Stability Analysis of a Large Cavern in Italy for Quarrying Exploitation of a Pink Marble

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Abstract*—The paper presents the results of a three-year research study carried out in the underground quarry of the "Cava Madre of Candoglia", which is a large underground cavern (80 m long, 21 m wide and 48 m high) located in the Ossola Valley of northern Italy, excavated for the exploitation of a vertical vein of pink marble. The research has shown that systematic monitoring and numerical modelling form the basis of a good design for these kinds of mining activities. A detailed back-analysis on ten years of displacement and stress measurements in the marble is presented and discussed. On the basis of the obtained results, the design of future mining excavations has been developed, taking both stability (with the support optimization) and economic mining aspects into account.*

1. Introduction

The "Cava Madre di Candoglia" is a large underground cavern (80 m long, 21 m wide and 48 m high) located in the Ossola Valley in northern Italy, excavated for the exploitation of a vertical vein of pink marble. The cavern is the main source of the marble that was used to build the historical gothic cathedral in Milan (Fig. 1).

This cavern has been exploited for more than two centuries and is also of great relevance today, since the marble used for repairs of the Milan Cathedral is still taken from this quarry because of its colour and mechanical behaviour. There is therefore a need for this quarry to continue operating.

This paper presents the results of a broad and in-depth study carried out for more than three years to analyse and improve the critical stability conditions of the pit.

The study was carried out by setting up a numerical model which was necessary to forecast the behaviour of the cavern for future mining operations.

The problem of a correct design of an underground ornamental stone activity in fact requires the following key points, which cannot be disregarded if the exploitation is to be well designed and an optimal exploitation of the ornamental stone orebody is to be obtained:

- Good knowledge of the orebody from both the geometrical and the geomechanical points of view (discontinuities, rock mass properties and layout) should be available.
- Good monitoring has to be planned and designed; without sufficient monitoring, the potential dangerous conditions cannot be pointed out.
- Numerical modelling is necessary for a correct forecast of the stress and strain development of the cavern during exploitation and also to have a reasonable analysis of the field stress around the void.

The example described in this paper is therefore of great importance because it can show that the correct use of in-situ measurements over a period of 10 years offered the basis of the study when an unexpected event occurred during the exploitation of the mine.

Exploitation of the mine is now carried out using wire diamond cutters, whereas in the past, conventional wire-saw cuts were used in the cavern.

During the cutting phase, carried out near the cavern face, the in-situ monitoring instruments measured an unexpected and relevant displacement of one of the two walls. This movement compromised the stability and safety of the cavern and created the risk of having to interrupt the mining development.

The research therefore had the aim of understanding the reasons behind the unexpected event; and then, as an upgrade of the in-situ monitoring, to define the remedial works and their possible influence on the development of the mining activity for the next 20 years.

2. Measurements and Monitoring

The rock mass characterisation has been carried out using a complete geological survey, both from the surface and underground, with five new holes also used to obtain the cores for the laboratory tests (uniaxial compression, three-axial and tensile tests). A camera investigation was also carried out from the core sampling, and the lithological contacts were defined. The average geotechnical para-

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meters of the involved rock masses were defined from all these data.

To obtain some information on the natural stress state, 17 tests were carried out using flat jacks and 26 borehole Slotter Stressmeter tests. The accumulated knowledge of the information on the walls and on the roof has been kept under control for 10 years using topographic instruments and convergence measurements.

3. Numerical Analyses

The numerical study here described was carried out with three different objectives:

1. Back analysis of the available measurements to define the correct geotechnical and undisturbed stress state conditions;
2. Analysis of the anomalous movement which occurred during the exploitation, to understand why it occurred; and
3. Forecast of the cavern behaviour for future mining activities and choice of the best supports for safe mining exploitation.

