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Rock slope stability of the quarries of Estremoz marble zone (Portugal)—A case study

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ABSTRACT: The Estremoz Marble Zone is one of the most important dimension stone production centre in the World. In these quarries located in the Alentejo Region (Southern Portugal), rock slopes, some of them with more than one hundred meters high, has been mined. This work emphasizes structural control in the marble quarrying and presents a case study, in which the analysis of the stability of a slope was based on a geological and structural data. The analysis was carried out in order to evaluate a possible failure of the slope due to the quarrying progress which could affect a surrounding quarry and a road close to the slope quarry.

1 INTRODUCTION

Portugal currently holds the seventh-largest global production of dimension stones, 2,950,000 t in 2007 (Montani, 2008). This maximum value of production reached in 2007, is misleading since there was a large decrease in the production of marble and a great increase of production of limestones. This has direct implications in reducing the overall value of the extracted matter and in large part, is responsible for the actual crisis facing the industry in Portugal.

Currently this area is responsible for significant part of the national production of dimension stone and is therefore a vital industry for the region, both economically and socially, to the extent that industry is the main employer in those Counties. However, the profound crisis we are experiencing in the extractive sector and manufacturing of dimension stone in Portugal, due to the complex and unfavorable international situation and the successive years of crisis through which Portuguese building lives, mean that the industry is going through a period of deep depression. This is reflected in the huge number of quarries in the municipalities of Estremoz, Borba and Vila Viçosa that are in suspended activity. Abandonment of the quarries results in a worsening of security in areas bordering them and is not always easy to assign responsibility when accidents happen.

The main region of marble dimension stone exploitation in Portugal is located in the district of Évora, in the range of Estremoz—Borba—Vila Viçosa, covering an area of 40 km by 7 km, from the Sousel in the Northwest until Alandroal in the Southeast. The geological setting places these marble quarries in the Estremoz Anticline (Ossa-Morena Zone, south branch of the European Variscan Fold Belt), a structure that presents a Precambrian core over which lies the Dolomitic Formation and then the Volcano-Sedimentary-Carbonated Complex of Estremoz, where occurs the dimension stone (Fig. 1). The age of this Complex is uncertain, probable age is the Upper Ordovician (Lopes, 2003).

These marbles have been quarried since antiquity as a valuable geological resource. In the 20th century, with the introduction of modern quarrying and manufacturing technologies, mainly in the 1970s, the marble industry expanded, and is now exported worldwide. However, due to the lack of geological knowledge by the owners of the quarries many mistakes have been made, with bad economic consequences. One of the most common situations is related to slope stability problems, because the quarrying orientation is not always made in agreement with geological structure. Moreover, the great depths of the quarries give rise to an increase of the in situ stresses in the rock mass mainly in the bottom levels and consequently to an increase in the intensity of fracturing.

The case illustrated in Figure 2 (point 2 in Fig. 1), depicts a situation in which the preferred orientation of grains in the marble dips in the opposite direction to the dip of slope face. This fact would be adequate to ensure the stability of the slope, but a heavy rain period caused an abnormal accumulation of water within the discontinuities that contributed to increased the water pressure on the face of slope, and at the same time decrease the shear strength of the discontinuities that occur in the rock mass (preferred orientation of grains in the marble, joints, tension cracks, contacts between different lithologies, etc.). This situation induced instability due to the water infiltration causing the decrease in the effective strength due to increased pore pressure and the consequent rock fall. Fortunately there were no personal injuries to register. Although a thorough analysis has not been done it seems that the drainage and sealing the top of the slope could contribute to improve the slope stability. This example portrays very clearly the urgency of carrying out stability studies where similar situations are recorded.

