

# Chapter 12

## Degradation Processes in Civil Engineering Slopes in Soft Rocks



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### 12.1 Introduction

The International Society for Rock Mechanics (ISRM) in 1981 defined soft rock as “rock with an uniaxial compressive strength in the range of 0.25 MPa to 25 MPa”, which can be classified as “extremely weak” to “weak”. However, this definition does not take into account the problems with weathering and deterioration of these rocks during the engineering time period. Since a proper definition of soft rock is not commonly acknowledged, a potential impediment is usually encountered in academic exchanges. Therefore, in theoretical research and engineering applications, the concept should indeed cover a variety of definitions of common laws and the essential characteristics of soft rocks and reflect their basic performances. For example, based on previous studies of the soft rock concept, He (2014) proposed a concept in association with geological soft rock and engineering soft rock. **Geological soft rock refers** to rocks characterised by low strength, large porosity, poor cementation, broken surface, and strong weathering-dependence, all of which basically contain swelling and loose clayey minerals and/or loose, soft, weak layers. **The concept proposed by ISRM is within the scope of geological soft rock.** **Engineering soft rock** refers to the rocks that can produce significant plastic deformation under the usual engineering loads. The concept of engineering soft rock emphasizes the importance of strength characteristics and engineering forces. Among other engineering tasks in soft rock mechanics, the problem with the soft rock definition concept can be considered through the stability of slopes in soft rock formations.

Surface degradation processes and landslides are quite frequent on slopes excavated or naturally formed in soft rock formations (marls, siltstones, mudstones, shales, claystone, etc.). These processes affect the safety and increase the

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maintenance cost of facilities situated at the bottom of these slopes, while also lowering the stability of facilities located at the top of such slopes. The excavation work in these mostly clayey rocks has to be conducted either by blasting or by means of heavy jack hammers. In other words, in the excavation phase, soft rock can be treated as “standard” rock mass. However, newly excavated slopes are susceptible to rapid weathering and, within several months to several years, that is, within the engineering period of time, the rock deterioration process starts both on the slope surface and within the rock mass. These processes can also be observed on many natural slopes formed in soft rock formations.

Examples of impact of weathering processes on slope stability at unprotected cuts can be found on many locations in engineering practice. In Fig. 12.1, an example of a cut slope with a developed process of marl degradation on the slope surface can be seen, as in addition to detached fragments at the bottom of the slope. Landslides on natural cliffs are quite frequent near town Split (Croatia) in flysch formations along the coastline (Fig. 12.2). The sliding process is continuous, as 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”.

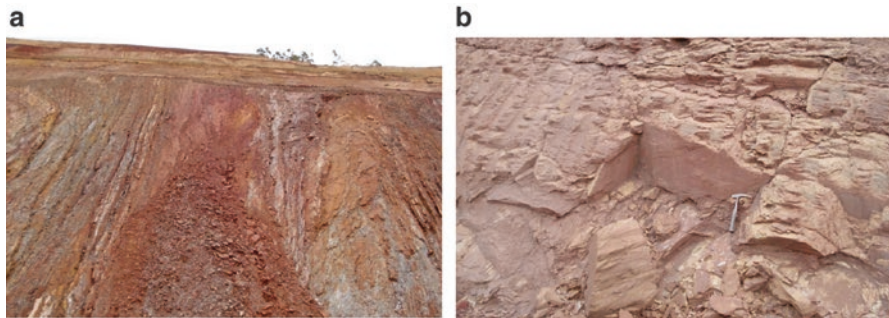
Other examples of the landslides in soft rock formation are shown in Fig. 12.3 from locations in Brazil (Quadrilátero Ferrífero region) formed in schist and sericitic phyllite rock formations (Lana 2016). An interesting point in Fig. 12.3 is the failure mode. Circular failures occurred in highly weathered rocks with strength varying from 0.25 to 5 MPa (Fig. 12.3a). In contrast, in a moderately weathered soft rock, in the range 5–25 MPa, structural failure mode occurred, as shown in Fig. 12.3b. Although schists and phyllites present an anisotropic behaviour due to foliation discontinuities, weathering and strength are often the determining factors of failure modes in slopes.

The presented situations are examples of hazards resulting from weathering processes. These hazards can be a threat to human lives, delay construction deadlines, result in closedown of vital roadways, etc.

**Fig. 12.1** Marl degradation on the cut slope surface at the Adriatic Coastal Road in Croatia. Location: Podstrana, Croatia. (Mišćević and Vlastelica 2012)



**Fig. 12.2** Landslide at the sea coast on the natural cliff in flysch formation. Location: Split, Croatia



**Fig. 12.3** (a) Sliding in sericitic phyllite rock formation, presenting circular failure. (b) Sericitic phyllite rock formation, showing wedge failure. Location: Brazil. (Lana 2016)

The 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 the weathering and landslides or rockfalls is still not well understood. This chapter will discuss the influence of the weathering process on the deterioration of the soft rock and the possible consequences of the deterioration processes on the rock slope stability. The main consequences of the deterioration are constant slope surface erosion and reduction of the material strength inside the rock mass slope. Results of the strength reduction are landslides and rockfalls on the natural or artificial slopes in soft rock masses.

## 12.2 Weathering of Soft Rocks

According to Fookes et al. (1988), the term weathering of construction materials within engineering time is defined as “the degradation or deterioration of naturally occurring construction materials under the direct influence of the atmosphere,

hydrosphere and, the activities of man, within an engineering time scale". The time factor considered is on an engineering time scale, that is, tens of years. Causes of soft rock weathering have been studied by many authors (for example: Alonso et al. 2010; Gökçeoğlu et al. 2000; Görög and Török 2007; Martinez-Bofill et al. 2004; Mišćević 1998a, b, etc.). Weathering properties of soft rocks and their behaviour during exposure to external influences are dominantly controlled by their mineralogical composition, preconsolidation history, composition of binding material in their structure, level of cementation, and rock texture. External conditions controlling weathering are climate, topography, chemistry of weathering solutions, hydrology, and vegetation (Huisman et al. 2006).

In the analysis of soft rock weathering, it is very important to recognise that weathering of soft rock occurs in the engineering time of scale when freshly excavated rock is exposed to weathering factors, that is, over a period from a few months to tens of years. For other types of rocks, weathering is correlated with the geological time scale, meaning hundreds and thousands of years.

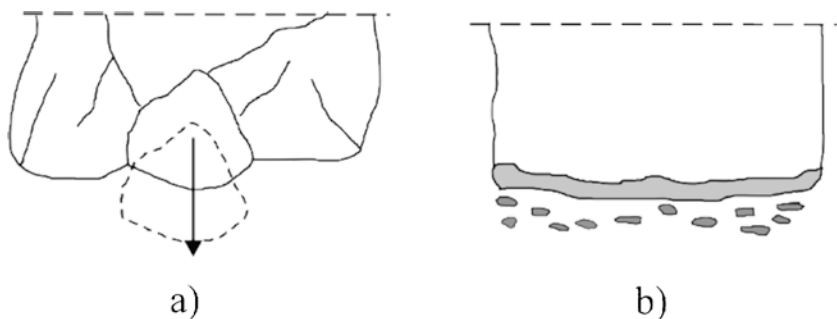
Weathering affects rock material and the discontinuities in rock mass. Weathering will affect rock masses from the slope surface and discontinuities into the material, and because of this, the material strength of discontinuity walls will be reduced compared to that of the adjacent rock material further away from the discontinuities. In the beginning stages of weathering, the walls will be weakened to a depth less than the height of asperities, steps, or other roughness components of the discontinuity, and the ultimate shear strength will be governed still by the unweathered material strength that needs to be overcome before asperities can shear through and large displacement can occur. On the slope surface, bedding joints are at most 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, that is, for example to the action of water that penetrates into the rock joints.

Water plays a crucial role in the weathering of these dominantly clayey rocks. This is conducted through the processes of drying and wetting, freezing and thawing (Martinez-Bofill et al. 2004; Yavuz et al. 2006; Sadisun et al. 2005; Pineda et al. 2014; Erguler and Ulusay 2009), and also through various chemical processes that include water. This influence is manifested as the decomposition of binding material from the clayey rock structure and as the disintegration of material into smaller fragments. In other words, this material is simultaneously affected by both physical and chemical weathering processes. An example of simultaneous physical and chemical disintegration of marl sample in contact with water is presented in Fig. 12.4.

Cracking is shown as an example of physical degradation, and dissolution from the surface as an example of chemical weathering. Deterioration caused by the weathering can be described with two forms of degradation process:

1. One form is disintegration in smaller parts with the development of the cracks system (Fig. 12.5a), Zhang et al. 2012. In samples with or without any cracks on the surface, under the weathering process, new cracks develop and all parallel

**Fig. 12.4** Simultaneous physical and chemical disintegration of marl sample in contact with water (1—cracking; 2—dissolution)



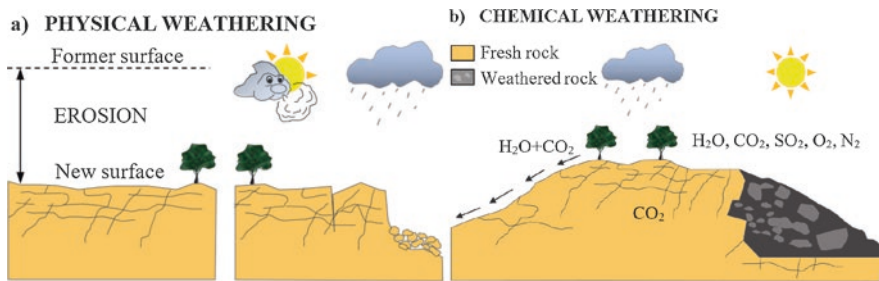
**Fig. 12.5** Forms of degradation processes. (a) Disintegration in smaller parts with the development of the cracks system; (b) exfoliation from the surface toward the inside (Mišćević 1998b; Ciantia et al. 2015)

cracks lengthen. The process usually develops near the surface, but can spread throughout the sample and break the sample apart into smaller pieces.

