Study of damage to rockbolts used in the foundations of protection structures against gravitational hazards

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Abstract. Fully grouted rockbolts are used to anchor protection structures against natural gravitational hazards. In recent years, contractors have observed a premature degradation of the steel bars of these rockbolts. In the dimensioning of a rockbolt, the choice of the steel bar is currently made only on its pure tensile strength. The objective of this study is to identify whether the degradations observed in situ are related to the metallurgical nature of the bar steel and/or the load conditions. 16 damaged rockbolts were taken from four different sites in the Alpine area. They were subjected to a metallurgical analysis and a supplementary analysis of their environment. In conclusion, it was underlined that the damages were due to a lack of knowledge of the effective loads transmitted by the snow-filled structures, but also to a lack of consideration of the deformation behaviour of the foundation. The loads applied to these rockbolt bars generated a bending depending on the nature of the surrounding ground. It has been shown that these loads can occur in successive jolts and with modification of their orientation in relation to the number of links between the rockbolt and the protection structure.

1. Introduction

Fully grouted rockbolts have been widely used for several decades to attach, to stable rock masses, protection structures against natural gravitational hazards (wire mesh attenuators, catch fences, anchored wire meshes, snow nets: [1], [2]). The principle of making a passive rockbolt is to drill into the rock mass to seal in a steel bar. A fully grouted rockbolt is thus composed of four principal elements [3], which are steel bar, grouting material, borehole within rock and external fixture to the borehole wall (figure 1). At the head of the bar, a steel plate tightened by a nut allows the anchoring of guy wires, nets or supports of the protection structure to the rock mass (figure 2).

In recent years, various contractors have noted in the field a premature damage of the steel bars of this type of anchors with the risk of causing a deficiency of the protection structures of which they ensure the foundation and thus contribute to the resistance to the loads (figures 3a and 3b). Premature failures have been observed for a long time in the mining field [4] and are therefore the subject of specific studies. The latter have highlighted in particular the problems of load combination and stress corrosion cracking [5].
The steel bars used for rockbolts are those designed for reinforced concrete (BA) and prestressing (BP). Between these two applications, the mechanical and metallurgical properties of the bars are different, linked to their fabrication methods and the expected use of each. The choice of the steel bar for rockbolt is currently made only on its pure tensile strength considering the elastic limit of the steel and the diameter of the bar [2]. However, the stresses generated in the rockbolts by the protection structures are not always in tension and static loading. The type of connection with the anchored structure can generate combined bending and axial load at the head of the rockbolt. Some natural hazards generate dynamic loads such as impact or repeated fatigue-type load. Moreover, contrary to the sectors of construction or civil engineering structure, rockbolt is rarely anchored in a competent and homogeneous ground. Thus, the environment in which the steel bar is installed does not have the same physico-chemical characteristics as those for reinforced concrete or prestressing.

In this context, this study aimed at identifying if the damages observed in situ on foundations of protection structures were related to the metallurgical nature of the steel bar (BA or BP) and/or to the loading conditions. First, the methodology applied in this study is described. Then, the results of the different analyses are presented. On the basis of these elements, first conclusions are given in terms of loads to be considered for the design of foundations of protection structures.

2. Methodology and results of the study
The study was carried out on foundations of avalanche protection structures found damaged in the field. The steel bars and their head equipment (nut, plate) were collected on four different sites in the Alpine area (figure 4: F, G, O, T).
For each rockbolt, an analysis of the in situ conditions in which it was located was performed. This analysis was completed by a metallurgical analysis of the failure zone on each bar. From all these elements, scenarios on the mechanisms that led to the failures could be formulated.

