Contribution to the geomechanical stability of marble underground openings using backfill

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Abstract. A stability analysis on the possibility of using room and pillar underground mining method, in a marble quarry in Alentejo (Portugal) with backfill, is presented. Given the data provided by the laboratory tests over marble samples and in situ tests as well as a thoroughly geology acknowledgment of the area, a new excavation design was presented for the underground phase, using Finite Element analysis, where global and local stability is assessed. Moreover, the innovative idea, for marble underground quarries, was to contribute to the circular economy and the current environmental policies by making a use of the quarry’s waste rock, as the principal aggregate for a backfill material, that not only reduces the impact of wastelands in the surface but also acts as support for the newly excavated area leading to residual pillars recovery. Given this, an overview of the stress displacement is presented, and the main potential instability zones are assessed. The results are a quantitative contribution to the characterization of the rock mass for alternative ways of ornamental marble production in this region.

1. Introduction

The production of natural stone in the Portuguese region of Alentejo, specifically in the Ossa Morena Zone (ZOM), has been historically popular and profitable throughout centuries [1]. This region, and inherently, the mineral deposit, is one of the top marble producers in the world. Despite its high profitability marble is a non-renewable geological resource and following the European standards of circular economy [2] operations in the quarries have seen the need to develop more sustainable and greener solutions for the extractive methods that produces big volumes of wastes, as well as to recover the maximum mineral possible without jeopardizing the environment and safety of workers and equipments.

According to [3], technical and economic problems in the Alentejo marble quarries arises when changing the excavation method to underground mining. In this case, the underground openings are excavated directly in the productive and massive rocks, avoiding the removal of overburden. According to this study, it is necessary to maintain stable structures in the rock (rib pillars and eventually thick horizontal beams) without excessive loss in block recovery. A stability analysis is the key to understand how the model will react to the given conditions [4]. The application of tools and models in rock mechanics to underground exploitations is justified for safety reasons, guaranteeing the stability of the exploitation in relation to workers and, for economic reasons, by controlling ground deformation and
excavation to prevent the disruption of the work [5]. For the room and pillar method, several works have studied the requirements of this mining type to ensure safety [6].

In the application of numerical techniques on underground mining structures, three stages should be considered related to modeling: the development of the model, its application and validity [7]. To carry the stability analysis, it is crucial to set the input data for the model as closely to the real case, for this, some information about the rockmass needs to be analyzed. Such information begins with the determination of the proper failure criterion that will be used, to describe its non-linear response up to failure with a suitable material model [8]. The simplest model used in practice is the elastic-perfectly plastic model combined with a Mohr-Coulomb failure criterion. The model is used to describe the real rock stress-strain response with an idealized elastic-perfectly plastic stress-strain curve, as it requires the minimum number of input rock parameters [9].

Further on, important information about discontinuities should be stated, like orientation and spacing, as well as the in situ state of stress.

The case study considered in this work is an open-pit in Vila Viçosa, that is reaching a point of its mining life where the pit opening has gotten too deep and, for further exploitation, it has become necessary to change the excavation method to underground room and pillar mining method. The study simulates the proposed room and pillar excavation with full recovery of the residual pillars, thanks to a backfill plan, where marble wastes from the exploitation are used as the main aggregate for the cemented rockfill. The backfill should act as main support for the lower level of the pit, right above where the excavation lies. Through numerical methods, the quarry model and its openings will be interpreted to conclude local and global stability of the project. For this, the Finite Element Method (FEM) software, RS3 from Rocscience Inc, was used, as well as the definition of key parameters to produce a reliable simulation on the model.

2. Case Study
The Monte d’el Rei MJ 5282 quarry is located in the area known as the “marble triangle” (Estremoz – Borba – Vila Viçosa) in Alentejo’s northeast, between Sousel and Alandroal villages. The marble deposit, corresponds to a geological structure that has a grossly symmetrical shape in anticline antiform. It has an elliptical form (45x8 kilometres) that extends, according to the major axis, from the settlement of Cano, northwest, to Alandroal, southeast [10]. The quarry has a pit that reaches down to 156 m in depth and the underground openings are two drifts created at pit level, one goes directly into the pit and the other one starts from a dome-like opening in the SW flank. From this point of view, it will be sensible to start the room and pillar excavation from the open pit cut, as in opposition of starting it from the top surface. To complete the model, laboratory and in situ tests were previously carried out to define stresses, elastic properties as well as a characterization of the geo-structural conditions. The characterization of the existing three main families of discontinuities (table 1) was made according to the four slopes of the quarry individually, namely: Slope NW, Slope NE, Slope SE and Slope SW [11].