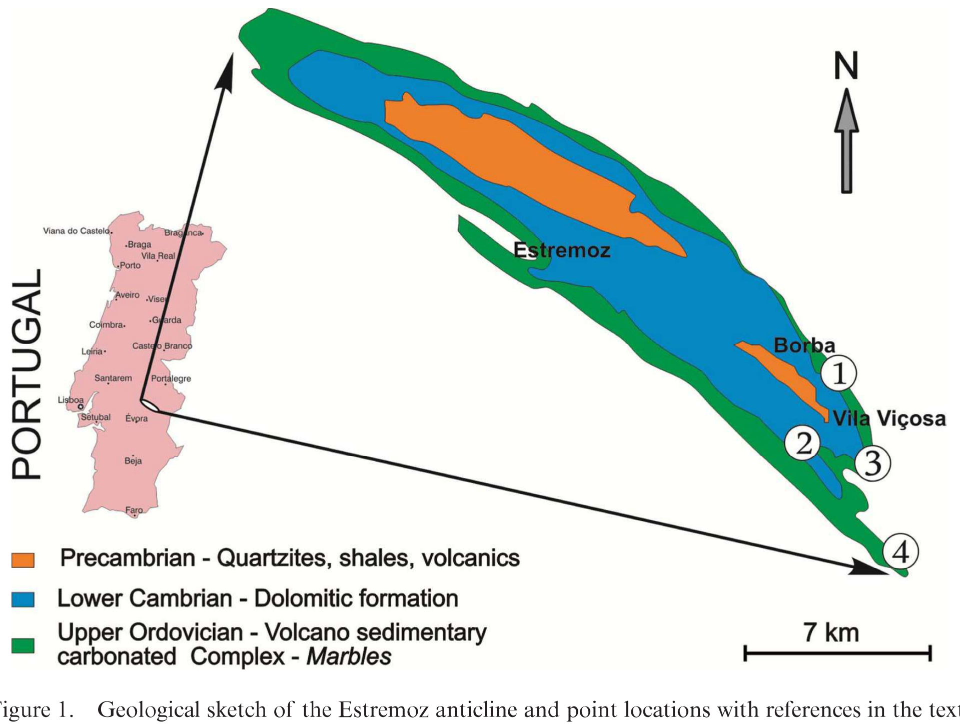

Figure 1. Geological sketch of the Estremoz anticline and point locations with references in the text. 1—Location of the case study. 2—Sliding in a quarry located in the southwestern flank of the anticline. 3—A 120 m deep quarry, located in the southeast periclinal end of the geological structure. 4—Karst cavity discovered as a result of earthquake, Alandroal.

Figure 2. Rock fall of the southwest slope of the quarry induced mainly by the effect of the water pressure within the discontinuities. This accident has also cut a road which profile is visible on the top of the slope. This quarry is located at point 2 in Figure 1.

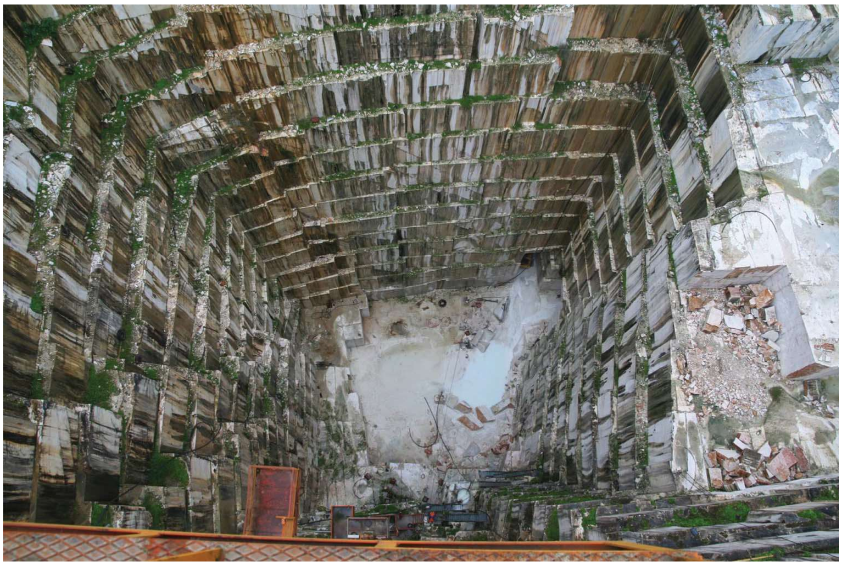

Figure 3. Vertical view of 120 m deep quarry, located in the southeast periclinal end of the geological structure. In the upper right at the bottom of the quarry can be seen the entrance of a gallery for the underground extraction of marble. This quarry is located at point 3 in Figure 1.

