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Underground Quarrying for Marble: Stability Assessment through Modelling and Monitoring

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Abstract: *This paper presents the approach for assessing the stability of underground quarries through the numerical modelling and the monitoring of the stress-strain state of the rock mass and of the support structures. On the basis of the practical experience and long term observation on different case histories, the key issues for a safe and profitable exploitation are given. The procedure is focused on the Candoglia cavern (named Cava Madre), a large mining void due to the exploitation of an high quality marble used for the Milan Cathedral (Duomo di Milano). The importance of the monitoring system for the back analysis of uncertain rock mass parameters and for the operation controls is discussed and emphasized, in order to provide practical design suggestion.*

Keywords: *underground quarrying, marble, monitoring system, cavern stability, back-analysis, numerical modelling, stress-strain state.*

1. Introduction

Underground exploitation of dimension stones has become an alternative method to traditional open pit exploitation, not only in cases where the underground option is imposed by the features of the rock mass, but also for environmental reasons that have gained relevance in recent years. Furthermore, the underground exploitation could be preferable in terms of economy and in cases where surface operations are not technically feasible (Oggeri, 2000).

In fact, the underground option can be necessary or preferable when (Oggeri, 2000): 1) the surface is very dipping and irregular (mountain zones); 2) the external surface is regular but the overburden is thick; 3) land costs and reclamation taxes are too high; 4) the selected rock mass is confined in a well-defined ore body; and 5) safety requirements and stability features are no longer suited to open pit methods. Five elements should be taken into account when the underground choice has to be considered: 1) good structural conditions of the rock mass (in ornamental stone quarries this aspect is generally satisfied); 2) technology of the excavation (mainly mechanical cutting to separate the blocks from the surrounding mass); 3) commercial features(some properties, for example colour and grain size, are not always the same, due to the limited homogeneity of the rock mass, where change of colour, and stains and inclusions can been countered); 4) economic profitability compared to the costs of the open pit exploitation, taking into account the probable lower recovery due to underground support structures such as pillars, but also the savings on overburden removal and muck disposal; and 5) safety and environmental reclamation.

The stability features in this particular type of void should be ensured on a long-term basis, without significant contribution from artificial supports: this is a quite common fact as the rock mass has obviously few joints, but nevertheless the rigid movement of rock wedges from the walls or from the roof can occur.

The geo-structural conditions and the rock abrasiveness influence both the exploitation plan and the excavation method that should be used to separate the blocks from the faces. The availability of geo-structural data of the rock masses where underground quarries have been developed and technical results after some years of exploitation experience can allow one to consider the above mentioned elements in a critical way. On the basis of these considerations, a rational design should consider (Oggeri, 2000):

- the location of the quarry, and the consequent stress state of the rock mass;
- the results of the geo-structural survey;
- the critical conditions produced by block movements or for induced plastic failures in the rock mass;
- the stability evaluation of pillars, rib pillars, walls, flat roofs and of the eventual used support systems (bolting, cable bolting);
- the results of the numerical modelling of the various exploitation phases;
- the definition of the monitoring systems, aimed to rock mass characterization by back-analysis (Oreste, 2005; Oggeri and Oreste, 2012), wedge movement control, support system loading control.

In this paper a description of each phase of the exploitation plan at the Candoglia Underground Cavern is shown, with emphasis to the developed numerical modelling and the performed monitoring system.

2. THE DESIGN PHASE

The excavation in marble quarries istoday carried out almost exclusively with mechanical cutting techniques: diamond wire saws and chain saws are used above all; they have reached such high levels of performance that it is actually disadvantageous avoid their use to maintain an efficient production. The importance of the use of such equipment during quarrying is due to the fact that it determines the correct geometry of the underground voids. In other words, efforts are made to "adapt" the geometry of the void for optimal performance of the chain or wire saws (Oggeri, 2000).

