Contribution to the geomechanical stability of marble underground openings using backfill

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Abstract

The present work carries out a stability analysis for a Portuguese marble quarry, in prospects of initiating a new underground excavation by means of the room and pillar method. Given the data provided by laboratory and in situ tests as well as a thoroughly geology knowledgment of the area, so called, Borba-Estremoz-Vila Viçosa anticline, and starting from a simplified model of the current open pit, a new excavation design was presented for the underground stage the quarry has started to transition. In order to elaborate, model and estimate the behavior of such excavation in three dimensions, the Finite Element Method software, RS3 from Rocscience, was used. Besides from studying global and local stability in the openings, an idea of contributing to circular economy and environmental sustainability was introduce by making an use of the quarry's tailings, 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 and a mean to recover the residual pillars.

Keywords: Finite Element Method, Rockfill, Underground quarrying, Stability analysis, Circular economy

1. Introduction

The exploitation of ornamental stone in the Alentejo Region, in Portugal, more specific, in the geological complex, the Ossa Morena Zone (ZOM), has been historically popular and profitable throughout centuries (Vintem et al., 1998). This region, and inherently, the mineral deposit, is one of the top marble producers in the world. In spite of its high profitability, marble is a non-renewable geological resource, and following the European standards of circular economy (Lèbre et al., 2017), operations in the quarries have seen a necessity to develop more sustainable and greener solutions for the extractive methods that causes great amount of tailings, as well as the important factor that is to recover the maximum mineral possible without jeopardizing safety neither for the environment nor for the people and equipment. In regards of this background situation, the quarry of this study, Monte d'el Rei 5258 MJ, located in Vila Viçosa, an open-pit exploitation, has reached a point of its mining life where the pit opening has gotten too deep and for further exploitation, considering more environmentally conscious practices as well as technical and engineering solutions, it has become necessary, in order to keep exploiting the mineral deposit, change the excavation method to underground room and pillar.

Having in mind both scenarios where a circular economy strategy for the quarry is demanded and the urge to exploit via underground methods, a study presented here analyses through a 3D simulation of the proposed room and pillar excavation with a full recovery of the residual pillar thanks to a backfill plan, where marble tailings from the exploitation are used as main aggregate for the cemented rockfill which will act as main support for the lower level of the pit. The simulation will proceed through numerical methods that consider a model of the open pit opening with the design of the room and pillar excavation to obtain results that will be interpreted to conclude local and global stability of the project. For this, Finite Element Method (FEM) software, RS3 from Rocscience Inc, was used.

2. Underground stability analysis

According to Oggeri et al., 2001, technical and economic problem 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 the 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 (Tesarik, 1995). 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 the deformation and excavation of the ground in order to prevent the disruption of the work (Cravero & Iabichino, 1997). For the room and pillar method several works have studied the stability that requires this type of exploitation to ensure safety, either for both equipment and workers or environmental (Correa, 1991). In order to produce a reliable simulation on the model, it is important that parameters that will eventually condition the analysis are pointed out. Main factors affecting mining stability are according to Herrera (2007):

- The field of efforts in situ
- The strength, deformability and other mechanical properties of the layers
- Groundwater conditions
- The method and quality of the excavation
- The support of the galleries
- The interaction between adjacent pathways

When assessing the efficiency or limitations of numerical techniques in mining, three stages should be considered related to modeling: the development of the model, the application of the model and the validity of the model (Harish, 2020). For this particular case, the FEM technique seems really appropriate. Developed by Courant (1943) it provides with an essential feature: discretization mesh of a continuous domain in a set of discrete sub-domains, generally called elements. Discretization involves dividing the geometry into a number of finite elements (mesh), the domain is then divided into finite triangular sub-regions to solve second order partial differential equations (PDE). 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 collected or analyzed. Such information begins with the determination of the proper yield criterion that will be used, to describe its non-linear response up to failure with a suitable material model (Kouretzis, 2018). The simplest model used in practice is the elastic-perfectly plastic model combined with a Mohr-Coulomb failure criterion referred to as the Mohr-Coulomb model for brevity. The model is used to describe the real rock stress-strain response with an idealized elastic-perfectly plastic stress strain curve, which is direct to define as it requires the minimum number of input rock parameters (González de Vallejo et al., 2002). Further on, important information about discontinuities performance should be stated as well as the state of stress in situ among others :

