Three-dimensional Distinct Element Method for stability analysis of marble quarries in the Apuan Alps (Italy)

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Abstract. The present article analyses and proposes an innovative dynamic planning methodology, supported by computer tools and in-situ measurements, for the optimization of the planning techniques of underground marble quarries. The abovementioned planning methodology has been implemented in ‘Cava Piastreta’, an underground marble quarry located in the Apuan Alps, Italy. The entire excavation area has been characterized with tridimensional topographic surveys, geotechnical traditional surveys, and radar surveys, as well as stress-level measurement campaigns through a CSIRO cell. When an underground excavation project concerning stone material is designed, it is mandatory to have an instrument allowing a forecast of the stress-strain behavior of the rock mass. To this end, the rocky outcrop can also be represented by different mathematical models to schematize the geomechanical behavior. The accuracy and reliability of the simulation of the mechanical response of the fractured mass depend on the exactness with which the rocky outcrop is defined. Therefore, the geometric modeling phase acquires prominent importance. To better address the discontinuous nature of the studied rocky mass, the distinct element method has been used in modeling the mechanical behavior of the mass itself. Given the peculiar geometrical characteristics of the excavation site in question, the deterministic approach has been chosen to simulate as closely as possible the position of the major discontinuities identified in-situ. The present article thus aims to briefly describe a study that has been developed over the last years intended to deepen the analysis of the geostuctural characterization of the excavation site, as well as to compare the obtained results through the geometrical tridimensional modeling with the values measured in-situ.

1. Introduction
As part of the design of underground crops of stone material, it is necessary to have tools that allow a prediction of the stress and deformation response of the rock mass.

To this end, the rock complex can be represented by different mathematical models designed to schematize the geomechanical behavior. The reliability of a simulation of the mechanical behavior of the fractured medium depends on the precision with which the rock mass is defined, so the geometric modeling part is very important. The modeling of fractured rock masses therefore consists of two phases; geometric and mathematical.

For the modeling of the mechanical behavior of the rock mass in question, the method of distinct elements is used, which considers its discontinuous nature. Considering the geometric peculiarity of the excavation, a “deterministic” treatment was opted for in order to faithfully simulate the position of the main discontinuities found on site.
2. Geographical and geological framework

The Apuan Alps (NW Tuscany) represent the lowest geometric part of the surface of the northern Apennines. Their formation is due to an evolution of sedimentary origin, therefore tectonic, of a sector of continental crust, which refers to the Adriatic Plate, involved in an accretion-collision system during the Upper Oligocene-Lower Miocene. The Apuan marbles are born from the limestones of the Liassica platform (200-180 million years) positioned on a Triassic dolomitic layer figure 1.

The Apuan Alps have a history of fragile deformation that makes them a homogeneous domain of "reduced stress", surrounded by main defects towards the East and the West, which separate them from the opposite tectonic depressions of the lower Lunigiana, Versilia and Garfagnana [1]. This structural framework is characterized by a not very advanced organization of the discontinuity systems within the rock mass, which show a very low degree of interconnection between the individual structures and with limited displacements (from metric to multidecametric) of the individual structures [figure 1].

![Figure 1. Geostructural scheme of the Alpi Apuane inlier [2]](image-url)
3. Site characterization

The site was the subject of an accurate survey campaign, which included three-dimensional topographic surveys of the quarry using photogrammetry from drone and terrestrial laser scanner, traditional geotechnical surveys, surveys of fractures in the main pillars by radar, stress measurement campaigns using a CSIRO Triaxial HI-CELL.

The survey through digital photogrammetry and laser scanner made it possible to memorize a large number of 3D points on the surface of the rock wall, which, once processed, provided a three-dimensional model of the excavation surfaces, from which the geometry of the underground cultivation was obtained.

The point cloud obtained by joining the photogrammetric survey with the laser one was also used to extract the discontinuity planes that emerge on the cultivation fronts. Thanks to special automatic or semi-automatic codes it is possible to have an estimate of the orientation of the discontinuity planes that emerge on a wall, without directly accessing them.

Traditional geotechnical surveys have allowed identifying the main discontinuities groups characterizing the underground site, representing them through Schmid stereographic projection. As far as the joints mobilizers resistances were concerned, empirical parameters have been evaluated, such as JCS (Joint Compressive Strength) and JRC (Joint Roughness Coefficient), and direct cutting tests have been performed on samples [figure 2].

![Schmidt stereograms relating to the relief in the “Piastreta” quarry](image)

Figure 2. Schmidt stereograms relating to the relief in the “Piastreta” quarry

The survey with GPR was carried out by the Department of Earth Sciences of the UniTo, on a pillar considered of significant importance, as it is crossed by a cataclastic belt with NE-SW direction. Several
strips were carried out at different heights on two sides of the pillar, in order to reconstruct a three-dimensional spatial distribution of the same. The radiograms were analyzed by converting the times in depth, thus obtaining the orientation of the planes by transformation figure 3a and figure 3b.

Figure 3. a) Configuration of the strips performed with GPR; b) Example of radiograms acquired at different heights, highlighting the significant reflection events [3]

The state of stress acting on this site was assessed by the staff of the USL Toscana Nord Ovest - U.O.C. Mining Engineering as part of the "Tensional States" project, using the CSIRO Triaxial HI-CELL test methodology, and creating three measuring stations for a total of six tests. The measurements were carried out in a slightly fractured area between two parallel cataclastic bands of the field, with a NE-SW tendency, within which the underground quarry cultivation developed [4].

The measurements were performed horizontally along the NE-SW and NW-SE directions, which represent the main directions of advancement of the underground, and approximately parallel and orthogonal to the N70 transcurrent fault system.

