The Cava Madre of Candoglia: The Centuries-Old Cavern from which the Marble is Extracted for the Construction and the Perpetual Conservation of the Milan Cathedral

(Article begins on next page)

The Cava Madre of Candoglia: the centuries-old cavern from which the marble is extracted for the construction and the perpetual conservation of the Milan Cathedral

by Pierpaolo ORESTE[1,*], Claudio OGGERI[1], Francesco CANALI[2], Marco SCOLARI[2]
[1] Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Italy
[2] Veneranda Fabbrica del Duomo di Milano, Italy
[*] corresponding author: pierpaolo.oreste@polito.it

Abstract

The Cava Madre of Candoglia is a centuries-old mining cavern of significant historical-architectural interest because it is the site from which the marble is extracted for the renovation of the external structure of the Milan Cathedral. This activity is continuous and therefore requires the guarantee of the supply of the same marble that was used for the construction of the Cathedral.

Over the time, block extraction and handling techniques have changed and evolved, ensuring their effectiveness and safety. Today diamond wire is used to detach the bank and to cut the blocks. The movement takes place using trucks capable of traveling along the access road to the quarry and transporting the blocks to the processing laboratories.

Some geomechanical aspects play a fundamental role: a careful characterization of the rock materials (marble vein and embedding rocks) in the laboratory and on site, a reliable numerical modeling capable of representing the evolution of the stresses and deformations in the rock and in the present support and reinforcement structures, continuous geomechanical monitoring to control the state of stresses and deformations that actually develop in the rocks and support structures.

1. Introduction

The Candoglia quarries are located in the municipality of Mergozzo, on the left of the Toce river, in Upper Piedmont in Italy. They involve a white-pink subvertical marble bank, of remarkable structural qualities, included in the metamorphites of the "lake massif" of the lower Ossola valley. Due to its natural beauty, Candoglia marble has been used over time as an ornamental stone for the construction of various prestigious buildings since Roman times (Bianchi C., 1892). Since the 14th century, Candoglia marble has been used for the construction of the Milan Cathedral, one of the main manifestations of Gothic Art in Italy and in the World.

The particular privilege granted to the Veneranda Fabbrica del Duomo of Milan in 1387 was implemented by the decree of 19 October 1927 n°1924, in which the existence of the perpetual easement due to the Duomo of Milan on the public and private funds of the Candoglia mountain was "confirmed to freely and free of charge excavate marble and flints for use by the Factory, with a ban on anyone from quarrying, transporting and selling the aforementioned material, without the consent of the Institution itself".

Since the second half of the 19th century, the marble exploitation has taken place at an altitude of 570 m, where the Cava Madre (currently a large underground cavern) was opened in 1680 (Figure 1); the marble is used for the completion of the front of the Milan Cathedral (Figure 2): it is still active and allows the continuation of the integral conservation work of the important monument, which develops in cycles with an average duration of 150 years (Ferrari da Passano, 2001).

The quarry, managed directly by the Veneranda Fabbrica del Duomo di Milano, has produced an average of 70 m^3 per year of first choice material for restorations over the last 50 years, originated from a run of quarry of about 150-180 m^3 per year. The excavation takes place in blocks approximately 5 m high and 10 m deep.

Since the excavation of the Cava Madre was conducted in a tunnel over the time, a large cavern was formed, today almost 90 m deep, with a maximum width of approximately 22 m and a height of approximately 50 m. The cap of the cavern, with little covering, was consolidated at the end of the 1960s, with large reinforced concrete portals; while three large reinforced concrete strut beams were built at the beginning of the 2000s to counteract the thrust of the walls and safely access the particularly valuable marble of the adit (Figure 3).

