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Abstract. Slope stability is a crucial aspect in case in quarrying, both in term of legal and technical restrictions. The availability of data regarding the rock mass characterization is not sufficient to guarantee a satisfactory stability analysis, which must be assessed by means of more accurate procedures. Limit equilibrium analyses have been used since many decades, as they can give satisfactory results for simple cases, such as planar or wedge blocks. Nevertheless, when dealing with more complex cases, such as opencast quarries and mines, where the slope geometry consists on several benches plunging in different directions, this simplified approach cannot give a satisfactory answer. In this scenario, numerical models can return a much more complete and accurate assessment of the overall stability. The paper describes a possible approach to evaluate the stability of the slopes of a limestone opencast quarry in Northern Italy. The country is experiencing a growing demand of limestone for the production of cement for the construction sector and this determined the need to expand the previous exploitations. Since the quarry experienced several expansion plans throughout the years, several site investigation campaigns have been carried out and the results were not always consistent with each other. Starting from the two most recent rock mass characterizations and by using 3D numerical models, the overall stability has been simulated by means of continuum and discontinuum analyses, to obtain a reproduction of the real episodes of instabilities that occurred in the past. The implementation of models with reliable data is essential to obtain results that are comparable with the reality: this would allow to proceed more effectively and safely with the exploitation of the future slopes.

1. Introduction

A quarry expansion always represents a challenge in term of a safe and efficient design. The planning of an exploitation moreover, in Italy, is constrained by a set of national and regional regulations (the main reference is the Royal Decree n. 1443/1927). Examples of technical limits are the inclination of the benches and their height.

Nevertheless, a pre-determined design of an exploitation usually requires a consequent adaptation of the layout in case of local instabilities. Numerical modelling represents an important and flexible tool for obtaining a reliable picture of what is occurring before the excavation, especially regarding the behaviour of the rock mass for the evaluation of the slope stability [1]. In this context, with complex geometries, 3D modelling represents nowadays the best option to get an effective scenario.

This paper considers the application of this type of analysis, more complex and time-consuming but capable of returning a more accurate and clear idea. For this purpose, a case history of a limestone quarry in Northern Italy has been selected. This case is particularly suitable because the original exploitation had to be expanded due to an increase in the demand for raw material. Due to its long mining activity, two different rock mass characterizations are available, but some important parameters are discordant. This can be considered in the 3D numerical model by examining both scenarios and comparing the results with the behaviour of the rock mass observed on site.

2. Geology

The exploited material is a limestone which belongs to the Eocene Epoch, called "Ternate formation". It is mainly characterized by the deposition of resettled marine sediments. This formation consists of a succession of organogenic limestone with granular support, interspersed with a grey-green marl [2]. The strata in Figure 1 confirm an evolution of the environment due to erosion and subsequent fluvial resettlement. Above and in contact with the carbonate formation, a Quaternary formation is noticed, made of detrital material, with different grain size and composition, and a variable thickness. The carbonate formation is slightly fractured, with discontinuities mostly perpendicular to the layers. The formation has a layering with a variable dip (10-25°) in the North-West-North direction, as also described by Mancin [3]. The orientation of the layers cannot not be verified on the West side of the quarry, due to the presence of an important overburden. Due to the intersection of systems of fractures, the erosive action of the meteoric waters is favoured, with the formation of voids, filled by fine material (clay).

Figure 1. Condition of the exploited face with rock and soil strata visible.

3. The quarry site

3.1. Exploitation design

The volume totally exploited is around 5 million m^3, of which 80% is limestone and 20% is moraine. The opencast excavation proceeds by sectors, from North to South and from the top to the bottom of the outcrop. The first stage is represented by the overburden removal: the moraine thickness ranges from a few tens of cm to the East up to 20-25 m in the West sector. Then, the project develops according to descending slices, with a height of the benches of 5-8 m, excavated by Drill & Blast: the scheme provides, in its standard configuration, a mesh of 2.5 m x 2.5 m of vertical holes having a 76 mm diameter and a 5.35 m length (for the 5 m benches), which can be adapted to operational needs. Based on the exploitation project, the morainic overburden is reused mainly for morphological rehabilitation.