Figure 4. Response curve observed during one of the overcoring tests at the quarry [4]
4. Geometric modeling
The creation of the geometric model was carried out with the aid of a calculation code specially developed by Itasca, Griddle. It is an extension to the Rhinoceros geometric modeling software, which allows you to reproduce with great fidelity the geometry of the excavation and the fractures detected in the characterization phases of the site.

The problem was discretized, defining the network of nodes and elements (mesh), and in the areas where strong tension gradients were expected, a denser mesh was used. To the developed geometrical model, constraints have been applied so to obtain a discrete model characterized by a finite number of degrees of freedom [figure 5.a].

5. Numerical modeling
The characterization of the mechanical behavior, elaborated through tests performed on rocky samples collected from the excavation site, has allowed understanding the geomechanical parameters and the geotechnical behavior of the excavation site itself.

Numerical methods exploit the stress design method, which consists in determining stresses and deformations in the rock mass, and usually in geotechnical engineering refers to two groups:

- methods based on the discretization of the contour only (Contour Elements Method);
- methods based on volume discretization (Finite Element Method; Finite Differences Method; Distinct Elements Method).

For rock masses, reference is generally made to the distinction between equivalent and discontinuous continuous models, essentially based on the structure of the rock mass and on the characteristics of the lithotypes.

The three-dimensional mathematical model of the problem under examination has been solved using Itasca's 3DEC calculation code figure 5.b.

5.1 Geomechanical parameters used
The constitutive model designated for the rock matrix is of the elasto-plastic type which considers the achievement of failure according to the Mohr-Culomb criterion, with deformability and strength parameters reported in table 1.

| Young's modulus E (GPa) | Density γ (kN/m3) | Poisson's ratio (-) | Internal friction angle φ (°) | Cohesion c (MPa) | Tensile strength σt (MPa) |
|------------------------|-------------------|---------------------|-------------------|-----------------|-------------------|
| 50.0                   | 27.0              | 0.3                 | 52.5              | 2.4             | 1.6               |

The constitutive model applied to the joints is of the elasto-plastic type with Morh-Culomb failure criterion, with deformability and strength parameters shown in table 2.

| Normal discontinuity stiffness Kn (GPa/m) | Shear stiffness of discontinuity Kr (GPa/m) | Residual internal friction angle φr (°) | Residual cohesion Cr (MPa) | Residual tensile strength σtr (MPa) |
|------------------------------------------|------------------------------------------|--------------------------------------|-----------------|------------------|
| 40                                       | 19                                       | 31                                   | 0               | 0                |
5.2 Definition of boundary conditions and calibration of the model

The boundary conditions were then defined by reducing the degrees of freedom of the system, inducing constraints on the displacements on the model boundaries and imposing a stress state on the boundary.

The data obtained from the stress measurements at the quarry showed a sub-vertical stress component ($\sigma_1$) with little constraint on the horizontal plane, with values higher than the corresponding lithostatic load ($\sigma_v = 2.5$ MPa) figure 4. Based on the actual measurements, the undisturbed stress state for the investigated area can be assumed to be equal to: $\sigma_1 = 10$ MPa (80/052), $\sigma_2 = 3$ MPa (10/256), $\sigma_3 = 2$ MPa (05/167).

An initial stress state equal to the lithostatic one was imposed on the model, also simulating the share of the stress state due to paleostress by adding an aliquot of vertical stress ($\sigma_1'$) variable from 0 to 7.5 MPa.

In a marble quarry, rock stress intensities and orientations are influenced by several factors such as tectonic origin, geo-structural conditions, rock mechanical behavior, sudden topographic changes, excavation geometry, rock relaxations and displacements induced by excavation.

The lateral tensions field $K_0$ has been then varied, assuming values between 0.25 and 0.75. This change has been performed to be able to get the estimation of the most realistic value backward, given the measuring performed on-site and of the tensional state [figure 6].

The comparison of the results was carried out considering a matrix of ideal points placed at a distance of 1 m from each other along the positions of the perforations in which the measurements were made. From the numerical analysis of the three-dimensional discontinuous model, by varying the boundary conditions and the input data, the solution that best simulated the physical quantities measured in the survey points is the one that assumes lateral stress values in the direction $OE$ ($K_{0x}$) $NS$ ($K_{0y}$), 0.33 and 0.5 respectively [5].

Finally, a Fish function (Itasca scripting language) was developed for the evaluation of the local safety factor, taking into consideration unconventional empirical failure criteria, developed for stone materials, which take into account the discontinuous matrix of the rock mass, the conditions of low confinement and the irregular geometries of the underground.

Specifically with regards to the Carrara marble, based on the experimental determination performed by “Azienda USL 1, Massa Carrara”, the empirical parameter that best approximates the breaking process is the Hoek Brown one, with the utilized constants being $m=0$ and $s=0.04$ [6].
6. Conclusions
The correct design of an ornamental stone quarry must involve multidisciplinary aspects, which must necessarily be coordinated by qualified technicians in the management and design of mining activities, in order to achieve adequate objectives in terms of safety, environmental impact and development of the cultivation.

The above considerations show a working approach which makes use of the most modern technologies such as the terrestrial laser scanner and GPR, which allows to reconstruct a three-dimensional geotechnical model with high accuracy and definition to be used with sophisticated three-dimensional numerical models.

The real challenge will be to develop new methods to fully exploit the potential of numerical models, developing systems capable of processing the behavior of the geotechnical medium in real time.

In conclusion, it can be stated that in order to develop an adequate project, it is necessary to deepen the knowledge of the geological, geostructural and geomechanical conditions of the site, and to foresee the most suitable design techniques, so as to be able to predict the stress and deformation response to the contour of future underground cavities, simulating different cultivation geometries in order to optimize the recovery of material in safe conditions.

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