2. The second form of degradation can be described as the exfoliation from the surface towards the inside (Fig. 12.5b) (resulting eventually in a mass of small angular fragments and flat slivers that could readily be scraped loose by hand). Exfoliation is usually a result of the solubility of clay minerals, but it can also be a result of all weathering processes acting on the surface of sample.

Material on the free slope surface can simultaneously undergo both of the previously described processes. As a result, the material is broken into smaller parts with a larger surface area, and the process of degradation is accelerated.

The above assertions are also confirmed by typical landslide behaviour at cut slopes realised in soft rock formations, that is, the sliding/material fall most often occurs after a period of abundant precipitation, especially if temperatures at the soil surface fall below freezing point during this period. 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



<i>Physical weathering process</i>	<i>Pressure applied (MPa)</i>
Freezing	200
Crystallization	2-20
Hydration of salts	100
Clay expansion	2

<b>PROCESSES:</b>	<b>EFFECTS:</b>
<ul style="list-style-type: none"> <li>• Differential thermal expansion and insulation</li> <li>• Wet-dry expansion</li> <li>• Freeze-thaw action</li> <li>• Wind and rain action</li> <li>• Crystallization &amp; expansion</li> </ul>	<ul style="list-style-type: none"> <li>• Unloading</li> <li>• Joints formed</li> <li>• Incipient fractures opened</li> <li>• Intergranular and rock mass disintegration</li> </ul>

<b>Chemical weathering</b>	<b>EFFECTS:</b>
<b>PROCESSES:</b>	<ul style="list-style-type: none"> <li>• Alteration of minerals: Feldspar+CO<sub>2</sub>+H<sub>2</sub>O→Clays+Silicas+Cations</li> <li>• Pyrite+O<sub>2</sub>+H<sub>2</sub>O→Ion Oxide-Hydroxide+Acid solutions</li> <li>• Dissolution of limestones: CaCO<sub>3</sub>+H<sub>2</sub>O+CO<sub>2</sub>→Ca(H<sub>2</sub>CO<sub>3</sub>)<sub>2</sub></li> </ul>
<ul style="list-style-type: none"> <li>• Chemical alteration</li> <li>• Volume change</li> <li>• Textural change</li> </ul>	

**Fig. 12.6** (a) Process of physical weathering; (b) Process of chemical weathering. (Adapted from Ciantia and Castellanza 2016)

penetrates the joints and the pressure builds up within such joints. In addition, the behaviour observed in nature shows that the influence of water pressure on the shear strength along joints/surfaces should be taken into account in stability analyses.

The general influence of physical and chemical weathering on cut slopes is shown schematically in Fig. 12.6 (adapted from Ciantia and Castellanza 2016).

### 12.2.1 Physical Weathering Processes

The physical weathering is manifested in the breakup of the material due to extension of existing joints or the development of new joints throughout the material (fracturing). Basically, the result of physical weathering is a fragmentation of rock without the change in rock material characteristics.

The breakthrough of joints is a result of the following processes.



### 12.2.1.1 Wetting and Drying

Due to wetting and drying, rock material swells and shrinks because of a varying quantity of water present in the material, or varying quantities of water bonded to or incorporated in minerals. The associated volume changes lead to a weakening of the material by the repeated tensile and compressive stresses, thus eventually leading to fracturing.

### 12.2.1.2 Slaking

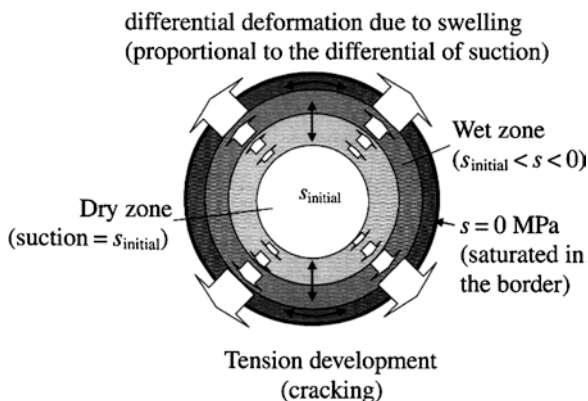
Slaking is a process associated with wetting and drying. The sudden absorption of water inside dry joints results in the development of pressure inside rock joints, which lead to the extension (deepening) of joints. Slaking is closely associated with the process of suction.

### 12.2.1.3 Suction

Wetting and drying cycles controlled by atmospheric changes are the main cause of suction changes, associated with the rock physical degradation, leading to the loss of mechanical properties (strength, cohesion—loss of cementation or bonding and stiffness). A possible explanation for the mechanism of degradation (Alonso et al. 2010) of marl fragments is schematically presented in Fig. 12.7 assuming isotropic behaviour.

When wetting occurs, the particle boundary is first wetted and a suction gradient is created inside the rock fragment. This suction gradient induces water transfer and reduces in time until it reaches a zero value when full saturation is attained. As long as there are suction gradients, differential swelling deformations will be developed inside the rock fragment. The geometry, stratification, and confinement of the fragment restrain the swelling displacements and lead to tensile and

**Fig. 12.7** Degradation mechanism explained by differential swelling displacements caused by suction gradients inside the rock (Alonso et al. 2010)



shear stresses, which eventually result in cracking and loss of structure. A similar mechanism can explain the degradation caused by drying (shrinkage instead of swelling deformations).

#### **12.2.1.4 Insolation**

Differential rates and amounts of thermal expansion and contraction in rock materials cause tensile stresses within the rock and rock mass. Thus, diurnal temperature changes will lead to tensile stresses and consequently to fracturing. Insolation is also associated with the drying process.

#### **12.2.1.5 Freeze and Thaw**

When water freezes into ice, a volume increase occurs of up to 9%. Therefore, freezing of water in pores, fractures, discontinuities, or other openings in a rock material or mass, causes tensile stresses that may be high enough to fracture soft rock.

#### **12.2.1.6 Crystallisation**

The volume increase during crystallisation of salts may be up to 5%.

#### **12.2.1.7 Stress Release**

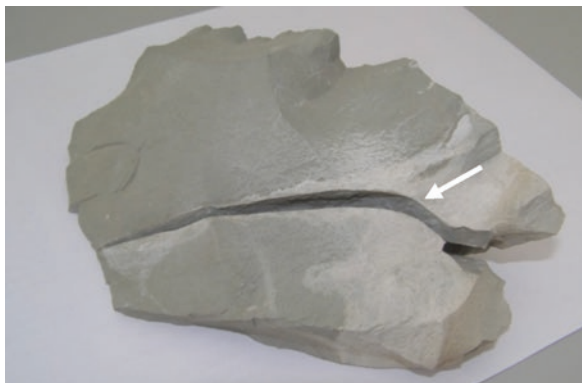
Release of stresses, provoked by the removal of material during excavation (relaxation) or erosion from the slope surface, causes development of new joints (listric joints).

#### **12.2.1.8 Swelling**

Swelling causes pressure that can disintegrate the rock, and it can develop in the presence of water only. In mineralogical composition, most soft rock contains minerals susceptible to swelling. Some of chemical processes result in materials with increased volume compared with the input ingredients. Increased volume of the material formed inside the joints also causes tensile stresses that may be high enough to fracture soft rock. For example, due to the mineralogical composition of the marl, when it is in contact with water, ingredients from marl form gypsum at the joint walls (Hawkins 2015). The volume of gypsum is up to 98% greater than that of the input components exuded from marl, and pressure is therefore created in joints where the gypsum forming process is under way. This pressure enlarges the



**Fig. 12.8** Gypsum growth on the surface of marl sample (white zone marked with an arrow) and developed new joint as a result of pressure caused with swelling in process of gypsum forming



existing joints and initiates formation of new ones. 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 also increases. This speeds up the process and increases the depth of its influence. An example of gypsum growth on the surface of marl sample is shown in Fig. 12.8.

### 12.2.2 Chemical Weathering Processes

Chemical weathering is a descriptive term for a range of chemical processes that may include a phase change (dissolution into ionic components), or a change of mineral type and structure. Some chemical processes induce mechanical disintegration of soft rocks (cracking), but basically chemical weathering changes the material properties. The development of new joints speeds up physical weathering and enables deeper penetration of chemical weathering effects. Typical weathering types are (Huisman et al. 2006; Oldecop and Alonso 2012):

- Dissolution (release of ions after a reaction of minerals with water).
- Oxidation (loss of electrons from elements, resulting in oxides, or hydroxides if water is present).
- Hydrolysis (during hydrolysis acids react with silicate minerals, releasing silica and metal cations).
- Hydration (involves the addition of water molecules to molecules, usually ferric oxides).
- Ion exchange (cations present in a solution in contact with clay minerals are exchanged with cations present in the clay lattices. This leads to a change in the type of clay mineral and the material properties).
- Chelation (occurs in silicate minerals, and describes the bonding of metal ions to ring-structured organics).

### 12.2.3 Weathering Intensity

Weathering intensity refers to the degree of weathering or deterioration at the time of observation, while time-dependent weathering intensity (or intensity rate) is the amount of weathering intensity change per unit time (Huisman et al. 2006). In general, factors controlling weathering intensity are previously explained (factors controlling physical and chemical weathering processes). Additional factors controlling weathering intensity on slopes are exposure of slope, orientation of discontinuities in relation to orientation of slope, slope angle, height of slope, method of excavation for artificial slopes, and implemented drainage measures.