In the last decades of the twentieth century a sharp increase in the production of marbles mainly due to technological advances in machinery and equipment used in this industry, thus some quarries are now reaching depths of more than one hundred meters. The quarries are well developed, with steps, so that the geotechnical issues related to slope stability acquire

Figure 4. Karst cavity opened near a marble factory. This opening is probably related to a seismic event. This factory is located at point 4 in Figure 1.

special significance (Fig. 3, point 3 in Fig. 1). The risks associated with the instability of the slopes are increased because it is a region of high seismic risk. Also, as in any carbonate rock region, there may be unknown phenomena of karstification depth. Figure 4 (point 4 in Fig. 1), illustrates a case where following a seismic event of 5.7 on Richter scale on 17th December 2009, subsoil movements led to the cavity represented.

2 CASE STUDY

2.1. *Introduction*

A stability analysis was carried out of the southwest slope of quarry 5145 (point 1, see Figures 1 and 5). This study aimed to evaluate the problem of possible instability of the slope that corresponds to the southwest limit of the referred quarry, based on the geological and structural data of the rock mass that were collected on the site.

The assessment of slope stability in study was considered fundamental due to the possibility that it may affect adjacent properties between Borba and Vila Viçosa, particularly the Plácido Simões quarry located to the east, and even the National Road EN255, due to their proximity to the slope.

The surface of the excavation that constitutes the slope in study is vertical with an orientation of N45°W and is on the Southwest side of the mining area of quarry 5145 located in Olival Grande, São Sebastião, Borba. Between the base, at elevation 383 m, and the top, at elevation 406 m, there is a elevation difference of 23 meters.

These quarries exploit the light colored marbles of the volcanic-sedimentary-carbonated complex of Estremoz, which is part of the Estremoz anticline (Fig. 1), of probable age attributed to the Ordovician (Lopes, 2003; Moreira & Vintém, 1997; Gonçalves & Coelho, 1974).

2.2. *Structural geology*

A geological site reconnaissance of the rock mass was made consisting of a survey of physical and geometrical characteristics of the main discontinuities sets in the exposed surface of the slope in study. Thus six scan lines were made observing and recording discontinuities.

