Add Water and Get Problems, to Solve: Geotechnical Problems with Steep Rock Faces in Soft Sandstone and Limestone Varieties, Including the Effects of Water

Ulf Köhler(✉) and J. Engelhardt

geoplan-ingenieure Dr. Köhler GmbH, Weimar, Germany
post@geoplanweb.de

Abstract. For stabilisation works of steep rock faces, which are often created as cuttings for roads, the latent processes of weathering (such as frost, gravity and water…), must be considered, in addition to fracturing and stratification, to a greater extent for "soft" rocks than in the case of hard rocks.

The selection and design of engineered structures and the life cycle of the structures clearly depend on how the weathering processes and their dynamics are considered. In many cases, this has relevant economic effects. It is not uncommon to have to weigh up what is necessary, and likewise the engineer has to go to the limits of still feasible technical solutions. Not only in nature, but also from cut slopes, water can flow out directly and act as water pressure on large rock bodies or flow through the weathered material behind steel wire mesh.

Selected examples will be used to show these processes, the associated geotechnical solutions and recommendations. One example will show how extensive monitoring can be part of a permanent solutions.

Keywords: slope stability analysis · computational geomechanics · advanced geotechnical monitoring technologies · slope stability

1 The Geotechnical Problem

Weathering and erosion of soil and rock are natural processes that always take place. Technological structures in rock - especially retaining structures – have to consider these processes to ensure that the structure is stable in the long term. In the case of slopes in rock with inclinations of more than 45° up to approx. 80… 90°, one is dealing in most cases, from a technological, engineering-geological and also an engineering-biological point of view, with two separate fracture phenomena:

(a) When natural slopes are steepened (e.g. by creating cuts), the gravitational forces or the elimination of previously existing support forces cause distortions and loosening even in faultless rock, preferably along tectonically pre-determined structures (fissures, bedding planes, etc.), which decisively change the stability.

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(b) The second, essential fracture mechanism is of a different nature. After exposing rock faces, the weathering process immediately starts along the exposed rock surface. Rain and wind, also in combination with freeze-thaw cycles and/or chemical reactions with the air, immediately start the weathering process. Weathered material is formed on the surface, which can either penetrate through the mesh to the outside or is "held" by the structure itself and thus becomes part of the new structure (Fig. 1.)

After exposure both processes run parallel. The speed and intensity is decisively dependent on the mineral composition and the tectonic preloading of the rocks. The process often starts a short time after exposure, often already during the construction phase. There is hardly any information about the speed of these processes.

In most cases, however, the formation of weathered material starts later; the fresh rock face gives the impression of sufficient stability. Both processes must be considered during the structural design of supporting structures in rock. In many cases, the effect of water (via fissures or surface water) is added and aggravates the situation. The constructive support measures in rock faces have to consider a potential dissection of the rock face into slices or large blocks in the case of global safety and obtain a finish of the surface that can hold the resulting weathered layer in place. For example, in the case of nailing with covering mesh, the outer skin must also be able to absorb the forces from the weathered layer that will form just after 50…100 years of operating life.

The process of creating a slope in rock is only a very short period in terms of the total operating life; in this stage, the excavated rock face is usually sound and unweathered. The technological expenditures have to be based on the strength / geological conditions (compressive strength, fracturing, stratification) encountered during the construction period. Blasting and milling or other techniques may be required in addition to conventional mining technology.

This article does not consider the closed construction methods with reinforced concrete, but the open construction methods, which use mesh to create the connection

Fig. 1. Two sites with soft limestone and sandstone. Left: Rock facee stabilisation with open mesh and a lot of lost material and right: Rock facee stabilisation with mesh and erosion control

Fig. 2. Rock face in sandstone with strong signs of alteration after about 55 years of standing.

between the anchor/soil nail and the slope surface. The stability and serviceability / dimensional stability of the slope depends on the extent to which weathered material can be eroded from the slope (process (b)). The erosion of material from the slope surface affects long-term stability. For example, at the time of construction of a mesh, the anchor plates may still be sitting tightly on the slope surface. But erosion of material in erosive rock often results in a situation in which the anchor plates and mesh are no longer connected to the rock surface after a short period of time. The weathered material that forms from the rock, can move freely, if it is not restrained.

The mechanical behavior of a weathered layer that gradually develops on the surface of rock, is not to be described with the properties of rock, but with those of a soil. In this case, the friction angle of the resulting soil (25…35°) on it's own is much lower than the inclination of the created slope (70…85°). This soil is therefore not stable at all (Fig. 1-left and Fig. 2).

In this sense, this paper deals with the geotechnical tasks for ensuring the stability of rock faces, taking processes (a) and (b) into account, where slopes in soft rocks (sandstone, limestone) had to be secured, using the example of construction projects in Germany. Due to the continental geological processes, a number of common mechanical features exist here, which are here referred to as the "European Cretaceous structure".

