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Dimension Stone Quarries Risk Assessment
Estremoz Marbles

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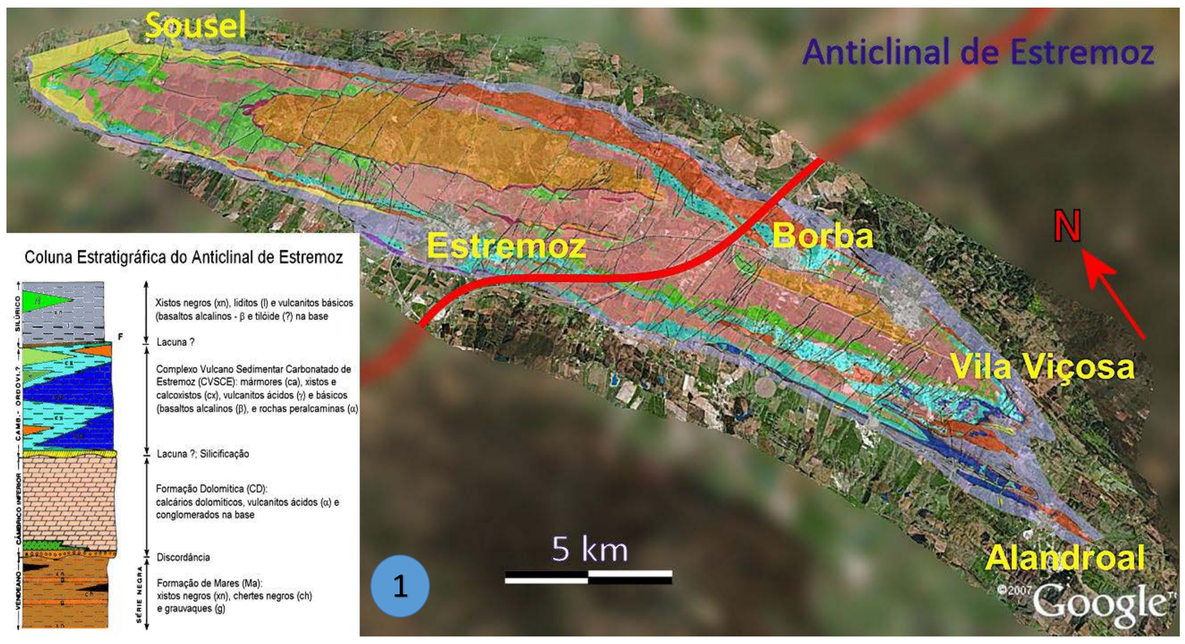
Abstract

For centuries, dimension stone marble exploitation from the Estremoz Anticline, south Portugal **(1)**, lead to a peculiar landscape consisting of hundreds of deep open pit quarries.

In the 80's of the last century, more than 180 quarries operate side-by-side simultaneously. The struggle for interesting outcrops, in addiction to private property, that legally characterizes the mineral masses in Portugal, led to a situation where the quarries very close to each other developed into a well and independently.

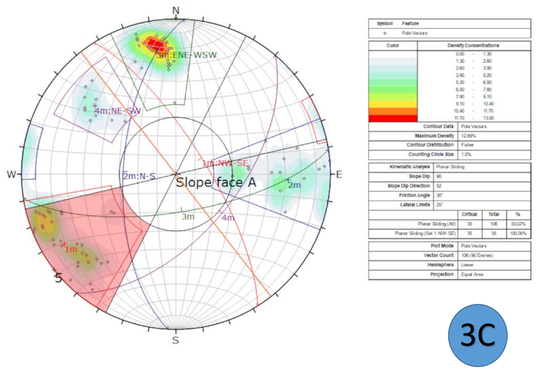
As the quarries reached greater depths, in several cases over 100 meters, issues related to the slope stability became more evident and dangerous **(2A)**. Even so, it took an accident that caused 5 deaths due to a slope collapse that destroyed a municipal road **(2B)**, for public entities to pay more attention to this issue.

Within the scope of the Intervention Plan in Quarries Under Critical Situations (2019-2021), approved at the meeting of the Council of Ministers, on February 7 (RCM 50/2019), the University of Évora carried out 34 slope stability studies in approximately 40 exploitation cavities for ornamental marble. The paper presents a summary of the main situations that were identified as well as the measures recommended for their mitigation.

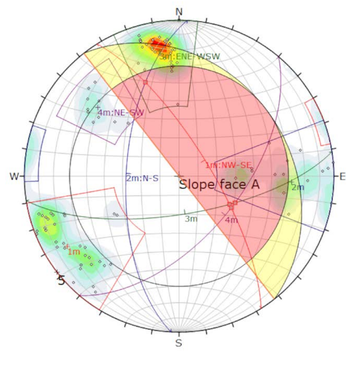


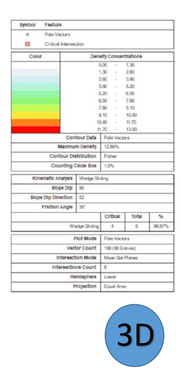
(**2A**) Quarry located next to the municipal road M255 that would eventually collapse (**2B**) at 15:45 on November 19, 2018, with an approximate length of 100 m. As a detail, note the lack of arboreal screen on the crest of the slope in (2B).

(3) Example of slope stability of the southwest slope in a quarry with suspended mining, which configures a situation like to that of the M255 road, with the "Dips" software. In truth, and luckily, situations like this are not the most common. (**3A**) View to the northeast; (**3B**) Southwest view; (**3C**) Planar sliding situation; (**3D**) Wedge sliding situation.