3.2. Instability phenomena occurred

During the exploitation of the quarry, some local instabilities occurred over the years, mainly triggered after major rainfalls. A first episode, in 2017, involved a limited planar sliding of the material: the presence of marly-clayey levels linked to the layering of the limestone with the same orientation, lead to the formation of weakness surfaces, even in cases where the inclination of the layers is relatively mild.

Another landslide of considerable extension occurred in 2019: the instability occurred starting from the bench at +320 m level with the opening of a tension crack that developed for about 95 m in width in North-South direction (subparallel to the bench); this fracture grew up in depth until reaching an extended sliding plane consisting of a marly-clayey level. The total surface (sliding surface + deposition area) had an approximate extension of 1,750 m^2 and the material mobilized had a volume of approximately 1,000 m^3. The landslide triggered due to an intense and persistent rainfall and the movement developed downstream with a translation of 10÷12 m.

Similar minor instability phenomena still occur with some regularity, in spite of the increase of the water pressure during the whole excavation of the East area of the quarry: in particular, after blasting, tension cracks develop close to the bench edge, potentially creating unstable volumes which can easily slide (Fig. 2).

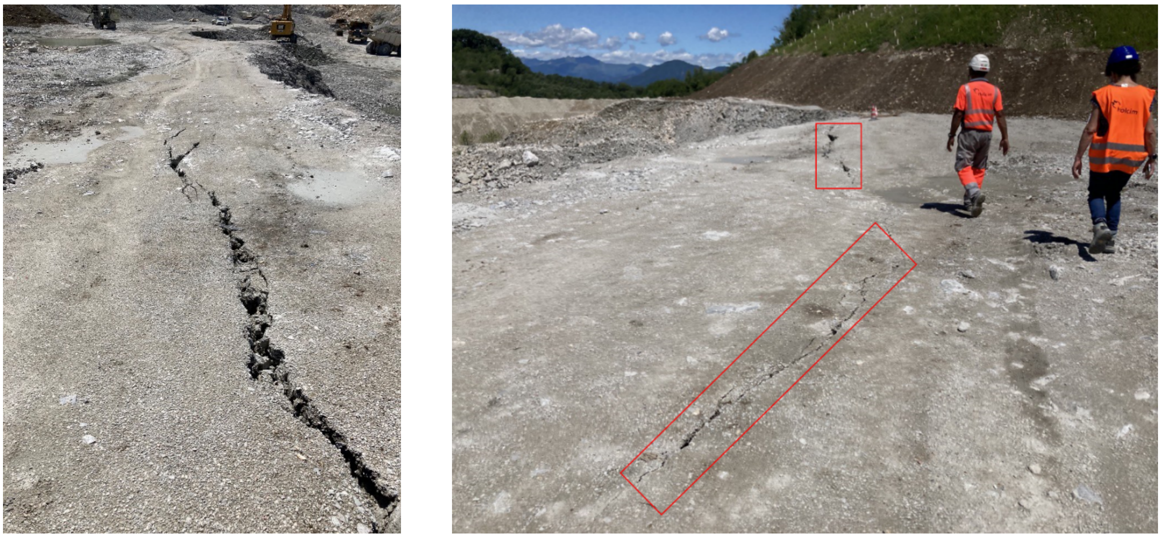

Figure 2. Example of tension cracks formed at the edge of the bench after blasting.

4. Rock mass characterization

Several surveys have been carried out over the years for assessing the geomechanical characteristics of the rock mass in the quarry area. Two characterizations deserve special attention: the first, dating back to 2011, was organised as a part of the extension plan of the quarry and covered the entire extension itself, therefore it contains a large amount of data distributed in a wide area; the second, dating back to 2020, has been developed after the most severe instabilities, with more accuracy and attention for identifying the weakness zone.

From the extended surveys of 2011, 3 main sets of joints were identified. The K1 joint set has a spacing of 15 ÷ 20 cm, while the K2 and K3 joint sets have higher values (50÷70 cm).