2.1. Description of the analyzed damaged bars
This study principle was applied to 16 bars of damaged rockbolts. For each bar, the diameter, the type of bar (BA, BP), the type of longitudinal part without thread (flat rib, hollow rib), the type of nut, the type of macroscopic damage observed were recorded (table 1). The steel grade for the BA type of bar is Fe500; it is unknown for the BP type of bar. For all bars, anti-corrosion paint is present upstream of the nut. Two main types of damage were identified: for type A (figure 5a), the failure occurred between 0.01 m and 0.05 m below the nut with part of the bar showing plastic bending deformation and another part, a low necking, for type B (figure 5b), the failure occurred at about 0.30 m under the nut with either a single bending of the bar or a double bending of the bar.

2.2. Analysis of the environment of each rockbolt
The environment of each rockbolt is described considering the type of surrounding ground, the structure for which it provides the foundation, the type of connection with the structure (table 2).
Table 1. Characteristics of the damaged bars studied.

| Site | N° Bar | Nominal diameter (mm) | Type | Rib | Type of nut base | Macroscopic damage | Additional metallurgical analysis |
|------|--------|-----------------------|------|-----|------------------|--------------------|----------------------------------|
| F    | F4     | 28                    | BA   | flat| Spherical        | Type A             |                                  |
| F    | F5     | 25                    | BA   | hollow| Spherical       | Type A             |                                  |
| F    | F6     | 25                    | BA   | hollow| Spherical       | Type A             |                                  |
| F    | F7     | 28                    | BA   | hollow| Spherical       | Type A             | Crack at the foot of the thread on the tensioned generatrice |
| F    | F8     | 25                    | BA   | hollow| Spherical       | Type A             | Transverse brittle propagation with radial lines Two crack initiation zones at the foot of the thread |
| F    | F9     | 28                    | BA   | hollow| Spherical       | Type A             |                                  |
| F    | F10    | 28                    | BA   | hollow| Spherical       | Type A             |                                  |
| G    | G1     | 28                    | BA   | flat| Flat             | Type A             | Initiation in the rib between the threads |
| G    | G2     | 28                    | BA   | flat| Flat             | Type A             |                                  |
| G    | G3     | 28                    | BA   | flat| Flat             | Type A             |                                  |
| G    | G4     | 28                    | BA   | flat| Flat             | Type A             |                                  |
| G    | G5     | 28                    | BA   | flat| Flat             | Type A             |                                  |
| O    | O1     | 25                    | BP   | flat| Flat             | Type B with double bending, under the nut and at 0.30 m | Initiation at the foot of the thread |
| T    | T1     | 28                    | BA   | flat| Spherical        | Type A             | Oblique ductile propagation with initiation at the foot of the thread according to 45° inclined crack |
| T    | T2     | 28                    | BA   | flat| Spherical        | Type A             | The bar is corroded under the grout and the grout has the shape of the curved bar: the bar seems to have flexed before the grout dried. |
| T    | T3     | 28                    | BA   | hollow| Spherical       | Type B with a single bend at 0.30 m depth |                                  |
Table 2. Characteristics of the environment of each bar studied.

| Site | Ground                        | Protective structure                          | Type of link                                                   |
|------|-------------------------------|-----------------------------------------------|---------------------------------------------------------------|
| F    | Soft ground on bedrock        | Flexible avalanche barriers with triangular nets | Link with the three net layers by means of a clevis and a loop of cables |
|      | (moraine on homogeneous coarse-grained granite) |                                |                                                              |
| G    | Bedrock                       | Flexible avalanche barriers with triangular nets | Link with the three net layers by a curved piece fixed on the bar and a shackle |
|      | (marly-limestone alternation) |                                |                                                              |
| O    | 1 m of soft ground on bedrock | Flexible avalanche barriers with rectangular nets | Link without clevis with the two surrounding cables directly positioned on the bar |
|      | (moraine on granite)          |                                |                                                              |
| T1   | Bedrock                       | Flexible avalanche barriers with triangular nets | Link with the three net layers by a curved piece fixed on the bar and a shackle |
| T2   | Bedrock                       | Flexible avalanche barriers with triangular nets | Link without clevis with the two surrounding cables directly positioned on the bar |
| T3   | Bedrock                       | Flexible avalanche barriers with rectangular nets | Link without clevis with the two surrounding cables directly positioned on the bar |
|      | (quartzite)                   |                                |                                                              |

