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Restoration and renovation works for the Catacombs of San Gennaro in Napoli, Italy

A. Flora, F. de Silva & M. Ramondini
Department of Civil Architectural and Environmental Engineering, University of Naples Federico II, Naples, Italy

N. Flora
Department of Architecture, University of Naples Federico II, Italy

ABSTRACT: San Gennaro Catacombs in Naples (Italy) are the clear witness of how the Greek city arose and then became the contemporary town. At the foot of the Capodimonte hill, cavities were excavated since the arrival of the first Greeks from Cuma (6th century b.C.) as underground pits of tuff, to be used to build the New Town: Nea Polis, Naples. In time, the catacombs of San Gennaro have been transformed into a religious site, becoming a place of widespread religious worship because of the burial of Saint Gennaro, protector of the city, and have been enriched with precious stuccos. After an unwavering abandonment and decline, and with the goal of a conscious reuse, the Catacombs are living a new life and are now one of the main attractions of the city. In the spirit of a consistent recovery and conservation program, there is now the idea to let the people into the catacombs from the original entrance. Therefore, works have been carried out on an adjacent cavity, connecting it to the catacombs. The new touristic path has been designed after extensive geotechnical investigation and analyses. The paper will present the numerical analyses carried out to assess the stability of the system of cavities, and the protection and restoration works under way. It is shown that the irregular pattern of existing fractures rules the mechanical behavior of the tuff around the cavities. The analyses allowed to identify possibly dangerous instability mechanisms close at the main entrance of the catacombs.

1 INTRODUCTION

The strong link existing between the underground-space heritage and the overground structures largely affects local traditions and culture. Then, cities hosting underground heritage bear this link in their history and, consequently, attract visitors. Cities as Napoli, Roma, Trieste, Matera, Orvieto are just some examples of such virtuous exploitation in Italy. The increasing demand to visit underground spaces of historic relevance arises issues about the design of interventions to make this possible, accomplishing the two opposite needs to respect their integrity and to allow safe fruition.

This is the case of the Catacombs of San Gennaro in Napoli, dated back to 6th century BC, when the quarried tuff was used by the settled Greek community to build the "*Nea Polis*". With the passing of time, the catacombs of San Gennaro became a place of widespread religious worship because of the later burial of Saint Gennaro, protector of the city, and have been consistently enriched with precious stuccos.

Recently, works have been planned to restore the original accesses to the Catacombs by connecting them with a close by abandoned underground quarry, also building a path to connect two main districts of Napoli (Sanità and Capodimonte), thus making the cavity not only an old heritage site

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but also a new way to cross the city. Indeed, strengthening the connection between its immaterial heritage and local people.

The paper describes some numerical analyses performed to investigate the stability of the system of cavities to be connected to the catacombs, accounting for the rock joints and the spatial variability of the rock resistance.

2 THE CATACOMBS OF SAN GENNARO IN NAPLES

The Catacombs of San Gennaro develop inside a complex and multilevel system of cavities extending for 1700 m^2 in a Neapolitan Yellow Tuff (NYT) hill below the Basilica of the *Incoronata Madre del Buonconsiglio* in the Capodimonte district of Naples (Figure 1a). The steep west side of the hill is limited by *vico San Gennaro dei Poveri* with a height variable between 23 m and 27 m and partially covered by man-made ground with a variable thickness (Figure 1b). The top of the west side is characterised by a buttress supporting the made ground covering the roof of the NYT. The system of cavities of interest in this paper is composed of two larger corridors extending along the N-S direction, i. e. parallel to the cliff, and by two narrower W-E aisles leading to two of the three openings in the cliff along vico San Gennaro dei Poveri. One of the N-S nave leads to the southernmost curved room, where tracks of a likely abrupt interruption of the excavation are visible, probably due to the detrimental effects of the quarrying activities on the neighbouring cavities.