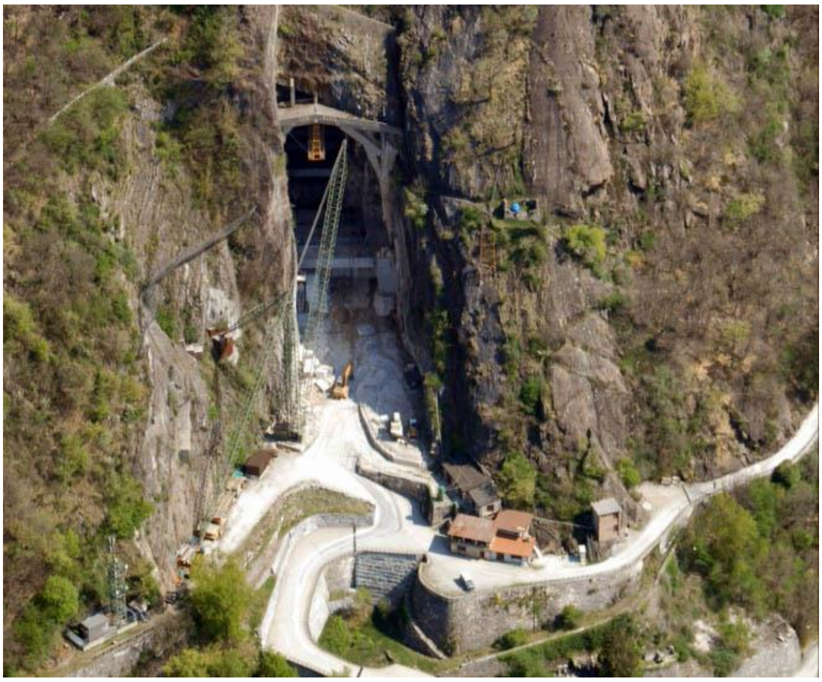

Figure 1. Aerial front view of the adit, access ramp and upper yard of the Cava Madre of Candoglia, from where the marble is extracted for the continuous renovation of the external casing of the Milan Cathedral.

Figure 2. View of the front of the Milan Cathedral (left) and details of the precious ornaments present along the entire external casing.

Figure 3. Detail of the entrance area of the Cava Madre (left) and detail of the three imposing strut-beams in reinforced concrete built at the beginning of the 2000s to counteract the lateral thrusts of the walls.

For about 20 years the extraction of marble in this cavern has taken place only in the entrance area, where it was first enlarged (going from a width of about 12 m to a width of about 22 m), shaping it into the right wall, and then lowered by a further two steps compared to the situation present at the end of the Nineties of the last century; before proceeding with the shaping and widening of the right wall, three old strut beams built at the end of the 1960s were demolished (Pelizza et al., 2000).

The extraction of the marble on the final internal face of the cavern was interrupted in the mid-1990s due to static problems found at the top of the right wall; some steel struts were then made to contrast the side walls and stabilize the cavern in that internal area.

Long term availability of the same high quality marble type is the aim of the Cava Madre. In the next decades the same yard visible in figure 3 will be progressively lowered (there is already about 6-7 m of debris now) to open at least 2-3 descending benches, but on long term planning a new lower sublevel cavern will be an option, by leaving in place a horizontal pillar of marble as natural support for static reason. Also partial backfilling with cemented debris could be locally adopted. From that opening, it will be possible to enter again along the vein into the mountain.

2. Marble exploitation and processing technique

The extraction techniques known in the past were very rudimentary and derived from those in use by the ancient Romans: the system used consisted of widening the natural fractures of the rock until causing the detachment of irregular blocks, introducing iron wedges of variable dimensions (“punciotti”) which were hammered with large square-headed hammers. When the natural cracks were insufficient, artificial grooves were cut into the rock using long pointed-headed rods, which were hammered down to form deep "V"-

shaped incisions in the rock, after which the block was normally detached with wedges and mallets (Figure 4).

Figure 4. Extraction techniques in the Roman Age: insertion of wooden wedges into cracks in the rock, possibly widened beforehand (left). Detail at right of the Roman Quarry of Fossacava in Carrara, from which it was possible to reconstruct the techniques and tools used by the Ancient Romans: width of the bench is about 12 m and height is about 6 m.

Starting from 1500, the use of black powder for the mining exploitation was also introduced in Candoglia: such a method was certainly not suitable for the type of material to be extracted and for this reason, starting from 1795 the use of explosives was prohibited.