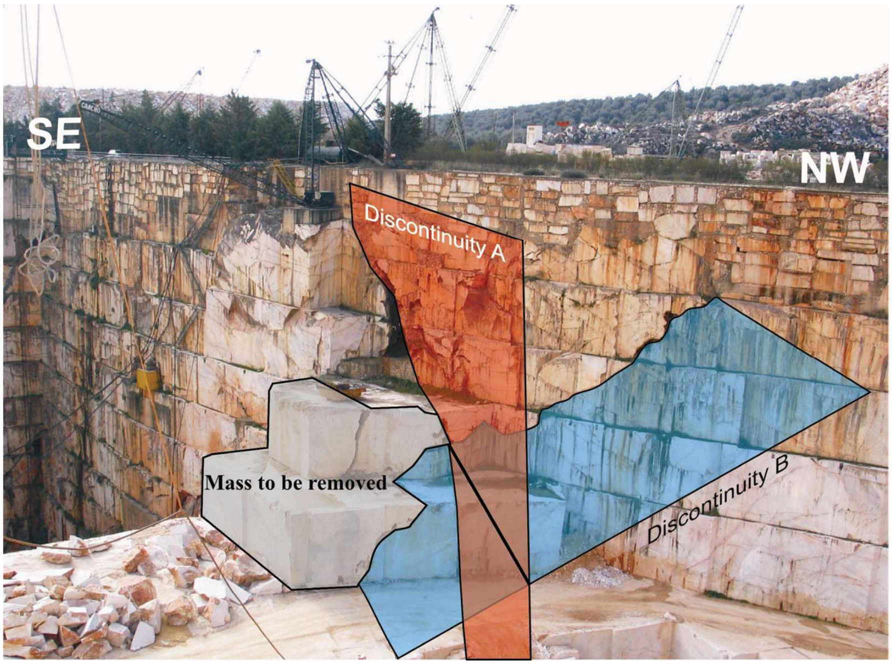

Figure 5. Southwest face of the quarry with the main discontinuities sets: A—open vertical discontinuity associated with karst cavity oriented N-S; B—planar discontinuity with orientation 50/072. The masses highlighted in gray are to be removed. This quarry is located at point 1 in Figure 1.

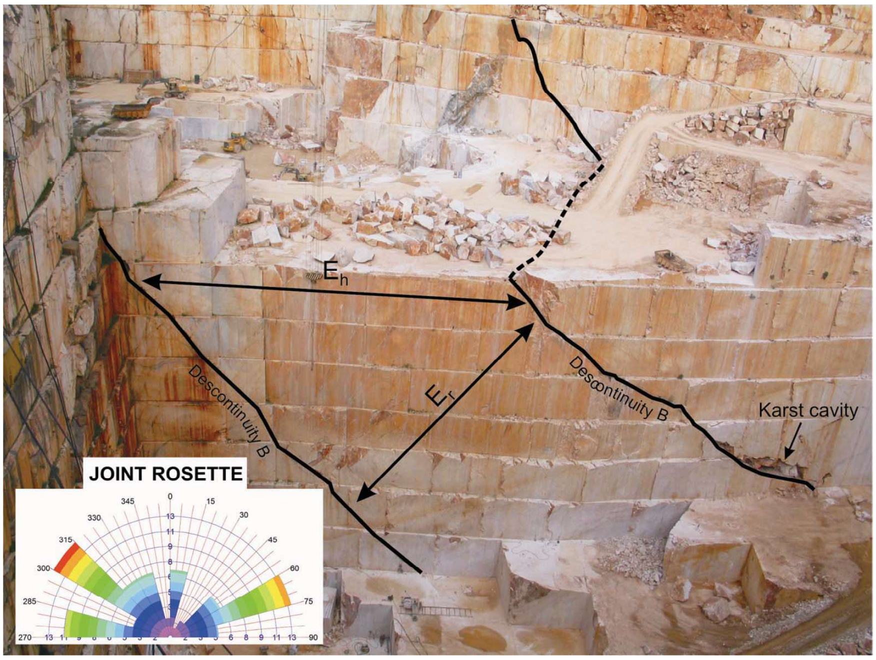

Figure 6. View to NW, which identifies the intersection of two discontinuities in set B. Horizontal (Eh) and normal (Er) spacing are indicated, and despite being apparent they are very close to the actual spacings. On the right is possible to see the development of karst depth, which demonstrates the unpredictable nature of these structures. A joint rosette inserted shows the joint sets identified in the quarry. This quarry is located at point 1 in Figure 1.

The structural data obtained in the field were subjected to analysis and processing leading to its graphic representation contour pole density plots of the measured fractures, and as a joint rosette (see Fig. 6).The analysis of these diagrams reveals the existence of five major sets of discontinuities, but there is a marked dispersion around their geometric centres.

It should be pointed out that the discontinuity set of greatest significance in these diagrams, (joint set B) has a spacing of the order of tens of meters (Figs. 5 and 6), and also provide a greater lateral continuity or persistence. Another very important aspect to consider is the limited persistence of many discontinuities observed in the quarry faces. This results in low connectivity between the discontinuities which contributes to the stability of the slope. It appears that set B, with high persistence and spacing of the order of tens of meters has greater influence on the stability of the slope under study (Fig. 6). This set presents an inclination that varies between 40° and 60° to the northeast (with an average slope of 50°) and an average dip direction of 072°, in other words, approximately parallel to the direction of the slope, which satisfies one of the fundamental conditions for plane failure (Hoek & Bray, 1981).