Once the geometry of the void has been chosen at a preliminary stage, numerical methods allow to evaluate in the detail the stress and strain conditions of the rock mass and of the support structures with a good margin of reliability. Numerical methods can be distinguished according to how the rock mass is considered: finite element calculation codes (FEM) and finite difference codes (FDM) consider the rock mass as a continuous body; distinct elements (DEM), considers the rock mass as a discontinuous body with intact rock and natural discontinuities.

It is difficult to identify the model that better reproduces the behavior of the rock mass in a specific case. For this reason, in some cases the analyses are usually carried out using both the mentioned models.

3. THE MONITORING PHASE

Monitoring represents a fundamental stage of the rational approach. There are basically three aims for monitoring underground excavations for ornamental stone quarries (Oggeri, 2000): a) validation of the hypothesis of the numerical modelling by means of in-situ measurements (back-analysis) (Oreste, 2005; Oggeri and Oreste, 2012); b) control of the behaviour of natural and artificial structures; and c)updating of the stress state and geo-structural conditions.

The directly measured parameters are usually displacements, stresses and loads, whilst the use of indirect methods allows one to define the fracturing state of the rock or the related physical properties (mechanical wave velocity and other geophysical parameters).The convergence measurements can be performed close to the portals and across transverse sections of the rooms, by adopting topographical measurements. The use of long-base extensometers inside the rock walls can put in evidence the rock movements around a void. In the same way, crack meters with potentiometric or vibrating wire transducers can measure the movements across the walls of the discontinuities. Monitoring sections can be equipped with rod extensometers, also passing through the entire pillar, with vibrating wire transducers.

Induced stress measurements in the pillars can be performed using flat jack equipment, but the measurement points must be repeated adequately because of the gradient of the stress near the corners. Alternatively, some measures can adopt the surface over coring technique with a large diameter of the over coring, or the over coring in the borehole with the doorstopper method. If a support system is installed, load cells or pressure cells can also be adopted to measure its stress state.

It is of primary importance to correlate the advance of the exploitation with the collected measurements, in order to manage properly the data and to interpret them in the most suitable way. Season's temperature variations and water table influence should also be considered due to the fact that both the temperature and the water pressure can influence stresses and strains in the rock mass and support structures.

4. THE UNDERGROUND QUARRY OF CANDOGLIA

The Candoglia Cavern (90 m long, 25 m wide and 48 m high) is an historical marble quarry (Figure 1); the marble, pink and veined, is used for the construction and maintenance of the Milan cathedral (Duomo di Milano, Italy). The marble deposit is constituted by a regular vertical vein around 28 m wide (Pelizza et al., 2000, 2006).

The quarry is located at the entrance of the Ossola Valley, in the Northern Alpine range. The particular historical interest of these quarry arises also from the patents given to the geological area, which can be used only by the Veneranda Fabbrica del Duomo, the owner of the Milan Cathedral, and also for the complex transportation system that has allowed during decades to move blocks, slabs and manufactured elements from the quarry to the city of Milan (Pelizza et al., 2000, 2006). During the last two decades the exploitation has been developed at the adit of the cavern (Figure 1 on the left), by adopting the wire diamond cutting and the chain saw cutting techniques, that allow higher recovery rates of the marble blocks. In the meantime geomechanical characterization, numerical modelling and a detailed site monitoring have been carried out, in order to better understand the static behaviour of the cavern and to reach satisfactory recovery rates.

Due to the reached huge size of the cavern in the zone of the adit, different support systems have been adopted to maintain the stability of the walls (Figure 1). An integrated and comprehensive monitoring system has been installed, adapted and maintained during the last years.

The case of the Candoglia Cavern is relevant, because it can show that the correct use of in situ measurements over a long period (25 years) offers the basis for a good interaction among the design stage and the exploitation stage(Pelizza et al., 2000, 2006).