The extraction operations proceeded as in the Middle Ages until 1934, when cutting by the helical wire technique was introduced: a steel rope made up of three wires wound like a helix that slide over the rock, dragging a mixture of water and silica sand between their coils. In 1988, diamond wire technology was introduced: a series of beads impregnated with sintered diamonds, supported by a stranded wire and plasticized to avoid violent and sudden dispersion of the beads in the event of wire breakage. The diamond wire is introduced into holes with a diameter of 90 mm and closed in a ring on a pulley moved by a special mobile electric machine, which moves back on a rack track. The cutting speed is of the order of 12 m^2/h (Figure 5 Left).

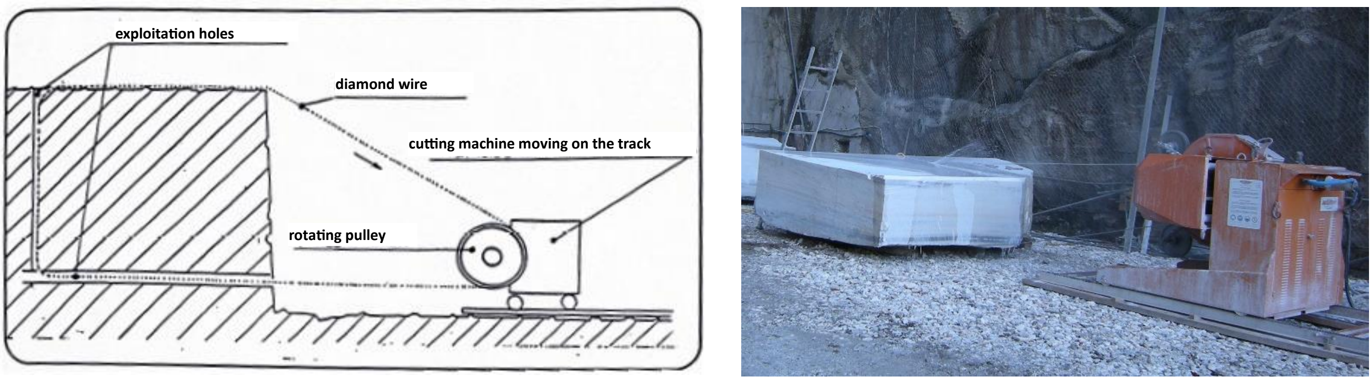

Figure 5. Left: operation scheme of the diamond wire system. Right: example of use of diamond wire system for secondary cuts at the front yard of Cava Madre, before transportation to the local workshop in Candoglia

for sawing in smaller and tailored elements. Destination and uses of marble blocks, when possible, are already decided at an earlier stage on the basis of integrity and veins, directly at the quarry yard.

Once the base, back and side cuts have been made, the marble block is thus completely isolated from the rest of the mass; subsequently, hydrodynamic cushions are introduced into the vertical cuts and inflated by introducing pressurized water. Consequently, the spacing of the cuts is increased until it is possible to introduce a hydraulic jack, with which the two lips of the cut are further moved apart until the block or parts of it are overturned; then they are, via a winch, dragged onto the quarry yard where they undergo an initial trimming using a further mobile wire cutting machine (Figure 5 Right).

Then the marble blocks are transported by trucks to the sawmill where the final squaring takes place using fixed wire cutting machines. With this operation, the "defects" of the block are eliminated: discontinuities, pyritized planes, levels characterized by unwanted mineralizations.

It was precisely the transport of the marble blocks from the Cava Madre to the processing laboratories that in the past represented the most complicated phase, which took the name of "lizzatura". A particular road had to be equipped on the mountainside, starting from the entrance of the cavern and the marble blocks were lowered very slowly through ropes and wooden planks and a series of operations aimed at not damaging the block and guaranteeing the safety of the workers (Figure 6).

Figure 6. Cava Madre of Candoglia. Ancient road (“via di lizza”) equipped to allow the transport of blocks (left) and the "lizzatura" phase using ropes and wooden planks.

Following mechanical pre-processing, the “Ornatisti” Laboratory proceeds to work in detail on the piece to be inserted on the external casing of the Milan Cathedral, using chisels and compressed air cutters. This results in a piece capable of replacing a similar one in the Cathedral, which had deteriorated over the time and due to the air pollution in decades when fuel used for domestic heating, car motion and industry was not so purified from sulfur content (acid rain) (Figures 7-8).