| Family | Direction | Dip            |
|--------|-----------|----------------|
| 1      | N50 - 70W | 30 - 85° SW/NE |
| 2      | N10 - 30W | 30 - 70° SW    |
| 3      | N30 - 65E | 30 - 80NW/SE   |

All the other families have continuity of 30 to 10 m, without apparent change. A fourth discontinuity was found but had a sub-horizontal direction with a length from 10 to 30 meters [12]. Following the work from the Laboratory of Geosciences and Geotechnologies (GeoLab) at Center of Natural Resources and Environment (CERENA) of Instituto Superior Técnico (IST), mechanical tests were done [13] to determine physical parameters, the Brazilian test for tensile strength determination, uniaxial compressive strength determination test (where Young’s modulus and Poisson coefficient were also
determined); triaxial compression strength determination test and joint direct shear strength determination test (obtaining cohesion and friction angle values, Table 2). These tests were done out of samples taken directly from the quarry domain in three different levels and from drill cores.

| Families of discontinuities | c (kPa) | Φ (°) |
|-----------------------------|--------|------|
| Family 1 (N60°E)            | 140    | 42   |
| Family 2 (N20°W, 72°S)     | 250    | 46   |
| Family 3 (N40°W, 72°N)     | 310    | 51   |

From the physical analysis, the density had an average value of the marble of 2687.61 kg/m³, the dry density 2687.07 kg/m³ and the saturated 2689.89 kg/m³ with a porosity of 0.003. The strength and elastic properties of the marble rock calculated were the tensile strength, σt, with a value of 7.31 MPa, the compressive strength, σc, 69.09 MPa, the Elastic module, E, 57.62 GPa; Poisson’s ratio, ν, 0.24; cohesion force, c, 11.15 MPa and the internal friction angle, ϕ, 54.67°.

3. Methodology
To estimate underground stability, numerical methods such as the Finite Element Method (FEM) are a valuable way to do it. The chosen software that adapts the FEM to a geotechnical problem is RS3 from Rocscience Inc.

To state the FEM problem, first the calculation of the excavation parameters to present a design and a dimensioning that optimizes the maximum recovery without jeopardizing safety [14] is performed. The procedure to design the layout of the excavation is carried out following the theory of the Tributary Area for the estimation of the stress involved on the pillars [15]. Taking from the studies carried out by [16] and with previous knowledge of [17] on pillar design for ornamental stone room and pillar excavations, pillar strength, S, can be estimated with the following Equation 1:

\[ S = k \times \frac{W^{0.3}}{H^{0.59}} \]  (1)

Where W is the width of the pillar, H is the height of the pillar and 0.3 and 0.59 are parameters related to the geomechanical conditions of the rock mass. With k being, a parameter related to rock strength (Equation 2),

\[ k = 0.65 \times UCS \]  (2)

The UCS will be retrieved for the calculation above, from the laboratory test, where it measured an average value of 69.09 MPa. An optimization procedure was applied, using the vertical stress equation and the stress equation for square pillars, \( \sigma_p \) [18]:

\[ \sigma_p = \sigma_z \times \left[ \frac{W_p + W_o}{W_p} \right]^2 \]  (3)

Where \( \sigma_z \) is the vertical stress, \( W_p \) is the pillar width and \( W_o \) is the width of the room. The confinement depth, Z, was considered adding the actual pit depth plus a roof beam of two meters [16].

Observing table 3, option A, with 10x10x7.5 m pillars, was selected, taking into account the safety factor typically used for such stone quarries (SF = 1.2) [16]. Having this information the study will proceed to analyze the geomechanical model, built upon a simplification of the quarry. The room and pillar excavation will reach an area of 36640.41 m² and a perimeter of 775.3 m, which allows a total number of 80 residual pillars.

