GEOTECHNICAL RISKS IN NATURAL STONE QUARRIES

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Geotechnical Risks

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Introduction

For decades, the marble quarries of the Estremoz Anticline, south Portugal (**1**), lead have seen proliferation of somewhat disorganized exploitation, leading to what is now a region with a profoundly modified relief. The predominantly agricultural Alentejo plain has been replaced by increasingly deep cavities with dangerously vertical slopes, intercalated with heaps that are increasingly high and visually impactful.

After the landslide of a quarry slope on November 19, 2018, which caused the collapse of the road between Borba and Vila Viçosa, Portugal (**2A**; **2B**), in which five people died, it became imperative to increase surveillance and slope stability studies in quarries in Portugal, and particularly the Estremoz Anticline.

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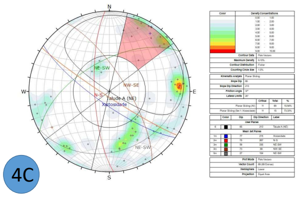
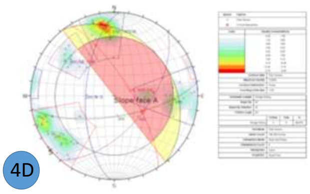
Over the years, as exploitation gets deeper, the most superficial areas of the slopes are inadvertently neglected, gradually becoming more unstable, for morphological reasons of the surface, due to inappropriate human intervention and weathering of the rock mass.

In fact, over all these years, marble quarrying has progressed without well-defined safety criteria, with industrialists investing in the rapid and efficient extraction of marble, especially during the periods of economic growth and high demand.

In many cases, the problems associated with the instability of quarry slopes, both cavities and heaps, were already known before the landslide of the quarry slope in Borba, particularly in the sequence of rockslides and rock falls, some with hazard and damage, but without media coverage. Gradually, the awareness of better extractive practices and greater environmental and safety concerns has been growing, and these aspects have been increasingly valued by a legal framework that aims to regulate the Natural Stone Extractive Sector.





Examples of two cases studied in different quarries where instability situations were observed, one situation involving a potential planar failure (**4A**) and another involving a potential wedge failure (**4B**) as demonstrated by the respective kinematic analyses performed with Dips software.(**4C** and **4D**)

Discussion

This paper reflects several studies carried out to understand the main causes and factors that influence slope stability in quarries.

After evaluating more than 40 cavities, the problems of slope instability are due mainly to the geological structure of the rock masses, which is exposed on the slopes with excessive height of these cavities, leading to different degrees of hazard. The risk of failure and mass movement is increased because the slopes are usually vertical without safety landings (**5**).

Given the evident percolation of water into discontinuities, its physical and chemical action is important, both in the karstification of marble rocks and in reducing shear strength in discontinuities, due to the effect of interstitial water pressures. (**6**)

Troublesome situations were noted, resulting from the proximity of discontinuities, some of them metrically distant, occasionally related to deeply weathered dolerite intrusions and materialized in slope deposits observable on lower floors, or in the accumulation of loose rock fragments on the levels between floors. The contact between marble and schist deserves special care, particularly when the schist planes converge on the cavity. This contact often forms a well-defined plane, facilitating the disengagement of rock fragments.(**7A; 7B**)

There is also the disorderly stacking of blocks, some of them shaped to fill empty spaces, evidence of crushing of tabular-shaped blocks, as well as blocks stacked in a cantilever above karst cavities or resting on a rock mass, revealing open fractures with potential planar or wedge fractures and inclination towards the cavity. (**8**)

There were situations that caused some incredulity, only understandable in old exploitations, where technical knowledge was precarious. We are referring to exploitation options that were interrupted, leaving deeply weathered and fractured rock masses in borderline positioning (**9A; 9B**)

It should be noted that this set of geological and geotechnical studies carried out shows that in the marble quarries of the Estremoz Anticline, the various families of discontinuities generally show little continuity or persistence, resulting in low connectivity between them, an aspect that contributes substantially to the stability of the slopes of these marble quarries and explains several situations in which, despite the unfavorable geometry of the discontinuities in relation to the face of the slopes, no rockslide occur.

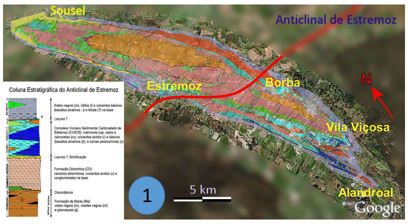
Concluding Remarks

The results of the study indicate three types of causes of failures in the several exploitation cavities, which compromise the integrity of the slopes with different degrees of danger: a) failures associated with the weathering and discontinuities of the rock mass; b) failures associated with exploitation techniques and mining planning, which are sometimes not very judicious and c) as a general rule, the role of the interstitial pressure of the water in the planes of the discontinuities, in reducing slope stability.