Figure 7. Creation activity of the decorative components based on the original shapes available in the historical documents of the Veneranda Fabbrica del Duomo of Milan.

Figure 8. View of the decorative elements ready for assembly on the external casing of the Milan Cathedral to replace those damaged by aging, acid rains and air pollution.

Regarding structural parts, during maintenance and inspection inside the cathedral at the beginning of 1900s, cracks and fissures were observed in the pillars of the naves and of the tyburium, with concerns for the static. Each pillar is made of an outer ring of Candoglia marble wrapping around a core made of a gneissic stone (sarizzo) (Figure 9), less stiff than the marble: this induced a noticeable stress concentration upon the outer segmental ring (Del Greco et al., 1993). The maintenance with repair and substitution of integer stone elements lasted for decades along the 1900s but fortunately now the substitution is no longer triggered by acid rain; all the old elements are stored in a site for historical recording.

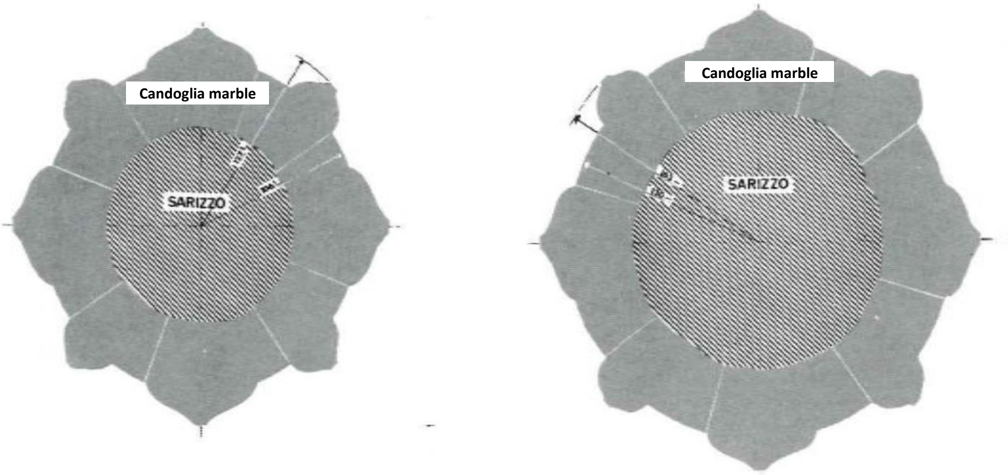

Figure 9. Cross section of the pillars of the nave and of the tyburium (Milan Cathedral).

3. Geomechanical aspects, numerical modeling and cavern monitoring

From an engineering and technical point of view, there are many aspects of interest and study. The size of the cavern has become considerable, especially in the entrance area, due to the particular vertical geometry of the marble bench; furthermore, the encasing walls, made of schistose and quartzite rock, present notable contrasts in stiffness with the marble. In addition to the aspects of overall stability of the walls, local stability must obviously also be ensured with regard to potential detachments of flakes or blocks that could detach or fall from the edge of the cavity.

In the Geomechanics laboratory of the DIATI department of Politecnico di Torino, numerous uniaxial compression tests were carried out on rock specimens obtained from cores taken during various geognostic surveys.

During the compression test, some strain gauges mounted on the lateral surface of the specimen were able to measure the vertical and horizontal deformations as the induced stress within the rock varied. Thanks to the strains measurement it is possible to obtain the trend of the stress-strain curve and also determine the value of the elastic modulus. Figure 10 shows the images of two marble specimens instrumented with strain gages and subjected to the compression test. In Figure 11 the same specimens after the test, once the breakage has occurred.

Candoglia marble is an anisotropic stone material whose geomechanical characteristics have been determined with detailed laboratory tests aimed at identifying the distribution of these parameters and the behavior in elastic conditions and in proximity to failure. The compressive strength detected varies between 45 and 150 MPa (average 68.7 MPa) and the elastic modulus from 40 to 100 GPa (average 71.6 GPa); some of the obtained lab data are presented in Table 1.