2 A Geological Excursion

In order to understand the mentioned "European Cretaceous structure" of the rocks, the basic lithological description, the history of the Earth in general and also the tectonic history of the European Continent itself has to be considered. Especially the developments of the Upper Cretaceous are area-wide causative for the present terrain of Central Germany. Besides the alpidic orogeny, the opening of the Atlantic Ocean led to a relative change of motion between Africa and Europe. Due to the increased opening of

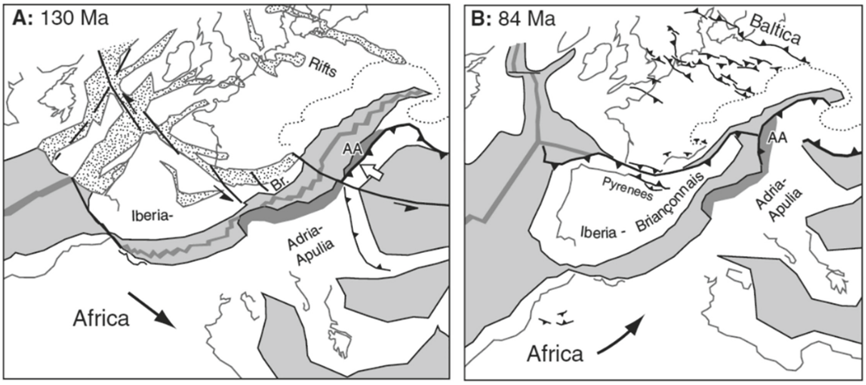

Fig. 3. NW-SE-striking direction due to the change of the relative movement between Africa and Europe in the Upper Cretaceous (original publication: Kley & Voigt, 2008 [1]).

the South Atlantic, Africa rotated in the Upper Cretaceous, closing the Neotethys and pushing parts of the land masses of today's Italy, Greece, Turkey as well as the Iberian Peninsula located in the sea against the European continent. The collision of Iberia and the land of today's France led to the uplift of the Pyrenees and a constriction zone between Iberia in the southwest and the Baltic Shield in the northeast. During this process fractured surfaces of former extension zones were partly reactivated and thrusted up or over in opposite direction of the former movement. This resulted in the NW-SE striking direction widespread in Central Europe, which is for example reflected in the terrain of the Harz Mountains and its foreland as well as in the Thuringian Forest or large-scale fold structures of the Thuringian Basin [1] (Fig. 3).

The resulting tectonic stresses with the including overprinting of the upper crust, which in turn have a terrain-shaping effect due to the formation of weakening zones and directions, are decisive for the measures to be applied in many rock construction projects and must therefore be considered at the start of the project. In addition to tectonics, which gives information about past and present stress fields of the crust, lithological studies and, in some cases, facies studies form the basis of all rock-engineering actions. Locations several hundred kilometres apart can have almost identical characteristics due to similar lithology and approximately the same tectonic overprint (Figs. 4 and 5). For example, limestones and dolomites of the Muschelkalk (Middle Triassic) on the northwestern Harz edge have almost the same structural characteristics as the stratigraphically associated formations in southern Thuringia and northern Bavaria.

3 Sandstone Weathering and Water

An essential role in the stable design of rock faces is the composition or grain size (friction angle) and the thickness of the weathered layer. These are the decisive parameters for the design of the mesh for rock protections. The formation of weathered layers during the operating life is often underestimated (left Fig. 1). Although the condition of this weathered layer should be described separately to the existing rocks in reports, in

