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3D numerical analysis of a historical hipogeum

Analyse numérique 3D d'un hypogée historique

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ABSTRACT: In this paper, based on 3D FLAC simulation, the applicability of the performance-based assessment to compute the safety condition of a historical hipogeum is investigated. The effectiveness of such approach is discussed with reference to the Fontanelle cemetery, a monumental pillar and room cave excavated in a tuff hill in Napoli, Italy. Non-linear static analyses were performed on a 3D model calibrated on the previous studies carried out in this pictoresque site. In particular the numerical model accurately reproduces the shape of the hill and of the cave, since the geometry detected on site through the laser scanner technique was directly imported in the numerical code. The mechanical properties of the materials are well known on the base of experimental studies carried out on pyroclastic soils and rocks at the laboratory of Federico II University. The numerical results were interpreted following the basic rules of the performance-based assessment, i.e.the factors of safety resulting along the nave were compared to threshold values associated to the damage and collapse limit states. The importance of the geometrical refinement was confirmed by a simpler model in which the vault span was approximated to the fully restrained beam loaded by the pozzolana weight.

RÉSUMÉ: Dans ce document, basé sur la simulation numérique FLAC, l’applicabilité du projet basé sur la performance est examinée pour calculer les conditions de sécurité d’un hypogée historique. L'efficacité de ces approches est discutée en référence au cimetière « Fontanelle », un pilier monumental dans une colline de tuf à Naples, en Italie. Des analyses statiques non linéaires ont été effectuées sur un modèle 3D calibré sur des études antérieures réalisées ici. En particulier, le modèle numérique reproduit fidèlement la forme de la colline et de la grotte, puisque la géométrie détectée sur le site par la technique du scanner laser a été directement importée dans le code numérique. Les propriétés mécaniques des matériaux sont bien connues sur la base d'études expérimentales menées sur des roches et des sols pyroclastiques au laboratoire de l'Université Federico II. Les résultats numériques ont été interprétés selon les règles de base de la conception basée sur la performance. En particulier, les facteurs de sécurité résultant du toit de la nef ont été comparés à des valeurs seuils. Les points de traction plastiques identifiés par le modèle correspondent à ceux mis en évidence sur site avant consolidation.

Keywords: Numerical analysis; 3D Flac; Tuff; roof cave stability; performance-based design

1 INTRODUCTION

Rock hills and shallow rock layers are usually crossed by complex systems of cavities resulting from the past quarrying activity. With the passing of time, the shape of the caves was transformed by natural events and their function was modified by human actions into the necropolis, cemeteries, houses or aqueducts (Aversa et al., 2012). Thanks to their resilience, some of them are nowadays preserved as world heritage sites; some of the most famous examples are the necropolis of Cerveteri and Tarquinia near Rome, the aqueduct below the Sassi of Matera in the south of Italy, the city of Petra in Giordania, the Hypogeum in Malta, the Cappadocia Region in Turkey, and so on. The increasing interest of tourists highlights the urgency to evaluate the static and seismic safety of cavities in order to ensure their preservation and safe fruition. Guessing the behaviour under gravity and dynamic loads becomes difficult because of the irregular geometry, the history of loads and the spatial variability of the rock stiffness, stress and strength (Scotto di Santolo et al., 2014a).

The most widespread approach was conceived for room-and-pillar in coal mines and is based on the separate assessment of pillar and roof stability mainly of a rectangular or circular room (Evangelista et al., 2002; Scotto di Santolo et al., 2018; Bertuzzi et al., 2016; Rastiello et al., 2015; Guy et al., 2017; Zhang et al., 2015; Suchowerska et al. 2012; Yang et al., 2011).

Only few seismic response analyses of specific case studies are integrated with evaluations on the stability under earthquake actions (Scotto di Santolo et al., 2014b; Scotto di Santolo et al., 2016; de Silva & Scotto di Santolo, 2018).

In the previuos studies the shape of the cave is generally flattened and the overburden is assumed to be uniform, due to the lack of an accurate geometrical survey or to reduce the time-consuming analysis. This paper demostrates that such approximation reduces the reliability of the results on the global behaviour of the cavity.

2 CASE STUDY

The Fontanelle cemetery is an ancient room and pillar cave located inside a 40m high Yellow Tuff hill, immediately outside the old Greek-Roman surrounding walls of Napoli (Figure 1). The Neapolitan Yellow Tuff (NYT) is covered by a pyroclastic soil layer, commonly named Pozzolana, with a variable thickness from 0m to 20m, as clearly visible along the cliff faces.