The intersection between the orthogonal naves close to the ridge generates a NYT pillar, characterized by an almost square horizontal cross section with each side 4 m wide. The latter is close to another pseudo-rectangular 4 m × 3m pillar and to a very irregularly shaped pillar 3 m and 9 m long respectively along the NS and WE directions. Where the four naves cross each other, i. e. approximately below the church dome, there is a larger and almost square 15 × 15 m pillar. Eleven circular pillars made of reinforced concrete were built around the latter NYT pillar, probably to sustain the church foundations.

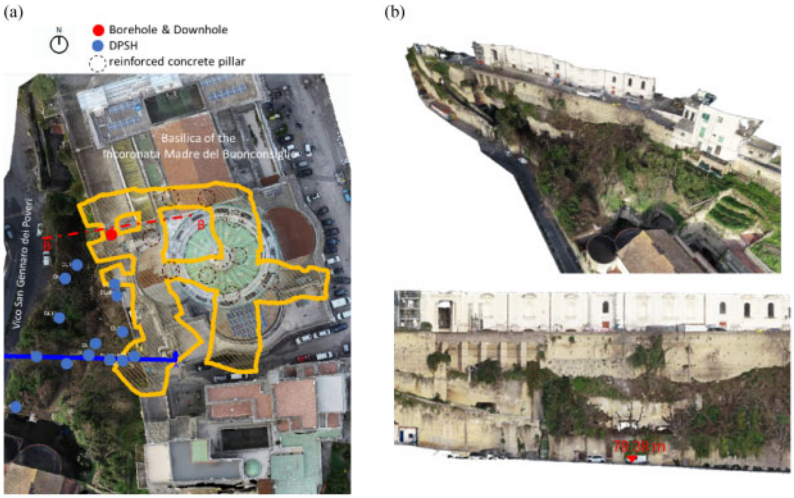

Figure 1. (a) Aerial view of the hill with the location of the portion of Catacombs of San Gennaro object of the present study and of the performed subsoil investigations, (b) views of the west side.

The inner walls of the cave are 10°–15° inclined leading to the typical trapezoid geometry of the vertical cross section of the aisles. The room height is variable around 5 m due to the irregularity of the current planking level, which does not correspond to the bottom of the excavation. In fact, tuff waste resulting from the quarrying activities and, later, debris resulting from the construction of the upper church were accumulated in the cavity with the passing of time. A borehole executed in the hill (and described in the following) revealed that the cavity was originally almost 10 m high and has been filled up to its half height, as already occurred in other cavities in Napoli (de Silva & Scotto di Santolo 2018). The thickness of NYT in the cavity roof is around 7.50 m, covered by almost 10 m of made ground. Except for some fractures close to the cavity openings, the NYT along the west side is quite intact. Conversely, inside the cavity there is a dense network of syngenetic fractures, which locally intersect causing the falling of rock blocks.

2.1 *Renovation works*

The system of cavities to be converted is today in complete abandonment. The goal of the project under course is that of converting the system in the new meeting point for visitors, (see Figure 2a–b). The renovation works consist in a suggestive path which connects *vico San Gennaro dei Poveri* in the Sanità district to the upper square of the *Basilica of the Incoronata Madre del Buonconsiglio* in the Capodimonte district. Since the two sites are at different elevations, a lift will be constructed in the cavity between two tuff pillars and near one of the cavity openings.