It should be referred the occurrence, in the southwestern slope of the quarry, a discontinuity that has a large karst cavity (discontinuity A), with an average N-S direction, vertical (see Fig. 5). The discontinuity A, belongs to a discontinuity set less common than the main discontinuity set B with which, in a first analysis, could lead to a possible wedge failure above elevation 381 m.

The analysis by stereographic projection of the planes of the two sets of discontinuities (A and B), concluded that the slope is potentially unstable but not all the conditions necessary for the occurrence of a wedge failure are verified, because in spite of $\psi_f > \psi_i$, is verified that $\psi i < \phi$, (ψ_f being the dip of the slope face, ψi the plunge of the line of intersection of planes A and B, and ϕ the friction angle of the line of intersection). Thus, the point that defines the line of intersection of the two planes lies outside the area enclosed between the circular arc defined by the slope face and the circle defined by the angle of friction. Moreover, the fact that the dip direction of plane B is much closer than the dip direction of plane A, to the dip direction of slope face, leads to the conclusion that the failure will be a plane failure along discontinuity B (Markland, 1972; Hocking, 1976).

2.3. *Stability analysis*

An analysis of the slope stability was made based on the analysis of geometrical and physical characteristics of the main discontinuity sets measured on the slope face located on the southwestern edge of the quarry. The mechanical behaviour and appearance of the rock mass resulting from the intersections of the main joint sets observed on the slope, influenced by the dismantling of the rock mass during the extraction of blocks is fundamental for the explanation of the slope failure that may occur.

The values of 225 kPa for cohesion and 42° for the friction angle obtained in rock masses with geological and structural conditions to the case study (Dinis da Gama, 1991) were adopted in the stability analysis because no values of strength parameters were available for discontinuity set B.

The calculation of the factor of safety was accomplished by the method of limit equilibrium, using two-dimensional analysis for plane failure (Hoek & Bray, 1981). The two-dimensional analysis was adopted instead of three-dimensional analysis because being the former more conservative than the latter, since the two-dimensional analysis does not consider the influence of the lateral surfaces of the volume to be moved (attributing to those surfaces a cohesion and an friction angle equal to those of the failure plane), leads to a lower safety factor.

For the case under analysis, since no tension crack parallel to the direction of the slope either in the slope face or in the upper surface of the slope, the influence of water pressure U, was only considered on the sliding plane. The analysis parameters were as follows: unit weight of rock $\gamma_r = 27$ kN/m^3; the slope face angle (ψ_f) approximately vertical; the dip of the sliding plane $\psi_P = 50°$; the slope height $H = 23$ m; the dip of the slope crest $\psi_s = 0$; the depth of the water on the sliding plane $z_w = 20$ m; the unit weight of water $\gamma_w = 9.8$ kN/m^3 (see Fig. 7). Thus, we obtained: $W_1 = 5739$ kN/m; $U = 2942$ kN/m where W_1 is the weight of the sliding block and U is the water pressure on the sliding plane.

The analysis of slope stability was carried out by the method of two-dimensional limit equilibrium, for a vertical slope section of unit thickness taken at right angles to the slope face, considering the following assumptions:

i. In this two-dimensional analysis the role of the connecting surfaces to the slide are not considered.
ii. The action of vertical loads due to the movement of heavy vehicles loaded (W_2) are considered in addition to the weight of the rock mass (W_1). The value of 500 kN/m was adopted.
iii. Vibrations were considered in the upper surface of the slope whether as a result of the movement of heavy vehicles on the National Road EN255, or as a result of the operation of the crane located in the top of the slope. It is considered that the combination of all those vibrations reach a value of one tenth of the acceleration of gravity.
iv. The presence of water on the sliding plane, considering the worst conditions for the stability of the slope, after the period of heavy rain.
v. The probable reduction in the factor of safety to the removal of adjacent frontal benches to the slope, should be compensated through the installation of rock bolts.