The hill is crossed by two 80m long corridors along the N-S direction and by a shorter NW-SE aisle named “Preti nave”, “Appestati nave” and “Pezzentelli nave”, since clergymen, victims of plague and poor children were buried there from the XVI century. The intersection of the three main naves with some secondary E-W rooms originates the nine pillars shown in Figure 2.

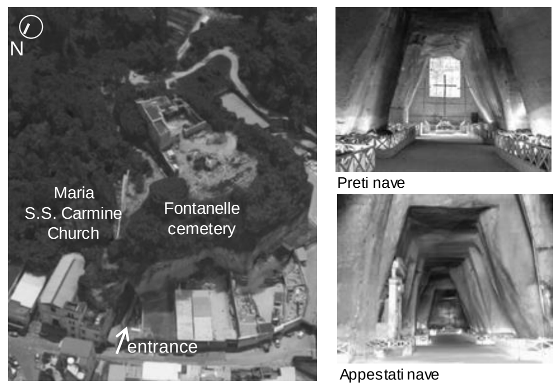

Figure 1. Aerial and internal view of the Fontanelle cemetery, Italy

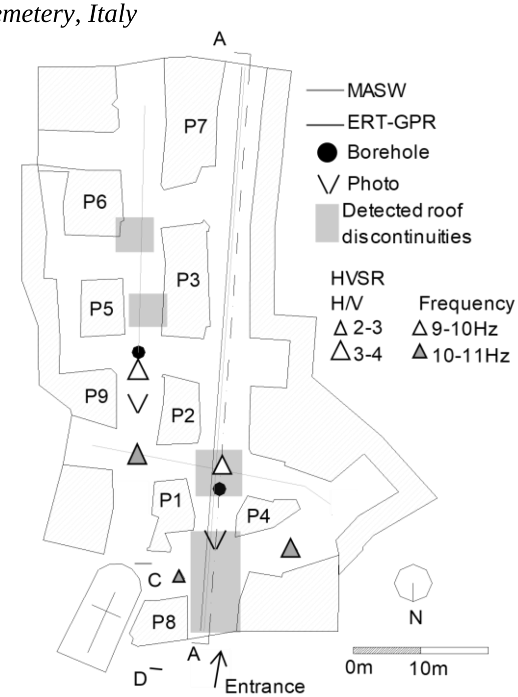

Figure 2. Plan of the Fontanelle cemetery with location of the performed surveys

The complex geometry of the cavity was detected through the laser scanner technique in 2016 (Scotto di Santolo et al., 2017). All the excavated rooms resulted around 10m high, except close to the entrance, where the height is around 15m. The inner walls of the cave are 10°-15° inclined leading to the trapezoid geometry of the vertical cross section of the aisles, as shown by the pictures in Figure 1 and the cross section in Figure 3. This inclination implies the reduction of the horizontal cross sections from the top to the base of the pillars, so the resistant section is the smallest where the highest actions induced by gravity loads are localized. The current planking level does not correspond to the bottom of the excavation, since tuff waste resulting from the quarrying activities, remains of human bones and debris flows deposits were accumulated in the cavity with the passing of time. Electro resistivity tomography and ground penetrating radar surveys confirmed that the bottom of the excavation is almost flat and 9m deep (Evangelista et al., 2016). The laboratory and in situ investigation carried out in the site are localizated in Figure 2. More details are reported in de Silva and Scotto di Santolo, 2018.

Basing on an accurate map of the discontinuity orientation, Scotto di Santolo et al. (2014a) highlighted that the cavity roof is still interested by syngenetic sub-horizontal and sub-vertical joints, typically affecting the stability of pyroclastic soft rock (Nocilla et al., 2009; Scotto di Santolo et al., 2015c). In 2000, rock bolts were installed in the ceiling close to the entrance and in pillars P4 and a buttress on piles was built to sustain pillar P6. The stability interventions aimed to prevent the detachment of blocks, which left tracks still visible in the cave.