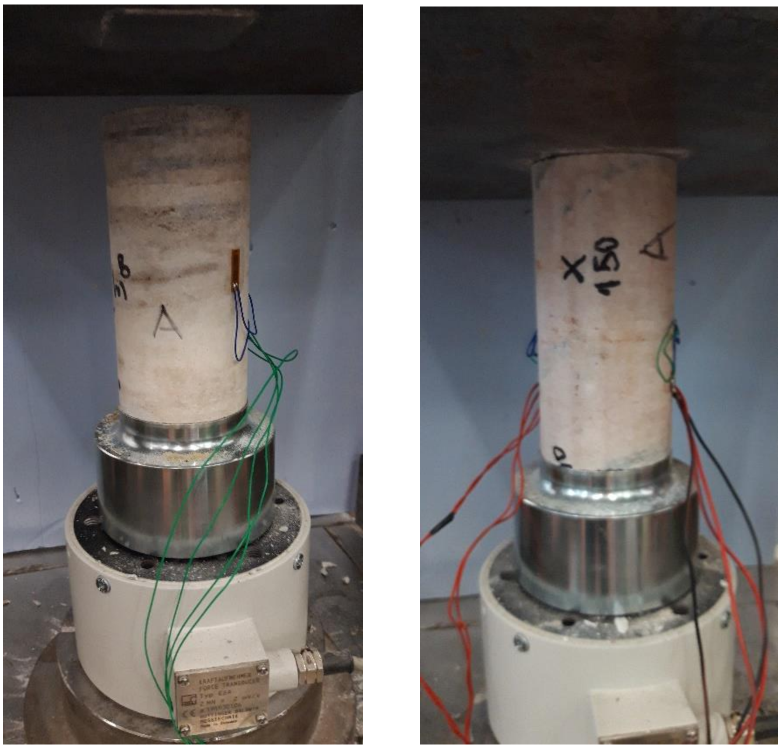

Figure 10. View of two instrumented marble specimens before performing the compressive test.

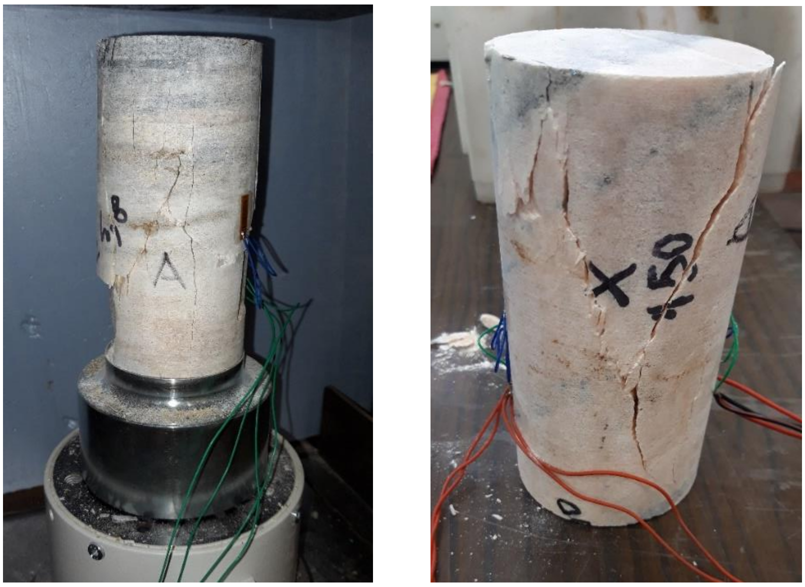

Figure 11. View of the two specimens after reaching failure, at the end of the compressive test.

Table 1- Main averaged parameters of principal rock types after series of laboratory testing. Other rock types are also present in the cavern area and have been investigated (quarzitic rocks, micaceous schists). Due to complexity of regional geology, also kinzigitic rocks, dolomitic marbles, silicatic marbles, anfibolitic rocks and even pegmatites are present in the mountainous area of the quarry.