- Orientation of the discontinuities in the rock mass
- Spacing of these discontinuities
- Condition of the discontinuities including roughness, separation, persistence, weathering and filling
- Characteristics of groundwater
- State of stress in situ
- Resistance and deformability of the in situ rock mass material

In the room and pillar method the design of the excavation is based on the compromise between security and the maximum economic use of the mineral deposit (Gabriel S. Esterhuizen et al., 2011). The roof between the pillars is required to remain stable during mining operations for haulage as well as access to the working areas as from Esterhuizen et al., 2010, roof and rib falls account for about 15% of all reportable injuries in underground stone mines. Factors such as stress, weak bedding planes, discontinuities and weak roof rocks are the main causes for pillar and roof span failure.

3. 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 geology where the quarry is located and by that means, the marble deposit, corresponds to a geological structure that has a grossly symmetrical shape in anticline antiform. It has an elliptical form (45x8 kilometers) that extends, according to the major axis, from the settlement of Cano, northwest, to Alandroal, southeast (LNEG, 2007). It has been studied and declared that the anticline holds 100 x 106 m3 of evaluated resources and currently the exploitation covers an area of 2550 ha. Monte D'El Rei MJ-5285 is located in the core of quarries of Monte D'El Rei, belonging to the parish of Bencatel, in the municipality of Vila Viçosa, Évora district. The quarry begins with an open pit exploitation with an opening reaching down to 156 m in depth. The underground openings are so far two drifts created at pit level, one goes directly into the pit and the other one starts from the dome 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 (Figure 1), as in opposite of starting it from the top surface.

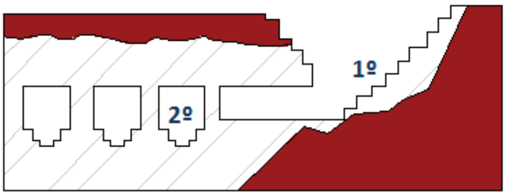

Figure 1. Stripping method sequence for quarries

In order 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 discontinuities was made according to the four slopes of the quarry individually, namely:

Slope NW, Slope NE, Slope SE and Slope SW. For the geo-structural characterization, families of discontinuities were pointed out (Table 1) (Lopes et al., 2019).

Table 1. Discontinuities families with correspondent direction and dip.

Families of discontinuities	c (MPa)	Φ (º)
Family 1 (N60ºE)	0,14	42,04
Family 2 (N20ºW, 72ºS)	0,25	46,05
Family 3 (N40ºW, 72ºN)	0,31	51,32

All the other families have a 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 (Lopes, 2007).

Following the work from the Laboratory of Geosciences and Geotechnologies (GeoLab) at Center of Natural Resources and Environment (CERENA) of Instituto Superior Técnico (IST) and the some tests were done (CERENA, 2019):

1. Test to determine the physical parameters of the samples;
2. Test for determining the resistance to indirect tensile strength (Brazilian test);
3. Test to determine the resistance to uniaxial compression with determination of Young's modulus and Poisson's ratio;
4. Test for determining the resistance to triaxial compression;
5. Test for determining shear strength, applied in joint samples from the three joint families (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.

Table 2. Cohesion and friction angle values for each discontinuity family.

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

From the physical analysis the density had an average value of 2 687,61 kg/m^3, the dry density 2687,07 kg/m^3 and the saturated 2689,89 kg/m^3 with a porosity of 0,003.

The strength and elastic properties calculated were the tensile strength, σ_t, with a value of 7,31 MPa, the compressive strength, σ_c , 69,09 MPa, the Elastic module, *E*, 57,62 GPa; Poisson's ratio, υ, 0,24; cohesion force, *c*, 11,15 MPa and the internal friction angle, φ, 54,67º.