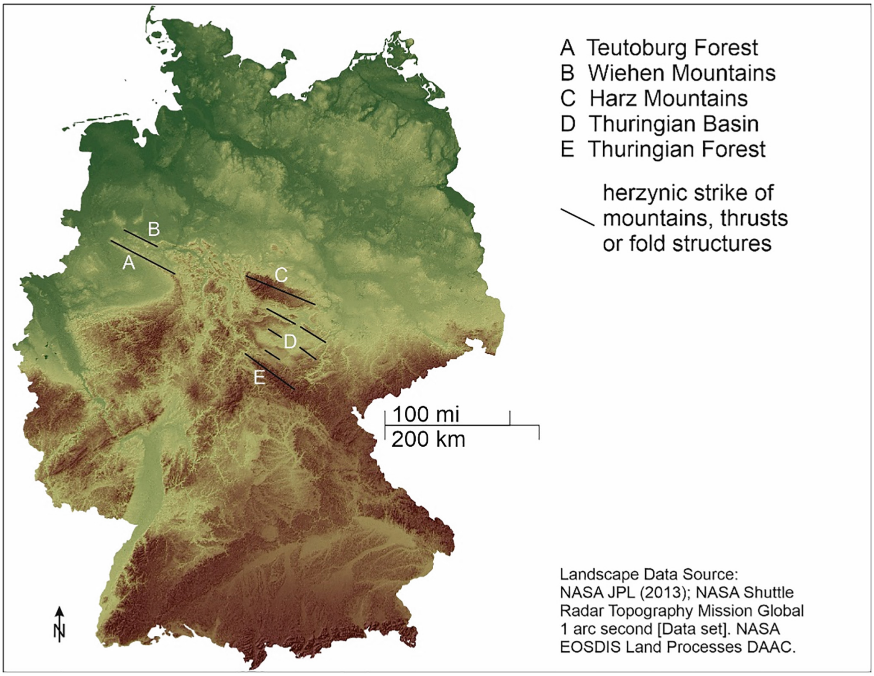

Fig. 4. Overview of Germany with some marked herzynic striking landforms in central Germany

Fig. 5. Two construction projects (Dornburg-Camburg and Holzminden) which are geologically very similar but 200 km away from each other

fact it is often difficult to get information on the thickness of weathered layers and their composition.

A particular case of a rock construction project in the Weser Sandstone (Early Triassic - Sollingen Formation) (Figs. 2 and 6) gives many important hints to these questions. An existing cut slope, which was constructed in the 1960s and secured only with a slack mesh without extensive anchoring, had already shown striking material erosion and local landslides for several years. The slope itself appeared to be largely stable. The weathered layer to be used for the design was initially estimated to be 50 cm thick. After the slope had been cleared, relevant deep-reaching loosening in the rock structure became apparent. During the 55 years of operating, weathered shells of up to 1 m thickness and locally deeper fissures had formed in large areas as a result of loosening. Individual larger and smaller rock towers up to a maximum height of about 7 m have collapsed (Fig. 6).

Every cut in a rock face changes the previous equilibrium. Loosening processes, as shown in Fig. 7, are the result. The decisive factor is the size of the rock fragments that will gradually form. The main effects are frost in combination with fissure water, water pressure and hydromechanical processes, which can lead to outpour of weathered material (Fig. 6).

The rock face in Figs. 2, 6 and 8 has been flowed through for a long time during the construction period, when it rained. During this time, fissure water has been formed in the slope and has flowed through the freshly exposed rock surface and leaked at different heights (Fig. 8).

These water leakages were initially not visible, because the weathered shell had detached itself from the faultless rock face, due to a significant opening of fissures, long before the construction work started.

Fig. 6. Sandstone slope with the eroded weathered layer.

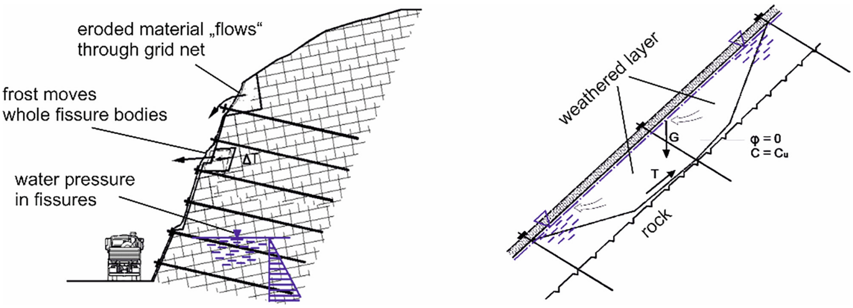

Fig. 7. Major mechanisms of destruction in rock faces and water in the weathered layer.

Fig. 8. Fissure water leakage (intermittently, after precipitation) from the sandstone slope

Based on the evaluation of processes (a) and (b), specifications had to be made for the stability verification in this design approach that took the actual situation into account.

Water: Although the slope was to be morphologically apparently free of groundwater, it turned out that water could rapidly fill up the fissure system and temporarily create water pressure. Therefore water pressure also had to be considered in the design. Since the exact height of the water level in the fissure system was not known, different water levels (1/2 H or 2/3 H) were investigated and evaluated (Fig. 9).

Process (a): Observation and geological measurements during the construction period showed that the entire rock face (Fig. 2) has apparently relaxed since the cut was made, so that not only water pressure, but also various tension cracks in the structure had to be considered. Tension cracks of different depth and inclination (78…90°) were assumed (Fig. 9).

Process (b): Observation during the construction period showed (Fig. 2 / Fig. 6) that the surface of the rock face is intensively loosened by weathering processes after completion of the construction work. In addition to the adaption of the anchors for the processes (a) and water influence, it was necessary to cover the rock surface with erosion protection mats in a partial area of the mesh. The covering can be differentiated, and has not to be continuously.