3.1. Definition of the model in RS3
From the creation of the geometry, other steps will come after as the procedure when doing Finite Element Analysis. First, it will be necessary to define the materials and the structural properties; and with this, the failure criterion will be selected. For this study, the most competent was the Mohr-Coulomb jointed, which implies defining various properties for the three families of discontinuities in this case. Marble material will be defined as ‘Geology’ and a second material, based on cement will go by the name ‘CRF’ and the results were taken from the literature (table 4). The geologic material will make use of the parameters calculated previously in the laboratory tests.

**Table 3. Pillar design optimization values.**

| Z=158 m | A | B | C |
|---------|---|---|---|
| Pillar width W (m) | 10.00 | 15.00 | 18.00 |
| Pillar height H (m) | 7.50 | 7.50 | 7.50 |
| Width to height ratio | 1.30 | 2.00 | 2.40 |
| Room width B (m) | 10.00 | 14.00 | 17.00 |
| Pillar strength S (Pa) | 27.29 | 30.82 | 32.56 |
| Actual pillar stress σ_p (MPa) | 16.43 | 15.35 | 15.53 |
| Safety factor SF | 1.66 | 2.01 | 2.10 |
| Recovery (%) | 75.00 | 73.00 | 74.00 |

**Table 4. Rockfill (CRF) properties for material definition.**

| Material | σ_t (MPa) | E (GPa) | v | c (MPa) | φ (°) |
|----------|-----------|---------|---|---------|-------|
| CRF | 3.17 | 3.50 | 0.30 | 1.50 | 40.00 |

For this particular model, it was necessary to create a refined mesh that covered all geometry. As the volumetric scope of the model was too big for small structures, e.g. a 10x10 pillar in comparison with a total depth of the volume of 256 m, a mesh refinement was needed. These refinements were focused on the drifts and in the room and pillar excavation. In general, the mesh selected was a 10-noded tetrahedral graded mesh. Boundary conditions need to be defined so as the program executes the simulation in a closed scope. Restains will be applied in every face of the volume parallel to the axis plane they are perpendicular to. The suggested process to lay and fill the drifts in the excavation follows a proposal made by [19] on the Ershike coal mine, in China. For this study, rockfill material will be taken as already consolidated and will focus on the layout of the backfill itself. Also, a full backfill, i.e. tightfill or cemented rockfill will be laid up until the roof of the excavation to avoid convergence [20].

The backfill method will divide the 80 residual pillars into three operational areas figure 1, where, starting from an already excavated stage, will continue in each area first with the creation of supporting pillars on the north and south face of each pillar, will continue with the removal of the remaining marble pillars and will finalize with the filling of the volumes left, giving in total, 10 stages, that begin with the excavated area until the total backfill of the underground opening. The rock-backfilling material is mixed and processed in a processing plan located near the opening. These materials are transported through filling pipelines to the excavation room for backfilling. The filling pipelines will end in the void created by the residual pillars and retaining walls, that once dry, they will be removed and placed onto the other ones [19].
**4. Interpretation of Results**

After computation, certain parameters should be looked upon to make a stability assessment. From the RS3 result tab, it is important to note the results given by the Strength Factor option. The strength factor is calculated by dividing the rock strength by the induced stress at every point in the mesh. In the case of elastic materials, the strength factor can be a negative value, since overstressing is allowed. When looking for weaker spots in the excavation, an isosurface of a certain desired value was created. The isosurface had a value near to 1, but slightly below, 0.9, so unstable areas can be studied for other parameters along all the stages. For the first stage, this is the excavation stage, where drifts are already created; no areas with a strength factor below one are spotted. This also happens for stage 2, where backfill starts but no residual pillars are removed yet. Only in stage 3, is when a strength factor of 0.9 starts to show. This can be explained due to the removal of the pillars and the support solely done by one set of backfilled pillars. These weak areas will be such that even with the second set of backfilled pillar around all the pillars that support the immediate walls from the pit figure 2, will create a potential failure.

![Figure 1. Division of the initial excavation into three areas, in blue, the residual pillars. The red arrow indicates backfill direction, leaving the ramp (black arrow) free for operations until the last stage.](image1)

![Figure 2. Last stage of the project with a strength factor isosurface equal to 0.9 (in red colour) presenting a shape that follows the open-pit opening contour, positioned immediately above on the Z axis in this image.](image2)
width, and not on the rockmass floor or/and roof figure 3, where the strength factor is displayed with the 0.9 strength factor isosurfaces.

