Use of a numerical model for underground stability evaluation

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Abstract

In recent years the tendency for re-evaluation and conversion of dismissed mines for touristic and scientific purposes (educational trails, laboratories, etc.) has been more and more diffused. To make these purposes possible in safe conditions it is necessary to evaluate the geological risk inside mines and execute proper stability studies. For the definition of geological risk, even for underground works (galleries, mines), it is not possible to prescind from the analysis of geological, geomorphological and mechanical aspects that compete for the definition of the three dimensional physical model. Only in this way will it be possible to simulate the behaviour of the rock mass and to forecast future risk sceneries, define critical thresholds and evaluate more suitable mitigation works. For a correct evaluation of the hydro geological problem using actual available means, the approach based on the physical-mathematical modelling of the problem is used more and more. This has necessitated the experimental observation of the mechanical behaviour of materials, the definition of constitutional laws, the modelling of soils and rocks systems, the formulation of holding equations, the development of analytic and numeric instruments for the solution of contour problems, the observation of the behaviour of real scale works, etc. The aim of this paper is to demonstrate the use of a numerical code for the evaluation of the stability of a part of the Piani dei Resinelli mines. The numerical model allows one to evaluate the tensional-deformational state of the rock mass. After geological, geomorphological and geotechnical analysis, we applied the 3DEC algorithm to the Piani dei Resinelli mines in order to obtain a three dimensional discontinuous model with distinct elements.

Keywords: 3DEC, hazard, mines, risk scenarios.

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1 Introduction

This study is based on a particular problem of recent years: the dismissed mines and the problem concerning the surrounding area. Sometimes these dismissed mines can generate some problems not only inside them but also in the contiguous area. For this purpose it is necessary to evaluate the stability of the mine with the definition of some risk scenarios. In the applied case shown in this paper the hydrogeological problem is a real problem because the dismissed mine analyzed is used for tourist and scientific purposes. Due to the purpose of this mine the geological hazard prediction in order to assess the safety condition is a real necessity.

The present work is part of a research with the purpose of developing a methodology for the hydrogeological analysis of the dismissed mines.

This paper focuses on a particular phase of this research: the applications of numerical modelling in underground mining. These simulations are necessary when some hydrogeological problems are possible but are an imperative condition when people, not usual in underground spaces, should enter in the mine for tourist purposes.

To assess the limitations and advantages of numerical modelling prediction, different simulations have been considered.

Numerical modelling has been used to investigate a variety of problems in underground mining and tunnelling: subsidence induced by longwall coal mining; stress generated when an open stope is filled with cemented backfill and the stability of exposures created during subsequent mining of adjacent stopes; the interaction of two tunnels; the effects of under-mining a pre-existing tunnel and shaft [2]. In this case some simulations for evaluating some possible scenarios were also made to assess the mine entrance for tourists. The real problem is that the abandoned mines are a real temptation for tourists but these spaces are very dangerous and only mining engineers, ready for the worst, have any business going into one of these mines. This paper shows the numerical models used to evaluate the real dangers in a mine, used as a prototypal case situated in Lecco.

2 Geological and geomorphologic context

Numerical modelling can assist geologists and engineers in underground excavation problems. It is important to understand the available data before starting with simulations because for high-quality simulations extensive geological and geotechnical data are necessary. Evaluation of underground instability mechanisms needs a good understanding of the geological setting, material behaviour, and physical mechanisms, as well as the use of adequate, flexible computational models to make the predictions.

2.1 The case study

With so many abandoned mines in Lombardia, it is natural to want to see what a mine looks like. Unfortunately, abandoned mines are very dangerous. Every year people die exploring abandoned mines. Fortunately tourist mines and the mining museum offer safe tours for people who are not experts in underground spaces. For safe tours through the world of mining it is necessary to analyze every risk scenario. This research deals with the evaluation of hydrogeological risk with the use of numerical models.

For the purpose of this paper the Piani dei Resinelli mines are analyzed.