Assessment of weathering intensity is usually done by descriptive methods or by index properties. Table 12.1 is an example of descriptive method proposed in the suggested methods for the quantitative description of discontinuities in rock masses (adapted from ISRM 1978; Ulusay and Hudson 2007). These methods are very susceptible to the observer subjectivity, but generally, assessments made by different observers are in very close range of the classification. Materials may sometimes well be somewhere between two classes. The major problem with these widely used descriptive methods is that they are developed for all types of rocks. This means that weathering classifications consider the geological time scale, and not the engineering time scale. For soft rock masses, the engineering time scale (from few months to tens of years) is more important because all weathering effects can occur in the short time after a construction from soft rock is built or a slope is excavated in a soft rock mass formation.

Index properties used for estimation of weathering intensity usually are some kind of strength estimation by simple methods (pocket knife, geological hammer, Schmidt hammer) or tests such as the slake durability test and loss slake index (Mišćević and Vlastelica 2011; Bryson et al. 2012; Vlastelica et al. 2018a). However, although strength estimates could be useful for engineering purposes, they do not usually give good correlations with the weathering intensity. On the other side, slake durability index and loss slake index can be useful to predict weathering behaviour of soft rock in a qualitative mode but cannot be used to predict the behaviour of the soft rock under natural conditions. Index properties tests can have severe

**Table 12.1** Weathering degree (adapted from Ulusay and Hudson 2007)

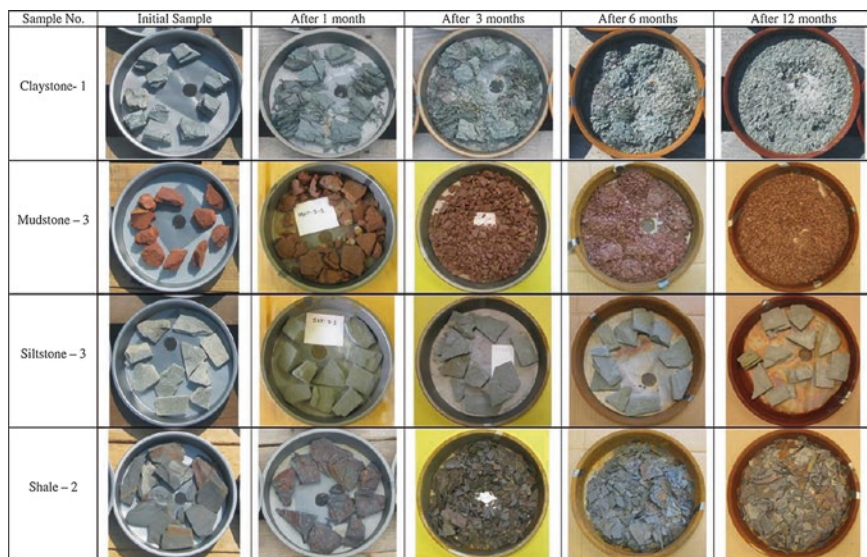
Grade	Description
W1	Fresh, no visible sign of material weathering.
W2	Slightly weathered. Rock strength partially affected by weathering.
W3	Moderately weathered. Rock strength affected by weathering.
W4	Highly weathered. Rock strength highly affected by weathering.
W5	Completed weathered. Rock disintegrates after immersion in water.
W6	Residual soil. All rock material is decomposed or disintegrated to soil.

limitations in predicting rock mass performance, especially when discontinuities influence weathering rock mass behaviour.

Weathering intensity rate is very important information for the maintenance of the slopes cut in the soft rock formation, because weathering induces material deterioration and degradation of soft rock strength. With the reduction of a shear strength of material on slopes, the stability of slopes decreases over time. With the deterioration of the material on a slope surface, problems with surface erosion occur. Time functions for weathering intensity are commonly empirical and based on experimental results. The time scale of weathering intensity rate in soft rocks is usually equal or even less than the time in which the construction is in use. It is therefore only important to examine whether the soft rock on the slope is liable to weathering in the engineering time scale. If the problems with weathering effects can be foreseen, then cut slopes should be shaped and protected with the intention to prevent weathering processes. For natural slopes, the same information about weathering intensity rate is essential for the decision about stabilisation measures.

An example of weathering intensity rate is shown in Fig. 12.9 for different soft rock samples (Gautam and Shakoor 2013).

*Weathering penetration degree*—The specificity of soft rock formation is that weathering penetrates inside to the rock forming weathered zone. However, the weathering intensity on the slope surface is not the same as on the end of weathered zone under surface. The weathering penetration degree generally depends on the same factors controlling the weathering intensity and on the additional factors con-



**Fig. 12.9** Examples of different weathering rates of some soft rocks (Gautam and Shakoor 2013)—initial samples and samples after 1, 3, 6, and 12 months of exposure to natural climatic conditions

trolling weathering intensity on slopes. The increase rate of the weathered zone usually decreases with an increasing thickness of that same weathered zone.

### ***12.2.4 Time-Dependent Slope Stability***

Analyses of slopes cut in flysch formation (mainly formed from marl and marly layers) are presented as demonstrative examples for the problem of the time-dependent slope stability. 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 (weathering penetration degree) is also significant for the analysis of the stability of cut slopes formed in marl. It was established by observing the behaviour of such cut slopes that the influence of water (drying and wetting) is operated in two ways.

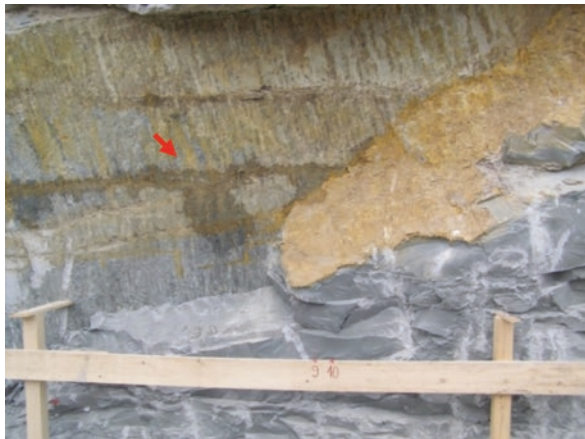
First, the process develops on the exposed surface of the rock, which results in constant “ravelling” of the material from the surface (Figs. 12.1 and 12.11). Transported by gravitation and precipitation, the degraded material accumulates at the bottom of the slope, where it eventually disintegrates into a material that can be classified as soil (clayey silt) rather than as rock. 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 the “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 the meteorological conditions, that is, 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.

Second, the weathering process also spreads deeper down into the rock mass and through the joint system that can easily be penetrated by water. An example of a cut slope on which wet zones near the joints can be seen, while the basic material is “dry”, is shown in Fig. 12.10.

In this example, yellow brown deposits on the surface of the bedding joints and secondary joints indicate that seepage occurred even prior to the excavation.

Both above described forms of weathering are documented with several pictures of the slope cut in flysch formations (location town Split in Croatia), which were taken during the observation period of 14 years after the excavation (Fig. 12.11). 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. The observations made on similar slopes have shown that the minimum depth of the material

**Fig. 12.10** Water seepage through joints formed in flysch



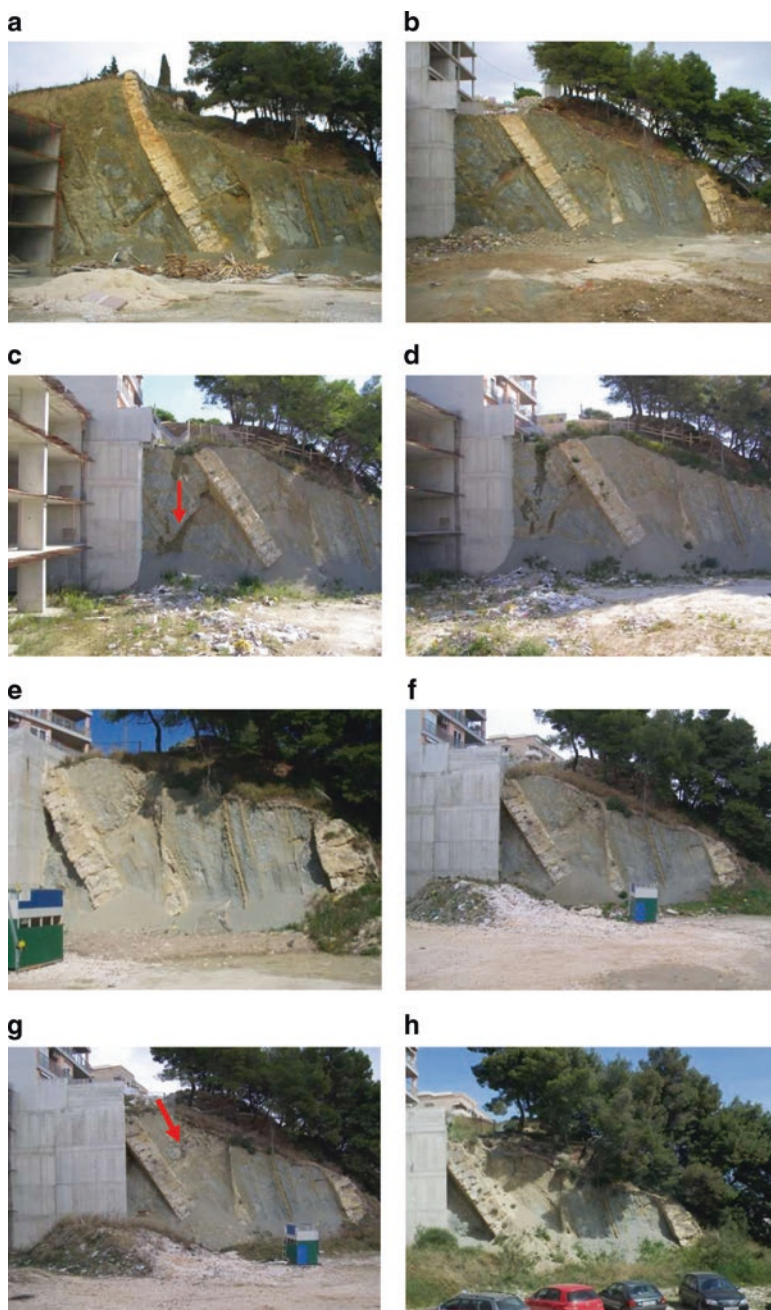
disintegrated from the surface of cut slopes in the Dalmatia (Croatia) region amounts to around 5 cm annually.