4. Methodology

In order to estimate values on underground stability, numerical methods such as the Finite Element Method (FEM) are a valuable way to do so. The Finite Element Method is a numerical technique for solving problems that are described by partial differential equations or can be defined as functional minimization (Sarathchandran, 2014). The chosen software that adapts the FEM to a geotechnical problem is, RS3 from Rocscience Inc, it will proceed with the FEM steps such as discretize the domain of the problem and by so create finite elements with an unknown function in each node; it selects then the interpolation function that will interpolate the field variables over the element, then it will find the domain related properties that will establish a connection between the nodal values of the unknown function to the problem properties; it assembles the element equations and solve the global equation system so nodal values of the sought function are produced as a result of the solution and finally additional results are computed, such as stress and strain values,

RS3 will ultimately proceed to do the steps aforementioned by creating geometry for the problem first. To do so, there is one step before that needs to be assessed, that is the calculation of the excavation parameters to present a design and a dimensioning that optimizes the maximum recovery without jeopardizing safety (US Bureau of Reclamation Engineering, 1977). 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 (Medina-Aguilar, 2017). Taking from the studies carried out by Esterhuizen et al. (2008) and with previous knowledge of Roberts et al. (2007) on pillar design for ornamental stone room and pillar excavations, pillar strength, *S*, can be estimated with the following equation:

$$S = k * \frac{W^{0,3}}{H^{0,59}}$$

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,

$$k = 0,65\ x\ UCS$$

An optimization was calculated, using as well the vertical stress equation and the stress equation for square pillars. The confinement depth was considered adding to the actual pit depth plus a roof beam of two meters (Esterhuizen et al., 2008).

Table 3. Pillar design optimization values.

Z=158 m	**A**	**B**	**C**
Pillar width W	10	15	18
Pillar height H	7,5	7,5	7,5
width to height ratio	1,3	2,0	2,4
Room width B	10	14	17
Pillar strength σ_r (MPa)	27,29	30,82	32,56
Actual pillar stress σ_p (MPa)	16,43	15,35	15,53
Safety factor FS	1,66	2,01	2,10
Recovery	75%	73%	74%

Observing Table 3, option A, with 10x10x7,5 m pillars, was selected.

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 36 640,41 m^2 and a perimeter of 775,3 m, which allows a total number of 80 residual pillars. From the creation of the geometry of the model other steps will come after as the procedure when doing Finite Element Analysis:

1. Definition of Material and structural properties. Here the yield 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 off of

cement will act as ‘Rockfill’ (Table 4). The geology material will make use of the parameters calculated previously in the laboratory and presented above in chapter 3.

Table 4. Rockfill properties for material definition

Material	**σt (MPa)***	**E (GPa)****	**υ****	**c (MPa)****	**φ (°)****
CRF	3,17	3,5	0,3	1,5	40

2. Mesh generation. 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 smaller structures, e.g. a 10x10 pillar in comparison with a total depth of the volume of 256 m. 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.
3. Boundary conditions need to be defined so as the program executes the simulation in a closed scope. Restrains will be applied in every faceof the volume parallel to the axis plane they are perpendicular to.

The suggested process to lay and fill the drifts in the excavation is a proposition from previous literature made by Zhou et al., (2019) on the Ershike coal mine, located in Hengshan County, Yulin City, Shaanxi Province in China. For this study rockfill material will be taken as already consolidated and will focus in the layout of the backfill itself. For this study it will be considered a full backfill, i.e. tightfill or cemented rockfill will be laid up until the roof of the excavation to avoid convergence (Murch, 2018). The backfill method will divide the 80 residual pillars into three operational areas (Figure 2), 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. In this simulation the project will scan 10 stages that begin with the excavated area until the total backfill of the underground opening.

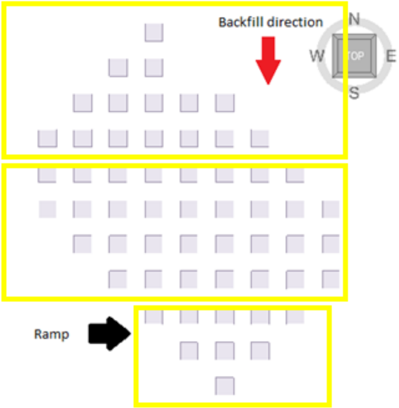

Figure 2. Division of the initial excavation

5. Interpretation of the Results

After the computation was done, there were certain parameters that 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 less than unity, since overstressing is allowed.

$$Strength\ factor = \frac{Rock\ strength}{Induced\ stress}$$

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.