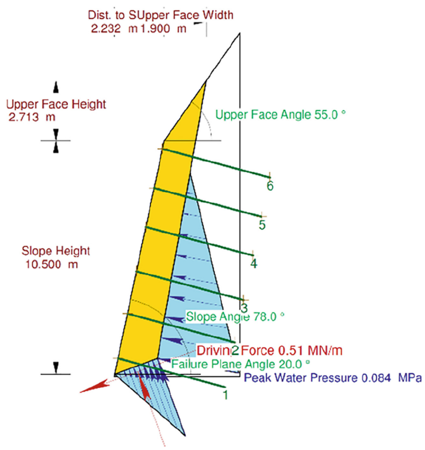

Fig. 9. Tension cracks with different shapes and water pressure were examined in the design – calculated with RocPlane (RocScience)

For these areas it was assumed that the weathered layer could be up to 1m thick. The design of the mesh was dimensioned for 1 m weathered layer and permeability. Figure 10 shows a part of the measure after completion with anchors, mesh and partly with erosion protection mats under the mesh.

The thickness of the weathered layer and the assumption whether permeability has to be applied, are important aspects in the planning of rock stabilisation. A closer look at rock stabilisation in "soft" rocks, which are intensively tectonically preformed, shows that the thickness of the weathered layer is not known in most cases, but could be assumed to be about 0.5 to 1 m. A clear differentiation by different type of rock is not possible, although most sedimentary rocks tend to form thicker weathered shells and finer alteration material. Water should always be included in the design if the rock face can be overflowed by rain water from above or if the rock is influenced by fissure water.

4 Limestone Fracturing and Measurements

4.1 Geotechnical Overview

The two construction projects in Fig. 5, which are geologically very similar but 200 km apart from each other, had a number of similar features that determined the structure and degree of weathering of the entire rock face at elevations up to over 40…80 m. In both cases, bed rocks were significantly formed by river erosion combined with folding processes and disruption, resulting in the typical K1-K3 alignment. Another significant influence on the stability was the cutting of roads, which made the rock faces significantly steeper.

Let's look at one of the two construction projects, the one on the right in Fig. 5 (Fig. 11).

The construction section is located on the west side of the erosion valley of the Saale river in eastern Thuringia. Geologically the construction section starts just above the

Fig. 10. Construction after completion with erosion protection mats applied in certain areas.

Fig. 11. Overview of the whole slope area and the Saale river on the left hand side – view to south-western direction [Data source: DOP20 and DEM1 – GDI-TLBG 2020].

boundary from the Lower Triassic to the limestone of the Middle Triassic. The stratigraphic formation is called "Wellenkalk" ("wave limestone"), which was sedimented under the influence of water waves, which led to a bumpy surfaced deposit.

The slope cut by the Saale river is part of a large-scale anticline. During folding, smaller secondary conjugated fissure systems were formed in the anticlines, caused by tearing near the fold axis, where minor thrusting took place (Fig. 12). These fissures are clearly visible in the wall at station 0+050 at an elevation between 170 and 180 m a.s.l.

The rock face was divided up into 3 structural complexes (SC) with typical features after the geological survey and evaluation of the drone images (Fig. 13):

- SC 1 – pillars
- SC 2 – shells
- SC 3 – strains, overhangs, bulges.

The pillars of SC 1 showed signs of break-off due to exceeding compressive stresses from weight forces as well as progressive weathering. The break-offs were so severe that collapses had to be expected during construction work. The red outline (Fig. 14) shows the formation of pillars and shells. The green outline shows the break-offs to the right and left of the pillar. The blue border shows the footing of the pillar, which has been severely damaged by weathering and break-offs.

Figure 15 shows SC 2 with staggered shells/walls (red lines: location of main fissures between two shells). The staggering of the shells had a great influence on the design. The fissures were so wide open and deep that the shells sometimes had no contact with the rock behind them up to great heights (Fig. 16).

In the rock face, cracks have developed due to straining as well as bulging of the (soft) marlstone and overhangs in the area of the limestone bench (Fig. 17). The vertical and horizontal offsets of the individual shells and fissure bodies are clearly visible and increase with higher elevation in the rock face. Towards the higher part of the rock face, the degree of rock fragmentation increases – stronger weathering of the rock surface is evident; the weathered products disintegrate into the gravel fraction with a high cohesive content (Fig. 1-left). In this unstable structure, break-offs were constantly expected.

These are processes that were referred to as process (a) at the beginning of the text. At this point, we can only show some highlights of the extensive design process.

4.2 Design Aspects

Based on the results of the geological investigation and surveying, it has to be assumed that uniform stabilisation by means of overlying mesh and nailing alone will not lead to sufficient stabilisation of the rock face. The two shells Fig. 14 must be considered mobile in a mechanical sense; they can rotate. The size of the weathered material produced during weathering regulates the size of the mesh; Fig. 2 left.