The sliding and weathering caused by seepage through joints can be seen in the given example at the left side of the slope. Several bigger blocks, formed at the joints through which the water penetrated, have over time been affected by sliding. The arrow in Fig. 12.11g shows the position of the last rock fall. In 2004 and 2010, the concrete protective structure was extended to protect the man-built facility situated above the cut slope, as the foundations of this facility were endangered by weathering and erosion of slope material underneath the foundations. It can be seen that the excavation was conducted very favourably with respect to bedding joints, that is, it was made perpendicular to bedding joints.

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 of material strength immediately after the excavation, or only from the aspect of position of bedding joints and other joints with respect to the cut slope position (Šestanović et al. 1994). 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 soft rocks. If the slope is not adequately protected so as to prevent weathering, the resistance of cut slope to weathering will be reduced over time.

A problem is also 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 the excavation method used. In addition, the weathering results in the extension of the existing joints and in the creation of new joints that penetrate into the basic material. This is





**Fig. 12.11** Progress of weathering process on slope cut in flysch formation, in period of 14 years. (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) Rock fall at cut slope (2012). (h) Situation in 2016



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 chapter. 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, random joints, or joints formed by weathering, and through the basic material (marl). The fact that the water seeps through these joints is proven by plant roots, which follow the spreading of such secondary joints.

To prevent long-term instability of cut slopes excavated in marl, it is of utmost significance to block the development of the weathering process. To this end, it is important to prevent the influence of factors that enable weathering, both on the slope surface and in the interior of the slope. Factors that dominantly influence the development of weathering are cyclic processes of drying/wetting, heating/cooling, freezing/thawing and so on. 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” and the water runoff over the slope should be controlled. 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 the penetration of the above mentioned influences along the depth. If 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  $31^\circ$  to  $38^\circ$  for marls, which means that it cannot be removed by precipitation. In addition, it is certain that vegetation cover will over time naturally develop on such a material.
2. Place surface protection that will prevent the development of these processes toward the interior of the slope (geosynthetics, vegetation cover, sprayed concrete, etc.).

It is therefore important to note that the surface behind the top of the slope must also be treated so as to prevent the penetration of water from higher areas into the slope zone. The weathering along the joints can be generated by water seeping through the 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). Owing to the occurrence of secondary joints and the 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 the slope material.

### 12.3 Deterioration of Soft Rock Slopes

Deterioration (or “decay”) of soft rocks, when analysing its impact on slope stability, is a serious problem that is important for infrastructure works and the safe construction of cut slopes (Calcaterra and Mario Parise 2010). Moreover, understanding of this problem and related processes is necessary for the proper prediction of the future behaviour of rock masses in slopes and therefore for the sustainable development in civil and environmental engineering.

Deterioration implies several fundamental processes, time-related and generally slow, acting on a slope, artificial or natural as well, which may cause a significant decrease in rock mass strength and slope stability. These primary processes are *relaxation*, *weathering*, and *erosion*, or in other words, deterioration occurs as a result of their combined action. Depending on the balance between the primary processes, deterioration usually progressively leads to alteration and disintegration of materials and rock masses (although the rock mass quality in some cases may be locally improved by weathering related processes, for example, formation of crust on the rock surface that is stronger than the material beneath it).

After the excavation and initial stress release (primary relaxation), deterioration or decay of a rock mass in geotechnical terms can be described as a process of seeking equilibrium between weathering and erosion as well as on-going stress and strain redistribution (secondary relaxation). For the duration of such a process, which is the rule rather than the exception in artificial slopes, three main situations can be recognised (Huisman 2006):

- Imbalance favouring erosion (weathering delimited).
- Equilibrium between weathering and erosion.
- Imbalance favouring weathering (erosion delimited).

To provide safe construction and predicted engineering lifetime of cut slopes, as well as to limit future economic and environmental risks, assessment of dominant deterioration processes/situations and affected geotechnical units in time, with the rate of decay of rock mass quality, should already be included in the geotechnical design phase (not only current, but also future geotechnical properties are important). However, that is not always possible since the process of deterioration of soft rocks slopes can be difficult to quantify and its mechanisms are still not recognised and understood well.

### 12.3.1 Relaxation

Excavations cause changes in stress along the slope (stress release or unloading; elastic relaxation and expansive recovery) so that stress distribution may become anisotropic, for example, on the slope face, the horizontal stresses are equal to zero. As the horizontal stress is removed as a result of the excavation, joints tend to undergo dilation. This may further result in the formation of a potential sliding block. Redistribution of stress and strain can be one of the causes of reduced joint roughness (broken “teeth” of the joint as a consequence of joint wall decay caused with weathering processes). In general, the fractured rock mass tends to expand along joints as a result of the stress relief and the removal of lateral confining pressure.

With zero horizontal stress on the cut surface and an unchanged value of vertical stress, shear stress can reach failure condition even in short periods after the excavation when weathering effects are not significant (Fig. 12.12).

Given these considerations, relaxation can be described as the redistribution of stress and strain following excavation (i.e., lowering of the confining stress level), leading to loss of structural integrity. Redistribution of stress and strain is a continuing process from *primary relaxation* as a direct result of excavation itself (volume increase), through deterioration of a rock mass due to the effect of weathering and erosion to *secondary relaxation* (creep).

Primary relaxation with the volume increase effect occurs directly after excavation, during the period of days to months (Huisman 2006), resulting in slightly opened discontinuities that allow access to water. Additional simultaneous effects (some, not necessarily all), linked to each other, are the decrease in normal stress on discontinuity walls and thus a decrease in shear resistance (Fig. 12.12), increased porosity and permeability due to the formation of microcracks, changed paths of water, increased aperture and hydraulic conductivity of the discontinuities, more intense water penetration and circulation, fluctuations in moisture content in the unsaturated zone, shear displacements along discontinuities resulting in breaking of

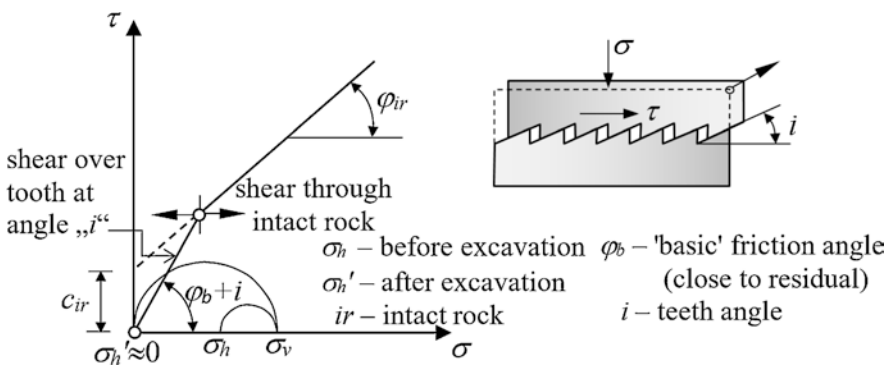


Fig. 12.12 Stress modification after overburden removal in comparison with the bilinear failure criterion of a discontinuity. (Adapted from Wittke 1990; Roje-Bonacci et al. 2009)



of minerals leads to long-term deposition of carbon dioxide, which affects the development of the global climate. Therefore, weathering occurs as a result of certain climate, but in the longer time scale, it affects and changes the same climate through the resulting products ( $\text{CO}_2$ ). From the previous discussion, it is evident that this is a key process that controls the morphological and ecological processes, and it has a direct impact on social issues (importance of soil/rock resource to the society). In general, the study of weathering is multidisciplinary, interdisciplinary and transdisciplinary, and requires coupling physical, chemical, and biological processes over a range of spatial and temporal scales and involves a variety of scientific and engineering disciplines. The “critical zone” of interactive physical, chemical, and biological processes, where the intensity of weathering is the most obvious, extends from the lowest levels of underground water to ground surface including vegetation cover. Variables such as the slope orientation and angle, climate, hydrology, tectonics, biological communities, and anthropogenic impacts, control the area affected by weathering, the amount of weathering and the place and the amount of disposal of degraded materials.

Regarding the engineering significance and target aspects of sustainability, durability, and slope stability, weathering is particularly important for soft rocks, which are subject to weathering in the time scale of the duration of human life, that is, they reduce the durability and can be studied within an engineering time scale. The question is how can we improve our ability to predict the process of weathering and its influence on the durability and future stability of the slope, and this is further discussed in Sect. 12.2.3 using the terms of *weathering intensity* and *weathering intensity rate*.

The result of weathering process is constant degradation of natural or artificial slopes. Rock profiles that result from long-term or short-term weathering can be highly inhomogeneous, complex, and irregular (Fig. 12.11), and that may lead to hazardous situations and create serious problems to the geotechnical engineer (rock-falls, plane or wedge sliding, remedial works, and similar).

Weathering affects rock masses in slopes from the slope surface and surfaces of discontinuities into a material or rock mass. The terms that describe this in the literature are *weathering penetration depth* (depth of advancement of weathering front into a slope) and *weathering penetration rate* (rate of advancement of the weathering front into a slope). Here, it should be noted that the water is an essential driving force of the weathering processes (exposure to water and initial opening of joints). Especially in soft rocks, most of these processes depend on the change in the water content, so that the weathering process mainly develops when a material is exposed to the wetting–drying changes.

There are many effects of weathering manifested in the alteration of rock material and rock mass (physical or chemical): an increase in aperture and the frequency of discontinuities; increased porosity, void volume, permeability, and flow rate; microfracturing; decrease in block size and intact rock strength; mineral alteration; weakening of intergranular bonds; reduced material strength and roughness of discontinuity walls; reduction of shear/tensile strength along the discontinuities and cohesion in the filling, and others (Fig. 12.14). Among them, the influence of weathering on discontinuities present in the rock mass is particularly important for the

**Fig. 12.14** Degradation effects of weathering (example of marl as soft rock)



slope stability. For example, shear strength along the discontinuity (and thus the stability) will significantly reduce when the weathering penetration depth exceeds the discontinuity roughness.