These mines, shown in fig. 1, are used for tourism. Every year a huge amount of people, especially students, visit the mines as tourists.

Figure 1: Piani dei Resinelli mines.

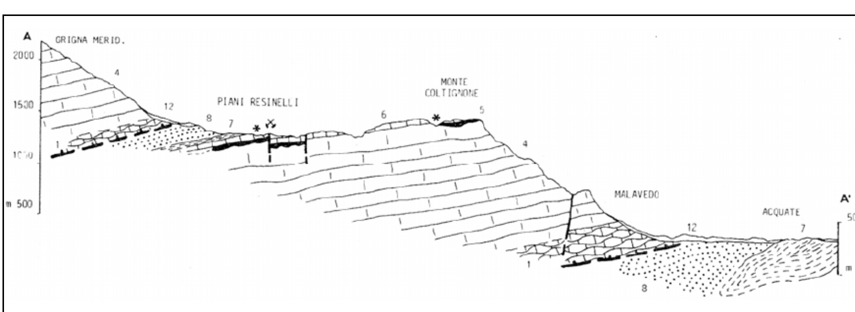

Figure 2: Geological cross-section from North to South. This section crosses the mine area (Rodeghiero et al. [6]).

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2.2 Area geological classification

Some authors (Rodeghiero et al. [6]) have studied this area from the geological point of view. In this paragraph a synthesis of these previous studies are presented. Figure 2 shows the surrounding area of Piani dei Resinelli.

In the studied area sedimentary triassic rocks outcrop: the "Calcare Metallifero Lombardo" and the "Calcare di Esino". The area is affected by some folds and faults. The Calcare di Esino is etheropic with Calcare di Perledo-Varenna. It consists of grey limestones and dolomites. These sedimentary rocks are affected by close fissuration, tending to divide into blocks, and by karst phenomena. Some joints and faults subdivide the bedrock in more or less dislocated blocks. For the mine it is important to analyze the transition facies among the Esino limestone and the Metallifero Bergamasco limestone.

3 Numerical model

Up to now numerical models have often been used for the scope of civil engineering.

Although based on scientific "first principles", complex numerical models inevitably require simplifications, judgment calls, and correction factors. These subjective measures may be entirely acceptable so long as the model matches the available data, acceptable because the model is not intended to be internally consistent with all the laws of physics, but rather to serve as an expedient means to anticipate behaviour of the system in the future. This paper shows the importance of the 3D model reconstruction for simulation. It is really important to analyze all data for a real or similar representation of the analyzed model.

It is important to define two different simulation typologies:

-if a great amount of geological and geomorphologic data are available it is possible to reconstruct a 3D model similar to the real case. In this case the simulations can predict deformations and stability;

-if not, the numerical model can be used to perform parametric studies. In this case it could be possible to have a series of possible risk scenarios but first of all it is necessary to define the key parameters.

For the case study we have enough data for a good 3D model reconstruction. With this model the simulations can predict the future behaviour, but for this study it is also important to understand the key parameters. For these we also made an analysis of the different results with some changes to the input data.

There are a lot of different numerical models for the stability analysis of rock slopes and underground excavations. The analysis technique chosen depends on both site conditions and the potential mode of failure, with careful consideration being given to the varying strengths, weakness and limitations inherent in each methodology [3].

For the hydrogeological problems of the Resinelli mines a 3D numerical model was used.

As we will later demonstrate, the use of the 3D model can significantly increase the future behaviour forecast.

Due to hydrogeological problems inside the Resinelli mine the 3DEC model was chosen.