According to the 2020 survey, 4 joint sets were identified: J1, coinciding with the rock mass layering, dipping towards WSW-WNW (dip direction 240°÷295°) with inclination ranging between 10° and 25°, with very high persistence, close to 100%; joint set K2, with dip direction towards NNW-NE (355°÷040°), inclination between 65° and 85° and medium persistence; joint set K3, with dip direction towards ESE-SW (110°÷160°), inclination between 55° and 80°, and low persistence; joint set K4, with dip direction E-NE (50°÷90°), inclination between 65° and 80° and with low persistence. The average position of the layers with dip direction, towards the West, implies that the stratification is linked to landslides on the Eastern side of the mining area; this aspect, combined with the presence of very continuous and extensive clayey levels, leads to the formation of areas of weakness with a relatively slight inclination of the layers (≥ 14-25°). Table 1 summarizes the main parameters obtained from the two characterizations.

Table 1. Main parameters from the two rock mass characterizations.

Parameter	Value (2011)	Value (2020)
Uniaxial compressive strength UCS	75 MPa	75 MPa
Young's modulus - intact rock E_i	155 GPa	20 GPa
Young's modulus – rock mass E_{rm}	1450 MPa	3000 MPa
Hoek-Brown criterion parameter m_b	0.072	0.65
Hoek-Brown criterion parameter s	$2.33 \cdot 10^{-5}$	$1.3 \cdot 10^{-3}$
GSI obtained	<5	35

Comparing the two rock mass characterizations, the parameters have different values in terms of intact rock and rock mass. Some criticalities are noticeable: the Young's Modulus E_i of the intact rock ranges from 20 GPa, according to the 2020 characterization, to 155 GPa for that of 2011. The range is very wide and it cannot be easily justified (155 GPa seems exaggerated for this type of rock and might depend on the representativeness of the samples), especially because the E_{rm} is lower in 2011 than in 2020. Based on the existing data, the computed in reverse GSI [4] would be 39 from the 2020 analyses and cannot be calculated with the 2021 data (with a GSI of 5, the value would be 4.1 GPa, which is almost 3 times that given in the 2011 value).

The Hoek-Brown criterion parameter m_i is 7 for both the characterizations and appears suitable for the type of rock considered (limestone). On the contrary, the rock mass parameters m_b and s are extremely different, appearing too small from the 2011 data and quite appropriate following the 2020 characterization. These considerations raise the problem of relying on scattered parameters with a high discrepancy: for this reason, numerical modelling has been implemented with these 2 sets of geomechanical parameters to compare the results and establish the most "reliable" rock mass characterization based on the site observation.

5. Numerical modelling of the quarry

As introduced in the previous sections, an effective methodology for evaluating slope behaviour during and after the exploitation is the use of a numerical model. In this case, due to the complexity of the geometry and the need of having a complete picture of the whole quarry area, a 3D model was chosen.

As a first step, a continuum model has been developed in order to simulate the overall stability of the slope, without taking into account the local scale: this is feasible because the jointing of the rock mass is quite extended, and the material can be simulated as a continuum equivalent. In this stage, the 2 sets of parameters were considered, to compare the results obtained with the observations.

5.1. Continuum model

The continuum modelling has been carried out with the commercial FEM Midas GTS NX software, which is very effective in simulating such complex geometries. The simulated area includes the whole extension of the exploited quarry, considering the existing quarry in the initial topography. An overview of the model is shown in Figure 3, where the volume to be exploited has been removed from the picture, to better appreciate the contours of the benches. As clearly visible from the picture, the Southern area of the quarry is characterized by the highest slopes. The overburden, consisting mainly of the moraine, has been neglected for the simulations.

The parameters used for the models are coinciding with the ones provided by the characterizations described in Section 4 and summarized in Table 1. Considering the geological context, only the gravimetric component of the in-situ stress has been used.