![Figure 3](image)

**Figure 3.** Last stage of the project with 0.9 strength factor isosurface on the pit contour.

Taking into account what has been seen above a further investigation of the problematic area is carried on. The results can be systematized under two representations of the stress distribution in the modelled excavation, namely the distribution of average stresses and shear stresses. A point in stage 5 was selected due to its low strength factor and the instability tendency around the pit contour. To visualize value gradation on a temperature map, an RS3 tool called ‘query line’ was drawn along the edge of a rockfilled pillar that covered the unstable point. To make a correlation between the strength factor and the stress state, it is essential to look values around the most problematic point in this query line along the stages. The lower the strength factor is, the higher the tensions will be for the given point. In this particular query line the lower value obtained was –8, in stage 5 (Light green line in figure 4; dark red line in figure 5).

![Figure 4](image)

**Figure 4.** Strength factor plot for the query line. The ‘x’ axis represents the points studied in the query line. The ‘y’ value represents the strength factor for each point. The multiple functions represent each stage.

![Figure 5](image)

**Figure 5.** Shear stress on XZ plane plot for query line. The ‘x’ axis represents the points studied in the query line. The ‘y’ value represents the shear strength for the XZ plane for each point. The multiple functions represent each stage.

The shear stress is divided into two components according to the Z axis, parallel to the gravity force direction. So for this case, graphs for XZ plane and YZ plane are studied. The maximum value for the XZ plane is approximately 4.0 MPa in stage 6. For the YZ plane the maximum tension is also reached in stage 6, but with a value of 2.5 MPa. As for the mean stress, it was seen that slopes were inversely proportional to the SF one, which means that principal stresses are not the main cause of failure for this spot and by extension, to the failure areas, mostly concentrated around the pit. The lowest SF point in the query line matches with the highest value obtained of the kinematic modes for the same point, which
in this case it is the shear stress on the XZ plane, indicating an inverse relationship. From the numerical model it was possible to observe how shear stress accumulates in the corners of the pit just above the excavation. This can be explained as principal stresses are very high in this area and shear stress from the plane of the slope of the pit and the planes from the pillars are in opposite directions and this resulting in the location of intersection having the highest values of shear stress.

Finally, total displacements are analyzed to measure the impact of the room and pillar excavation in the existing pit, i.e., slopes and surface foundation. From a contour plane, in the last stage, the most affected due to the total backfill of the area, values from total displacements can be seen in figure 6.

![Figure 6](image)

**Figure 6.** Temperature map on displacements on XZ plane. The circle marks the biggest displacement of the simulation, around the corner of the pit and above the rockfilled volume.

There is an area near the left corner of the pit, where displacement reaches its highest value. Despite this, this value is approximately 0.0051 m and represents little concern for global or local stability.

### 5. Conclusions

This work meant to contribute to the present European policies on circular economy particularly for the mining sector. It was suggested a business strategy where residual materials or tailings from the exploitation, accumulated in wastelands, were given a purpose to improve mining recovery and act as an added support for the excavation. From this particular case, where an underground room and pillar excavation for marble was introduced to a backfill scenario, making use of the quarry’s wastes, little information was proven to be found and, from that, it can be concluded that this paper, is, to say the least, innovative in this field of work. The importance of the state of stress to determine local and global stability for the proposed excavation was key to this study. After presenting the results in the chapter above some conclusions can be drawn upon:

- It appears an area following the pit’s contour, regarding the strength factor as a mean of determining stability, will not perform as expected and will inevitably cause failure on the pillars.
- The main component in the stress state, main source of lower strength factor, is the shear stress in the plane XZ. As it is expected due to pillars with low strength factor will lead to failure because of reaching the value of shear strength. It is also important to mention that failure will be exclusively done on the rockfill volume and in no way it appeared that the floor or the roof of the excavation will cause rockfall or failure.
- Displacements will occur as a local event, in the area where the shear stress is concentrated; this is, in the bottom corner of the pit. These displacements are millimetric and present little to no impact on the quarry stability, neither on the slopes of it nor in the surface.
To ensure stability it is recommended that the removal of marble pillars and the following backfill is done individually for each volume, i.e. when a pillar is removed, before removing the others from the same area, backfill immediately and so on.

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