Factors or conditions that control weathering in artificial slopes are of different nature:

- *Internal*: properties of rock/soil material and rock mass (porosity, permeability, composition of materials—fabric, physical, and chemical stabilities of coexisting mineral phases and their mutual interrelation, surface properties, inner strain, and discontinuities).
- *External*: those related to the environment (climate, topography, chemistry of weathering agents, hydrology, and vegetation).
- *Geotechnical*: design parameters (slope orientation, angle, height, excavation method, and drainage).

Thus, according to the current cognitions, rock mass deterioration results from interaction of internal material features with external conditions and biogenic activity and is further influenced by rock mass characteristics, geotechnical factors, and boundary conditions. In contrast, the durability of rock material is a complex function of the mentioned internal material features.

### **12.3.3 Erosion**

Together with relaxation and weathering, erosion is a primary process in the deterioration of soft rock slopes, which refers to the removal and transport of previously weathered material by water, gravity, or wind, that consequently destroys the rock mass structure. In comparison with weathering, there is a strong distinction: erosion is the process of material transport, while weathering is a process of material change.

Surface erosion is a natural continuous process that acts on the products of weathering, removing them from their original location, and thus exposing “fresh”



material to weathering (former and new surface, Fig. 12.6a). It can be said that erosion sets a boundary condition for rock mass weathering (Huisman 2006), and contributes to the overall process of deterioration on a larger scale of rock mass (while weathering acts on a relatively small scale, on in situ materials). Although it affects all types of soil and rock mass, erosion is more evident in the rocks with a higher frequency of discontinuities and small blocks (either weak in a fresh, that is, unweathered state, or weakened by weathering), and in unconsolidated soils. Eroded material may be subjected to further weathering during erosion.

The term *erodibility* signifies the susceptibility of particular soil or rock masses to erosion, and the properties that determine erodibility (aggregation, shear strength, hydrological conditions, and others) generally strongly depend on climatic factors (such as rainfall distribution, daily temperature changes, and frost) with systematic seasonal variations. Therefore, erodibility is a dynamic variable, where a small variation in the parameters of material and mass properties and composition can change it on shorter time scales, for example, between and during separate events such as rainstorms.

In certain conditions of climate, rock mass properties, and the geometry of the slope, erosion may cause substantially increased incidence of slope failures. Joints and fissures in their systems in rock mass can be either temporarily closed or partly opened. In open joints, the water circulates in the direction of gravity (in closed joints water flow is capillary), forming small channels, where the erosion effect of the water becomes more intensive with the degree of slope inclination (Roje-Bonacci 1996). Failure can be caused by additional external forces, as the hydrostatic pressure in surface joints connected to the potential sliding surface and change in the stress state (pore pressure) due to the effect of hydrostatic pressure. As shear strength within the rock mass is smaller along joint systems, it is of importance in slope stability problems, for example, landslides and slips on high cut-offs. Slips of this type, where joints reach the potential sliding surface and wide are so that water can circulate through them by gravity, occur during heavy rainfall.

The other examples where erosion may be the primary deterioration process (smaller influence of weathering) are *erosion by sheet wash (sheet erosion)*, *rill (and interrill) erosion*, and *gully erosion*. If soil is transported by overland flow, that is, if *wet erosion* occurs, a certain critical shear stress on the soil surface needs to be exceeded before erosion could occur. In theoretical studies, erosion is determined by multiplying exceeded shear stress and “erodibility” as the proportionality constant representing the soil erosion susceptibility. Using such simplified models with average values of critical shear stress and erodibility leads to an overestimation or underestimation of soil loss by erosion, and the variations in these parameters should also be taken into account. Quantitative evaluation of erosion (mean erosion and/or specific annual degradation) is possible on the basis of known (measured) data on the amount and mode of distribution of deposited sediments, if they are not removed by activities such as the regular maintenance of roads.

In exposed slopes of the rock types such as hard marls, the erosion mechanism includes two stages: exposure of the surface to the impact of precipitation, and then mobilisation of surface disturbance as the raindrops are lifting soil particles into suspension ready for transport (Kollios 1993). As more and more particles are

picked up, a dense suspension with erosive power is formed, and due to variations in surface morphology, flow is channelled and local ravines formed. The velocity of the suspension and its erosive capacity increases as it moves downwards. Therefore, the key to reducing erosion is to slow down the water run-off velocity (geosynthetics as possible intervention). According to the well-known Chezy–Manning equation for open channel flow:

$$V = \frac{1.49}{n} \cdot R_h^{2/3} \cdot S^{1/2} \quad (12.1)$$

where  $V$  is average run-off velocity,  $R_h$  is hydraulic radius corresponding to the area versus wetted perimeter,  $S$  is slope or hydraulic gradient, and  $n$  is roughness coefficient; the other possible measure is to increase the surface roughness coefficient (vegetation).

Among others factors, some factors of relevance regarding the rate of erosion on slopes are the occurrence of heavy rainfall (trigger effect, increased rates of erosion), slope angle and length of the slope, presence of cracks and macropores (infiltration conditions), surface roughness/vegetation, discharge over the slope, and moisture content of slope material. As a result of changing moisture conditions, erodibility for a given slope angle can change significantly over short time scales during rainstorms. Together with the “static” moisture conditions, seepage is also an important factor that influences erosion, where cracks provide preferential pathways for water infiltration and transport of solutes. Rill and gully formation are enhanced if seepage occurs. Also, if hydraulic impedance is present near the slope surface, erodibility can increase.

By observing the process of natural slope degradation in flysch formations near the sea coast (middle Dalmatia, Croatia), it is determined that material from the bottom of the slope is constantly removed by *wave erosion*, with the consequence of recession of the coastal cliffs at a rate 3–18 cm/year (Vlastelica et al. 2017). This represents a very high recession and erosion rate, if the denudation classification (Kossev 1990) given in Table 12.2 is taken for comparison.

Spatial and temporal variations in rock mass properties and climatic factors, those that change erodibility, in combination with human activity during slope design and construction (slope location, orientation and angle; method of excavation), influence the *development of erosion profiles* in slopes. This may result in the

**Table 12.2** Classification according to denudation velocity

Denudation class	Denudation velocity $h$ (mm/year)
Very low (1)	<0.50
Low (2)	0.50–1.00
Average (3)	1.00–2.50
High (4)	2.50–5.00
Very high (5)	>5.00

occurrence of *differential erosion* and weathering, and consequently in hazardous effects of erosion. Namely, erosion of particles formed by weathering (flaky particles and similar product of weathering, Fig. 12.11) leads to a decrease in the slope angle in exposed soft rock layers. Such previous erosion of underlying soft rock layers (especially when unfavourable joint systems are present in the rock mass) undercuts otherwise strong and durable limestone, dolomite or sandstone banks or blocks, which usually results in toppling of layers or rockfall.

Steep artificial cut in soft rocks, a lot steeper than the inclinations of natural slopes in such materials, leads to rapid erosion, and therefore to the sliding and receding of the slope and the undercutting of the otherwise resistant rocks types. Within the long-term continuous process of slope development and deterioration of soft rock slopes, the short-term episodic events influenced by rapid erosion and gravity—sliding, undercutting, rockfall, toppling, etc., will generate some scatter in the observation data.

## 12.4 Slope Stability in Engineering Timescale

For any analysis of change in geometry of the cut, the depth to which the soft rock mass is affected by weathering has an important role. Since the processes of weathering and erosion occur simultaneously, their combination causes further decomposition of rock mass on the face of the cut, with additional relieving effect through the redistribution stresses. The relative ratio of erosion and weathering has a significant impact on the development of the slope surface of cuts.

Although erosion is most commonly associated with a weakened and weathered soil or rock, it is also present on solid (unweathered) surfaces with lower intensity. Comparing the intensity of erosion and weathering in soft rock mass, one can notice three fundamental relationships of these processes, as discussed previously.

The potential erosion and weathering relationships depend upon the weatherability of rock immediately after excavation, and therefore, depending on their relationship, five basic situations can be noticed, as shown in Table 12.3.

With regard to the type of material and climatic features of the area of research, slope degradation models based on weathering can be used only when the process is in the range of balance of erosion and weathering to an imbalance in favour of weathering, that is, the erosion always takes place on the weathered material.

For example, by observing cuts in flysch rock mass in the Dalmatian region, the Mediterranean climate combined weathering and erosion effect is mainly found to be imbalanced in favour of erosion (Vlastelica 2015).

When steep cuts are observed, it is noticed that weathering is developed on the exposed surface, and erosion is present at a constant rate, which is always lesser than the observed weathering rate. Transported by gravity and precipitation, weathered material builds up at the base of the slope, where it eventually additionally transforms into a soil-like material (Roje-Bonacci 1998). This process has more impact on the cost of maintaining the facility than on global stability. The accumu-

**Table 12.3** Combination of weathering and erosion of slopes (Huisman 2006)

	Description	Weathered material present from previous step	Thickness of weathered layer	Weathering intensity on the slope surface	
Imbalance in favour of erosion	Only erosion	No	0	Constant	
		Yes	Decreases due to erosion, after that 0	Decreases due to erosion, after that constant	
	Some weathering, erosion penetrates faster than weathering can develop	No	0	Constant	
		Yes	Decreases due to erosion, after that 0	Decreases due to erosion, after that constant	
	Balance between erosion and weathering	Erosion and weathering penetrate at the equal rate	No	0	Constant
			Yes	Constant, larger than 0	Constant
Imbalance relations in favour of weathering	Some erosion, weathering penetrates into the depth of cut faster than weathering	No	Increasing	Increasing	
		Yes	Increasing	Increasing	
	Only weathering, no erosion	No	Increasing	Increasing	
		Yes	Increasing	Increasing	

lated material at the bottom of the slope is usually required by owners to be removed regularly, and therefore, the slope is “moving away” from the original position. In time, this can cause additional instabilities, such as rockfalls or planar sliding on the secondary joint systems.