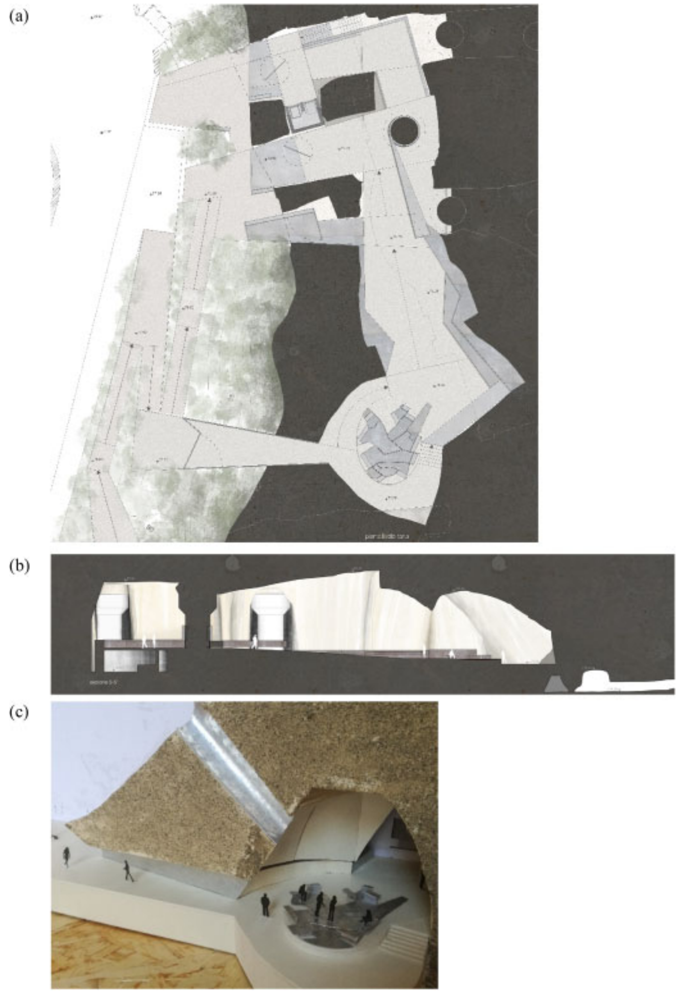

Figure 2. (a) Plan, (b) section and (c) detail of the renovation project.

Even though the Sanità district is in the center of the city, its lower zone is currently an outskirt due to the lack of efficient road connections. Hence, such connection has a social relevance for the citizens because concretely links the Sanità to the rest of the city.

The project restores the original accesses, allowing a chronological tourist tour, which proceeds as the excavation progressed, contrary to what happens today with access from above.

The cavity spaces will host finds from the excavations of the catacombs, which are now stored in not-accessible deposits, as well as staging points for visitors. Two additional openings will be constructed in the southernmost zone: the upper to illuminate the actual darkest zone, the other at the level of the walkway to facilitate the exit of visitors. These openings will also improve the natural circulation of air inside the cavity. Benches made of Corten iron will be installed in the largest circular room, whose design schematically reproduces the intersections of the main streets in the Sanità district (see Figure 2c).

The hill front, slightly higher than the close road, will be arranged in public gardens, connected by slightly inclined ramps that allow disabled and elders to walk independently.

2.2 *On-site and laboratory geotechnical investigations*

The feasibility of the design interventions was supported by an extensive on site and laboratory investigations on the hill and cavity, whose location is shown in Figure 1.

Dynamic Probing Super Heavy tests were executed along the hillside to individuate the thickness of the loose soil covering the tuff. Along the same vertical in which the elevator will be constructed, a borehole was drilled from the top of the hill up to a depth of 30 m, i. e. crossing the cavity and the filling material placed on the floor. The layered soil resulted to be mainly constituted by 8.50 m of man-made ground overlying the Neapolitan yellow tuff. The cavity is 10 m high and filled of debris up to 5.5 m.

A down hole test was executed in the borehole leading to a shear wave velocity around 280 m/s both in the upper man-made ground and in the cavity filling, while a value of 626 m/s was measured in the tuff. Such values are typical of the Neapolitan subsoil.

Regarding the peak uniaxial compression strength of the Neapolitan yellow tuff (σ_{UCS}) this parameter varies between 2 MPa and 7 MPa, with the most recurrent values included in the range 3–4 MPa for samples with a natural unit weight of 15 kN/m^3. Such a variability is associated to the void ratio and distribution of lithic fragments, pumices, crystals and glass in the rock matrix (Evangelista and Pellegrino, 1990). Such inhomogeneity makes the tuff resistance strictly dependant on the local rock features. For this reason, uniaxial compression tests were executed on six samples taken from the abovementioned borehole and four samples taken from the hill side through horizontal drillings. The initial stiffness of samples taken from the borehole and from the horizontal drillings resulted very similar, as well as the variability of the peak strength with the dry unit weight, suggesting that all the results can be fairly interpreted in the unique distribution, shown in Figure 3.

