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Overburden Stability of Rock Slopes in Quarries

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GENERAL ASPECTS

Many ornamental and industrial stone quarries are located along steep slopes or within particular geostructural domains in the Italian Alpine Range. The stability of a quarry face should be considered within the exploitation method and can be solved by means of rock mechanics studies and by adopting appropriate excavation techniques. A detailed geostructural survey and a characterization to determine the strength parameters are necessary to plan an exploitation in order to perform a stability analysis, from which the various failure mechanisms can be highlighted. At the same time, the choice of the excavation tecnique is related to the type of rock and to the structure of the mass, and it influences, for example, the heigth of the benches, their length and the general exploitation plan in terms of spatial development of the excavations. The stability of the overburden formations, such as detritic or cohesionless materials, blocky and altered elements or morainic formations, can be compromised by exploitation activities. In other cases there is a natural evolution of the slope, due to singular but diffused phenomena such as block falls, or due to global movements caused by gravity and water interaction. All these facts involve safety aspects not only for the quarrying activities but also because of the possible interference with other nearby structures such as roads, electric power lines and railroads.

In order to ensure correct safety margins it is therefore necessary to apply a comprehensive approach: knowledge of the geostructural context of the quarry slopes, study of the possible evolution of the phenomena and the related causes, a numerical modelling of the phenomenon, monitoring of the area and the choice of adequate passive and active protection and stabilisation works. Some points should however be mentioned: the economic costs for preventive and remedial works must be consistent with the budget of the quarrying activities; monitoring is often involved with fast and sudden phenomena, and it should therefore be suitable to particular requirements, in order to be effectively useful; the final configurations of the residual slopes should allow a reclamation of the area, in particular if landfills are foreseen. On the basis of the following examples, some suggestions are given in order to obtain an operative scheme, that is also easily adaptable to monitoring and protection of civil excavations of slopes.

STRUCTURAL FEATURES OF QUARRIES

Italian quarries in mountainous areas (Alpine Range, Apuane Range) are exploited both for ornamental stones (gneiss, diorite, ophicalcites, marbles, slate) and for aggregates (andesite, olivine, limestone). In some regions open pit mines also exist (quartzite, feldspar, albite).

Landslides in research, theory and practice, Thomas Telford, London, 2000.

Overburden is usually intended as the geological formation that covers the useful part of a rock mass or of an orebody. In the studied cases three main situations have been encountered. The first one is relative to morainic strata on a bedrock surface. The thickness of this overburden formation varies, but the common range is between less than 1 m to about 15 m, at least where the exploitations are carried out. These formations are characterized by a very heterogeneous material, with a very wide grain size distribution; a cohesion is sometimes present. Water is present in concomitance with meteoric events, because of the relative high permeability of the morain. In some cases lenses of fine materials can act as local reservoirs of water inside the formation.

The geotechnical parameters that should be determined in order to perform the relative stability analyses are, in particular, cohesion and friction angle. Due to the different scales of the laboratory tests and of the actual formation it has not been possible to carry out a direct determination of the parameters. Generally, it was only possible to carry out a back analysis of limit equilibrium situations (safety factor $\approx$ 1.0), and this was integrated with a detailed description of the material and the applied loads. Some information can also be obtained from a grain size distribution, provided it can be performed and that a relationship between the size distribution and friction angle can be applied. In some cases an overall dip angle of 35° for residual slopes has been assumed for long term stability and a value of 40° has also been accepted for local or short term conditions.

The second case is relative to detritic and colluvial sediments (materials that have been transported) or soils (in site origined). The geometry of these deposits is very irregular. A direct determination of the grain size distribution is possible, and back analyses in critical situations can give appropriate values of the friction angle and cohesion for the mass.