The mentioned before geotechnical risks are increased by the excessive height and verticality of these slopes, without safety platforms and, in many cases of suspended mining, without the removal of unstable rock masses highly fractured and weathered, as well as blocks stacked on console above karst cavities or lying on the rock mass, revealing open fractures with potential planar or wedge failure into the cavity.

The main stabilization and mitigation measures suggested were: a) cleaning the top of the cavity, so as to keep soil and rock fragments away from the edge of the cavity at a distance that ensures that it cannot fall into the cavity; b) model the geometry of the slope, remove loose blocks and smooth the slope so that it has the same dip as the potential failure surface and when applicable, regularize the platform at the top of the slope and waterproof the top of the slope using geosynthetics, in particular the installation of a geomembrane; c) Cleaning the landings between floors when they are full of rock fragments; d) construction of a fence using non-saleable but mandatory uninformed blocks, never exceeding two rows, laid on a leveled surface that cannot be altered by atmospheric agents, being acceptable it's placement at a minimum distance of 2 m from the edge of the cavity (**10**); e) reinforcement with high-strength steel wire mesh, fixed and molded to the slope by bolting and where appropriate, reinforced with steel cables both inside and on the periphery of the bolted metal mesh (**11**); f) steel fiber reinforced shotcrete with an internal drainage system for the rock slope, consisting of geodrains, and g) slope instrumentation, for geotechnical monitoring of surface displacements and internal displacements of the rock slope, etc.

However, the main conclusion to be drawn from the work carried out is that many situations of slope instability risk in this marble quarry area could be resolved if the perimeters of the cavity cuts were extended by joining adjacent cavities, developing an integrated exploitation approach.



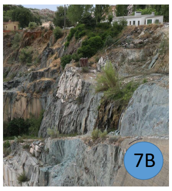
Google image showing the geology of the Estremoz Anticline (**1**) and the landslide of the quarry slope on November 15, 2018, with a length of 100 meters (**2A**), which was located next to the M255 municipal road, causing it to collapse (**2B**) and deep cavities with dangerous vertical slopes, interspersed with increasingly high and visually striking rock heaps Anticline (**3**).

Methodology

The methodology used in the geological and geotechnical studies of the Marble Quarries of the Estremoz Anticline, in addition to consulting the literature, was based on field work which included visual observation of each quarry (cavity slopes and heaps), collection of structural and hydrogeological data, characterization of the lithologies, photographic recording of critical situations.

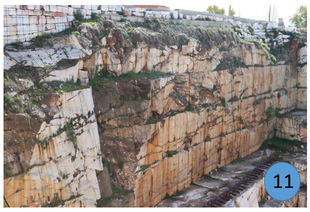
The field work included an analysis of the different lithologies and the contacts between geological formations, an analysis of the physical and geometric properties of the discontinuities, with emphasis on the relationship between their geometry and the slope faces.

This preliminary analysis, based on visual observation of the outcrops, is fundamental for the detailed characterization and assessment of the types of slope instability, making it possible to identify the most obvious critical situations and define the areas of greatest risk, thus making it possible to decide on corrective measures and possibly, whenever justified, the need for detailed studies. In the study of the potential instability of cavity slopes, the methodology of Hoek & Bray (1981) was considered, using the Markland method (Markland, 1972) to distinguish between planar failure (**4A;4C**) and wedge failure (**4B;4D**). The kinematic analysis was carried out for all the slopes in the cavity under study, but above all, in the case of permanent slopes or temporary slopes near work fronts or adjacent to an access route to the quarry or nearby quarries. For these slopes, which require a more detailed analysis of their stability, an assessment of the slope's stability conditions was then made using the limit equilibrium method for the most likely type of failure.



Reporting some situations…

(**5**) Cavity approximately 100 m deep with completely vertical walls, without safety landings.
(**6**) Karstification due to the dissolution of marble rocks as a result of water percolation through discontinuities;
(**7A**) Discontinuity related to deeply weathered dolerite intrusions in the marble rock mass, with poor geomechanical behavior;
(**7B**) Contact between marble and schist with the schist planes converge on the cavity;
(**8**) Heap near the cavity cut and careless stacking of blocks revealing strong instability inside the cavity;
(**9A**) Crane base in imminent danger of collapse due to inadequate design and complete erosion of the base;
(**9B**) Remaining mass showing inverted cut and open discontinuities compromising stability (red arrows).



Examples of stabilization and mitigation measures suggested: (**10**) Gabion wall with adequate fencing at the top; (**11**) reinforcement with high-strength steel wire mesh, fixed and molded to the slope by bolting and where appropriate, reinforced with steel cables both inside and on the periphery of the bolted metal mesh

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