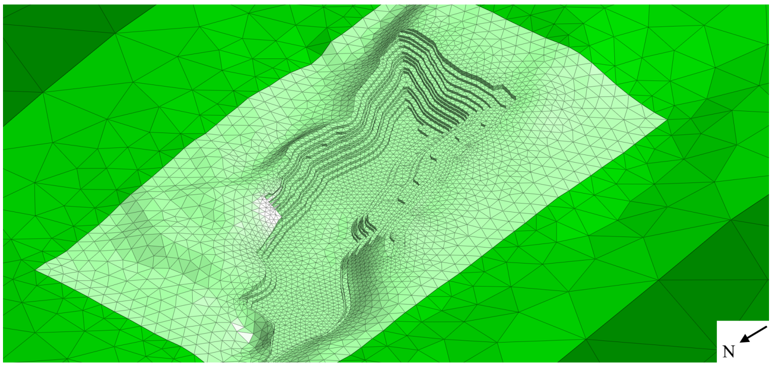

Figure 3. Detail of the exploited area (the excavated volume has been removed to show the benches).

The results of the two models are notably indicative for determining the most appropriate set of parameters which more realistically describe the actual behaviour of the slopes. In fact, the total displacements in the model with the sets of parameters from 2011 point out an excessive extension of the movements of the rock mass, well beyond the expected behaviour of the slopes (Figure 4 on the right). On the contrary, the model carried out through the 2020 characterization shows displacements totally aligned with the expected ones, with a peak of 30-40 mm visible in the South-East area (Figure 4, right). A similar trend is evident by analysing the expected equivalent plastic strains (which in Midas GTS NX are often used as an indicator for assessing the position of potentially critical slip surfaces): with the latest parameters, the potential slip surface is limited in the South-East area while from the 2011 characterization the situation appears much more critical than in the reality (Figure 5). This is a clear indicator that the latest characterization most effectively describes the actual behaviour of the exploited rock mass, and it should be the one being considered for new studies or models.

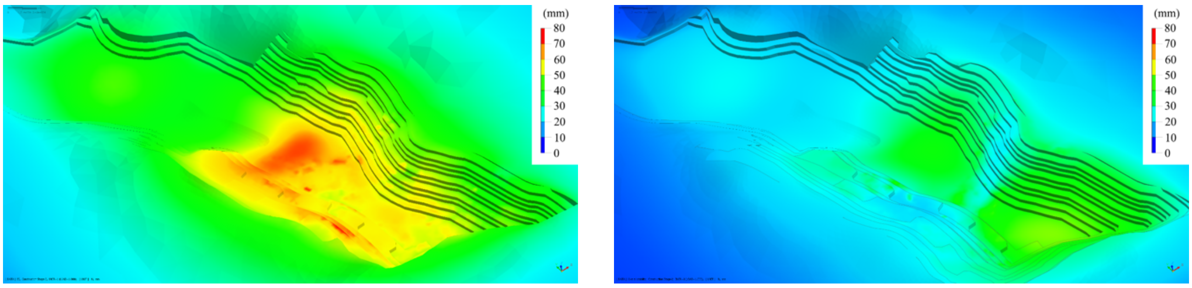

Figure 4. Total displacements of the slopes at the end of the exploitation with 2011 (left) and 2020 (right) parameters.

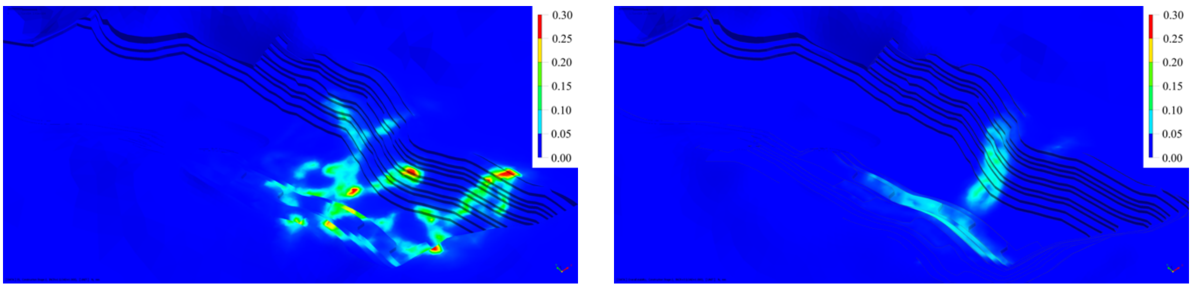

Figure 5. Equivalent plastic strains of the slopes at the end of the exploitation with 2011 (left) and 2020 (right) parameters.