The detritic masses are usually made up of angular elements, as they are broken rock fragments with no reshaping due to transportation. The talus cone can belong to this category of overburden, as can the waste muck piles constructed along the slopes. In this case the parameter angle of repose is sometimes adopted in the analyses, and this corresponds to the angle of the slope that can be held by a loose pile of rock fragments. Talus cone slopes



Fig.1. Overall view of an albite open pit mine with morainic cover during exploiation.

usually exhibit angles of between 34° and 38°, even though single benches could probably be excavated with steeper angles, but in conditions of temporary and limit equilibrium (42° to 45°). Some laboratory tests, such as direct shear tests are also possible. It should be recommended to perform both tests and consequently analyses, with different water contents and different shearing velocities, as slides can occurr under both dry and wet site conditions. New computational codes (such as PFC from Itasca, based on the equations of distinct element method) are used both for back analyses and design.The third case is relative to altered and weathered rock masses, with the possible filling of soils and clay inside the voids among the blocky elements.

The geomechanical parameters can be determined by means of compression, tensile and shear tests on the rock matrix, and by means of shear tests on discontinuities and on the filling materials. It would be very useful to have tilt tests at large scale. Once again a back analyses can be performed by using, for example, distinct element codes (e.g. UDEC by Itasca). In this case, the geometry of the overburden is usually more regular and can be similar to the structure of the exploitable rock mass. The debris elements are, in general, angular and the mass is quite permeable.



Fig. 2. Ornamental stone quarry with detritic and colluvial overburden.

A common element for the three situations is the need to determine the geometry of the contact between the overburden and the bedrock, as this morphology, together with the geomechanical parameters are the elements which affect the type of surface slides, the mechanisms and the evolutions of the phenomena. It is important to try to recognize, from the large variety of cases of quarries and overburden morphologies, the common features that allow one to classify possible slide types and, in particular, the operative suggestions for retaining and mitigation structures.

In addition, the thickness of an overburden of rock masses for ornamental stones and also for various industrial minerals or aggregates, when it is not negligeable, influences both the rentability and also the method of exploitation today adopted for the quarries.

Apart from the case of an overburden ratio that is so unfavourable that an underground exploitation has to be considered (1:1 the ratio between the thickness of the exploitable strata to the overburden, for the case of ornamental stones, with a recovery factor of at least 50%),

the general rule for open pit quarries is the adoption of descending horizontal slices, both when the overburden is cohesive or not, and the thickness is limited. The environmental reclamation of the uphill slope is therefore carried out progressively at the same time as the advancing of the downhill exploitation. Fot intermediate situations with medium thickness of overburden the old traditional method of ascending vertical slices still seems to be the most common adopted, as it allows production in a relatively short time without creating removal of that large surface layers. A compromise between the previously described methods could be that of the adoption of sequential and superimposed stripes in which the vertical slices are exploited progressively in descending order. This would allow the reduction of the removal of the overburden during the initial productive cycle of the quarry, and would easily carried with the environmental rules. Another important decision factor for the exploiting method is the selectivity of the mineral or rock blocks, in order to improve rentability. For example, when it is possible, the selection is operate at different benches in a open pit exploitation of limestone for the cement industry, in order to separate waste dolomitic layers from in the rock mass, while also taking the dip of the benches imposed by stability features into account.

FAILURE MECHANISMS AND EVOLUTION

The here described cases can be classified, in terms of both the failure causes and the evolution of the slide events. These two phases are obviously not independant, as each type of rock structure or material may preferrably induce a particular slide mode. In this note the slope movements along overburden formations focuse on their correlation with the exploitation activity, especially when this activity together with structural features and meteoric events are the causes of a slide. In other cases a quarry can be subjected to damage due to consequences of slides that are not directly linked to the quarry itself. In both cases the study of the landslide can help in the choice of the appropiate remedial and protection works.

The basic approach of analyses methods, such as the limit equilibrium method, and the common characterization of the parameters are suitable, at least for simple geometries. When also considering the evolution of the movements, other sometimes new and innovative approaches are more suitable. In this sense it is of great interest to classify the type of landslide, following, for example, one of the recently available engineering classifications (Varnes, Takahashi, Hutchinson). As different slide types depend on the overburden, the following remarks can summarize the main situations.