Parameter	Main geomechanical parameters for veined marble and embedding gneiss			
	Symbol	Unit	Veined marble	Embedding gneiss
Unit weight	ρ	kg/m^3	2620 - 2830	2300 - 2690
Uniaxial compressive strength	C_0	MPa	44 - 155	29 – 157
Indirect tensile strength	T_0	MPa	1.8 – 12.3	5.8 – 10.8
Tangent elastic modulus	E_t	GPa	50 – 90	24 – 70
Secant elastic modulus	E_s	GPa	40 – 98	14 – 115
Tangent Poisson coefficient	ν_t	-	0.18 – 0.39	0.20 – 0.32
Longitudinal wave velocity	v_p	m/s	3210 - 6390	2120 - 2920

Marble exploited and useful for the artistic sculptures has a massive structure, somewhat foliated, and fine to medium grain size. Main components are calcitic coarse grains, associated with minor silicatic minerals such as quartz, phlogopite, plagioclase, K-feldspar, diopside and hornblende, as well pyrite and magnetite.

Sculpture with manual tools or with air-compressed stonemason devices can be used thanks to the workability of the marble (figure 7) , that does not propagate fissures and microcracks; on the contrary, it could be affected by moderate bending and creep deformation in thin slabs.

In the rock mass there are 5-6 large-scale discontinuity systems that influence the behavior of the rock masses surrounding the cavern (Figure 12).

Figure 12. Bench opened in years 2020 – 2021, in the half-left side of the cavern, at the current level of the yard visible in the previous figure 3. Bench is about 5.5 m high. Joint with alteration is visible at face, lateral smooth cutting by wire saw is leaving an undisturbed surface and anisotropy of marble is put in evidence by alternate colors white – pink – grey or dark grey, following the main orientation of the subvertical vein and also of the embedding rocks. Stereonet of the joints in marble at the adit of the cavern is reported in the left corner: the red line represents the axis of the cavern.

The behavior of the large cavity is studied with three-dimensional and two-dimensional numerical models which have made it possible to highlight the static conditions in the rock and in the support and reinforcement structures that are present. The models also retraced as faithfully as possible the history of the exploitation phases in the various sectors of the cavern, since its origins, to better represent the stress and deformative evolution that occurred over time. The most interesting numerical calculation results to analyze are:

- stresses both in the rock mass and in the structural elements (in particular inside the concrete strut beams);
- the movements of the cavern walls;
- any plasticization in the rock mass surrounding the cavern.

The analysis of the stress state has a significant influence on the behavior of the structural elements already completed and those planned in the future. Numerical modeling, therefore, represents a very helpful tool to support the planning of marble extraction activities and for the design of the support and reinforcement structures that are necessary to guarantee the stability and safety of the activities.

Figure 13 shows the result of the three-dimensional numerical modeling in terms of vertical stresses in the rock and concrete in the cavern entrance area and on the external vertical walls in the current mining situation. Figure 14 shows the trend of the safety factor in the same area, always in the current condition: the safety factor represents an interesting parameter capable of providing an indication of the distance, in terms of stresses, from the possible failure of the material; values higher than 1 indicate a condition of stability, with an increasingly greater margin as the value increases; values lower than 1 indicate a possible critical condition for safety in relation to the failure of the material (rock or concrete) simulated in the numerical model.

Thanks to the numerical study it was possible to identify the structural elements necessary for the continuation of the excavations and in particular for the containment of the lateral walls of the cavern in the entrance zone. In addition to strand or bar tendons, it is necessary to create a new row of concrete contrast beams, at a lower level than the existing ones. This contrast system is able to guarantee the stability of the cavern even in the presence of a further lowering of the foot, in relation to the development of the mining exploitation.