Figure 1. *Left: The adit of the Candoglia Cavern, where the marble exploitation is now developing. Right: The inner zone of the Cavern, where the mining activity is now abandoned.*

<u>Mechanical characteristics of the intact rock</u>

The rock is a grey–pink marble, veined and fine grained. The properties have been determined in laboratory tests using rock sample by different sites of the quarry (Table 1)(Pelizza et al., 2000, 2006).

Table 1. *Intact rock mechanical properties of the exploited marble in two different campaign at the Candoglia quarry(Pelizza et al., 2000, 2006).*

Parameter	Simbol	unit	N° test	min	max	average	Stand. Dev.
Unit weight	(γ)	[kN/m^3]	25	26,2	28,3	26,8	0,54
Un comprsterngth	(C_0)	[MPa]	11	75,8	142,2	98,3	11,38
Indirect tensile strength	(T_0)	[MPa]	9	5,93	11,8	8,6	1,83
Tangentdefmodulus	(E_t)	[GPa]	16	51,9	83.0	66,7	7,26
Secantdeformationmodulus	(E_s)	[GPa]	16	50,6	86,0	67,4	10,0
Tangentpoisson ratio	(ν)	[-]	11	0,18	0,39	0,29	0,07
Longitudinalwavevel	(V_p)	[m/s]	16	3213,5	6395,3	5389,3	783,3
Transversalwavevel	(V_s)	[m/s]	16	2141,0	3606,0	2937,4	364,8
Dynamicmodulus	(E_d)	[GPa]	16	27,5	84,8	60,2	14,2

Parameter	Simbol	unit	N° test	min	max	average	Stand dev.
Unit weight	(γ)	[kN/m^3]	-	-	-	-	-
Un comprsterngth	(C_0)	[MPa]	12	44,0	155,4	103,2	35,2
Indirect tensile strength	(T_0)	[MPa]	20	1,8	12,3	7,0	2,8
Tangentdefmodulus	(E_t)	[GPa]	6	50,0	90,0	70,0	16,0
Secantdeformationmodulus	(E_s)	[GPa]	6	40,0	98,0	70,0	20,0
Tangentpoisson ratio	(ν)	[-]	-	-	-	-	-
Longitudinalwavevel	(V_p)	[m/s]	-	-	-	-	-
Transversalwavevel	(V_s)	[m/s]	-	-	-	-	-
Dynamicmodulus	(E_d)	[GPa]	6	-	-	110,0	40,0

Rock mass characteristics

The marble is embedded in gneiss and quartzitic formations, subvertically oriented. Some main joints are persistent and can affect both the stability of the wedges around the void and also the rock blocks recovery ratio. Critical aspects for the stability are represented by the wedge formation on the walls and by the general structure of the lateral walls, which extend vertically and are affected by horizontal stresses. The Tables2 and 3 represent the natural joint orientations at the site and the obtained rock mass parameters, respectively(Pelizza et al., 2000, 2006).

Table 2. *Natural joint orientations in the marble and the embedded rock at the Candoglia quarry(Pelizza et al., 2000, 2006).*

Mainquarry	**Eastwall**
Marble	*gneiss*
140/83 – 320/83	142/73
210/71	-
230/57	240/56
190/40	-

Table 3. *The obtained rock mass parameters at the Candoglia quarry(Pelizza et al., 2000, 2006).*

Rock type	unit	gneiss leftwall	Gneiss fractured zone	Marble on the left side	Marble on the right side	Gneiss on the right zone
ν	[-]	0,25	0,30	0,25	0,25	0,25
γ	[kN/m^3]	27,5	26,5	25,5	26,5	27,5
peak						
c	[MPa]	0,6	0,25	3,8	3,8	0,9
φ	[°]	35	25	40	42	38
E	[GPa]	7	2,5	30	47	14

residual						
c	[MPa]	0,18	0,075	1,2	1,5	0,27
φ	[°]	30	20	35	37	33
E	[GPa]	4,5	1,5	16	25	8

5. THE EXCAVATION TECHNIQUE AND THE EXPLOITATION METHOD

The marble is exploited by means of a benching method, adopting a mechanical cut operated by a diamond wire saw. For the initial cut, near the walls, also a light belt cutter saw is used. Benches are usually 5 m high and cover all the span of the cavern. Each block is then obtained after that larger slices (5 m x 2 m x 6 m) are separated from the bench.

