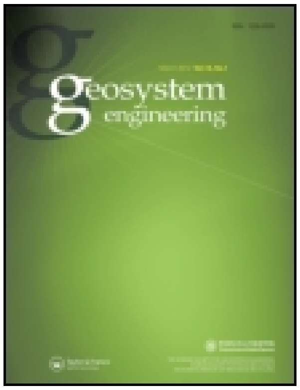

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RESEARCH ARTICLE

Geological survey and numerical modeling of the potential failure mechanisms of underground caves

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Natural or man-made underground caves potentially represent a serious hazard to the built-up areas. Urban development and construction of infrastructures is generally carried out without taking into account the possibility of interacting with subsurface cavities, and the corresponding hazard these might pose. In addition, loss of memory of man-made cavities under the historic part of many towns adds further problems. This is especially true for countries with a long history, such as Italy, where during the centuries a large number of artificial cavities have been excavated underground for different purposes. Assessment of the stability of rock masses in these settings is not an easy matter, since it requires, in addition to the geological and engineering background, speleological skills and techniques in order to explore and survey the cavities, identify the type of failures occurring therein, and collect the data necessary for the implementation of specific numerical analyses, these being aimed at defining the stress–strain state of the mass. In this article we present an approach involving cavers, geologists, and engineers to assess the rock mass stability in natural and man-made caves, aimed at determining the control of rock failures in the formation of sinkholes. The methodology is described through the application to a natural karst cave and an anthropogenic cavity in Apulia, SE Italy. In both cases, following a detailed speleological survey which was specifically addressed to define the complete cave geometry, the geomechanical characterization of the carbonate rock mass was carried out and the data so obtained used to evaluate the rock mass stability by means of numerical modeling.

Keywords: karst; rock stability; caves; underground quarrying; numerical modeling

1. Introduction

Any type of underground caves, regardless of the origin as a natural or man-made cavity, potentially represent a serious hazard to the built-up environments. As a matter of fact, urban development and construction of infrastructures is rarely carried out taking into account the possibility of interacting with subsurface cavities and evaluating the corresponding danger these might pose (Delle Rose, Federico, & Parise, 2004; Parise, 2008, 2010a; Waltham & Lu, 2007; Zhou & Beck, 2011). Furthermore, loss of memory of old man-made cavities under the historic parts of many towns is very frequent, thus resulting in additional problems. As a consequence, the need to properly evaluate the stability of rock masses in underground settings comes out as a very difficult task that requires, in addition to the geological and engineering background, other contributions. Namely, speleological skills and techniques are necessary to explore and survey the cavities and correctly represent them on maps, showing the likely interactions with the anthropogenic environment. In addition, caving activity is also useful for the recognition and identification of the type of failures occurring underground, as well as for the collection of the data to be used for implementing specific numerical analyses (De Waele, Gutierrez, Parise, & Plan, 2011; Lollino, Parise, & Reina, 2004; Parise & Gunn, 2007; Parise & Trisciuzzi, 2007). Moreover, the effects of environmental factors giving rise to the degradation with time of the rock properties, such as wetting/drying processes, humidity, chemical effects, thermal loading for soft porous rocks as calcarenite, or karst for limestone, need to be accounted for when dealing with the stability of underground caves (Aydan, Genis, Sugiura, & Sakamoto, 2012; Aydan, Sakamoto, Yamada, Sugiura, & Kawamoto, 2005; Didier et al., 2009).