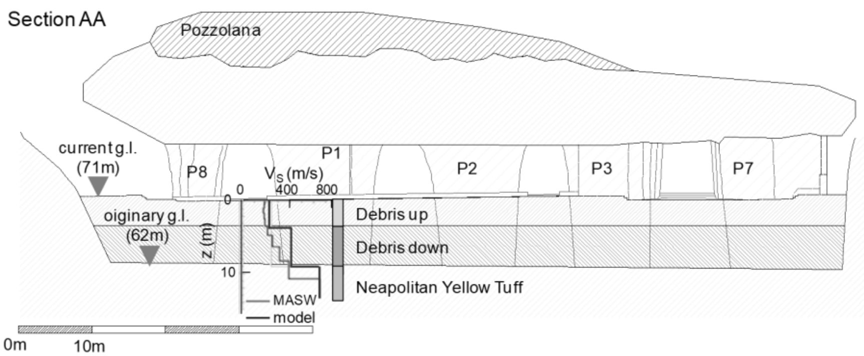

Figure 3. Section A-A reported in Figure 2 of the Fontanelle cemetery

3 NUMERICAL SIMULATION

3.1 Geometric model and analysis parameters

The numerical model of the Fontanelle cemetery was realized through the three-dimension finite element software FLAC3D (Itasca, 2015). The high modelling capability of the software allowed to import surface obtained from the laser-based survey. The shape of the hill and the complex geometry of the cavity rooms were consequently reproduced as shown in Figure 4.

A Mohr-Coulomb constitutive model was assigned to all materials, with the properties reported in Table 1.

Table 1. Soil parameters

Soil layer	γ (kN/m^3)	G_0 (MPa)	ν (/)	φ (°)	C (kPa)	σ_t (kPa)
Pozzolana	15	129	0.30	33	30	11
NYT	14	603	0.17	29	753	120
Debris up	13	53	0.37	26	40	12
Debris down		202	0.37			

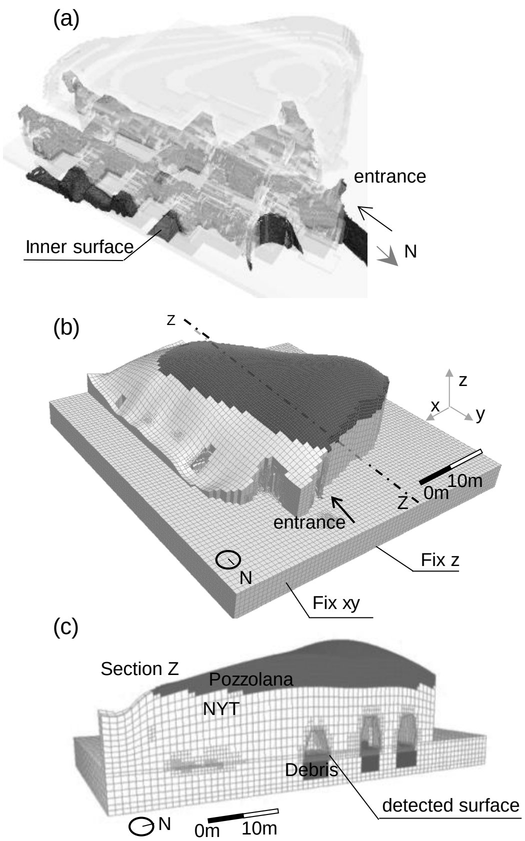

Figure 4. Introduction of the surface into the model (a), global view (b) and cross section (c) of the FLAC3D model

The small strain shear modulus, G_0, and the Poisson coefficient, ν, of the NYT and Debris sublayers were computed from the shear wave velocities, measured through the field surveys. All the unit weights, γ, as well as the mechanical parameters of the Pozzolana layer are the typical values inferred from the experimental data collected at the Federico II University during the numerous researches on such materials (Scotto di Santolo, 2000; Picarelli et al., 2007). The value at yielding of the friction angle, φ, and the cohesion, c, reported in Table 1 were assumed constant for the Pozzolana and Debris materials. A reduction of the cohesion until a value c=423kPa with increasing shear strain was introduced for the NYT to simulate the reduction of uniaxial compression strength, σ_c, revealed by laboratory tests. The tensile strength, σ_t, was limited to the to 1/20 σ_c of the NYT formation and 1/10 σ_c of the other soil layers.

3.2 *Static condition under gravity loads*

Three static construction stages were simulated in the FLAC3D model:

1) lithostatic conditions of the hill;

2) static equilibrium of the hill with the cavity inside, to recognize the effects induced by the excavation;

3) static equilibrium after the cavity is filled with the Debris until the current planking level.

The contours of the vertical stress acting in the cross section of the model after the three construction stages are plotted in Figure 5, assuming the positive compression.