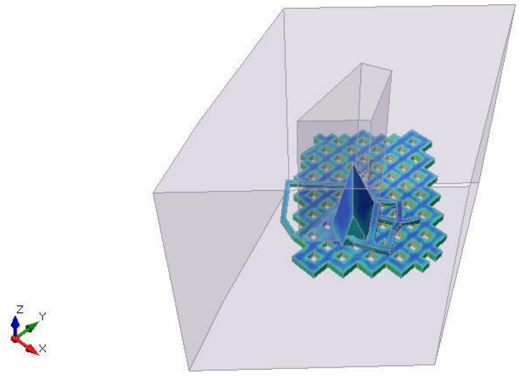

Figure 3. Stage one of the project

For the first stage, this is the excavation stage, where drifts are already created (Figure 3); 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 (BF2), 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 4), will create an stability failure.

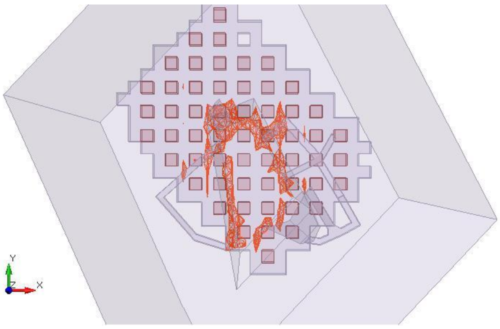

Figure 4. Last stage of the project with 0,9 strength factor isosurface on the pit contour.

It can be appreciated a contour area around the pit floor that extends approximately 5 m. This area increases in the north side of the open pit, indicating the influence of an already existing underground opening at level 156 m. It is important to notice that these instabilities will only occur in the excavated opening width, and not on the rockmass floor or/and roof, as it shows Figure 5, where the strength factor is displayed with the 0,9 strength factor isosurfaces.

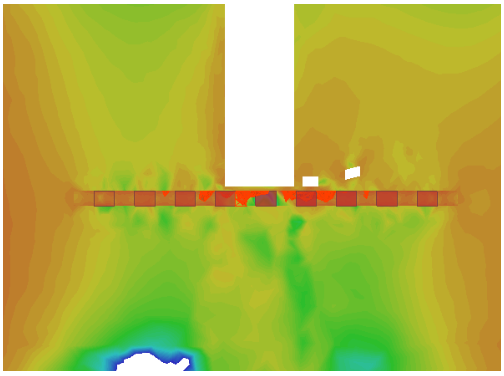

Figure 5. Strength factor on XZ plane.

Taking into account what has been seen above; a further investigation on the problematic area is carried on. The results can be systematized under two representations of the stress distribution in the modeled excavation, namely the distribution of average stresses (p) and shear stresses ($\sigma_{i,j}$), defined as follows:

$$p = \frac{\sigma_1 + \sigma_3}{2}$$

and

$$\sigma_{i,j} = \frac{\sigma_1 - \sigma_3}{2}$$

A point in the stage stage 5 was selected due to its low strength factor and the instability tendency that shows around the pit contour. In order to visualize value gradation on a temperature map, a RS3 tool called ‘query line’ it was placed in said problematic spot. In Figure 6, the query line can be seen where the strength factor was lower.

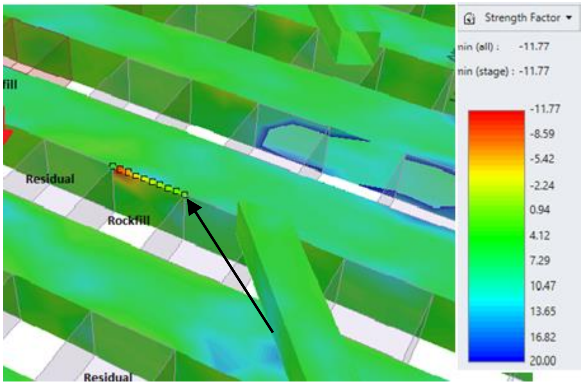

Figure 6. Display of the studied query line

To actually 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 (Figure 7).

