REINFORCEMENT DESIGN AND CONTROL OF ROCK SLOPES ABOVE TUNNEL PORTALS IN NORTHERN ITALY

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Abstract: The stability features of slopes located above the portals of tunnels along important roads are here presented, together with two examples for reinforcement and protection works. The investigation phase and the reinforcement works have considered also the purpose of avoiding the interruption of the traffic when this would cause unacceptable consequences. The first case refers about the construction of a portal along a narrow and steep valley in a volcanick rock formation. The control of the vibration of the blasting action has been carried out for the period of the excavation in order to foresee the occurrence of potential dangerous situations. The second is the case of the portal of the East access to the Highway n.10. Even though the adits are protected by two portals, the occurrence of rock and debris falls from the upper part of the mountain could create a dangerous situation. Above the portals the morphology of the slope is characterized by two subvertical rock slopes, which are separated by an intermediate zone of debris material.

Keywords: Tunnel portals, rockfall protection, blasting vibration, slope stability, traffic safety.

1. GENERAL FEATURES

The location of tunnels in mountainous areas often involves careful conditions for the portals, both during the construction and the operation, for the possible consequences that instability phenomena could cause to the traffic safety. In addition, most part of tunnels built approximately before the 1970 presents technical and safety criteria that today are no longer acceptable. In these cases it is necessary to adopt new works whose arrangement could cause interferences with the traffic circulation.

There are various aspects that influence the stability conditions of the tunnel adits and the possible reinforcement works; among the main aspects, the following can be mentioned:

the morphology of the site;

the geological conditions;

the existing stability conditions (old landslides, snow avalanches);

the hydrological and hydrogeological conditions (rivers, streams) ;

the occurrence of surface constraints (constructions, existing roads);

the advancement direction of the excavation (inward or outward);

the environmental constraints (landscape, noise) and the architectural context;

the safety of the vehicle traffic (lighting of the road, the direction of the road and of the tunnel, the visibility along the road, other possible elements next to the adits).

First of all the stability of the slope influences the preparation of the site area for the adits and the portals:

1) direct excavation is possible in rock masses of good quality or when there is a relatively low dip of the slope, through the creation of high sub-vertical artificial slopes;

2) it is necessary to adopt some reinforcement technique in fractured rock masses, in soil formations or, finally, along high and very inclined slopes, e.g.: a) the improvement of the rock mass parameters and stability conditions; b) the construction of preliminary supporting systems.

In case 2a) it is possible to adopt, for example, drainage techniques, or grouting, both at low and at high pressure; in case 2b) it is possible to adopt jet-grouting columns, retaining and anchored walls, micropile anchored walls, large diameter piles.

The geomechanical features, in particular, are based on a combined study which examines the geological, geostructural, hydrogeological, geomorfological and geotechnical characteristics, while all the possible contributions of the geophysical investigations are also taken into account.

All the aspects related to the characteristics of each rock mass portion are then evaluated, both considering the stability problems at a small scale (for example rock falls) or considering large scale effects (slope stability), while also carefully considering the interferences with the external water streams or with seasonal phenomena (debris flows, avalanches). Each of the afore mentioned aspects should be examined in detail, and their causes, the possibility of their evolution and their magnitude should be studied. The result should be a structural and architectural design, in which the requirements, in terms of safety factors of the work and a safe traffic operation conditions are both satisfied.

Special attention should be devoted to monitoring that should be performed during the excavation, and also, for a certain period, after construction, especially in the case of improvement of the safety conditions in the portal areas of old tunnels.

2. REINFORCEMENT TECHNIQUES AND DESIGN IN SOILS

Adits in soil formations or in detritic overburdens (morainic or debris) suffered severe limitations in the past due to stability problems. The only possible solution was to remove any loose material when this was possible. Grouting techniques have greatly improved in the last three decades and heavy duty equipment is today available: it is therefore now possible to considerably reduce the amount of external excavations.

The main geotechnical problems in soils are linked to:

- large sliding movements of the slope;
- the presence of water;
- soft layers of material with low bearing capacity;
- subsidence, when thin overburdens are present.

Some local stability problems can also occur when a thin overburden covers the surface and this overburden can be washed away during heavy rainfalls, thus causing local mud flows, with great risks to the safety of the traffic.