The factor of safety can be obtained by the following expression (Wyllie & Mah, 2004):

$$FS = \frac{cA + \left[(W_1 + W_2)\cos\psi_P - U - \alpha W_1 sen\psi_P \right] tg\phi}{(W_1 + W_2) sen\psi_P + \alpha W_1 \cos\psi_P} \quad (1)$$

where W_1 is the weight of the block (5739 kN/m), W_2 is the action of vertical loads due to the movement of heavy vehicles loaded (500 kN/m), ψ_P is the dip of the sliding plane (50°), A is the area of the sliding plane (30 m^2/m), c e ϕ are respectively, the cohesion (225 kPa) and friction angle (42°) of the sliding plane, U is the water pressure along the sliding plane (2942 kN/m), and α is the seismic coefficient due to vibrations produced by equipment (0.1).

In agreement with the suitable values of the several parameters for the most unfavorable situation (saturated slope), the factor of safety has a value of 1.29 which indicates unstable slope stability conditions even for a temporary slope. The slope under analysis must be considered a permanent slope according the existing physical constraints affecting the development of quarry mining and the National Road EN255 proximity. The safety factor calculated is lower than the recommended value for a permanent slope. However, as the water table is always below the bottom floor of the quarry, for mining operational reasons, originates favorable stability conditions due to the annulment of the water pressure along the sliding plane and therefore a value of 1.81 for the factor of safety is obtained, which indicates a good stability for the slope under study.

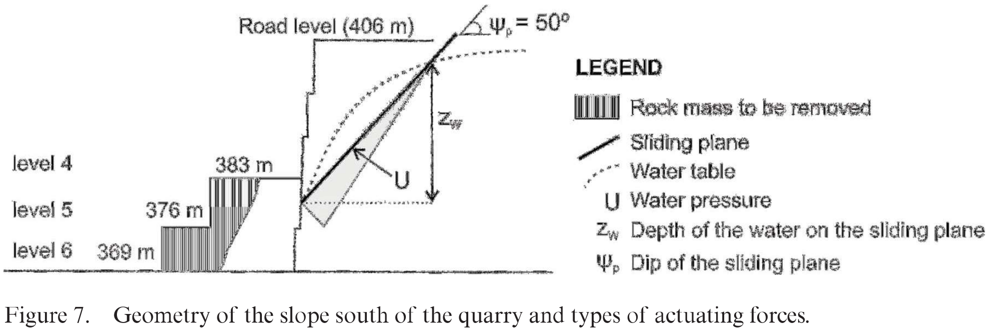

Figure 7. Geometry of the slope south of the quarry and types of actuating forces.

3 CONCLUSIONS

This paper highlights the importance of the knowledge of the structural control in the marble quarrying in the Alentejo Region (Southern Portugal) and presents a case study.

These marbles have been exploited since the antiquity as a valuable geological resource. Nevertheless, due to the lack of geological knowledge by the owners of the quarries, a lot of mistakes have been carried out, in this mining activity, with serious economic consequences. One of the major problems is related with the instability of the quarries slopes, because the orientation of the quarrying is not always made in agreement with geological structure. Moreover, the big deep of the quarries, gives rise to an increase of the in situ stresses in the rock mass mainly in the bottom levels and consequently to an increase of the intensity of fracturing.

This paper contains references to some recent examples on the influence of discontinuities on the rock slope stability of the quarries of marble located in the Alentejo region as well as on the geomechanical behaviour of the rock masses which if not adequately addressed can decrease the safety of people and cause material damage.

In the case study presented, the analysis of the stability of a slope was done, based on a geological and structural data, in order to evaluate a possible failure of the slope due to the mining evolution that could affect a quarry and a road next to the slope of the quarry in analysis. It appears that the slope has an adequate stability with factors of safety above the equilibrium limit, despite the unfavorable orientation of the main set of discontinuities in relation to the slope. The non-removal of the rock mass that constitutes part of the front benches of the 5th and 6th floors (see Fig. 5), will contribute to the stability of the slope, reducing the works of reinforcement of rock mass by rock bolts. The limited extension of the discontinuities and therefore its low connectivity has the same effect.

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