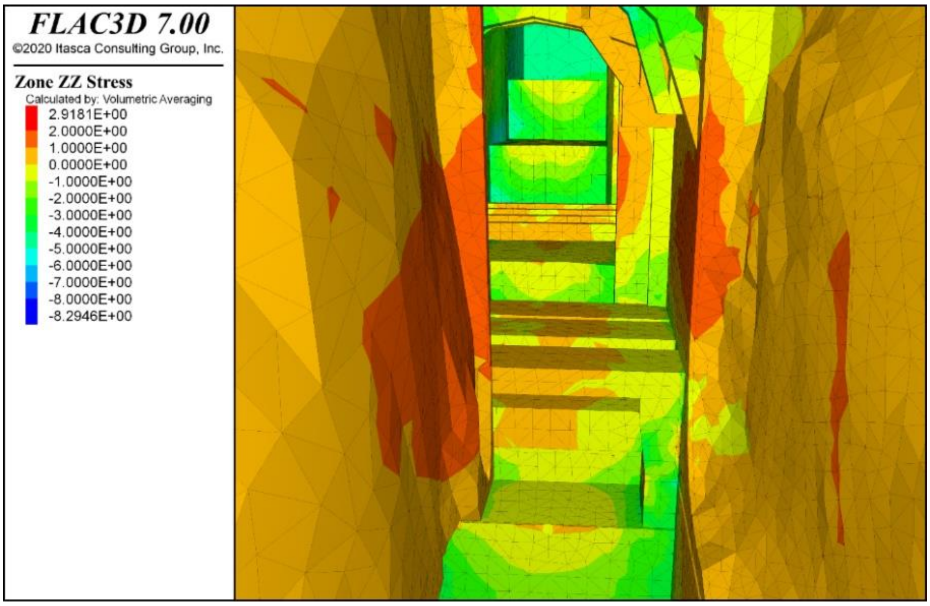

Figure 13. Vertical stresses in the entrance area of the Cava Madre in the current condition. Values mapped in colors refers to the intervals of the legend in MPa. It is possible to detect the vertical stress state in the exposed rock faces in front of the cave entrance and in its internal area: by comparing the existing stress state with the ultimate stress it is possible to detect the risk of rock failure.

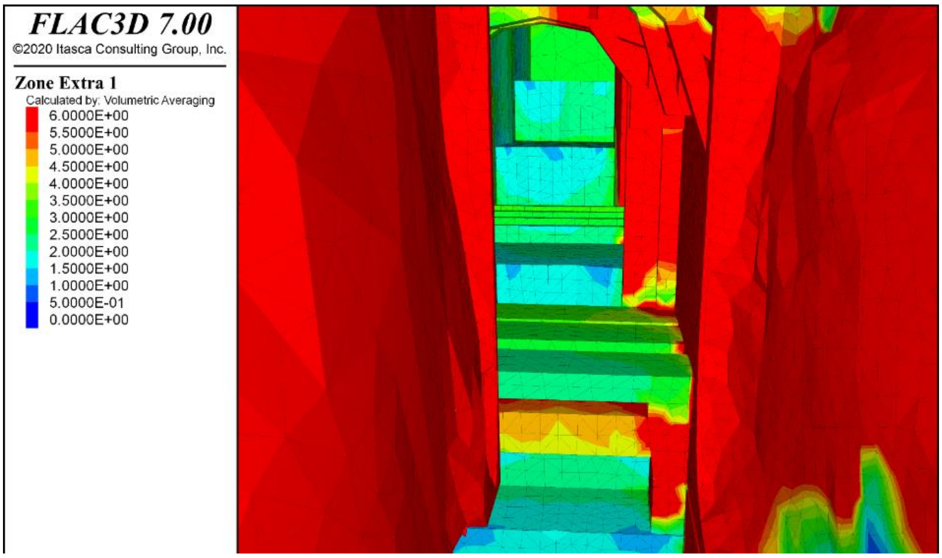

Figure 14. Safety factors in the entrance area of the Cava Madre in the current condition. The safety factor represents the ratio between the ultimate stress state at failure of the rock or concrete and the existing stress state. By analyzing the safety factor on exposed surfaces of rock or concrete, it is possible to detect any risk zones for the necessary countermeasures.

Particular attention was paid to the monitoring system which allows the stress-strain conditions of the cavern to be checked periodically. This system includes topographical targets, strain gauges, crack gauges, load cells, clinometers and pendulums, the regular reading of which makes it possible to facilitate the choices of individual excavation operations, correlating them over time, and to provide feedback to numerical simulations. The monitoring, in particular, focuses on the convergence measurements of the walls of the cavern entrance and on the stress state of the support elements such as the tendons and the concrete strut beams.

The variety of instruments and the complexity of the system are due to the characteristics of the excavation (large sizes), as well as the historical-architectural importance of the extracted material and of the site.

