. 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 was disintegrated into smaller fragments due to weathering action.

4. Depth of weathering influence

Other than the fact that marl strength decreases with the elapsed time of exposure to atmosphere, the depth in which the layer is affected by such influence is also significant for the analysis of stability of cut slopes formed in marl. It was established, by observing behaviour of such cut slopes, that the influence of water (drying and wetting) is manifested in two ways.

Firstly the process develops on the exposed surface of the rock which results in constant "ravelling" of material from the surface (Fig. 1). Transported by gravitation and precipitation, the degraded material is eroded and accumulated 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 that 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 (Fig. 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, the quantity and intensity of precipitation, the exposure of slope to the influence of sun, and the change in air temperature in the area where the slope is located.

Secondly, the weathering process also spreads deeper inside the rocks and 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 Fig. 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 observed even prior to excavation. However, as can be seen in this example, the actual disintegration of material occurs only after excavation, in form of material bursting in the vicinity of joints (arrow in Fig. 9). The bursting (fracturing) started some 20 days after excavation despite the fact that there was no precipitation in the meantime. The depth that the process can advance is presented in Fig. 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 Fig. 2.

Fig. 9. Water seepage through joints formed in flysch.

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

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 excavation (Fig. 11). The quantity of material that is detached from the slope surface can be considered 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 level as the surrounding layers, but was not eliminated with weathering. It can be concluded that the weathering rate in this example is: 0.8 m of the sandstone overhang/8 years = 10 cm 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 been affected by sliding over elapsed time. The arrow in Fig. 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. 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 a cut in marl should be considered neither only from the standpoint of material strength immediately after excavation, nor only from the aspect of position of bedding joints and other joints with respect to the cut slope position (Šestanović et al., 1994; Chigira and Yokoyama, 2005; Miščević et al., 2009). 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

(a) First year following the excavation (2003).

(b) First phase of protective structure completed (2004).

(c) Seepage through secondary joints (2006).

(d) Situation in 2007.

(e) Second phase of protective structure completed (2010).

(f) Situation in 2011.

(g) Material fall at cut slope (2012).

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

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 significantly 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 (Fig. 4).

A greater problem is the weathering that occurs along the joints and through the basic material (marl) 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 resultant 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 the rule that favourable excavation with respect to dominant bedding joints to ensure 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 (Fig. 12), random joints or joints formed by weathering, and through basic material (marl).

An example of landslide along secondary joints is shown in Fig. 13 (enlarged detail from Fig. 11g). The fact that water seeps through these joints is proven by plant roots (marked in the figure) which follow the spreading of such secondary joints.

The parametric analysis of wedge sliding along the joint at an angle α (cross section in Fig. 14) was conducted in the scope of analysis of shear strength at which the sliding occurs. This analysis was conducted for the side cut 10 m in height. The rock mass was modelled with the unit weight of $\gamma = 23$ kN/m^3, and the cohesion

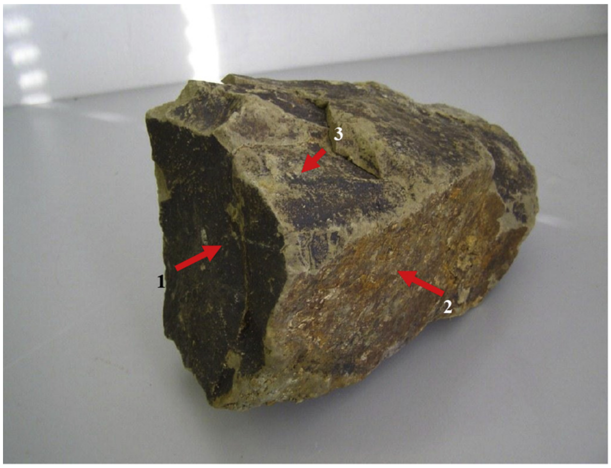


Fig. 12. Marl sample with three joint systems almost perpendicular to each other (first and third – secondary joints; second – bedding joints).

Fig. 13. Sliding along secondary joint set.

and joint inclination toward the side cut (α) were varied for the constant angle of friction along joints $\varphi_j = 30°$. The value of the angle of internal friction was selected based on shear strength measurements for marl, as shown in Tables 2–4, 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 analysed under assumption that the bottom end of the joint was still non-weathered immediately prior to fracturing, i.e. water could not have escaped toward the bottom end of the joint. Thus the hydrostatic pressure was modelled along the joints (example from Fig. 10). The following expression was derived from these conditions:

$$c_j = \frac{\frac{H}{2}\gamma \cos\alpha - \left(\frac{H}{2\tan\alpha}\gamma\cos\alpha - \frac{H}{2}\gamma_w\sqrt{1+\frac{1}{\tan^2\alpha}}\right)\tan\varphi_j}{\sqrt{1+\frac{1}{\tan^2\alpha}}} \tag{1}$$

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 values 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

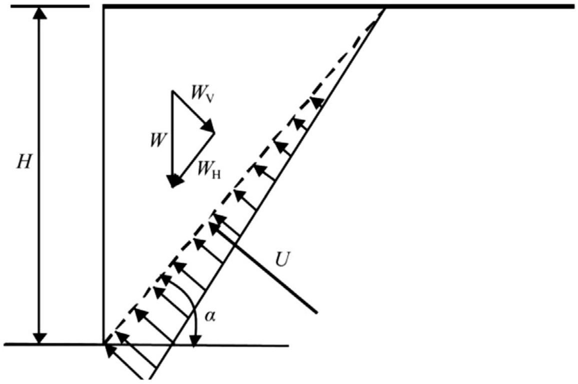


Fig. 14. Model of wedge sliding along the joint, as used in parametric analysis.

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

reason, the shear strength at which the failure and sliding occur can only be taken as an average value along the failure surface.

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. In this case, the pore pressure occurs in joints after the period of significant precipitation.

6. Conclusions

Two basic forms of slope instability can be differentiated in flysch formations that are mainly formed of marl layers: surface “exfoliation” of weathered material and 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 formations. An indirect influence on slope stability is the change of slope geometry as a result of this process. If the degraded material is deposited onto a roadway/railway facility, the safety of traffic may be affected. This process may also cause functionality problems for facilities on top of the slope.

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” reaches a sufficient length, it will detach and slide down the slope. At unprotected cut slopes in flysch formations, the landslides/material fall phenomena may develop in the period of several months to several years, depending on the weathering rate along the depth of the slope.

To prevent long-term instability of cut slopes excavated in marl, it is of utmost significance to block the development of weathering process. Factors that dominantly influence development of weathering are the cyclic processes of drying–wetting, heating–cooling, freezing–thawing, etc. In order to block the influence of these processes, the slope surface must be “sealed”. The rock can be sealed in two ways:

(1) 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°, suggesting that it cannot be easily removed by precipitation. In addition, it is certain that a vegetation cover will over time naturally develop on such material.

(2) 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 between the top of the slope must also be treated so as to prevent penetration of water from higher areas into the area of interest in the slope. 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, or in the cases when groundwater 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). 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 cannot 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.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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