Rock falls. These are present in altered rock layers, in particular in ornamental stone quarries. They are often associated with toppling failures of both the productive strata and of the surface blocks and are very dangerous for the safety of the workers.

Soil slides. These are more common in colluvial deposits. The movements can be progressive or assume high velocities and are often associated with meteoric events.

Debris flows. These phenomena are generally observed in quarries at the beginning, when considering colluvial overburden but also morainic covers.

Complex failures. These are present in irregular contact bedrock geometries. They are usually progressive and result in the accumulation of pile cones in quarries.

Plane failures. These are relative to altered blocky strata and are dangerous because of their quick evolution and the large volumes involved.

Landslides involving thick colluvium are usually relatively slow moving rotational slides that rarely exhibit subsequent disaggregation, while when the overburden is thin the initial translational movement can easily transform into a debris flow. This combination of soil slide and debris flow seems the most common failure mode involving colluvial slopes.

In slope talus cones of detritic elements there is a continuous feeding of fragments, and rock falls and movements are frequent. Talus deposits are mainly made of coarse grained sub

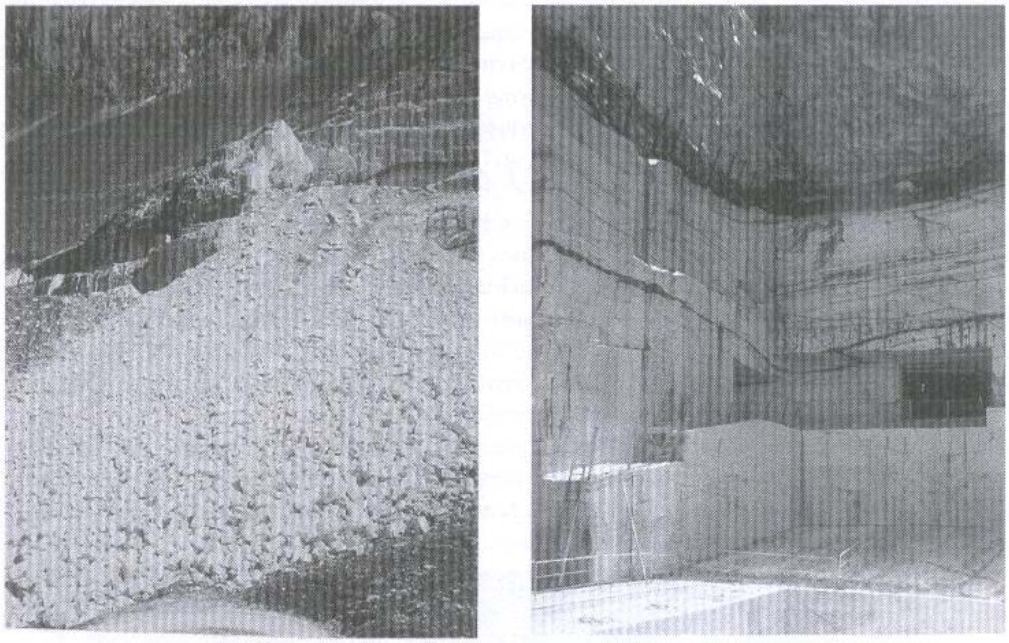

Fig. 3 . Overall view and detail of a marble quarry: lanscape and protection from rock chutes.

angular shaped fragments with a variable percentage of fine fragments and large rock elements. When the percentage of coarse material is high the talus can be more unstable, because the overall deposit may have a configuration in which the loads are transmitted with sudden realignements of the fragments, whilst when the fine matrix is compacted a more cohesive behaviour can be observed and larger elements float in the finer matrix. Each of these talus categories behaves differently in a kinematic sense.