An essential element of the stabilisation must be that weathered material generated during operating life is held in place on the slope, because otherwise the rock face's weathering or the erosion of material around the anchors/nails already changes the static system of stabilisation within a short period of time (a few years).

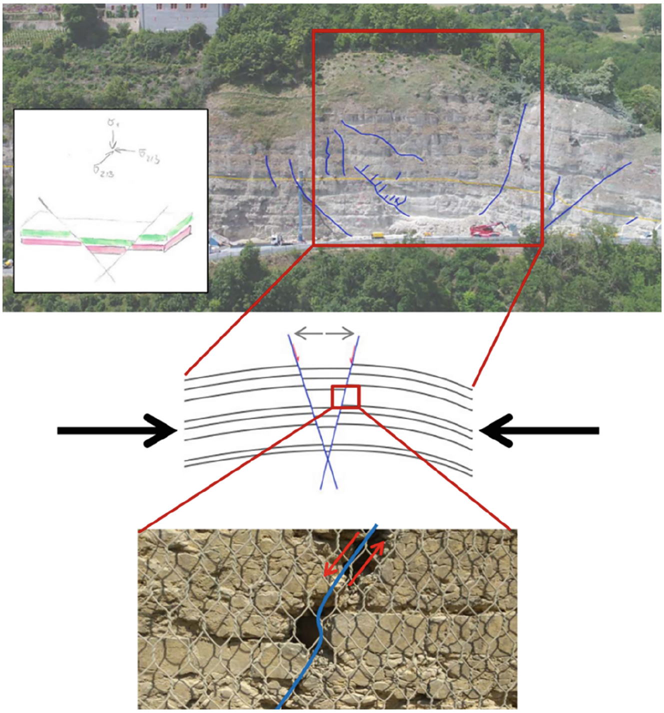

Fig. 12. View of the entire slope area with recorded fissures; simplified sketch of the maximum of the anticline with transverse fissures due to the resulting distortion at the top; detailed view of a transverse fissure with sinistral sense of motion