5.2. Discontinuum model

The previous step of calculation, consisting of the two overall continuum models, allowed to determine the most suitable characterization parameters, which in this case are those gathered in 2020. Starting from this survey, carried out after a partial exploitation of the extension which revealed additional outcrops for collecting data, also a more accurate joint set determination was made possible. This determination includes the geometrical and geomechanical properties of the sets themselves (Table 2), which can then be used for preparing a discrete model to simulate more effectively the area where the local instabilities occurred. The joint set dip and dip direction angles have been then modelled by considering a standard deviation calculated based on the population of surveyed sets. The normal stiffness k_n shown in the table, which were missing from the survey reports, has been obtained by means of the well-known correlation by Barton [6], linking the mean joint spacing, the intact rock Young's modulus, and is the rock mass modulus. The shear stiffness k_s was therefore considered to be 5% to the normal stiffness k_n.

Table 2. Joint set parameters determined after the 2020 site survey.

Set	Dip/DD (°)	Persistence	k_n (MPa)	k_s (MPa)	φ (°)	c (MPa)
J1 (green)	18/268	1	750	37.5	28°	0.05
J2 (red)	75/50	0.6	750	37.5	24°	0.05
J3 (purple)	68/135	0.4	750	37.5	24°	0.05
J4 (cyan)	73/70	0.4	750	37.5	24°	0.05

Figure 6 shows the model that was prepared for this purpose by means of the commercial software Itasca 3DEC: on the left, the presence of a continuum area (in green) surrounding the discrete area with the blocks is evident; these blocks are more identifiable on the right picture, with the middle cross section of the discontinuum area (the different colours of the joints identify the joints listed in Table 2). Even in this case, the in-situ stress is limited to the gravimetric component.

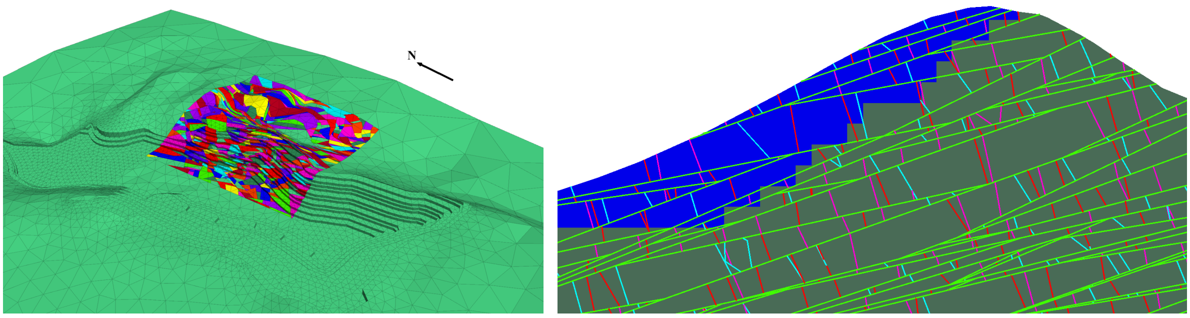

Figure 6. Overall view of the DEM model with in green the continuum part (left) and cross section of the discontinuum part with the joints highlighted with different colours according to the ID from Table 2 (right).

The results of the discontinuum model shows that, with the set of parameters chosen, the rock mass appears stable and that no major sliding blocks can be expected. This even more demonstrate that a major instability can occur if an external event is somehow perturbing the joint parameters, such as a major rainfall. Most of the displacements, as visible in Figure 7, are within a limit of 2 cm, and only a few smaller blocks achieve a maximum total displacement of up to 5 cm. Furthermore, a slight lifting effect is also observable, mainly due to the stress distribution along the deformable blocks (modelled in order to transmit the stresses induced by the excavation). Nevertheless, the fact that the dip and dip direction angles have been modelled with a standard deviation, which anyway is an almost standardized procedure, might reduce the formation of sliding blocks. This is particularly important for Set J1, where the dip angle is quite low and, in some locations, the standard deviation is further reducing this value. Anyway, this can be considered as a preliminary assessment, and should be further investigated by including a possible triggering event (major rainfall) and by considering the most critical angles.