3.1 Program 3DEC

This program is provided by Itasca Consulting Group, Inc. It is a 3D numerical program based on the distinct element method for discontinuum modelling. 3DEC simulates jointed rock mass subjected to either static or dynamic loading. The discontinuous medium is represented as an assemblage of discrete blocks. The discontinuities are treated as boundary conditions between blocks; large displacements along discontinuities and rotations of blocks are allowed. Individual blocks behave as either rigid or deformable material. Deformable blocks are subdivided into a mesh of finite difference elements, and each element responds according to a prescribed linear or nonlinear stress-strain law. The relative motion of discontinuities is also governed by linear or nonlinear force-displacement relations for movement in both the normal and shear directions. 3DEC has several built-in material behaviour models, for both the intact blocks and the discontinuities, which permit the simulation of responses representative of discontinuous geologic, or similar materials. 3DEC is based on a "Lagrangian" calculation scheme that is well-suited to modelling the large movements and deformations of a blocky system [5].

4 Modelling applications

This part of the paper models the underground space in Piani dei Resinelli.

The simulations have two different purposes. The first is to simulate the stability of the tunnel in order to define the risk scenarios and the other type of simulations were made to analyze the most critical parameters and the influence on stability.

Before analyzing the simulation results it is important to develop a good 3D model with all the features and boundary conditions.

4.1 The 3D model of the Piani dei Resinelli mine

By an analysis of geological data, a field survey and geomorphological examination, it is possible to build up a 3D physical model of the tunnel.

The most important phases for the 3D model reconstruction are:

Phase 1: Model generation

In this phase it is necessary to define the model geometry. It must represent the physical problem to a sufficient extent to capture the dominant mechanisms related to the geological structure in the region of interest. It is important to define the detail for the geological structure. Figure 3 shows the mine plant and the consequent reconstruction of the geometry of the tunnels.

Then, for model creation, it is necessary to generate joints. Some data were analyzed and then the most important set of discontinuities were chosen for the model reconstruction.

In this phase material properties were also defined for both the intact blocks and the joints set. Tables 1 and 2 show these material properties.

Phase 2:Deformable or rigid blocks

This is an important aspect of this program. It is necessary to decide which kind of block simulates in the best way the real behaviour of the mine. In this case the rigid blocks option was chosen.

Phase 3:Boundary and initial conditions

For boundary and initial conditions the situation of the mine was analyzed. It is important to define the vertical stress on the underground roof. It could change in the same tunnel so for this case all the different stresses were reported in each track of the tunnel. For the case study analyzed in this paper, the track of the mine is located at different depths:

-at the mine entrance it is 0 m in depth;

-at the end of the track it is 15 m in depth.

4.2 Simulations

Knowing the tunnel model it is possible to start with the simulations. Before tunnel generation some simulations were made to find the initial equilibrium of the block with the joints sets. With the initial equilibrium state the tunnel generation can be performed. Through a simplification of the real situation the tunnels were generated into the models.

Figure 4 shows the unbalanced force after the tunnels excavation. As it is possible to see, after 4000 cycles the model reaches equilibrium.

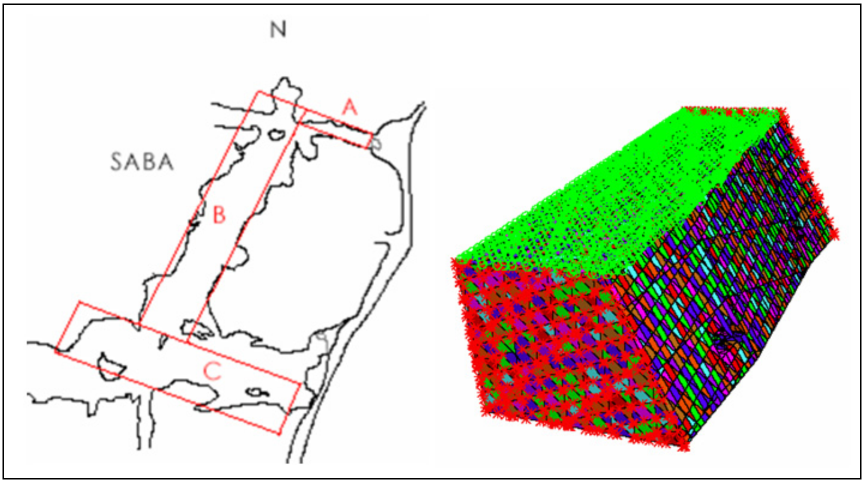

Figure 3: Model geometry.