The remedial techniques that can be applied in these situations are:

- modification of the slope geometry, eventually using geosynthetic materials (geogrids, geonets, etc);
- the use of drainage systems, inside and outside the tunnel, using different techniques, and sometimes even a drainage tunnel;
- reinforcement of the soil formations through grouting, both directly at the face or from the external surface;
- reinforcement of the soil formation through nailing at the face;
- insertion of a preliminary support consisting of anchored tiewalls.

The monitoring should generally be aimed at following both the evolution of the geological formations (movements, piezometric levels, settlements), and the performance of the structures (loads in the tunnel supports, convergences of the undergorund excavations, stress and strain condition in the concrete lining, behaviour of retaining structures in the slope above the portals).

3. REINFORCEMENT TECHNIQUES AND DESIGN IN ROCK SLOPES

Adits in rock formations are generally excavated by means of blasting. In this case problems exist due to the possibility of rock falls, especially when the mountain sides are high, or to the movement of rock blocks and wedges or slabs. These problems can occur both during construction and during the tunnel operation. For this reason it is necessary to carry out a careful monitoring of vibrations and eventual displacement of the blocks during the construction; it is also necessary to maintain the reinforcement or protection structures during the life of the tunnel. In the various cases scaling and bolting of the residual rock mass are common practices, after trench excavation. If no other problem arises the portal can simply be adapted to the shape of the excavation, otherwise some segments of artificial tunnel can be built on the outside for rock fall protection purposes. When there are particular environmental, landscape or architectural requirements, the shape of the portals can be adapted using appropriate techniques in order to insert them into the landscape with the minimum disturbance.

Active remedial works prevent stone elements from detaching from the slope. These can be classified, according to the action they perform, as follows:

- reprofiling of the slope through the creation of benches, removal of the unstable rock volumes, selective mining with explosives or local induced failures using chemical products;
- interventions that modify the hydrogeological conditions, for example, waterproofing of the exposed surfaces, creation of sub-horizontal drainage holes, or other drainage works;
- protection from surface alteration, covering with wire mesh and cables, underpinning with concrete;

Passive remedial works have the scope of intercepting or deviating stone elements when they are already in movement. The following works can be mentioned:

- installation of metallic barriers (net fences), with different levels of dissipation energy and different strain modes;
- protection walls, trenches and embankments, where sufficient space is available.

The design of these works is based on a detailed knowledge of the rock mass structure (fracture network of the rock mass) and of the study of the trajectories of the rock blocs in movement.

When rock falls can occur, the type of the round blasting and the quantity of the explosive can be carefully adapted according to the results of the vibration monitoring.

Finally, it should be pointed out that the installation of measurement and alarm systems are not always advisable, as the studied events sometimes present a quick evolution. For these reason in many cases the creation of an artificial section of the tunnel can prevent undesirable events, and the portal becomes a protection structure in itself. In this latter case, however, a specific design of this structure, on which dynamic and concentrated loads act, should be drawn up. For this reason, these artificial segments are overdimensioned and integrated with other dissipative elements, such as the covering with geogrid reinforced embankments, also on the basis of eventual practical rules or regulations.

4. THE CASE OF VAL D'EGA TUNNEL

The first case refers to the construction of a road tunnel excavated in a fractured rock mass in North East region of Italy. The geologic formation includes phorfides and vulcanoclastites. The tunnel project was based on the protection of the traffic along a mountain road characterized by an high risk of rock falls.

One of the adits was arranged with limited excavation at the external part of the steep and high rock slope, with heavy reinforcement of the rock mass and with the installation of passive protection; the rock reinforcement has been made by means of rock bolting and wire mesh, sometime coupled with shotcrete, while the passive protection has been made of net fences.

In the area surrounding the adit also some detritic surface formation occurred and for this reason the remedial works were made of wire mesh and bolting (for the fractured rock mass) and net fences (for the debris protection).