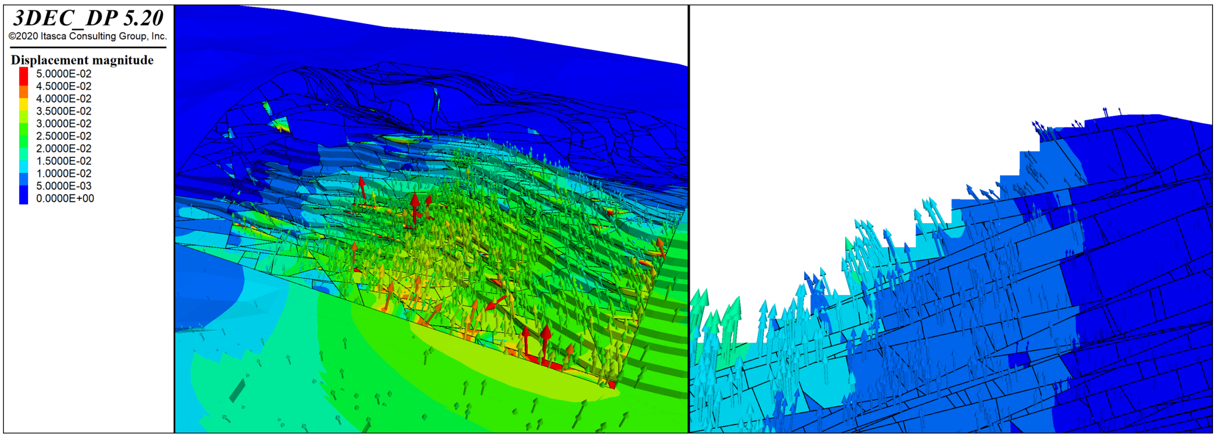

Figure 7. Total displacement registered at the end of the exploitation. On the right, the overall 3D view of the S-E slope and, on the left, the middle section of that slope.

6. Conclusions

During the exploitation of an opencast quarry, various phenomena of instability occurred, which required in-depth investigations. Starting from the existing characterizations of the rock mass and from the stability analyses, this work has identified some critical issues with respect to the previous numerical modelling, and has developed a three-dimensional approach.

As a first approach, a continuous model was created to evaluate the global stress-strain behavior of the quarry, considering some simplifications in order to obtain a manageable model. As for the input data, a back-analysis was carried out to verify the most effective datasets, examining the characterizations of the rock masses carried out in 2011 and 2020. The FEM results confirm that the 2020 parameters are the most representative, with a maximum displacement of 45 mm. The equivalent plastic strain and the plastic state of the material underline the inadequacy of the 2011 parameters due to an unrealistic extension of the yielded and unstable areas.

After this phase, a discontinuous model of the quarry was developed to take into account the presence of the joints. Due to the large size of the model, the analysis was focused by setting the presence of the joints in the unstable area. The elements are discretized, each block is deformable, and the same meshing, staging, and input data conditions as the previous model are used. Most of the displacements were observed to be within a 2 cm limit and only a few smaller blocks achieved a maximum total displacement of up to 5 cm. Anyway, this should be considered as a preliminary assessment, and should be further investigated by including possible triggering events and by considering the most critical angles.

Numerical modelling of a real case presents a challenge in terms of geometry, meshing, staging, input data, boundary conditions and simplification of the problem. The comparison between different models can be favourably employed in the design phase but also when problems arise during exploitation. Using a 3D model allows you to represent reality more accurately, but requires a greater level of information in terms of parameters and geometry, and a greater effort in terms of model preparation. The results presented here show the effectiveness of using this tool to evaluate the stability of the quarry analysed, as it can provide a much more reliable and clear picture of the possible instabilities and criticalities that could occur during the exploitation of the quarry.

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