Table 1: Block properties.

BLOCK PROPERTIES				
mass density	→	ρ	2400	N/mc
friction angle	→	ϕ	33	°
cohesion	→	c	3,5	MPa
shear modulus	→	G	12000	MPa
Young's modulus	→	E	30000	MPa
Poisson's ratio	→	v	0,25	

Table 2: Joint properties.

JOINTS					
Joints sets	**joint normal stiffness kn**	**joint shear stiffness ks**	**linear persistence**	**cohesion**	**friction angle**
	Pa	***Pa***	***%***	***Pa***	**°**
SO	$5\ 10^9$	$5\ 10^9$	85	$0{,}525\ 10^6$	30
K1	$5\ 10^9$	$5\ 10^9$	50	$1{,}75\ 10^6$	30
K2	$5\ 10^9$	$5\ 10^9$	30	$2{,}45\ 10^6$	30
K3	$5\ 10^9$	$5\ 10^9$	50	$1{,}75\ 10^6$	30
F1	$1\ 10^9$	$1\ 10^9$	100	0	30
F2	$5\ 10^9$	$5\ 10^9$	60	$1{,}4\ 10^6$	30

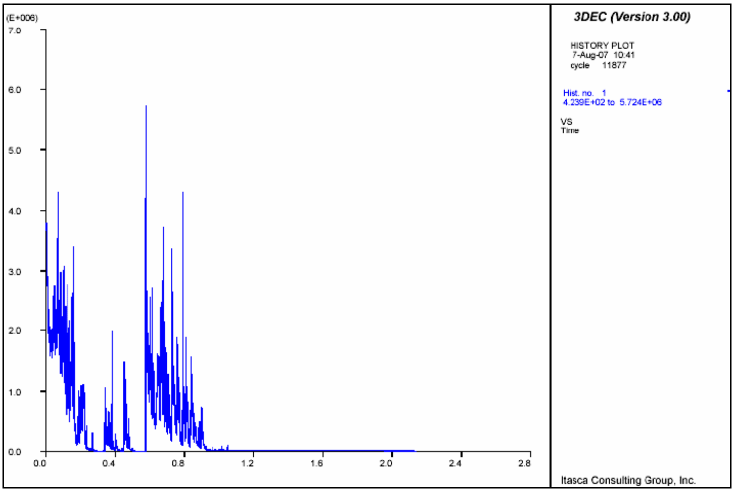

Figure 4: Unbalanced force.

The velocity and displacement history plot graphics were examined. The value is about 10^{-6} m for displacements and 10^{-6} m/s for velocity. During the simulations different parts of mine were analyzed. As reported in figure 3 the tunnels are called: tunnel A, tunnel B and tunnel C.

Cross section plots of each tunnel were generated. Figure 5 shows one of these. There is a vertical distribution of displacements but this is not dangerous for the limited value.

Instead it is important to analyze the behaviour in the track where a fault is present. Figure 6 shows the displacements and the velocity vectors of this track. It is really dangerous to have the same vertical direction of the velocity and displacement vectors, but also in this case, the situation is not critical due to the limited value of vectors.