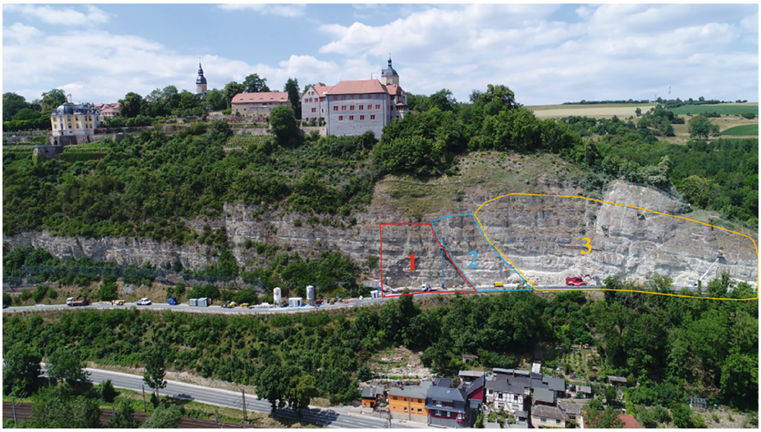

Fig. 13. Division of the wall into three structural complexes

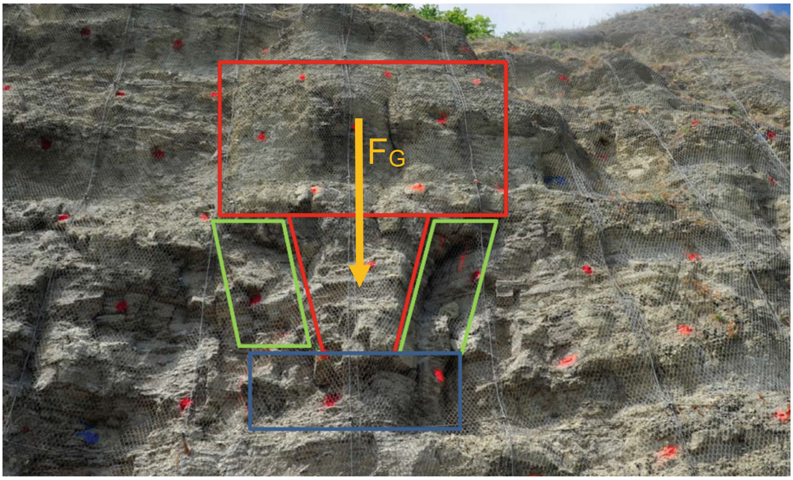

Fig. 14. Pillar detail of SC 1

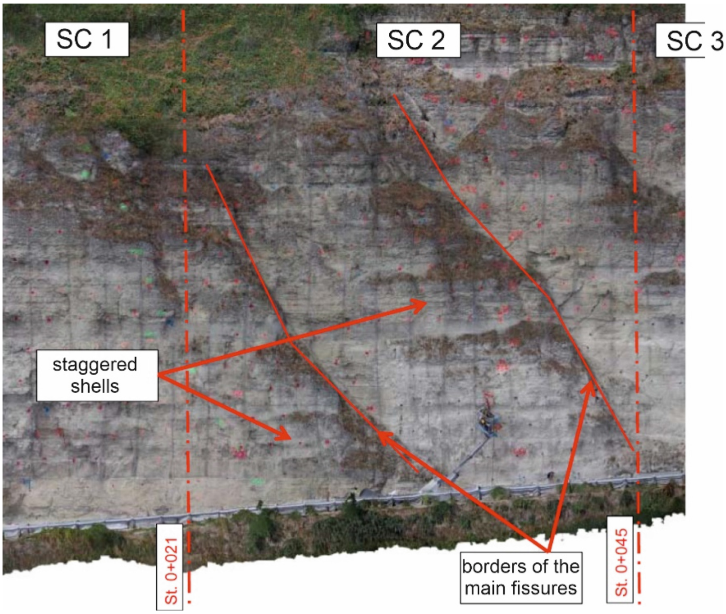

Fig. 15. Staggered two big shells/walls in SC 2

To minimise the risks to personnel in due course of installing the stabilisation, it has to be ensured that rotation of the shells is prevented. For this purpose, the stabilisation means (anchors/nails, mesh, shotcrete) must be installed from top to bottom.

Furthermore, it is compelling that the individual shells, which are separated by the large fissures, must be fixed against rotation. This means that they have to be connected

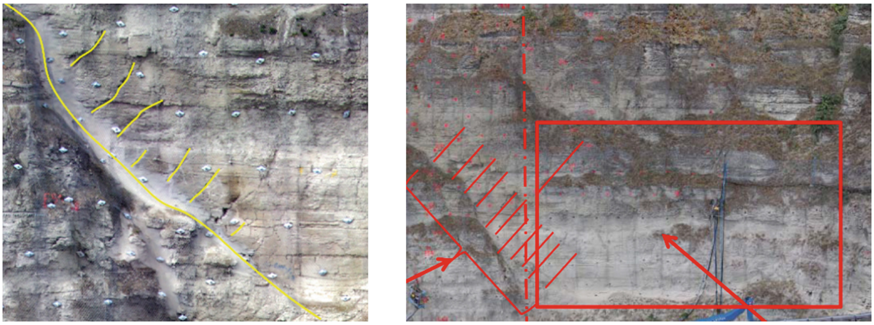

Fig. 16. Tension cracks and areas with overhanging rock formations and bulging of soft rock in SC 3

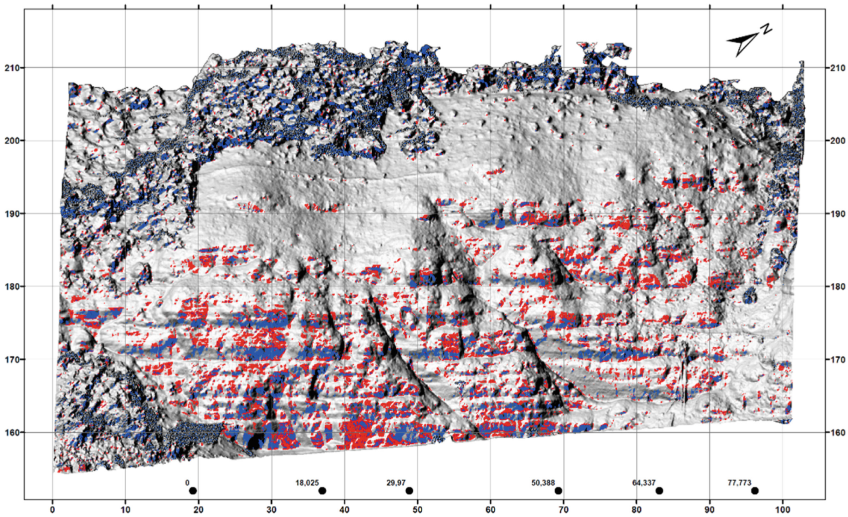

Fig. 17. Inclination analysis based on drone photogrammetry: blue: overhanging areas; red about 90°.

by long anchors until a sufficiently stable "monolith" is formed. Structurally unstable areas had to be filled with shotcrete in several stages. Reinforced shotcrete could only be installed after 1 or 2 unreinforced layers had been installed. In some areas, a set of anchor plates was placed on top of the anchors prior to the final shotcrete shell in order to increase stability during construction. The construction process was therefore very challenging. It was necessary to adjust the final design step by step considering all observations on site, especially the results of many anchor stress tests. Figure 18 shows one of the many cross sections.