Figure 1. *View from the upper part of the rock slope: some net fences are visible and in the right side the existing road.*

As the construction of the tunnel was made by drill and blast technique, a systematic monitoring of the vibrations of the blasting was performed during the excavation of the last 150 m of the tunnel length, and some surveys were repeated along the slope. As a base for the study some steps have been followed:detailed geomorphological and geostructural surveys, with investigation on the

- location of sismographs, measurement of vibration parameters and interpretation of data;
- determination of the eventual correlation between round parameters, induced vibrations and instability phenomena;
- definition of the trajectories of the blocs and, consequently, of the possible reinforcement works along the slope and of the protection works along the existing road.

Some topographic meaurements were also performed, taking into account the absolute movement of reference points located along the slope, detected by precision theodolites; it should be observed that in this case it would have been better to directly monitor some rock fractures using a displacement transducer.

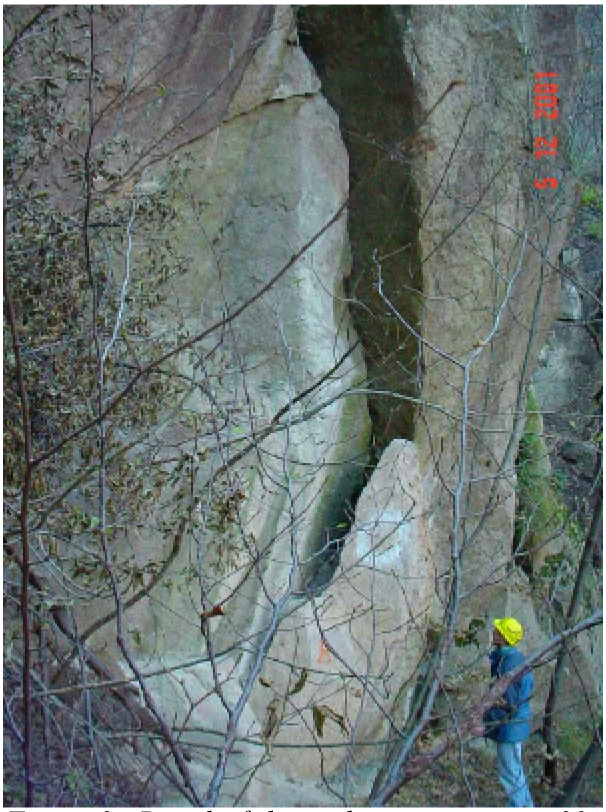


Figure 2. Detail of the rock mass structure 30 m above the tunnel portal.

The vibration were recorded for each face advancement by using 3 seismographs located above the portal area, in representative points.

The measured data have been conventionally interpreted on the basis of the peak particle velocity (ppv), adopting the site correlation

$$v = k\left(\frac{Q^{1/2}}{R}\right)^m$$

where: v is the peak particle velocity, expressed in mm/s,

Q is the charge for each delay, expressed in kg,

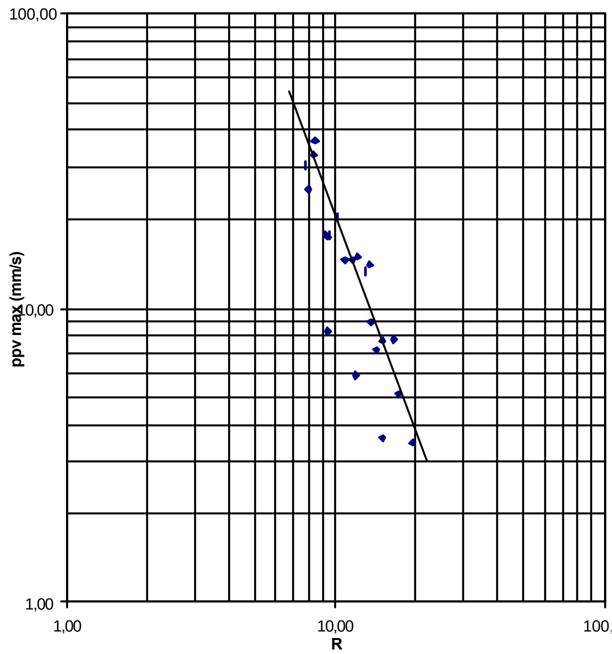
R is the distance between the signal source and the measuring point, expressed in m,

k and m are empirical coefficient that depen on the type of the blasting method and of the ground.

The maximum recorded values have been of about 40 mm/s, thanks to the careful control during the round preparation.