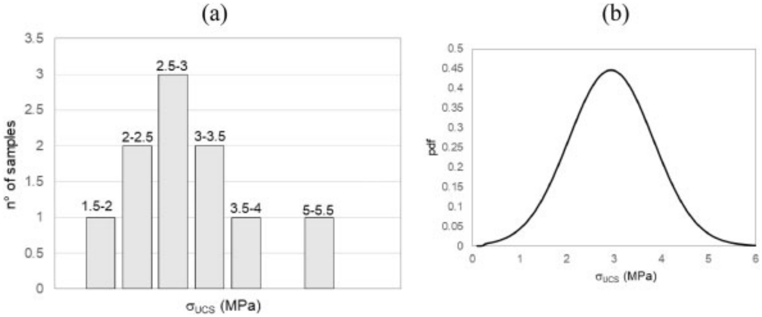

Figure 3. Distribution of the uniaxial compression strength resulting from the laboratory tests (a) and adopted in the numerical analyses (b).

Five out of 10 tests led to σ_{UCS} ranging between 2 MPa and 3.5 MPa, with the most recurrent values included between 2.5 MPa and 3 MPa. With respect to all the other specimens, very few pumices are included in the only specimen resulting in a strength higher than 5 MPa. Excluding the outlier specimen, the σ_{UCS} values were exploited to calibrate the Gaussian distribution plotted in Figure 3b, with a mean equal to 3 MPa and standard deviation equal to 238 kPa.

3 STABILITY ASSESSMENT OF THE ROCK CAVITY

3.1 *Numerical model*

The numerical model shown in Figure 4 was analysed in the finite difference code FLAC 2D (Itasca 2011) in order to assess how the cavity safety is affected by the uncertainties on the rock strength and the presence of rock joints. The geometry reproduces the vertical cross section AA in Figure 1, where the elevator from the cavity to the church level will be constructed. The model is almost 40 m long and 21 m high with the west side shaped according to the actual cliff. The tuff resistant section of the cavity roof is 5 m thick as inferred from dynamic penetration tests performed on site. Horizontal and vertical sublayers 0.5 m thick were generated in the 2.5 m of roof closer to the cavity and in the pillar respectively, to vary the joint location. The mesh size was consequently refined close to the geometric irregularities and the sublayers.

The model base was fixed while only horizontal displacements were retrained on the east side to simulate the on-site conditions.

The anthropic filling inside the cavity were not inserted since its complete removal is planned in the design of renovation works. The weight of 13 m thick loose soil covering the tuff roof and the accidental loads was substituted by an equivalent vertical load equal to 234 kPa applied at the ground floor. The load was increased up to 368 kPa where the church is present to account for its weight.

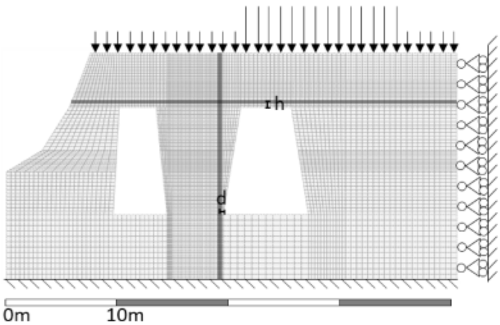

Figure 4. Numerical model of the section AA of the cavity.

The mechanical response of the intact rock was simulated through the Mohr-Coulomb constitutive model, while the Ubiquitous joint model was adopted to simulate the joints. In the latter case, the program distributes inside the material planes in which the mechanical properties are reduced to simulate the rock joints. The inclination of such planes can be chosen according to the orientation of the fractures detected on site.