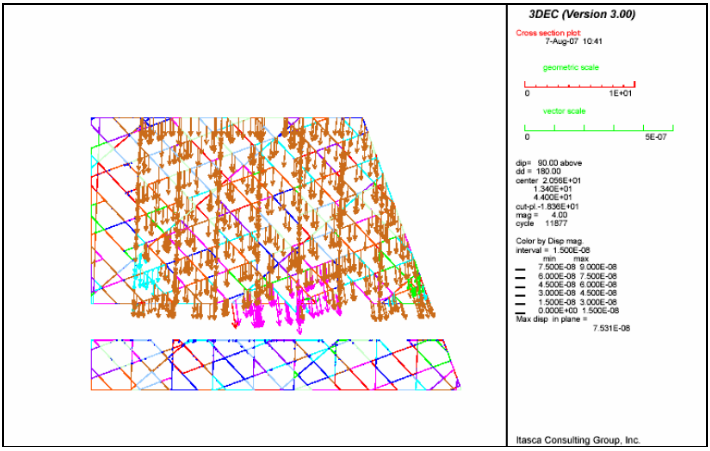

Figure 5: Cross section tunnel A: displacement vectors.

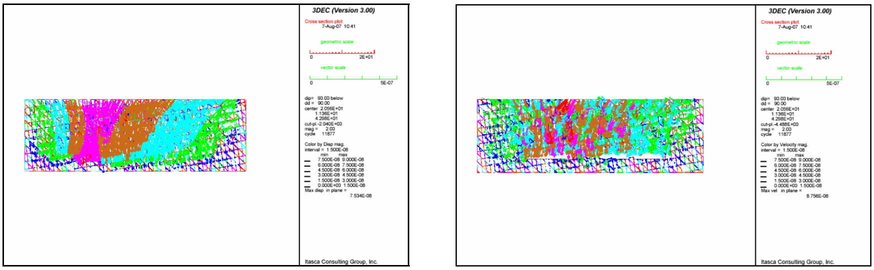

Figure 6: Displacement and velocity vectors in the track near the vertical fault.

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4.2.1 Persistence analysis

During simulations it is important to define the most critical parameters not only for the risk scenarios generation but also for a best definition of site investigation and material testing.

One of the most difficult to define is persistence. Through lots of different simulations a judgment of this parameter was made.

A comparison of the different simulations show that the persistence is not a critical parameter for the failure mechanisms of the Piani dei Resinelli mines. The values of displacement and velocity vectors are the same as the previous simulations.

The analysis of this parameter was made only because the persistence is very hard to investigate.

4.2.2 Cohesion analysis

To identify the collapse mechanism the cohesion was changed. This is one of the most critical parameters for stability problems, especially for the types of blocks formed in tunnels. A lot of different simulations were made with a continuum reduction of cohesion.

Table 3 shows the results of the simulations.

Table 3: Cohesion analysis.

Cohesion reduction	displacement	velocity
10%	10-2 m	10-7 m/s
20%	10-2 m	10-4 m/s
30%	10-3 m	10-5 m/s
40%	10-3 m	10-5 m/s
50%	10-2 m	10-1 m/s

The value of the displacements and velocity is dangerous.

In the last simulation the most critical parameters were joined in order to define the failure mechanism. With an average persistence, common at all discontinuities, and a reduction of cohesion at 1.75 MPa value, some movements were registered. The collapse mechanisms defined are:
-the sliding blocks due to the presence of a k2 joint set;
-movements around the vertical fault.

5 Conclusion

In this paper we have shown the improvement in risk evaluation using a numerical model. 3DEC is a great advance in numerical approaches. It allows one to simulate the underground space in three dimensions. One of the most critical parts is the reconstruction of the 3D physical model. In this research standard methodologies must be defined in order to evaluate the hydrogeological risk in underground mines used for tourist purposes.

The real goal is to define specific risk scenarios with the use of numerical models. In this case the simulations show that the mine is stable. But if some changes in cohesion and persistence are possible the failure mechanisms defined by simulations are sliding and movements near fault. Through proceeding interactively it is possible to define detailed scenarios and so guide geotechnical design work in underground mining and construction.

Another important item is to evaluate the simulation results through warning signs observed in the mine. For this purpose a lot of monitoring systems were located in the most critical parts of the three tunnels analyzed. These instruments allow one to measure the displacements (crack meters) but also accelerations (some MEMS were located on the critical blocks to measure acoustic emission, which can then forecast new movements).

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