The instrumentation for geomechanical monitoring has been installed and integrated several times over the years, both to follow the development of the excavations and to take into account the installed supports; the purpose of the monitoring measures is that of static control of the excavations and supports also in relation to the progress of the works, and of comparison with the assessments resulting from the updating of the numerical modelling.

In 2014, a maintenance intervention was carried out on the monitoring system, which involved: the replacement of the wiring of the load cells of the instrumented tendons; the centralization of the related measurements through an automatic remote data transmission system; the centralization of the readings of the remaining electrical instrumentation in correspondence with the different areas of the cavern.

To date, most of the instrumentation is managed with periodic reading through the use of data acquirers, these being electric vibrating wire or strain gauge transducers. Some measurements are performed using topographical methods. Finally, there is the recording of meteorological conditions, in particular air temperature, which shows a certain influence on some types of measurement.

The comparison of the monitoring measurements with the results of numerical modeling has allowed to develop mathematical procedures known as back-analysis techniques, capable of determining some geomechanical parameters considered uncertain, but fundamental for a correct numerical simulation. In particular, the elastic modulus of the marble rock mass and the lateral thrust coefficient at rest, which represents the ratio between the horizontal and vertical stresses on site, before starting the excavation operations, were considered uncertain. Thanks to the back-analysis procedure, it was possible to eliminate the uncertainty and identify precise values of the two parameters, necessary to develop the calculation with a high degree of reliability (Oreste et al., 2023).

4. Conclusions

The Cava Madre of Candoglia has for centuries represented the cavern from which the marble, which was necessary for the completion of the works on the Milan Cathedral and the continuous renovation of its external casing (due to the deterioration of the present components) and internal structural parts, was extracted. Due to this continuous mining work, the cavern has now reached significant sizes.

The extracted marble, of considerable value, is then worked in the "Ornatisti" Laboratory in order to obtain the pieces to be inserted in the Milan Cathedral to replace the degraded ones.

Over time, the techniques for excavating and transporting rock blocks have evolved greatly. Today diamond wire is used to detach the marble banks and proceed with the sectioning of the blocks. Transport takes place safely using suitable machines to avoid damage to the blocks and dangers for workers.

Some significant geomechanical aspects are taken into consideration at the Cava Madre of Candoglia: a careful characterization of the materials (marble and other embedding rocks) also through laboratory tests, due to their anisotropy and intrinsic variability; a sophisticated numerical modeling of the behavior of the cavern with the evolution of mining works; a continuous monitoring of the stress and deformative behavior of the cavern and the rocks present around it.

Funding Declaration: No funds, grants, or other support was received.

Competiting interests: The Authors have no conflicts of interest to declare that are relevant to the content of this article.

Author Contributions: All Authors contributed to the paper conception. Material preparation, data collection and analysis were performed by all the authors under the coordination of P. Oreste, and all Authors commented and improved the subsequent versions of the manuscript. All Authors read and approved the final manuscript.

5. References

Cesa Bianchi P. (1892). Della cava marmi alla Candoglia per la Fabbrica del Duomo di Milano. Veneranda Fabbrica del Duomo di Milano.

Ferrari da Passano C. (2001). Le sorgenti del Duomo – Le cave di Candoglia. Veneranda Fabbrica del Duomo di Milano. 63p.

Pelizza, S., Oreste, P. P., Peila, D., & Oggeri, C. (2000). Stability analysis of a large cavern in Italy for quarrying exploitation of a pink marble. Tunnelling and underground space technology, 15(4), 421-435, doi 10.1016/S0886-7798(01)00011-6.

Oreste P., Oggeri C., Canali F., Scolari M. (2023). Numerical modeling and back-analysis approach on a monitored underground cavern for the extraction of marble for ornamental uses. Applied Sciences 13(23), 12893, doi 10.3390/app132312893.

Del Greco O., Ferrero A.M., Oggeri C. (1993). Experimental and analytical interpretation of the behaviour of laboratory tests on composite specimens. Int. Journal of Rock Mechanics and Mining Sciences, Volume 30, Issue 7, doi 10.1016/0148-9062(93)90153-5