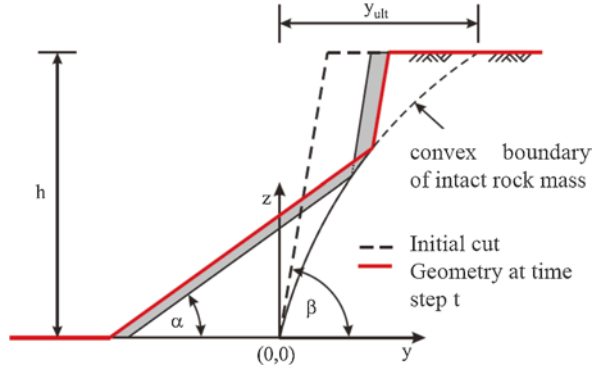
It was observed that the effect of weathering on the surface of the slope can be developed to a depth of several centimetres to 10 cm (Mišćević and Vlastelica 2014). The depth depends on the share of carbonate and clay marl components, position of primary and secondary cracks in relation to the position of the slope, and the angle of the slope. The total thickness of the surface layer depends also on meteorological conditions: number of dry and rainy seasons, quantity and intensity of rainfall, exposure to the sun, and variation in air temperature.

## 12.4.1 Slope Degradation Models

### 12.4.1.1 Fisher–Lehmann Model

This model is a combination of Fisher’s (1866) mathematical description of degradation of abandoned, initially vertical cut in chalk deposits without the accumulation of eroded material at the bottom of the slope, and Lehmann’s (1933) generalised model, which introduces the possibility of initial sloping curvature and accumulation of eroded material at the base of the slope (Fig. 12.15).

**Fig. 12.15** Fisher–Lehmann model (Lehmann 1933)



Change in the morphology of the cut can be described by the following (Eq. 12.2):

$$y(t) = \begin{cases} h \cdot ctg\beta & \text{for } t = 0 \\ h \cdot ctg\beta + R_{y,s} \cdot t & \text{if } 0 < t < (y_{ult} - h \cdot ctg\beta) / R_{y,s} \\ y_{ult} & \text{if } t \geq t_{ult} = (y_{ult} - h \cdot ctg\beta) / R_{y,s} \end{cases} \quad (12.2)$$

where  $h$  is the height of the cut,  $\beta$  is slope angle, and  $R_{y,s}$  is annual erosion rate.

According to Hutchinson (1998), erosion of the cut is not necessarily a linear process in time. In an example of a 1.75 m height cut, based on intermittent observations over a period of 15 years, he concluded that the process was non-linear (Fig. 12.16).

Usually, it is possible to notice high initial erosion of cuts (Fig. 12.17); however, this effect should perhaps better be attributed to the initial relaxation of rock mass and local instability depending on the condition and quality of excavation.

Taking this into account, instead of the parameter  $R_{y,s}$ , a nonlinear function  $R_{y,s} = R_{y,s}(t)$  can be introduced or the linear criterion described in (Eq. 12.2) can replace the bilinear criterion (Vlastelica 2015):

$$y(t) = \begin{cases} h \cdot ctg\beta & \text{for } t = 0 \\ h \cdot ctg\beta + n \cdot R_{y,s} \cdot t & \text{if } 0 < t < t_1 \\ h \cdot ctg\beta + R_{y,s} \cdot t & \text{if } t_1 < t < (y_{ult} - h \cdot ctg\beta) / R_{y,s} \\ y_{ult} & \text{if } t \geq t_{ult} = (y_{ult} - h \cdot ctg\beta) / R_{y,s} \end{cases} \quad (12.3)$$

where  $n$  is the coefficient of initial relaxation of the cut;  $t_1$  is the time within the effects of initial relaxation of the cut manifests. For example, in the Hutchinson model (Fig. 12.16), these parameters would be  $n = 10$  and  $t_1 = 3$  years.

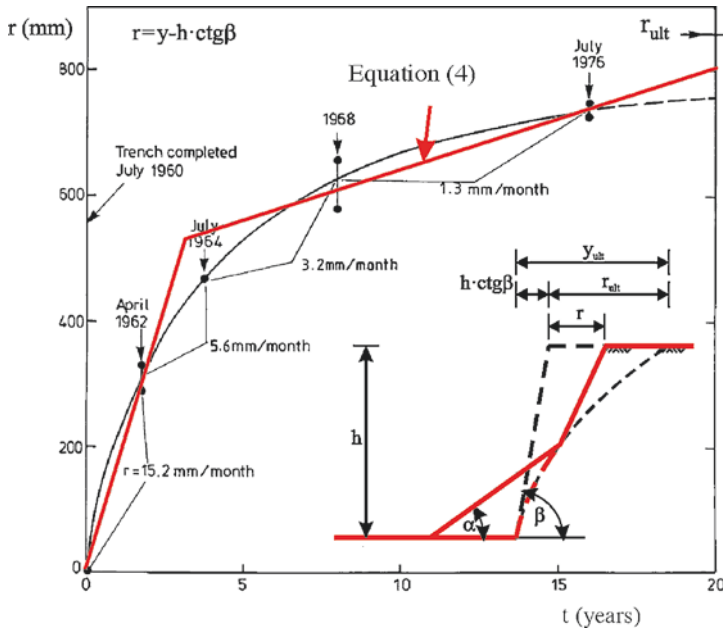


Fig. 12.16 Yearly erosion of “Overton Down” cut, UK (Hutchinson 1998; modified by Vlastelica 2015)

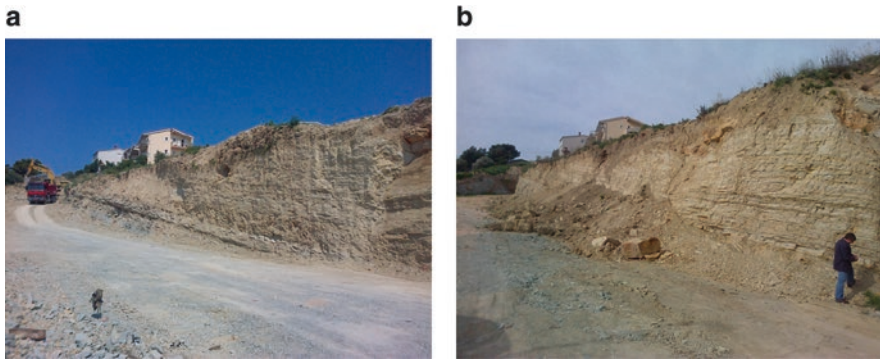


Fig. 12.17 An example of a quick initial change of the profile of the cut, Brnik (Vlastelica 2015). (a) Immediately after excavation (July 2013). (b) Situation after 7 months (February 2014)

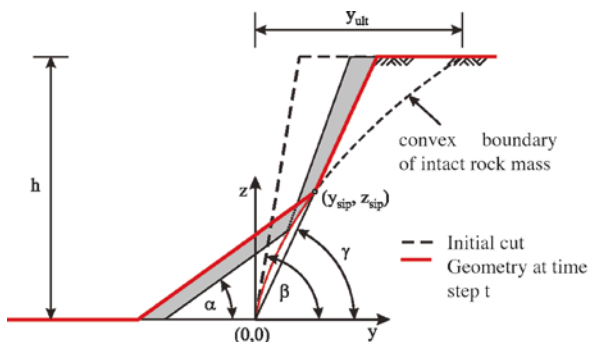
### 12.4.1.2 Bakker–Le Heux Model

The basic assumptions of the Bakker–Le Heux (1946) model are similar to that of the Fisher–Lehmann, except for the way the free face of the slope face is eroded.

This model assumes uneven wear of the face of the cut (Fig. 12.18), according to which the erosion front rotates around the bottom of the cut. Change in the morphology of the cut can be described by introducing the following:



**Fig. 12.18** Bakker–Le Heux model (Bakker and Le Heux 1946)



$$\gamma(t) = \begin{cases} \beta & \text{for } t = 0 \\ \beta - R_{\gamma,s} \cdot t & \text{if } 0 < t < (\beta - \alpha) / R_{\gamma,s} \\ \alpha & \text{if } t \geq t_{ult} = (\beta - \alpha) / R_{\gamma,s} \end{cases} \quad (12.4)$$

where  $\gamma$  is the slope angle at selected time step;  $R_{\gamma,s}$  is the average annual change of slope angle due to erosion.

By introducing time dependency  $t$ , it is possible to determine the position for the top of the scree at a given moment (Huisman et al. 2011):

$$\begin{pmatrix} y_{sip} \\ z_{sip} \end{pmatrix} = \begin{pmatrix} \frac{z_{sip}}{tg(\gamma(t))} \\ h \cdot \sqrt{\frac{1}{1-2c} \cdot \left( e^{\frac{1-2c}{c-1} \ln\left(\frac{a \cdot tg(\gamma(t)) - 1}{(a-b) \cdot tg(\gamma(t))}\right)} - 1 \right)} \end{pmatrix} \quad (12.5)$$

Also, the form of the slope:

$$y(t) = \begin{cases} y_{sip} - a \cdot (z_{sip} - z) & \text{za } 0 \leq z \leq z_{sip} \\ z \cdot ctg(\gamma(t)) & \text{za } z_{sip} \leq z \leq h \end{cases} \quad (12.6)$$

Although these models are independent, in some cases, combination of both is possibly more accurate. By comparative analysis, Vlastelica (2015) found that after initial relaxation of the cut, the Fisher–Lehmann model best describes erosion at selected pilot locations in the Dalmatia region. For this reason, the Bakker–Le Heux model is preferably combined with a Fisher–Lehmann model for the simulation of initial relaxation of steep cuts.