Table 1 reports the mechanical properties adopted for the tuff and the joint in the numerical analyses. The unit weight, γ, is the mean value measured on eleven samples taken on site. The shear modulus, G, and the bulk modulus, K, derive from the shear and volume wave velocity of the tuff obtained through the down-hole executed in the S1 borehole. Values of σ_{UCS} and δ are the mean and the standard deviation of the strength calculated from data of uniaxial compression properly executed uniaxial compression tests. The friction angle, φ, was inferred from measurements by Evangelista and Pellegrino (1990) during extensive research on the Neapolitan Yellow tuff. The cohesion was back calculated from σ_{UCS} and φ.

Finally, a tension cut-off, σ_t, equal to 20% σ_{UCS} was assigned to the Mohr-Coulomb criterion. The parameters of the rock joints are the same assumed for the intact rock except for the friction angle and the cohesion, respectively reduced to 20° and 0 kPa, to simulate the residual strength of fractures. The so calibrated Mohr-Coulomb criterion is equivalent to the resistance obtained by the empirical equation by Barton (1973) in which the joint roughness JRC coefficient is conservatively assumed equal to 0.

Table 1. Mechanical proprieties of the tuff and joints set in the analyses.

	γ kN/m3	G MPa	K MPa	φ °	c kPa	σ_{UCS} kPa	δ kPa	σ_t kPa
Rock	12	491	1431	28	882	2936	259	147
Joint	12	491	1431	20	0	0	/	0

The model was solved firstly to reproduce the lithostatic conditions and then to calculate the stress modification induced by the presence of the cavity with the wished in place approach.

Four sets of analyses were performed:

1) one with a constant uniaxial compression strength of the tuff;
2) one hundred with a spatially variable uniaxial compression strength of the tuff, obtained by assigning to each element of the mesh a different value of the cohesion compatible with the distribution of σ_{UCS} in Figure 3;
3) seven with a constant uniaxial compression strength of the tuff and a horizontal joint in the roof;
4) six with a constant uniaxial compression strength of the tuff and a vertical joint in the pillar;

Each analysis was aimed to calculate the factor of safety FoS. In details, a reduction factor is applied to the cohesion and the tangent of the friction angle of the tuff, together with the friction angle of joints in the third and fourth sets of analyses. Increasing values of the reduction factor are applied and the FoS corresponds to the value producing the failure.

3.2 *Failure mechanisms resulting from the different sets of analyses*

Independently of the constant or spatially variable distribution of the tuff strength, the failure mechanisms resulting from the first, the second and the third set of analyses mainly involves the central pillar and the roof of the inner cavity. The plastic state occurring in the bottom of the vertical free tuff wall suggests the incipient development of a slippage surface crossing the two rooms. Figure 5 shows the distribution of the achieved plastic states for one illustrative case in which the tuff strength is spatially variable.

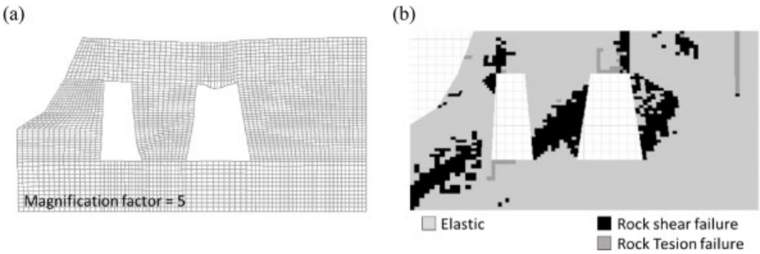

Figure 5. Deformed shape (a) and plastic state (b) of the cavity at failure resulting from one of the analyses with a spatially variable tuff strength.

The introduction of a vertical joint within the pillar leads to a slippage along the joint, which modifies the deformed shape and the distribution of the plastic state when the joint is closer to the inner room, as can be observed by comparing Figure 6 to Figure 7 or 5.

In any case, roofs appear to be enough resistant to support the surcharges, while the inner pillar is the most crucial element for the stability of the whole cavity.