The calculation method used in the numerical analyses was the finite difference method. The code adopted was FLAC (Fast Lagrangian Analysis of Continua) (Cundall, 1976; Itasca Consulting Group, 1993; Itasca Consulting Group, 1994), which develops Lagrangian analyses on a continuum subdivided into quadrilateral elements. Every differential equation that controls the investigated problem is described through algebraic equations in terms of field variables in defined points in the space.

The bi-dimensional numerical model developed for the study of Cava Madre is composed of 6930 quadrilateral elements (arranged in 77 columns and 90 rows, for a total model width of 230,5 m and height of 348,5 m).

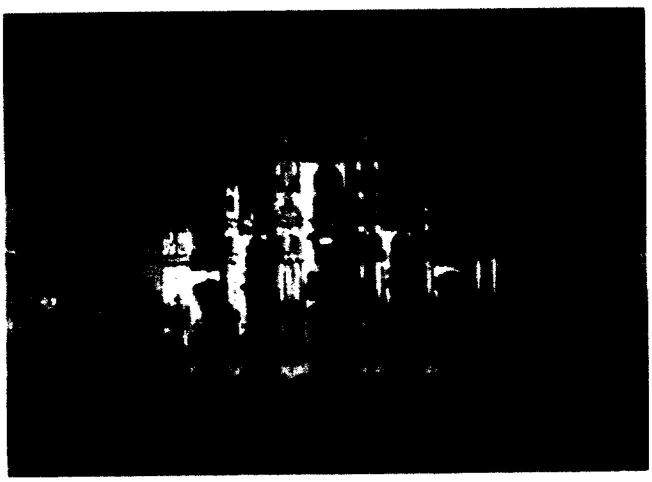
The area studied is the one near the face that produced static problems during the execution of a recent exploitation cut. The analyzed sections are sections 9 and 10 (shown in Fig. 2), which, despite having the same general geometry, present some differences regarding the reinforcing elements on the cavern walls.

The models that were developed are summarised in Table 1; Figure 3 shows the mesh that was set up for the numerical modeling.

The model was set up to allow the correct simulation of the succession of the operative mining phases in the cavern which have been developed over the last 10 years. Table 2 reports in detail the operative phases simulated in this back analysis study.

3.1 Geotechnical Properties of the Rock Masses

The rock mass is simulated as an equivalent continuum, with an elastic-brittle plastic behaviour law. The strength criterion adopted is Mohr-Coulomb with a non-associated flow rule.



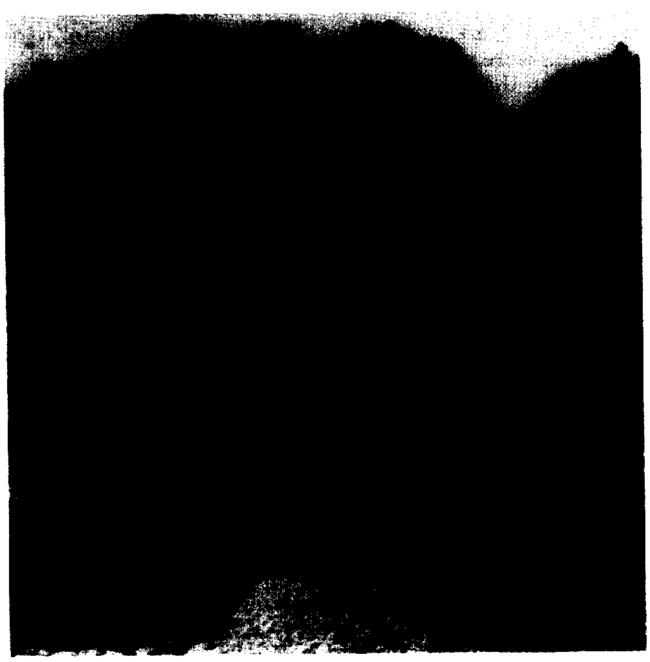


Figure 1. Top: View of the Milan Cathedral; bottom left: the portal of "Cava Madre" underground quarry; bottom right: the zone near othe face.