2.3. Metallurgical analysis of the failure zone of each rockbolt

The study of the fractography at the macroscopic scale was carried out for the 16 bars. Due to the bending, the initiation of the fracture zone is located on the surface line in tension of the bars, at the foot of the thread or in the longitudinal rib (figures 6a and 6b). According to the observations, the failures can be divided into two main families (table 1): one ductile with an oblique propagation until the final failure (figure 7a), the other with a globally brittle-like aspect with a radial transverse propagation and peripheral shear lips (figure 7b). The oblique propagations go to final failure while the transverse ones with radial lines end with shear lips at about 45°.

Figure 6. (a) F8: crack at the foot of the thread; (b) G1: initiation in the rib between the thread.

Figure 7. (a) T2: oblique propagation, then with irregular topography (initiation on the right); (b) F9: transverse propagation with radial lines (initiation on top).
One sample with a "ductile-oblique" fracture appearance (T2) and another with a "brittle-transverse-radial" fracture appearance (F9) underwent further fractographic analysis of the failure surface. This additional analysis was carried out at microscopic scale after chemical cleaning of the two failure zones in order to remove the corrosion products. Then binocular and scanning electron microscope observations were performed.

For sample T2, the initiation is located at the foot of the thread and inclined at about 45° over a shallow depth. After a change of direction at 90°, the propagation remains oblique until the middle of the section, then becomes complex. The first part is ductile with oriented cups (figure 8), then alternate brittle and ductile zones. It is a semi-fragile fracture.

For sample F9, chemical cleaning revealed a second zone of cracks at the foot of the thread at an angle of 60° to the first one. The fracture surface therefore contains two initiation zones, at the same stage of corrosion. The one that led to the fracture contains a small corroded zone that does not show the characteristics of stress corrosion (absence of corrosion lunula). Oriented cups are observed which are indicative of a shear mechanism (figure 9), which excludes the fatigue hypothesis. After change of orientation with respect to the initiation zone, the crack propagates transversally with radial lines. The final fracture is in the form of peripheral shear lips oriented at about 45°.

Chemical analysis of the steel was performed on three samples (T2, F9 and O1). It does not indicate any material quality problem.

3. Analysis of failure mechanisms by studied site
All the information for each rockbolt was analyzed in order to identify the failure mechanisms at the origin of the observed damages.

3.1. Site F
The nine anchors at Site F were installed at two different times. All of them were linked to three triangular net layers by a clevis and a cable loop and embedded in a ground composed of a soft soil on the surface and a more resistant bedrock at depth (table 2). These are bars for reinforced concrete reinforcement (BA – table 1). Following the winter of 2017 - 2018, below the nut, flexural failures with low necking were found for all nine rockbolts (§ 2.1). Other anchors at the site that could not be sampled failed at depth. On a finer scale, it was found that the failure was initiated by the development of a crack on the surface line in tension in the narrowest section (foot of the thread or rib area). This crack can be doubled by a second crack spaced at 60°. This spacing corresponds to the angle formed by the surrounding ropes of the two triangular nets that are attached to the rockbolt. A potential surge failure has been identified.
Since regardless of the type of bar, the same pattern of failure on a macroscopic scale was observed, indicates that these nine anchors failed under the combined forces of the surrounding rope of each of the two triangular nets. The resulting force was expected to be inclined at the top of the bar. Because the top of the ground in place was relatively soft, the bar bent. The force was transferred just below the nut forming a first hinge. A second hinge could have developed at depth at the junction with the resistant bedrock if the deflection of the bar was sufficient. Moreover the double initiation identified on a microscopic scale for F9 (§ 2.3) indicates that the resultant of the forces is oriented along one of the surrounding cables and this orientation varies. This is consistent with a snow load in a snow net that varies with the day and the season according to temperature and snow quantity variations [6].