It is important to put in evidence that the marble production is very low, about 1000 m^3 per year, as it is reserved to the sole Cathedral maintenance.

During the last 10 years the exploitation has moved towards the adit of the cavern, due to static problems in the internal part of the cavern and to the good quality of the marble found at the entrance zone. The old support structures have been removed and the shape of the cavern in the adit zone has been modified, mainly at the right side; 3 new concrete beams have been installed (Figure 2). A detailed geological survey and some core drillings confirmed that the entrance zone presented good perspectives for marble recovery. It was also clear that the old static conditions were going to change, so monitoring and modelling were cross correlated in order to obtain the new stress and strain state of the rock mass around the cavern.

Figure 2. *Left: The adit of the Candoglia Cavern before the substitution of the concrete beams and the enlargement on the right side (2000)(Pelizza et al., 2000, 2006). Right: The adit of the Candoglia Cavern after the substitution of the concrete beams and the enlargement on the right side (2014).*

The figure2 on the right represents the start of the exploitation at the adit of the cavern (2000) and the recent geometrical configuration (2014). After 14 years the old beams have been removed and on the right wall the marble has been excavated; also 3 new greater concrete beams have been installed and a new bench has been opened on the complete span of the cavern. The entrance level has recently been lowered of 5 m. In the future further bench lowering will be possible. The marble quality is high and so also the block recovery ratio is high 8 (however generally no more than 60 %, because only the best quality of marble is used for the substitution of the external body of the Cathedral).

6. THE USED SUPPORT STRUCTURES AND THE MONITORING SYSTEM

The cavern walls at the entrance zone are supported by different structures (Figure 3 and 4): cemented bolts, tensioned cable anchors, wire mesh, concrete large beams.

Monitoring in that zone is based on several measurement types:

- topographic measurements, carried out with fixed reference points outside the quarry and checking target points located at the cavern walls;

- vibrating wire extensometers;
- biaxial clinometers and tilt meters;
- crack meters for measuring fracture opening;
- load cells at the head of the strand tendons to check the induced force;
- pressure cells inside the concrete beams;
- vibrating wire extensometers inside the concrete beams connected to steel reinforcing bars;
- two suspended pendulum.

The data acquisition is partially centralized and remote controlled. Each data set is correlated with the temperature of the site and with the excavation phases.

The more interesting data are those of the walls convergence, the stress state inside the concrete beams and the load measured at the tendons head. It is important to notice that for this kind of rock material, with a brittle failure mechanism, low values of movement and convergence are admitted (some mm,up to few cm).

In Figure3 an instrumented tendon head is shown; in Figure 4 the location of some measuring point at the wall in the cavern entrance zone is shown.

7. THE PERFORMED NUMERICAL MODELLING

The numerical modelling of the Candoglia quarry has been carried out on a3D and on a 2D basis, by adopting the FLAC code (ITASCACouns. Group). The development of the excavations has been created in the 3D model (Figure 5) (Pelizza et al., 2006); the rock mass parameters have been back-analysed by the 2D model located at the more critical section in the adit zone (Bertotti, 2014; Romice, 2014).

The aim of the numerical modelling was to put in evidence the stress state evolution and the occurrence of yielding zones around the cavern in function of the evolution of the mining activity. The obtained results have led to the understanding of the future exploitation plan, correlated with the presence of the horizontal concrete beams, which have the role of limiting the free vertical extension of the lateral walls (Romice, 2014).

The Figure6 shows the stress state (horizontal stresses) in the rock mass and in the structures for the reached geometrical configuration of the cavern at the end of 2014(Bertotti, 2014; Romice, 2014). Figure 7 shows the plastic zones at the end of the simulated excavation phases, after three further bench lowering at the foot of the cavern (Romice, 2014).