### ***12.4.2 Change in Shear Strength Due to Degradation***

Repeated drying and wetting has a dominant influence on the development of a series of physical and chemical weathering processes that degrade soft rocks. A question arises whether, following the introduction of processes that cause degradation, it is possible to measure the trend of changes in strength. The strength of rocks, as well as all known classification of soft rocks, is usually displayed by uniaxial compressive strength (UCS) determined in a hydraulic press on cylindrically shaped samples. However, this procedure requires a set of monolithic specimens, which is usually difficult to obtain when sampling a soft rock material. Chiselling and sanding of sample sides would produce a more ideal specimen; however, these techniques are not practical on samples subjected to weathering; therefore, it is necessary to find an alternative (Mišćević and Vlastelica 2009).

An alternative way of quantifying the strength of the material is to define its shear strength, usually by Mohr–Coulomb shear strength criteria. However, in this case, conventional laboratory equipment is not adapted to the whole range of appearance and friability of soft rock, which makes it necessary to devise new equipment specifically for this type of material or to adapt the existing equipment to testing requirements (Mišćević and Vlastelica 2010; Buocz et al. 2010; Yin et al. 2016). Since the use of existing equipment is more rational from an economic point of view, it is proposed to simplify the experiment by using a portable direct shear apparatus for rocks. When slightly modified from the standardised procedure, the apparatus would make it possible to test the soft rock in both intact and degraded state of the samples subjected to laboratory simulated weathering. For marginal cases, direct shear apparatus for soil is used; however, it is necessary to clearly distinguish in which cases is this appropriate (Roje-Bonacci 1998; Vivoda Prodan et al. 2016). Based on these observation and series of testing on marls from Dalmatian region, Vlastelica et al. (2016a) proposed guidelines for the application of laboratory-simulated weathering on soft rocks, by using standard laboratory equipment (Table 12.4).

### **12.5 Monitoring of Soft Rock Slopes**

Each new insight into the processes that cause the instability of slopes in soft rock, such as erosion or rockfalls, can help mitigate the possible consequences. The development of new technologies in the field of geodesy, TLS (terrestrial laser scanning, sometimes called LiDAR—Light Detection and Ranging) and GB-InSAR (Ground Based Interferometric Synthetic Aperture Radar) opens new paths for monitoring changes in the slope surface and the material from which it was created. These remote sensing technologies can be used on a global level to cover wide areas (InSAR is used for a couple of decades on the spaceborne and airborne platform), but also at the local level as terrestrial or ground-based instruments. This is very

**Table 12.4** Guidelines for the application of laboratory-simulated weathering on soft rocks

	The applicability of the portable direct shear apparatus		Laboratory-simulated weathering procedure <sup>c</sup>	
	Unweathered material	Laboratory weathered material	Recommended number of cycles	Remark
Type I	Yes	Yes	>8	–
Type II	Yes	Yes	Do 8 (4 <sup>a</sup> )	For a larger number of cycles, it is recommended to use the device for direct shear of soil
Type III	Yes	Limited	1 <sup>b</sup>	It is recommended to always use the device for direct shear of soil

<sup>a</sup>For Type II marl bordering with Type III (generally with smaller CaCO<sub>3</sub> content or LSI  $\approx$  0.5) maximum of 4 cycles of laboratory-simulated weathering is recommended

<sup>b</sup>For direct shear of intact rock use the direct shear apparatus for rock. Testing of degraded material is usually not possible and usage of direct shear apparatus for soil is recommended

<sup>c</sup>When selecting the proper procedure, it is always recommended to use information about CaCO<sub>3</sub> content, absorption,  $I_{44}$  and LSI index of the rock. If it therefore can be concluded that it is a borderline sample between two categories, it is recommended to use a method of the higher category, and if it is necessary correct the procedure during the testing

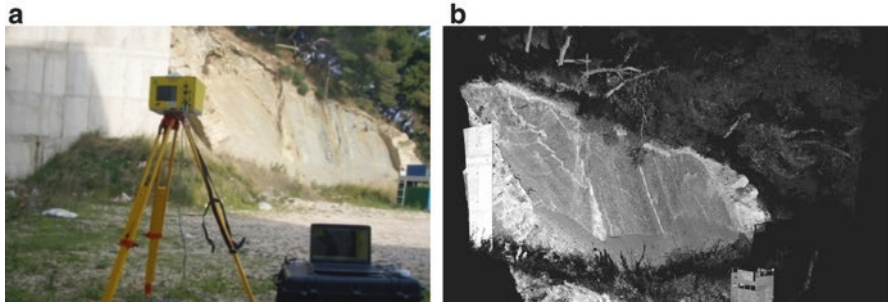
important for monitoring of cuts and steep slopes, where usually it is not possible to acquire data without properly positioned ground based units.

Although GB-InSAR provides displacement measurements of up to a few square kilometres with sub-millimetre precision and high temporal frequency of acquisition (Ferrigno et al. 2017), resolution is still very rough (from couple to dozen meters, at ranges from 800 to 4000 m). It is therefore not suitable for small-scale problems, such as those occurring in soft rock strata or flysch deposits.

On the other hand, TLS provides sub-centimetre accuracy (Kordić 2014) with resolution of measurement in centimetres (at ranges of a couple hundred meters), which can provide very usable data for engineering geologists and geotechnicians, such as very precise slope morphology, prefailure deformation detection when long-term monitoring methodology is implemented (in certain types of rock masses that are more deformable, such as flysch), and information about the spatial distribution of rock-type properties (when additional information about the intensity of the return laser beam is considered). Lately, RPAS (Remotely Piloted Aircraft System) is used to collect images, which are then processed by Pix4D mapper (structure from motion technology) to generate a point cloud as with TLS, and this method is getting more precise and cost effective (Török et al. 2018).

Spatial distribution of material properties in flysch such as steep slopes can be very important, especially for detection of weak layers, which are more prone to erosion (causing differential erosion), or as a method of detecting faults and discontinuities (Fig. 12.19).

When a sufficient number of checkpoints are referenced in the global coordinate system, then the whole cloud of points can be oriented in the same system, and



**Fig. 12.19** (a) Typical cut in flysch rock mass; (b) Result of laser scanning is a point cloud with approximately 4 million points. On each point, intensity or return beam is added as grayscale, thus numerically distinguishing points of same reflective properties (Vlastelica et al. 2016b)

information about slope and discontinuities orientation can also be collected. The points can be further specified with colour, that is, RGB component can be associated, when scanners have an integrated and calibrated digital camera.

The use of TLS in this work is presented solely from a basic user's perspective. For more information about the principles of measurement, technology, and instrument performance, readers are referred to additional literature (Kordić 2014; Petrie and Toth 2008; Teza et al. 2007).

### 12.5.1 Methodology for Detecting Changes in Slope Morphology

The change in morphology of cuts is carried out by comparing the point clouds from different epochs using the following methodology (Vlastelica et al. 2016b):

- Obtaining a reference point cloud (Combine multiple point clouds in case of more scanning positions. Preferably georeferencing is done to determine spatial orientation of a cut).
- Creating a Triangle Irregular Network (TIN) model of the surface of the cut—reference surface ( $S_0$ ).
- Obtaining new point cloud after a certain period ( $PC_1, PC_2, \dots, PC_n$ ).
- Preparing the data for alignment between the multiple epochs.
- Comparing of the  $PC_i$  with the  $S_0$ .
- Calculating the difference for each different epoch. Distance of each point in  $PC_i$  and  $S_0$  is calculated using the “Data vs. reference comparison”, wherein the direction of comparison is determined by the direction of the vector perpendicular to the reference plane  $P_0$ .
- Creating cross section for comparison or directly comparing point cloud with  $S_0$  in three dimensions.

Preparation of data for comparison (fourth bullet point) between different epochs of measurements is defined by the alignment matrix of the new point cloud with the reference surface. Preferably, the alignment matrix is defined by using a fixed object in the environment (buildings near of cuts or geological members, which are not subject to weathering in engineering time scale), in the following four steps:

- Identification of the stable part of the cut or an object in vicinity of the cut.
- Removal of the part of the point cloud where the changes take place (detachment and deposition) and any unwanted measurements (vegetation, moving objects, etc.).
- Alignment of the chosen stable part using Iterative Closest Point (ICP) algorithm, which defines the alignment matrix of the point cloud.
- Using the alignment matrix on the original point cloud.

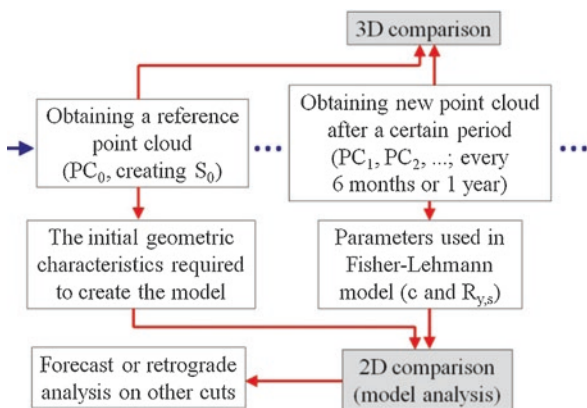
Data collected by TLS can be analysed for the whole surface of the cut to give us a three-dimensional insight into the behaviour of the erosion process. Additional identification of the geological members of cuts, through photos and/or intensity of the returned laser beam, is a basis for further analysis of other phenomena, such as landslides, rockfalls, and toppling. Some results can be attributed to the measurement error or errors in methodological approach; therefore, they must be carefully assessed (Vlastelica et al. 2014).