Areas with overhangs, which had to be filled with shotcrete before installing the anchors. Are marked in blue (Fig. 18). Below, blue/yellow/red show the three layers of reinforced shotcrete that were required to fill the largest voids. Step 1: blue- 1st layer of shotcrete; Step 2: Drilling of anchors and installation of 1st set of anchor plates to ensure bonding of anchors to reinforced shotcrete in the time before completion. 3rd step: installation of 1st layer of reinforcement and application of "yellow" shotcrete. 4th step: Installation of 2nd layer of reinforcement and application of "red" shotcrete and installation of 2nd set of anchor plates. Red lines show the location of the main K1 fissures. The majority of anchors reached at least 2, the longer ones reached 3 shells. The analysis showed that not all anchors needed to be anchored in the 3rd shell.

Different types of mesh were chosen, e.g. Geobrugg SPIDER. Due to the coarse mesh size, a second fine mesh had to be installed underneath the coarse mesh to secure the rock surface.

No ground water seepage was observed in the slope. But the accumulation of rain water in fissures after wet periods cannot be excluded. Considering this case, a water level of 50% of the height of the first major fissure K1 above the limestone bench was considered as an "abnormal situation" in the analysis for design of the long anchors, to prove the resilience of the system.

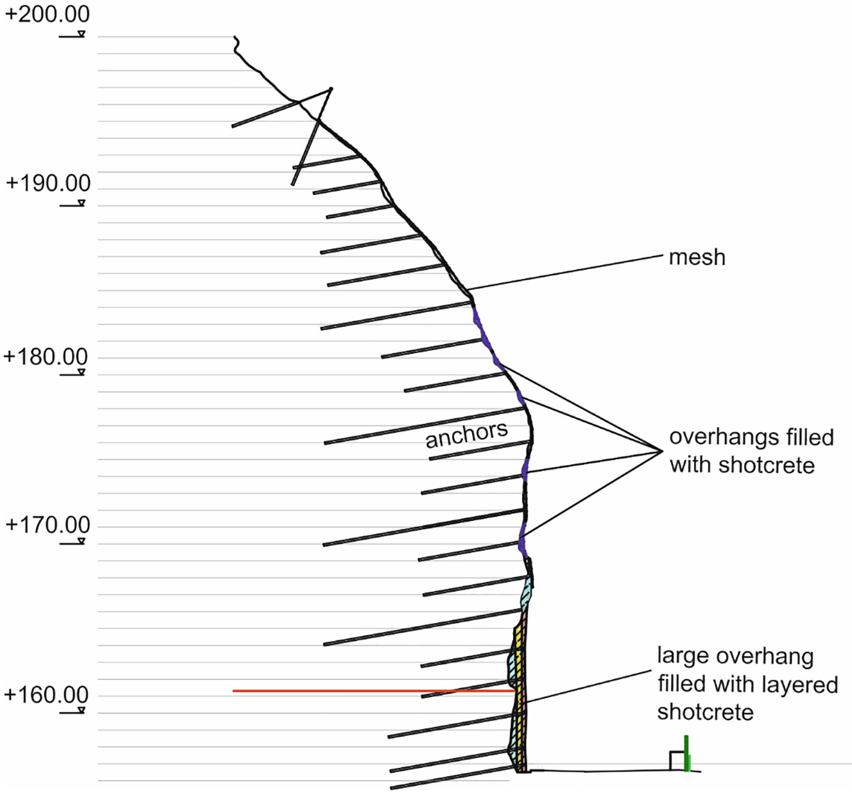

Fig. 18. One of many design sections - simplified

4.3 Monitoring

A number of changes and adjustments had to be made in the course of construction. Particularly in the SC 1 area, the installed nails including mesh have the task of unify the unstable rock pillars and pinning them to the solid rock. The analysis model could not capture changes in the rock and fissure structure over the time of the operating life. Therefore, continuous monitoring and evaluation of possible deformations of the rock surface is necessary to avert hazards to road traffic. The measurement concept has the following elements:

- installation of 24 measuring marks at the heads of selected nails/anchors
- initial measurement 06.06.2019
- 4 measurements in 2020
- 1 measurement in 2022 (Fig. 19).

The movements were divided into classes:

- Non-critical: $\leq$ 15 mm
- Warning value: $>$ 15 mm
- Thresholds / limit: $=$ 22 mm
- Alarm value: $\geq$ 25 mm

The monitoring is a combination of a high-precision tachymeter for single point measurement of the attached measuring marks and a high-precision drone survey with photogrammetric methods.