The slopes of these talus cones often reflect the repose angle of the material. As a consequence, when steeper angles are obtained with artificial cuts thanks to temporary cohesion, rock fragments can ravel from the artificial faces resulting in a continuous failure. This situation requires a stable passive protection of the quarry area, and active works for hydraulic stabilization of the deposits. The energy of the mass and the morphology of the slope can be described by means of the travel angle α = arctan H/L, where H is the difference in elevation between the crown and the tip of the landslide, while L is the length of the landslide.

Particular attention must be paid to rock chutes or rock avalanches above detritic deposits or piles because of the possibility of starting off debris flows, even in the case of dry deposits, which are similar to "sturzstrom" phenomena, even when small volumes of rock are involved.

REMEDIAL WORKS AND FINAL REMARKS

The removal of a portion of an overburden at the crown of a quarry determines the exposure of a face in which the material is free to fall and slide down.

It is necessary to carry outa series of stabilisation (preventive) and mitigation (protective) wotks. Within the economic balance of a quarry the final reclamation and also the provvisional operation for safety and stability must be paid by the production of the stones. In the case of two or more quarries with common or dependant for structures a coordination should also be ensured by the official mining bureau. A classical example is that of the debris

waste landfill of a quarry that may influence the safety of another quarry at a lower elevation (e.g. the Apuane basin in Tuscany), or the contemporary exploitation of old landfills for secondary materials while the quarry is still active for raw material extraction.

Among the stabilisation works, the following can be mentioned: a) resloping of the overburden face in order to reach less steep slopes; b) scaling, in order to remove the loose rock elements; c) stabilisation of debris piles and cones by means of ground sills and check dams in order to reduce the erosion effect of surface water; d) adoption of an appropriate sequence of exploitation in the quarry in order to allow the gradual exposure of the overburden; e) perimetral collection and removal of surface water. Among the protective works the following can be mentioned: a) benching of the quarry face in order to alterate the free fall path of rock elements; b) artificial barriers and fences at the crown of the quarry in order to catch the blocks that fall from the overburden; c) creation of areas inside the quarry, like yards, for the accumulation of any possible collapsed material; d) construction of embankments and ditches at the base of the quarry.

The contemporary revegetation of surface zones at the crown of a quarry and eventual monitoring of surface movements of singular elements or discontinuities or of the whole area above a quarry are complementary but indispensable tools that guarantee a higher level of safety during work operations and land reclamation.

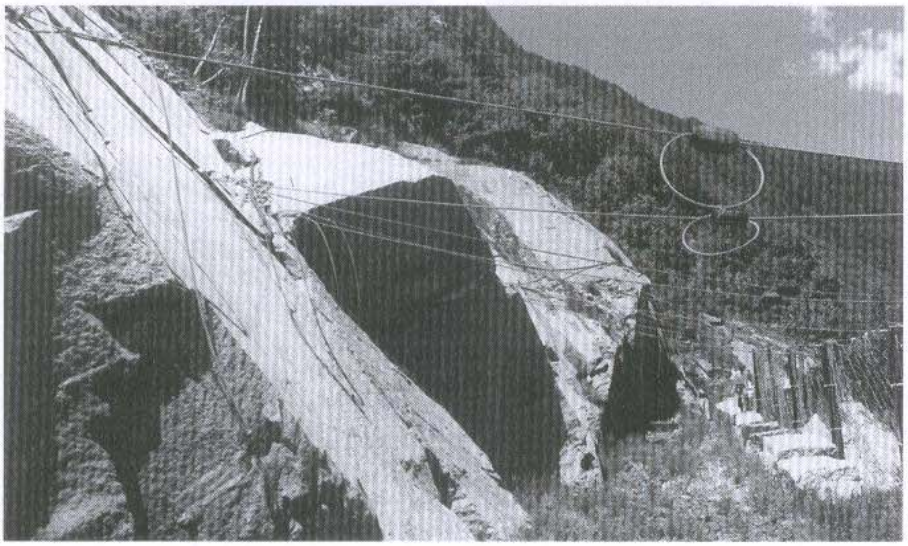

Fig. 4. Protection at the top of a geiss quarry with fences.

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