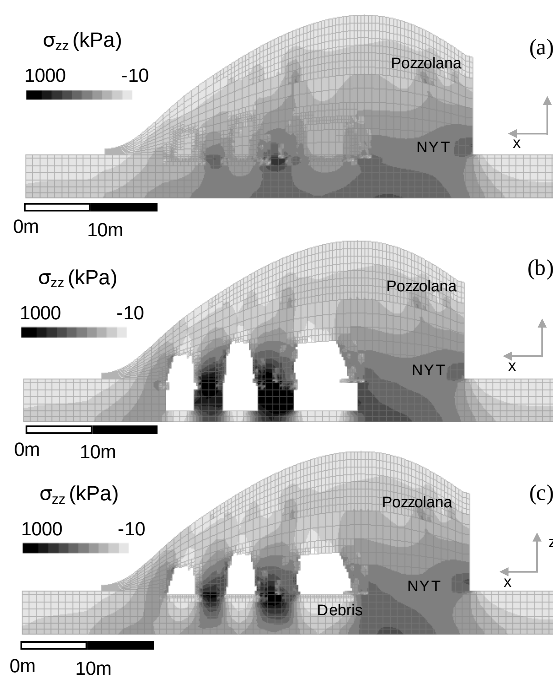

Figure 5. Vertical stress distribution in the cross section before (a) and after (b) the excavation and after the filling with the Debris (c)

After the excavation, the vertical stress induced by the gravity loads increases along the height of the pillars, with the maximum value achieved at the base. After the cavity is filled, the most elevated stress level is reached 2m below the planking level, i.e. in correspondence of the top of the lower Debris sublayer. The soft upper Debris appears irrelevant, while the stiffer and deeper filling material exerts a restraining effect on the underground height of the pillars so that the most stressed section is located immediately above the contact height between the lower Debris and the tuff pillar. The restraint turns to be beneficial for the stability of the Fontanelle cave, since the shallower pillar sections are larger and consequently more resistant than the base.

The solution of the equilibrium after the realization of the cavity inside the Fontanelle hill (second construction stage) led to the local achievement of the tension strength in the cavity roof, shown by the plastic state in Figure 6 and by the σ_{xx} stress diagrams induced in some resistant sections of the NYT roof, superimposed to the section of the Appestati nave in Figure 7. As expected, the compression stress tends to reduce from the top to the bottom of the NYT roof following the typical pattern induced by bending loads.

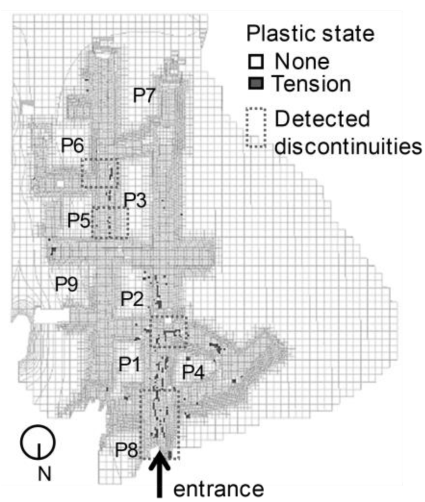

Figure 6. Plastic state achieved in the ceiling after the third construction stage

The permanent tension strains are mainly accumulated close to entrance, where the Appestati nave reaches the maximum height and the thickness of the tuff below the Pozzolana layer is minimum. Few plastic points are localized in the ceiling of the Preti nave between pillars P3, P5 and P6. The damage pattern fully reproduces the localization of the roof discontinuities detected on site, shown by the dashed lines in Figure 6.

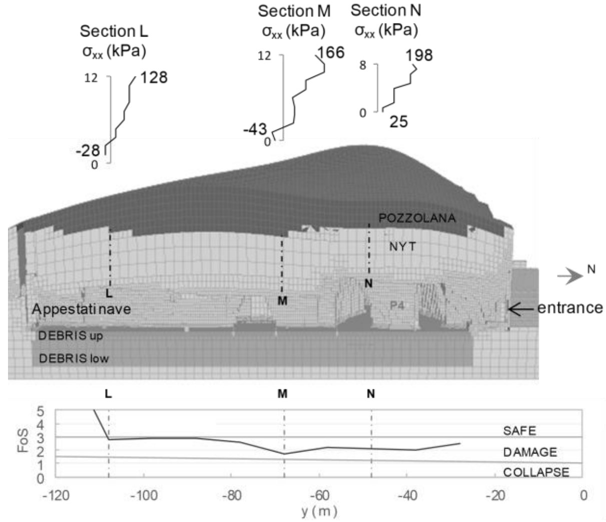

Figure 7. Variability of factor of safety along the Appestati nave

3.3 Assessment of roof stability

The safety of the rooms was assessed with reference to the failure of the vaults due to the crushing induced by the achievement of the strength, σ_{cf}, in the compression zone of the roof resistant section together with the attainment of the tensile strength, σ_{tf}, in the ceiling. The resistant moments M_f was consequently computed with reference to the stress distribution qualitatively shown in Figure 8.