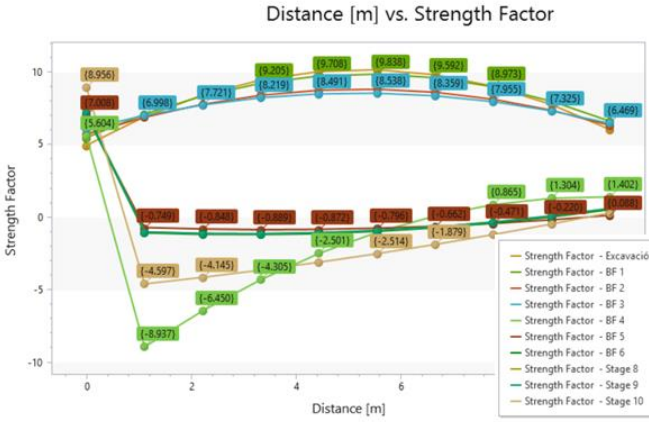

Figure 7. Strength factor plot for the query line

The shear stress is divided in two components according to the Z axis, parallel to the gravitation force direction. So for this case, graphs for XZ plane and YZ plane are presented.

The maximum value for the XZ plane (Figure 8) is approximately 4 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. The graph has a similar slope as the shear stress on XZ plane but lower values.

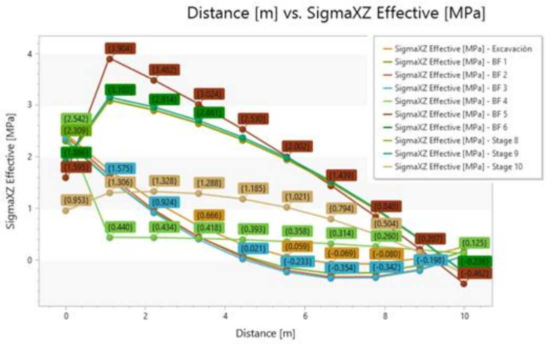

Figure 8. Shear stress on XZ plane plot for query line.

As for the mean stress, the distribution of normal stresses will provide important information in terms of failure planes and concentrated tensions.

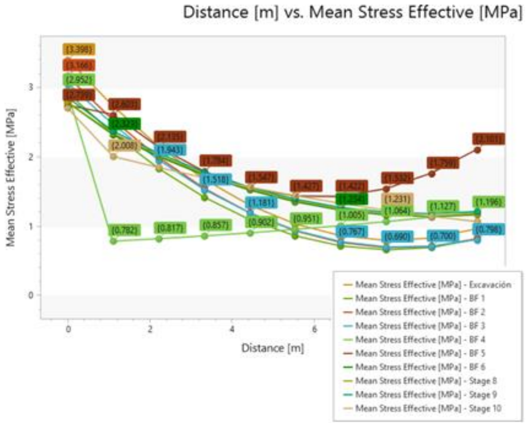

Figure 9. Means stress plot for query line

From this graph (Figure 9) it can be deduced that slopes are inversely proportional to the strength factor 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.

Finally, total displacements are analyzed in order to measure the impact of the room and pillar excavation in the existing pit, this is slopes and surface foundation. From a contour plane, in the last stage, the highest affected due to the total backfill of the area, values from total displacements can be seen (Figure 10).

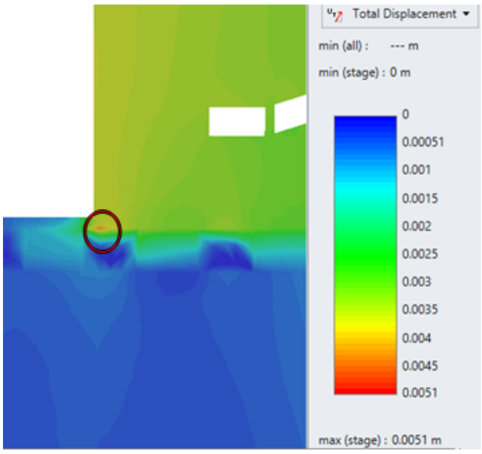

Figure 10. Temperature map on displacements on XZ plane.

There is an area near the left corner of the pit, where displacement reaches its highest value. Despite of this, this value is approximately 0,0051 m and represents little concern for global or local stability.