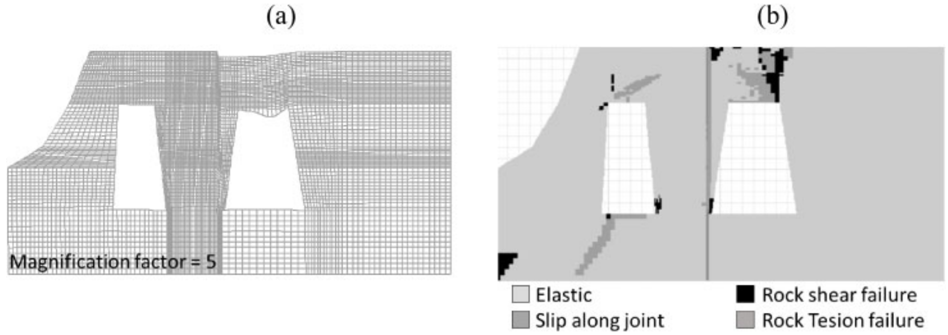

Figure 6. Deformed shape (a) and plastic state (b) of the cavity at failure when a vertical joint is introduced at a distance d = 0.4 m.

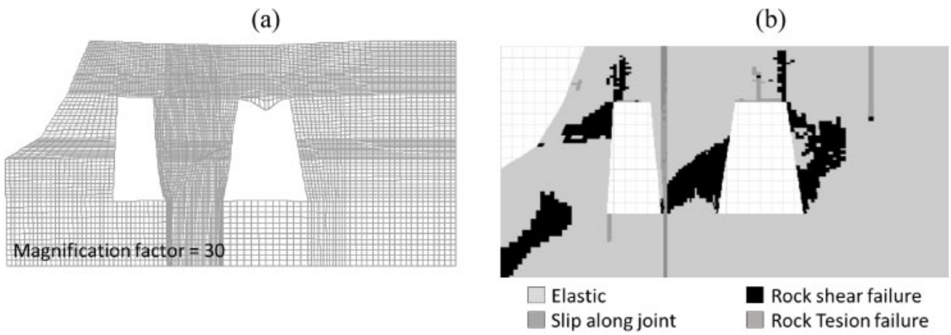

Figure 7. Deformed shape (a) and plastic state (b) of the cavity at failure when a vertical joint is introduced at a distance d = 4.8 m.

3.3 *Effect of the strength variability on the Fos*

Figure 8a shows the FoS values obtained from the second set of analyses, in which σ_{UCS} varies within the model. In any case the FoS is lower with respect to that obtained with a constant $\sigma_{UCS} = 2936$ kPa. Neverthless the reduction is limited to the 10% and reached only in about five out of one hundred cases.

The distribution in Figure 8b highlights that in most cases the FoS ranges between 5.1 and 5.2, i. e. up to 0.95% and 0.96% of the FoS obtained with a constant tuff strength. Hence the σ_{UCS} spatial variability appears negligible for the case at hand, which is characterized by a high FoS value. Conversely, it is worth to be considered for cases in which the static conditions are prone to failure, where the same reduction may lead to a FoS value lower than unit.

3.4 *Effect of rock joints on the FoS*

Figure 9 shows the factors of safety resulting from the analyses in which a horizontal joint is modelled in the roof (a) or a vertical joint in the pillar (b). The introduction of joints in the roof modifies very slightly the factor of safety and only when the joint is placed very close to the roof intrados. Such results confirm that the roof stability is not the most critical aspect for the case at hand, as already observed from the analysis of the failure mechanisms.