3C





3D

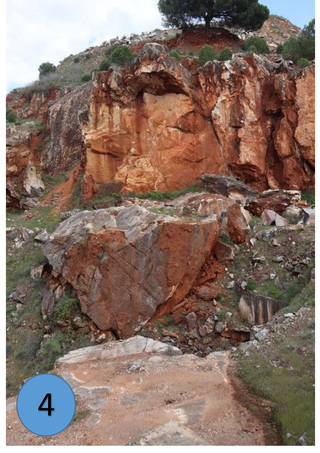
Physical and mechanical characteristics of the Estremoz Anticline marbles. **Mean values for 36 samples (Casal Moura et al. 2007).**

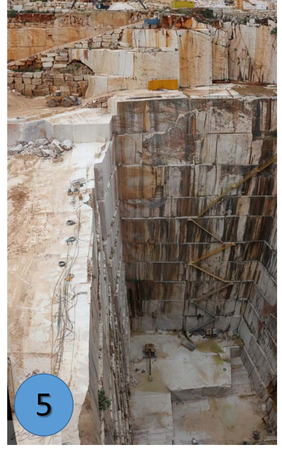
		Máx.	Mín.
Compressive strength	(MPa)	108,56	59,04
Compressive strength after freezing test	(MPa)	103,66	67,18
Mechanical strength to bending	(MPa)	29,52	14,51
Dry density	(kg/m^3)	2726	2703
Absorption of water at atmospheric pressure	(% height)	0,11	0,03
Open porosity	(% volume)	0,32	0,05
Dilation coefficient	(x10-6 °C)	16,3	5,4
Wear resistance	(mm)	3,8	1,4
Shock Resistance	(mm)	70-75	45

Geotechnical properties of marbles from Lagoa area, Estremoz Anticline (Silva, 2001).

Lithology	E(GPa)	ν	σc(MPa)	σt(MPa)	c(MPa)	ϕ(°)
Cream marble without stripes	66	0.222	94	10.4	13.1	50
Cream marble with stripes	57	0.39	61	9.0	10	48
Grey marble with stripes	59	0.38	64	9.0	19	47

E(GPa) Young´s modulus	σ_t (MPa) Tensile strength
ν Poisson´s ratio	c (MPa) Cohesion
σ_c (MPa) Uniaxial compressive strength	ϕ (°) Friction angle





Reporting some situations...

(**4**) fall of a large block in an abandoned quarry with the heap invading the cut;
(**5**) two quarries with no defense zone between them but with different exploitation levels;
(**6**) northeast slope of quarry with several situations of imminent risk identified;
(**7**) geotechnical intervention aimed at consolidating the slope at risk of falling, note that the bottom of this quarry reaches 150 meters (**9**), and only when there is no risk of fragments falling or any rupture, into the cavity , is that it will have an exploitation license again;
(**8**) details of the work carried out;
(**10**) example of bad practices by ambitious mining with development of an underground quarry following the marble deposit but leaving behind slopes in shale whose stabilization requires costly intervention, the exploration was abandoned.

Results

For the slope's potential instability study, the methodology of Hoek and Bray (1981) was considered, having resorted to the Markland method, considering the refinement introduced by Hocking to this method, in the distinction between the type of planar failure and the type of failure wedge rupture. Regarding the analysis of the potential instability through toppling failure, the conditions proposed by Goodman and Bray (1976) were used. In the stability evaluation, the friction angle value of 30° was considered for the most open fractures and filled with terra rossa. This situation basically corresponds to the characteristics of the more open fractures that exist at the most superficial level of the quarries.

This situation is predictable due to the existence of a late stress field of regional expression, with maximum compression tilting around 30°, which originates oblique conjugate fractures in relation to the vertical slopes of the cavities.

Moat critical situations detected:

1. Built structures instability in the vicinity of the cuts;
2. Derrick cranes even had to be removed because they did not have fixing bases in good condition;
3. Poor sanitation was found at the top of the slopes with probable and/or effective fall of soil and rocks into the cavity;
4. Most superficial geotechnical horizon of the rock/mass, is frequently altered (W4-5) and moderately fractured (F3);
5. Karstification can go beyond 5 meters, with residual soil filling (*terra rossa*), favouring material slides (rock blocks and soils), from the top of the slope to cavity interior;
6. Wedge failure will be the most likely to occur;
7. Planar rupture situations are frequent;
8. Toppling failure was only occasionally observed in the field.

Although the late stress fields are well known, it should be noted that the local geological conditions at the quarry's scale define the orientation of the present discontinuities. For example, the existence of a dolerite dyke, metavolcanics rocks and dark shales interbedded in the marbles, among other factors, will determine the geometry and density of the discontinuities that occur in each quarry.

Concluding Remarks

From the analysis carried out, it is concluded that most risk situations can be mitigated or even eliminated if future mining plans include several adjacent licenses. In this way, unnecessary defense zones are eliminated, recovering that volume for commercial purposes while substantially improving the safety conditions of workers.

As expected, since confined stress deeply increases it was found that fracture density decreases at depth, and the existing discontinuities also tend to be more closed. On the other hand, the connectivity between fractures is low, which explains that despite the large extension of the slopes, only one accident occurred on November 19, 2018, at EM 255 in Borba, which caused 5 victims. Although three more cases are known in 40 years, fortunately without victims.

A very conservative assessment of the existing raw material in the anticline (Lopes and Martins, 2015), point that even at the highest annual production rates ever achieved, there will be enough quality marble for another 550 years of uninterrupted mining. For this to happen, must be changed, both in exploitation methods, aiming at optimizing mining and mitigating the risks associated with it, as well as in the business model and organization of the companies.

Acknowledgements

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