The stress state (Figure 6) obtained by the numerical modelling can help in the dimensioning of a new row of concrete beams able to make stable the chamber walls.

The plasticity indicators (Figure 8) show some plasticized portions of the marble pillar on the left wall; in order to avoid a possible extension of the plasticized zones at the base of the pillar on the left wall, a further support systems (a new row of concrete beams) are requested to proceed with the bench excavations at the cavern foot.

Figure 3. *Instrumented tendon head on the left wall of the cavern: an anular load cell at the tendons head with a tiltmeter.*

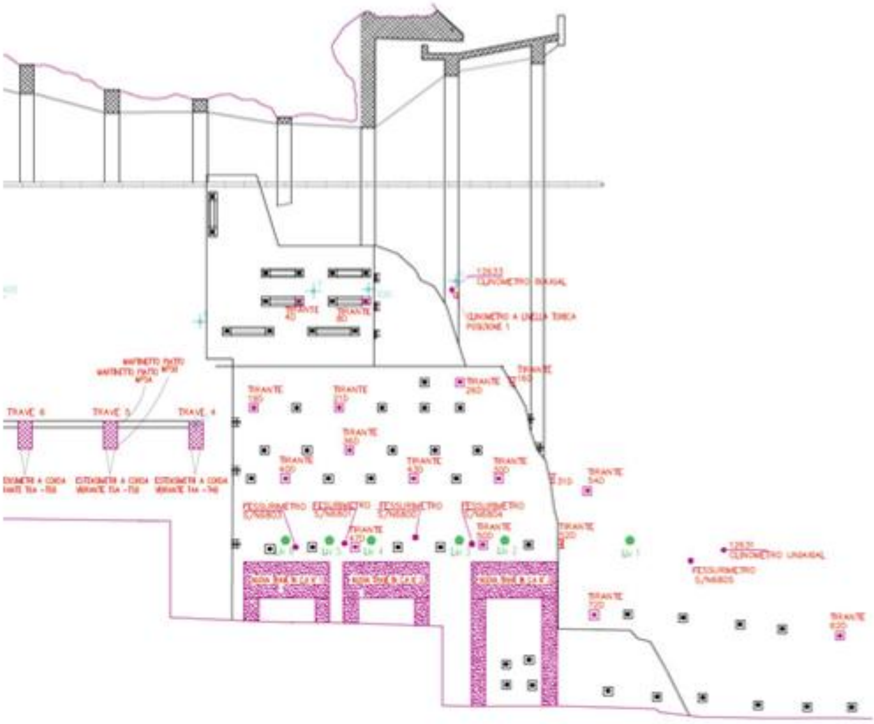

Figure 4. *The location of the measuring points at the right wall of the cavern in the entrance zone.*

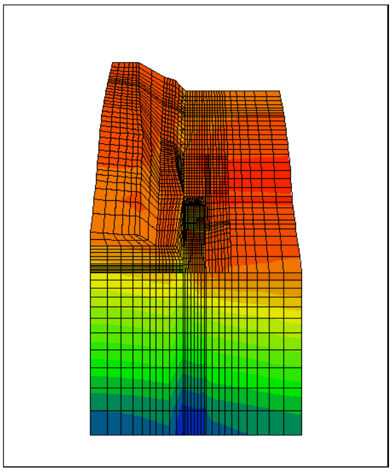

Figure 5. *View of the 3D numerical modelling developed to study the general behavior of the Candoglia cavern (Pelizza et al., 2006).*