6. Conclusions

With this project it was also intended to contribute to the present European policies on circular economy and especially on the mining sector, where environmental laws have strictly dictated technical and financial feasibility. For this, it was suggested a way to follow this new pattern of business where residual material or tailings from the exploitation, accumulated in waste lands, was given a purpose not to only become a more environmentally-sound quarry but also a mean 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 tailings, 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 tension in order to determine local and global stability for the proposed excavation is key to this study. After presenting the results in the chapter above some conclusions can be draw upon:

1. It seems to exist an area following the pit's contour, regarding the strength factor as a mean of determining stability, will not perform as expected and will inevitable cause failure on the pillars. For this reason is recommendable that if ever exploited this area should be looked carefully.
2. It can be concluded that 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 rock fall or failure.
3. 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. It is important to mention that these displacements are milimetric and present little to no impact on the quarry stability, neither on the slopes of it, nor in the surface.
4. As it can be seen on the sequential removal of the pillars, great instabilities appear when removing all residual pillars at once from one area. To ensure stability it is recommended that the removal of these 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.

7. References

CERENA. (2019). *Estudo da estabilidade das escavações subterrâneas na pedreira Monte d'el Rei MJ - 5282*.

Courant, R. (1943). Variational methods for the solution of problems of equilibrium and vibration. *Bulletin of the American Mathematial Society*, *49*, 1–23.

Cravero, M., & Iabichino, G. (1997). Geomechanical study for the exploitation of an underground marble quarry. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *34*(3–4), 663.

Esterhuizen, G S, Dolinar, D. R., & Ellenberger, J. L. (2008). Pillar strength and design methodology for stone mines. *Proceedings of the 27th International Conference on Ground Control in Mining. Morgantown WV: West Virginia University*, *9*, 241–253.

Esterhuizen, Gabriel S., Dolinar, D. R., & Ellenberger, J. L. (2011). Pillar and roof Span Design in Stone Mines. *Department Of Health And Human Services, NIOSH*, 75.

Harish, A. (2020). *Finite Element Method - What is it? FEM and FEA explained*. SIMSCALE Blog. https://www.simscale.com/blog/2016/10/what-is-finite-element-method/

Herrera, J. (2007). *Diseño de Explotaciones de Cantera*.

Kouretzis, G. (2018). *Fundamentals of Geotechnical Engineering and their applications*.

Lèbre, É., Corder, G., & Golev, A. (2017). The Role of the Mining Industry in a Circular Economy: A Framework for Resource Management at the Mine Site Level. *Journal of Industrial Ecology*, *21*(3), 662–672.

LNEG. (2007). *Mármores e calcários ornamentais de Portugal*.

Lopes, Luís. (2007). O triângulo do mármore: estudo geológico. *Monumentos: Revista Semestral de Edifícios e Monumentos*, *27*, 158.

Lopes, Luis, Pinho, A., Duarte, I., & Martins, R. (2019). Caracterização e avaliação de riscos geológios e geotécnicos na pedreira nº 5282 Monte d'El Rei MJ. In *Journal of Chemical Information and Modeling* (Vol. 53, Issue 9).

Medina-Aguilar, V. H. (2017). Diseño de cámaras y pilares basado en las características geomecánicas del macizo rocoso en la corporación Minera Ananea S.A. - 2016. In *Universidad Nacional del Altiplano - Puno*.

Murch, A. (2018). *Dimensionamento de Bancadas Ascendentes Engenharia Geológica e de Minas*. Instituto Superior Técnico - Universidade de Lisboa.

Roberts, D., Tolfree, D., & McIntire, H. (2007). Using Confinement As a Means to Estimate Pillar Strength In a Room And Pillar Mine. In *1st Canada - U.S. Rock Mechanics Symposium* (p. 7). American Rock Mechanics Association.

Sarathchandran, A. (2014). Three dimensional numerical modelling of coal mine roadways under high horizontal stress fields. *University of Exeter*.

Tesarik, D. R. (Douglas R. . (1995). *Stability analysis of a backfilled room-and-pillar mine* (U. S. B. of Mines. (ed.)).

Vintem, C., Lopes, L., Lamberto, V., Barros, R., & Costa, C. (1998). Mármores de Estremoz: Geologia, Prospecção, Exploração, Valorização e Ordenamento da Jazida. *Livro Guia Das Excursões. Instituto Geológico e Mineiro*, 191–200.

Zhou, N., Yan, H., Jiang, S., Sun, Q., & Ouyang, S. (2019). Stability analysis of surrounding rock in paste backfill recovery of residual room pillars. *Sustainability (Switzerland)*, *11*(2), 1–13.