In this situation it was possible to check and adapt the blasting parameters, and reduce the excavation surface of the advancing face in the last 35 m of the alignment (from 85 to less than 40 square meters). Only local rock falls were recorded during the excavation of the adit, without any consequences for the safety of the traffic.

Figure 3. Diagram of the peak particle velocities



vs the scaled distance R. This is a conventional tool to control the effects of blasting.

It is fundamental that monitoring and surveys should be carried out until all remedial works have been terminated, in order to control also the damage effects on the unstable rock elements.

5. THE CASE OF SIESTRO TUNNELS

The case concerns the A10 Highway which run close to the border between Italy and France, along th Ligurian coastline. In particular, the stability conditions of the slope above the portal of the tunnel crossing the Siestro hill are examined. The highway enters the hill through of two tunnels at the base of two sub-vertical slopes. Even through the adits are protected by two portals, the occurrence of rock falls from the upper part of the mountain could create a dangerous situation.

The geological structure is characterised by two sub-vertical rock-slopes, which are separated by an intermediate zone of debris material. The rock consists of a well-cemented limestone conglomerate made up of smoothed gravel ranging between 5 cm and 30 cm in size. The rock is approximately horizontally stratified in thick banks with inter-bedded thin sandy-arenaceous levels.The rock mass is subjected to several persistent sub-vertical joints, which separate consistent volumes of potentially unstable material.

The investigations that were carried out for the study of the static conditions of the slope and of the reinforcement works concerned:

- direct surveying of the geological and geostructural conditions of the natural formation;
- geophysical surveys of the rock walls, using electrical tomography and georadar;
- photogrammetrical surveying from a helicopter, given the inaccessibility of most of the structure, so as to define the morphology;
- laboratory tests for the characterisation of the rocks;
- in situ tests in order to determine the resistance of the anchorages that are made up of metallic reinforcement elements (bolts and cables installed in the conglomerate at the base of the slope, above the portals, in relatively integral rock).

The main aims of the geophysical survey was to detect the thickness of the debris materials in the middle of the slope and to detect the main sub-vertical fractures along the rock slope.

Two different methodologies were adopted: 2D electrical resistivity tomography for the characterisation of the debris materials and georadar profiles along the rock slope to detect the main fractures. The electrical resistivity tomography pointed out that the potentially unstable debris layer has a mean tickness of 5-6 m, showing a greater tickness of fine overburden materials with water circulation (low resistivity values) underlying a near surface more resistive layer of dry coarse debris material.

The radar survey with low frequency antennas put in evidence a series of sub-vertical fractures in the rock slope above the tunnel entrance. Different sub-parallel discontinuities were also shown at a depth of 10-12 meters from the slope surface . Some characteristics of the conglomerate were determined through quick laboratory tests performed on prismatic samples taken in the area adjacent to the tunnel entrance.

The unit weigth of about 2500 kg/m^3 was determined on the integral cubic sample of about 30 cm of edge and the scelometric index was determined through the use of a conglomerate sclerometer (mean value of the index equal to 25, corresponding to about 17.2 MPa). The compressive strength on the cubic probe gave a value of about 16.4 MPa, this being in quite good agreement with the sclerometric correlation.

Correlation with similar rock types allowed the authors to find a cohesion value of about 0.12-0.10*C, obtaining a value of about 1.6 MPa.

Taking care to impose a further reduction of about 25% of the thus obtained value to obtain the cohesion of the rock mass $c_m \approx 0.75\ c = 1.2$ MPa.

On the basis of visual observation of the rocky structures and on the results of the geophysical and geotechnical investigations that were carried out, the risk situations due to instability phenomena above the tunnel portals were identified:

- a rock volume in the highest part of the slope, above the southern portal, delimited by an extremely dipping fracture; at its base this volume appears to be at least partially connected to the continuous rock mass. The base discontinuity is open, although the exact geometry and persistence are not known precisely. The discontinuity can represent the surface of possible sliding of the entire rock block. The volume of this bloc can be evaluated as 110-120 m^3; its detachment, with sliding and collapse phenomenon, would involve at first the intermediate detritic slope and afterward directly the motorway lanes;
- the area of the slope above the tunnel that divides the two sub-vertical walls has a noteworthy dip of 40° and is subjected to the presence of a debris material layer. This intermediate area of the slope is also subject, during the heavy rain periods, to falls of considerable water flows which, over the years, have created flow paths without affecting the road.
- the presence of weaker areas in the conglomerate mass and of debris material in the intermediate area of the slope could cause the detachment and fall of small rock volumes whose trajectories could reach the motorway below and other structures closeby.