3.2. Site O
The single rockbolt investigated at the site was linked to two rectangular nets directly by the loop of their surrounding rope (table 2). It was embedded in ground consisting of soft soil on the surface and stronger bedrock at depth. The bar is a pre-stressed bar (BP – table 1), i.e. its elastic limit is higher than that for reinforced concrete. The bar broke at depth by bending but there was also bending below the nut. Thus, the same mechanism is observed as for the double plastic hinge cases at site F.

3.3. Site T
The three rockbolts collected at this site were embedded in bedrock, a priori without any soft soil on the surface (table 2).

Two of the rockbolts were linked to two triangular nets by an angled connecting piece and a shackle. They broke under the nut by bending as for site F (table 2). At the microscopic scale, the behavior seems to have been more ductile than at site F (§ 2.3). The differences in behavior between these two cases that could justify this observation are a different bonding system, a stiffer surrounding ground on site T and a different bar quality.

The third rockbolt at the site was linked to two rectangular nets as for the rockbolt at site O, with a direct link between the steel bar and the loops of the ropes surrounding the nets (table 2). In the same way as at site O, there was a failure at depth. The conditions that differentiate these two cases from the fourteen other anchors studied, which failed just below the nut, are the type of net (rectangular) and the bar-cable connection (direct without a connecting piece).

3.4. Site G
For the five rockbolts of site G, the configuration is exactly the same as for the first two rockbolts of site T (rigid surrounding ground, triangular nets, connection by angled connecting piece). They broke in the same way, by bending just under the nut.

4. Discussion
Whatever the type of steel bar (BA or BP), the same fracture mechanisms have been observed. In these cases the type of bar does not seem to influence the failure mechanisms involved.

The chemical analysis of the steel indicates that a defect in the quality of the steel or the shaping of the bars is not a cause of failure either. In particular, no defect was observed at the foot of the thread that could justify the initiation observed in this area.

The internal structure of the steel of the prestressing bars increases its sensitivity to stress corrosion. In fact, for reinforced concrete bars, failure anticipate corrosion. However, according to the observation of the fracture surfaces, whatever the type of bar, stress corrosion is not to be considered as a cause of the observed damage.

In the studied cases, the same observations lead to the same conclusion regarding fatigue: fatigue, even oligo-cyclic, is not a cause of failure.

Finally, the accessory failures also observed at the head of the anchorage (cable loop and clevis) confirm that this zone of the rockbolt is a point of weakness.
All the bars failed by bending due to the propagation of cracks that started in the narrowest section (foot of the thread or rib area) on the tensioned generator. Indeed, in this zone, there is less material and therefore the stress is higher. This bending is generated by an inclined load at the top, due to the snow load in the net layers. It forms below the nut but can develop further down if the bar can be deformed sufficiently before reaching a more resistant ground.

Consequently, the premature failures observed on the rockbolts studied are due to a lack of knowledge of the effective loads received by the rockbolts when the snow nets are loaded by snow. They are also due to the omission, during the design phase, of the deformation behaviour of a bar loaded at the top and anchored in a ground made up of materials that are more or less soft at the surface and resistant at depth.

5. Conclusion
The analysis of damaged rockbolts taken from avalanche protection structures indicates that the damage is due to a lack of knowledge of the effective load generated by the snow-filled structure, but also to a lack of consideration of the deformation behaviour of the foundation. The quality of the components or the installation cannot be blamed.

The load applied to the rockbolt bar by the avalanche protection structure generates a more or less marked bending depending on the nature of the surrounding ground. It has been shown that this load can occur in successive jolts and with modification of its orientation in relation to the number of links between the rockbolt and the protection structure. The failure then occurs in a more or less ductile way.

This specific load needs to be qualified and quantified for a better design of the bar. In addition, in order to take into account the resistance of the rockbolt, it seems appropriate to analyze its deformation behavior during a head load and considering different stiffnesses of the surrounding environment. The conclusions of this study allow us to consider a larger research program in order to establish recommendations on the choice of the steel bars used for the foundation and the securing of the protection structures.

References
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