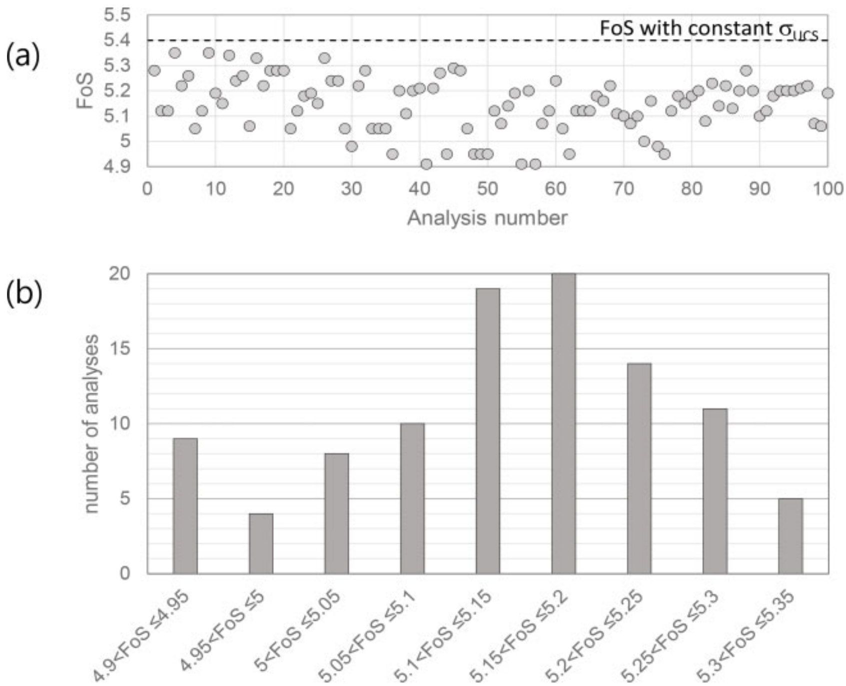

Figure 8. Values (a) and distribution (b) of the factors of safety resulting from the analyses including the spatial variability of the uniaxial compression strength.

Conversely, the sensitivity of the FoS to the vertical joint in the pillar appears more pronounced. Actually, FoS reduces up to 66% of its value with a constant σUCS, when the joint is very close to the inner room. As the joint is moved towards the outer room, the FoS increases and becomes equal to the value with a constant σUCS when the joint overcomes the half thickness of the pillar.

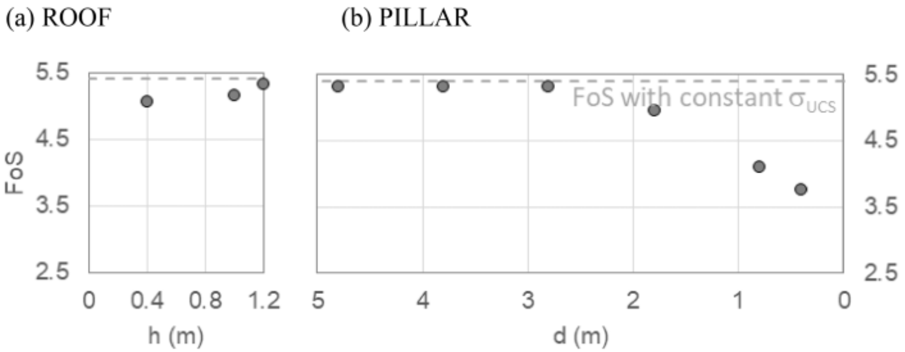

Figure 9. Factors of safety resulting from the analyses with horizontal joint in the roof (a) and vertical joint in the pillar (b).

4 CONCLUSIONS

The paper investigates the effect of joint position and of spatial variability of the strength of Neapolitan Yellow Tuff on the stability of the most critical vertical section of the system of cavities under renovation to be connected to the Catacombs of San Gennaro, with the goal of making them the new entrance, meeting point and visitors information point. The failure mechanisms resulting from all the performed analyses mainly involve the central pillar. In all the analyses a negligible reduction of the factor of safety was caused by the existence of sub-horizontal joints. On the contrary, the existence of a vertical joint considered in the pillar influences the factor of safety. In any case, from the analyses carried out safety conditions seem to be ensured whatever the case. Spatial variability of tuff strength reduces the safety factor, in comparison with the results obtained by neglecting such a variability. This reduction may become critical if the vertical and horizontal bearing parts of the cavity have a low safety factor, which was not the case for the cavity under analysis. However, the results also demonstrate that the spatial variability of rock strength and the position of joints, sometimes not immediately visible at a visual inspection, both need to be carefully considered not to overlook on possible critical mechanisms.

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