In order to verify the stability conditions obtainable by means of the remedial works, some stability analysys were carried out, also for the study of rock blocs trajectories.

The remedial works to improve the static conditions of the geological structure above the tunnels portal were carried out progressively according to the criteria of urgency.

Before all was carried out the cleaning of the top edges to remove even small sized elements that could easily detach from the edge following the superficial flow of the waters.

Two kinds of protection barriers placed in the middle of the debris ridge on the lower edge was build up to intercept the blocks detached from the upper slope or unintentionally moved during protection works. The types of barriers that are advised are those that can absorb energy of 1000 kJ for the first order and energy of 500 kJ for the

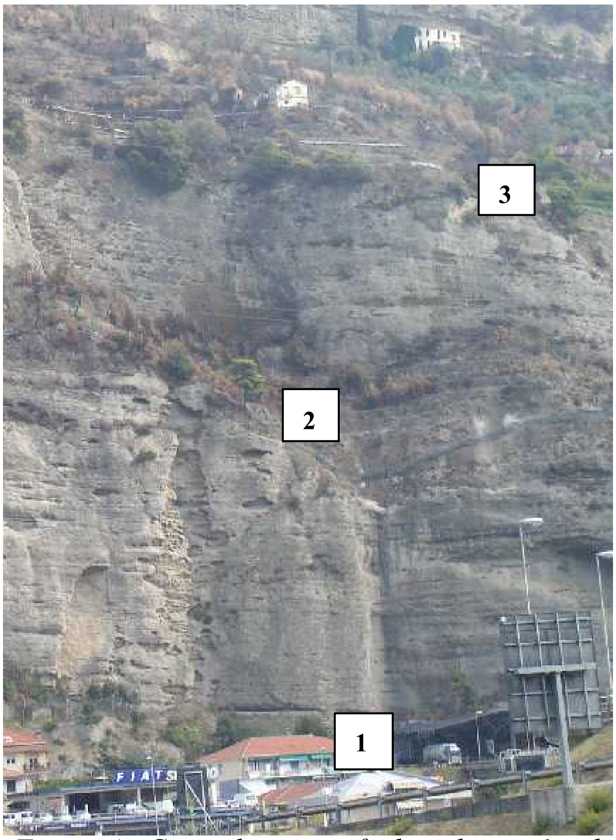


Figure 4. General view of the slope: 1- the portals, 2- the detritic formation, 3- the unstable isolated rock element.

second order, with a height of 5 and 2 metres, respectively. Particular attention has been paid to the anchorage of these barriers, as the debris layer has poor geomechanical characteristics. Both the metallic vertical rod foundations and the anchorage section of the cables required a stress-strain approach in order to evaluate the stresses transmitted to the ground by an impulsive event to the greatest extent.

The debris strip will be reorganised to permit an easy flow of the waters that come from above to prevent the dragging of debris.

The surface of the 110 m^3 rock volume will be temporarily consolidated with a harness of cables and will also be arranged for the possible removal of the blocks through slice cutting using a diamond wire cutter and removal with hoists towards the summit of the slope; this choice was made to allow a progressive improvement of the safety of the slope.

Finally, a monitoring of the main fractures close to these volumes is foreseen for any possible emergency interventions. This monitoring is based on measurements using crack gauges and load cells to evaluate the development of the forces on the anchorages and on the containment cables.

The general approach that has been adopted has proved effective to obtain the data that were necessary for the study, then allowing the choice of interventions that were contemporaneously aimed, on one hand, at the progressive reduction of risk and, on the other, at the minimum possible interruption of the road traffic for the improvement interventions.

Now the final solution will be the new design of tunnel portals, by means a prolongation of the artificial lining and its insertion inside the landscape.

Figure 5. Detail of the unstable element (ref.3 in fig.4)

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