The measuring marks (Fig. 20) have a size of 7x14 cm, with a hole in the upper half so that the plates can be pushed onto the anchors/nails. A target is attached to the lower half of the plate, which is very easy to aim at for tachymetric measurement and can also be identified very well in the drone image. The plates have been angled in the middle so that the measuring marks can be targeted when surveying from the road.

The measurements are performed with tachymeters as well as with UAV/drones and photogrammetry. The resulting aerial image has an accuracy of about 1.5 cm. The 3D point cloud is classified into ground marks and non-ground marks. By combining the

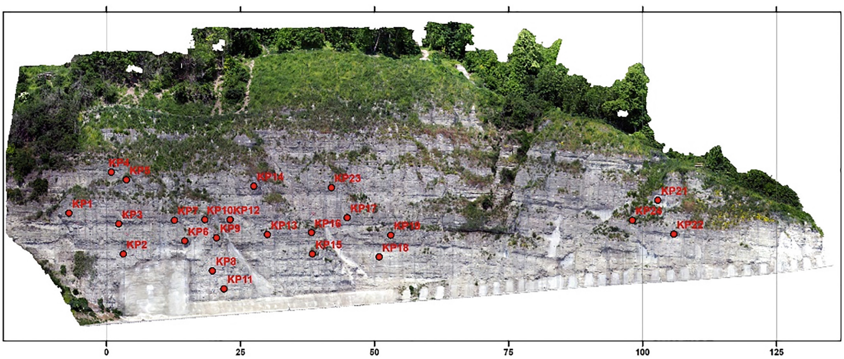

Fig. 19. The installed measuring marks on the finished wall

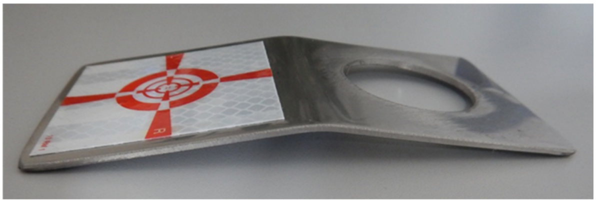

Fig. 20. Measuring marks

aerial image and the 3D point cloud, a full 3D visualisation and evaluation of the rock surface is feasible (Fig. 21).

As expected, the largest movements occurred in SC 1. All movements are in the range of about 10 mm, although few exceedances of the warning values occurred, but not in all measurements. This type of measurement (also in combination with UAV/drone aerial surveys) has proven to be very suitable. The measuring marks can be obscured by vegetation. Maintenance work such as clear cutting have to be taken into account.

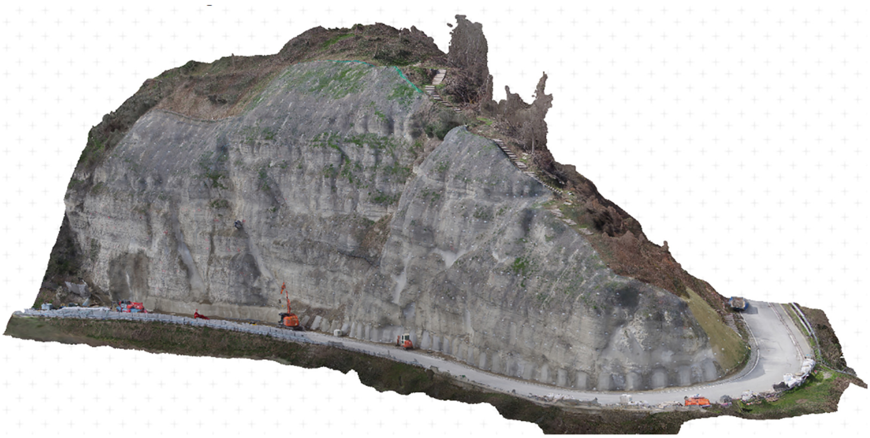

Fig. 21. 3D visualisation and evaluation of the rock surface.

5 Concluding Remarks - Outlook

Constructions in rock faces rise to great challenges in every respect, both for engineers and geologists, who carry out the exploration work, as well as for the project engineers and, last but not least, for the construction companies. With the modern developments in surveying technology through the use of UAV/drones and laser scans, we have been able to make great progress in the planning of challenging morphological and rock mechanical objects. Nature does not perform senseless work. Weathering processes always end when material that has become mobile break-offs or slide-offs. In rock faces, this means in many cases that the remaining rock body has a stability safety factor of only 1.0 or just above. It is important to note that in nature / in rock faces relevant stability deficits are often not or not well visible and/or explorable. This is where our diverse and interesting work starts, and especially in rock construction the way to the final structure is often a process, because we often only get the final information for planning and design when we have to clear the slope with heavy technology and then further develop the planned technical solutions.

Reference

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