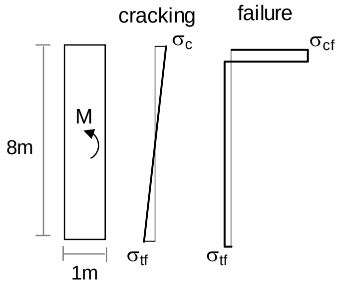

Figure 8. Scheme of the NYT central section of the naves adopted to compute the resistant moments.

The corresponding factors of safety, FoS, were obtained as the ratio between the resistant moment and the bending moment, M_{load}, calculated by properly integrating the σ_{xx} acting in the central sections of the naves.

The basic instruments of the performance-based design (Harr, 1987) were adopted to evaluate the performance of the vaults with reference to the limit states inferred from the damage scale proposed by Evangelista et al. (2002):

1) "damage limit state" occurring when the factor of safety is lower than 3,
2) "collapse limit state" associated to the factor of safety lower than 1.5.

As an example, the FoS variability along the Appestati nave is plotted in Figure 7 with the thresholds defining the limit states. The vault never approaches the failure (FoS<1.5), but the damage limit state (FoS<3) is reached from the entrance to the half-length of the Appestati nave, where the resistant NYT layer is thinner. The results are consistent with the localization of tensile plastic points in the ceiling of the numerical model and the discontinuities detected on site before the remedial works carried out in 2000.

3.4 *Effect of curvature on the roof stability*

de Silva & Scotto di Santolo (2018) compared the plastic state of the roof (see Figure 6) with the results of an additional FLAC3D model in which the shape of the vaults were assumed to be flat. The damaged zones resulting from the latter model are widespread and almost the whole span of the aisles is involved in the plastic state. The comparison between the outcome of the two models and the real state of the roof highlighted that the more refined shape improves the reliability of the numerical results.

The role of the geometry in the roof stability was better investigated by approximating the most recurrent vault span to the fully restrained beam shown in Figure 9, in which the length, L, was set constant and the central deflection, δ, was progressively increased to vary the beam curvature δ/L. The acting bending moment was calculated for each beam-scheme loaded by the weight of the pozzolana layer, characterized by the mean thickness detected on site. The moments associated to cracking and failure of the NYT resistant section were then computed, basing on the stress diagrams and the section heigth shown in Figure 8.

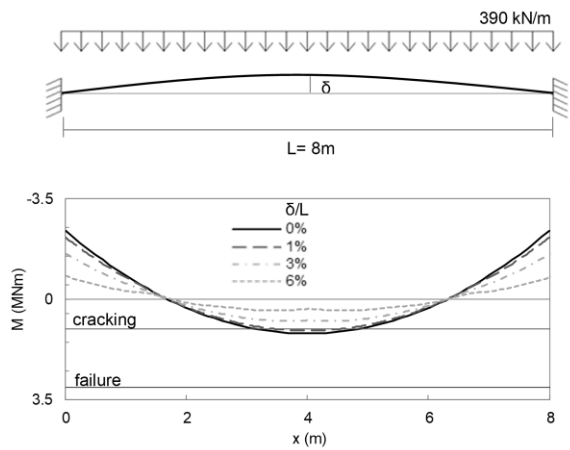

Figure 9. Bending moments acting in fully restrained beams with different curvatures

Figure 9 compares the loading and resisting moments. As expected, the failure is never reached. The cracking threshold is overcome by the moments acting in the central zone of flat beams (δ/L=0%, δ/L=1%). A benificial effect of the even slight curvature of the other schems (δ/L=3%, δ/L=6%) was found, since the associated bending moments are significantly reduced along the whole span.

The results confirm that the detailed reproduction of the roof geometry can be crucial in the evaluation of the room stability.

4 CONCLUSION

The applicability of a performance-based approach to assess the stability of irregular underground cavities under gravity was demonstrated in the paper with reference to the case study of a Neapolitan room-and-pillar cave. The hill and the cavity shape were carefully modelled, since the data acquired during laser scanning-based geometrical survey were directly imported in the 3D numerical code. Such advanced model reproduced the track of the cracks detected in the ceiling vault. The importance of the geometrical refinement was confirmed by a simpler model in which the vault span was approximated to the fully restrained beam loaded by the pozzolana weight.

Safety factor, FoS, of rooms associated to their typical failure mechanisms was computed, evaluating their distance to the thresholds corresponding to the “damage” and “collapse” limit states proposed by Evangelista et al. (2002). The results highlighted that the damage limit state was achieved in the roof of the main naves of the cave almost where tensile plastic state occurred in the numerical model and cracks were detected on site.

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