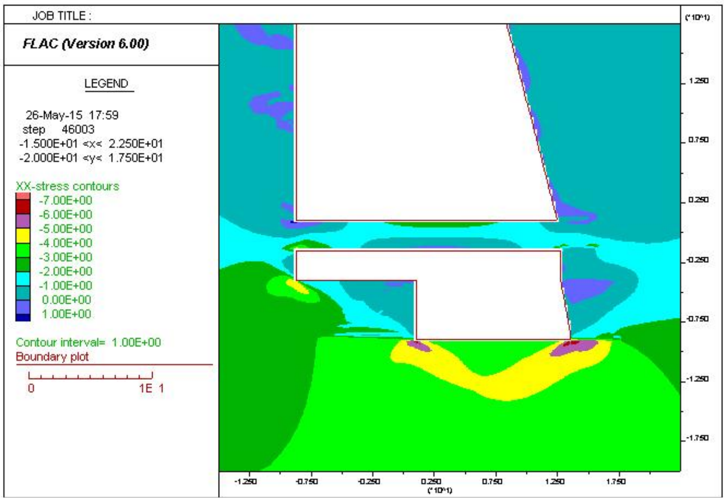

Figure6. *Details of the horizontal stresses in the rock mass around the void and in the existing concrete beams according to the 2D numerical modelling, for the geometrical configuration of the cavern reached at the end of 2014. Bertotti, 2014; Romice, 2014.*

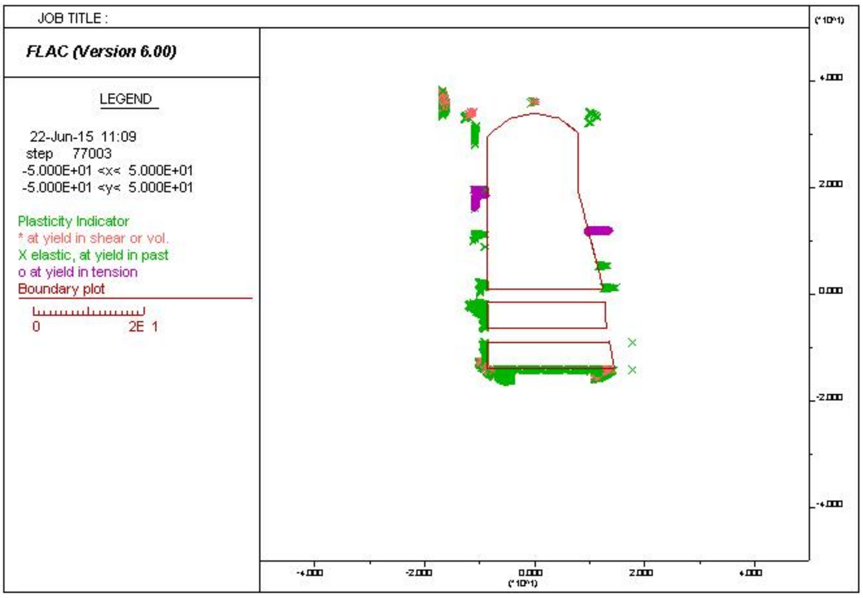

Figure 7. *Plastic zones in the rock around the void according to the 2D numerical modelling, after 3 more excavation benches at the foot of the cavern, hypothesizing the installation of a further row of concrete beams.*

8. Conclusions

The Candoglia quarry is a cavern of particular interest as it supplies the veined pink marble for the Milan Cathedral (Duomo di Milano). This case has been studied by the correlation among geo mechanical characterization, a careful long term monitoring and the 2D and 3D numerical modelling. The monitoring system has been used both for static control and also for the back-analysis of the numerical modelling.

The numerical modelling has demonstrated the possibility to check different possible scenarios for the development of the mining excavations in the adit zone of the cavern, where the marble has a good quality. At the entrance zone of the cavern some geo structural and exploitation problems have been encountered and solved: the brittle behavior of the marble, the need for maintaining under control the convergence of the walls, the induced plasticity in the pillar marble at the left side of the cavern, the stress state in the support systems (a row of concrete beams recently constructed).

With the help of the numerical modelling, an exploitation plan was developed in order to extract the marble by bench lowering of the cavern foot, in the entrance zone of the cavern, hypothesizing the realization of a further row of concrete beams.

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