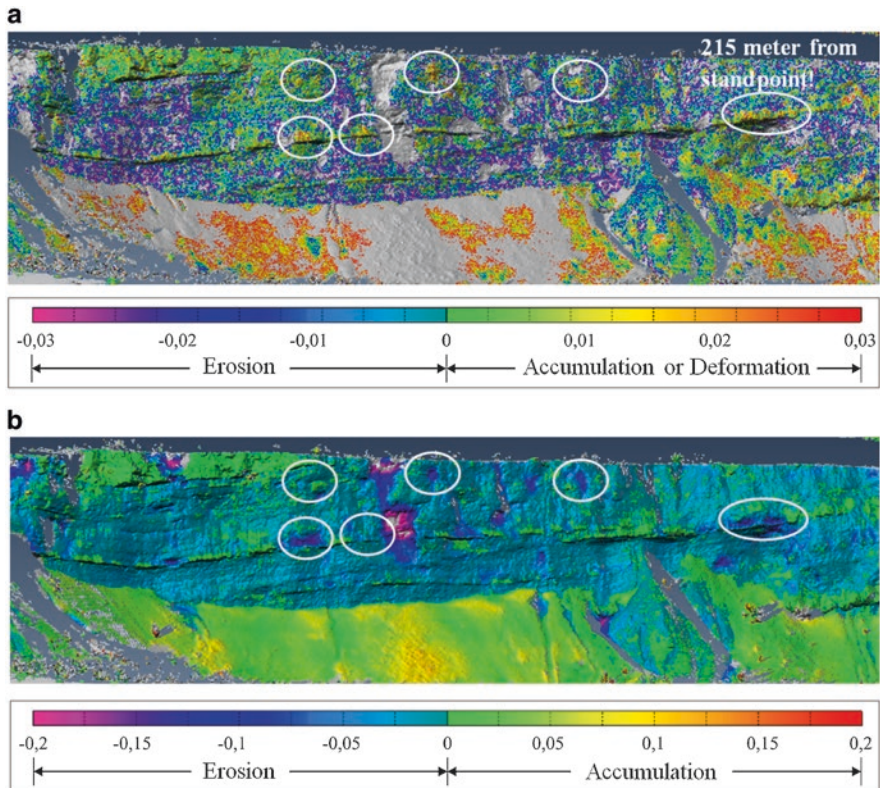
### 12.5.2 Presentation of Results as Input to Degradation Models

Comparisons of different epochs can be displayed three-dimensionally as a field of differences in the face of cuts or two-dimensionally through selected representative cross sections (Fig. 12.20).

In three dimensions, the distances are shown through a field of values (Fig. 12.21).

**Fig. 12.20** Flowchart presenting data-obtaining procedure and presentation of results (Vlastelica et al. 2016b)





**Fig. 12.21** Example of comparison of point cloud  $PC_1$  with the reference surface  $S_0$  with prefailure deformation detected (Vlastelica 2015). (a) Comparison 3.4.2014–27.6.2014 (in meters). (b) Comparison 3.4.2014–8.10.2014 (in meters)

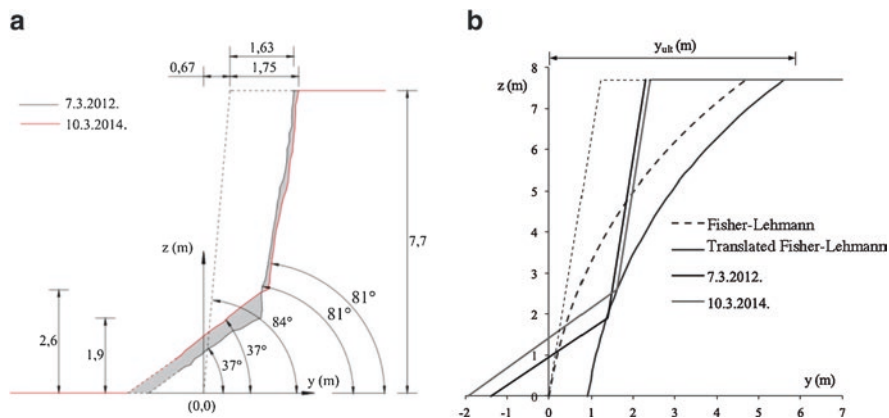
Negative values indicate a lack of material in a given epoch (erosion), or separation of larger rock fragments. Positive values indicate the accumulation of eroded material in the form of talus at the base of the cut or larger blocks due to rockfall (Fig. 12.21b). The positive shift towards the instrument, if it is in the open face of cuts, may indicate a displacement that preceded the rockfall (Fig. 12.21).

Figure 12.22 shows the representative cross sections as a result of observation during a period of 2 years (7.3.2012–10.3.2014), while Fig. 12.22b shows the result of numerical calculation based on the Fisher–Lehmann model of erosion of the cut for the same time period.

Field observation on this and the other pilot sites reveals that, after the initial relaxation of cuts, the Fisher–Lehmann model correctly describes the change in the profile of cuts in soft rocks that occurs alone or in the Dalmatian flysch sequence.

After the models are calibrated by field observations, it is possible to provide retrograde analysis for existing cuts, or to forecast the time needed for complete slope reshaping in the form of talus (Vlastelica et al. 2018b).





**Fig. 12.22** (a) Results of observations carried out on pilot location “Žnjan 1” as a typical cross section of the epoch  $PC_0$  (7.3.2014) and  $PC_4$  (10.3.2014). (b) Fisher–Lehmann model based on the results of observations carried out on same pilot location (Vlastelica et al. 2016b)

## 12.6 Conclusions

Newly excavated slopes are susceptible to rapid weathering and, within several months to several years, that is, within the engineering period of time, the rock deterioration process starts both on the slope surface and within the inside of the rock mass. These processes can also be observed on many natural slopes formed in soft rock formations. The main consequences of the deterioration are constant slope surface erosion and reduction of the material strength inside the rock mass slope. Results of the strength reduction are landslides and rockfalls on the natural or artificial slopes in the soft rock masses.

The deterioration is caused with the weathering processes. Weathering properties of soft rocks, and their behaviour during exposure to external influences, are dominantly controlled by their mineralogical composition, preconsolidation history, composition of binding material in their structure, level of cementation, and rock texture. External conditions controlling the weathering are climate, topography, chemistry of weathering solutions, hydrology, and vegetation. This material is simultaneously affected by both physical and chemical weathering processes. Weathering affects not only the rock material, but also and the discontinuities present in the rock mass. Weathering will affect the rock masses from the slope surface and discontinuities into the material, and because of this, the material strength of discontinuity walls will be reduced compared to that of the adjacent rock material further away from the discontinuities.

Weathering intensity refers to the degree of weathering or deterioration at the time of observation, while time-dependent weathering intensity (or intensity rate) is the amount of weathering intensity change per unit time. In general, factors controlling weathering intensity are factors controlling physical and chemical weathering processes. Additional factors controlling weathering intensity on slopes are the

exposure of slope, orientation of discontinuities in relation to the orientation of slope, slope angle, height of slope, method of excavation for artificial slopes, and implemented drainage measures.

Weathering intensity rate is very important information for the maintenance of the slopes cut in the soft rock formation, because weathering induces material deterioration and degradation of soft rock strength. With the reduction of the shear strength of material on slopes, the stability of slopes decreases over time. With the deterioration of the material on a slope, surface problems with surface erosion occur. Deterioration implies several fundamental processes, time-related and generally slow, acting on a slope, artificial or natural as well, which may cause a significant decrease in the rock mass strength and slope stability. These primary processes are relaxation, weathering, and erosion, or in other words, deterioration occurs as a result of their combined action. Depending on the balance between the primary processes, deterioration usually progressively leads to the alteration and disintegration of materials and rock masses (although the rock mass quality in some cases may be locally improved by weathering-related processes, for example, formation of crust on the rock surface that is stronger than the material beneath it).

In order to block the influence of weathering processes, the slope surface must be “sealed” and the water runoff over the slope should be controlled. The rock can be sealed in two ways. One is to prevent the 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 vegetation cover develops on such a surface, the layer will become “reinforced” by roots. The other is to place surface protection that will prevent the development of deterioration toward the interior of the slope (geosynthetics, vegetation cover, sprayed concrete, etc.).

With regard to the type of material and climatic features of the area of research, slope degradation models based on weathering can be used only when the process is in the range of balance of erosion and weathering to an imbalance in favour of weathering, that is, the erosion always takes place on the weathered material. When steep cuts are observed, it is noticed that weathering is being developed on the exposed surface, and erosion is present at a constant rate, which is always less than the observed weathering rate. Transported by gravity, precipitation, weathered material builds up at the base of the slope, where it eventually additionally transforms into a soil-like material. This process has more impact on the cost of maintaining the facility than to global stability. Accumulated material at the bottom of the slope is usually required by owners to be removed regularly; therefore, the slope is “moving away” from the original position. This can cause additional instabilities, such as rockfall or planar sliding on the secondary joint systems.

A question arises whether, following the introduction of processes that cause degradation, it is possible to measure the trend of changes in strength. The strength of rocks, as well as all known classification of soft rocks, is usually displayed by uniaxial compressive strength (UCS) determined for cylindrically shaped samples. However, this procedure requires a set of monolithic specimens, which are usually difficult to obtain when sampling a soft rock material. Some authors suggest a method of chiselling and sanding of the sample sides, which would produce a more

ideal specimen. However, these techniques are of no practical use when using samples subjected to weathering; consequently, this method is not suitable for the analysis of changes in strength, and it is necessary to look for an alternative.

Each new insight into the processes that cause the instability of slopes in soft rock, such as erosion or rockfalls, can help to mitigate the possible consequences. The development of new technologies in the field of geodesy, TLS (terrestrial laser scanning) and GB-InSAR (ground-based interferometric synthetic aperture radar) opens new paths for monitoring changes in a slope surface and the material from which it was created. These remote sensing technologies can be used on global level to cover wide areas, but also at the local level as terrestrial or ground-based instruments. This is very important for monitoring of cuts and steep slopes, because it is usually virtually impossible to acquire data without properly positioned ground-based units.

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