Starting from the above considerations, the possibility of occurrence of rock failures in underground environment under static conditions is dealt with in this article, by examining a natural karst cave within a limestone fractured mass and an artificial cavity in a soft calcarenite deposit located in different sectors of the Apulia region (south-eastern Italy, Figure 1). Both the case studies will be examined through an approach involving cavers, geologists and engineers to assess the rock mass stability aimed at determining the likely control of rock failures in the formation of sinkholes. Following a detailed speleological survey which was specifically addressed to

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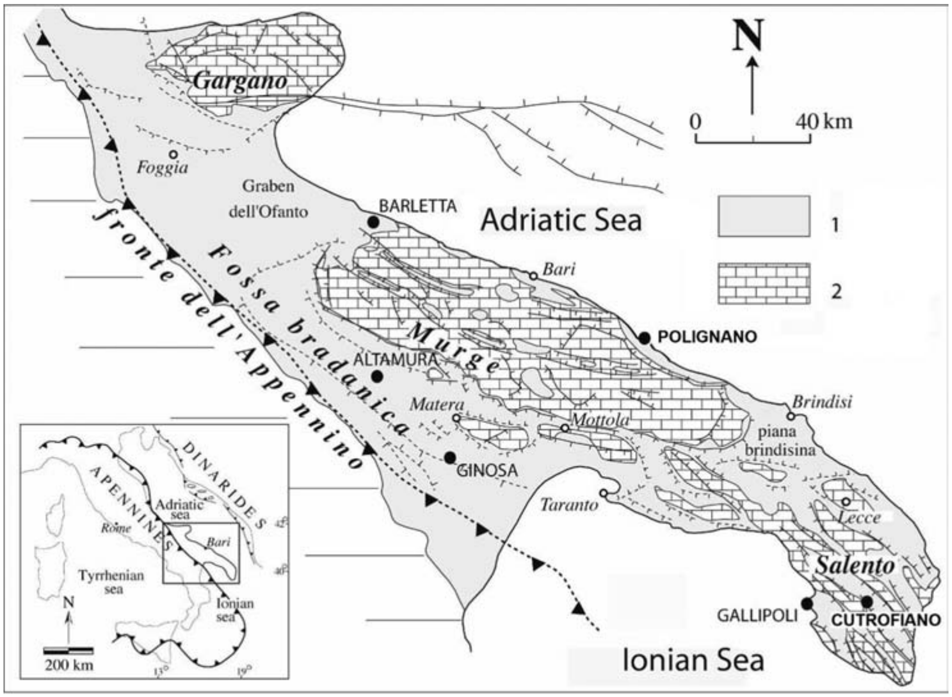

Figure 1. Sketch geology of Apulia (modified after Pieri, Festa, Moretti, & Tropeano, 1997) showing the main karst areas of the region (Gargano, Murge, and Salento). The two study sites (Polignano a Mare and Cutrofiano) are indicated in bold upper case. Key to simbols: (1) Bradanic Trough sediments and terraced deposits (Pliocene–Pleistocene); (2) carbonate units of the Apulian Foreland (Mesozoic–Cenozoic).

define the complete cave geometry, the geomechanical characterization of the carbonate rock mass will be described, and the resulting data will be used to evaluate the rock mass stability by means of numerical codes.

2. Case studies

2.1 The Rondinella Cave (Polignano a Mare)

The territory of Polignano a Mare is one of the most important coastal karst settings in Apulia, with over 70 caves that have to be counted in this stretch of coastline, mostly as a result of the action by the sea waves on the limestone cliffs of the Adriatic coast (Figure 1). Rondinella Cave (number PU 71 in the regional register of natural caves, managed by the Apulian Speleological Federation, www.fspuglia.it) is the largest karst cave in the sector north of Polignano a Mare and is located in a stretch of the coastline with cliffs lower than 10 m. The cave has a double access (Figure 2) that from the sea leads to a small pebble shore, whilst inland a collapse sinkhole, produced by the fall of the rock diaphragm above the cave, represents the main entrance. In the past, Rondinella Cave was already the object of a research focused on its breccia deposits (Rudnicki, 1990) and of mineralogical analysis that brought to discover a new variety of francoanellite, that is the phosphate mineral phase $H_6K_3Al_5(PO_4)_8{\cdot}13H_2O$, which represents a lower hydrate of taranakite (Balenzano, Dell'Anna, & Di Pierro, 1979).

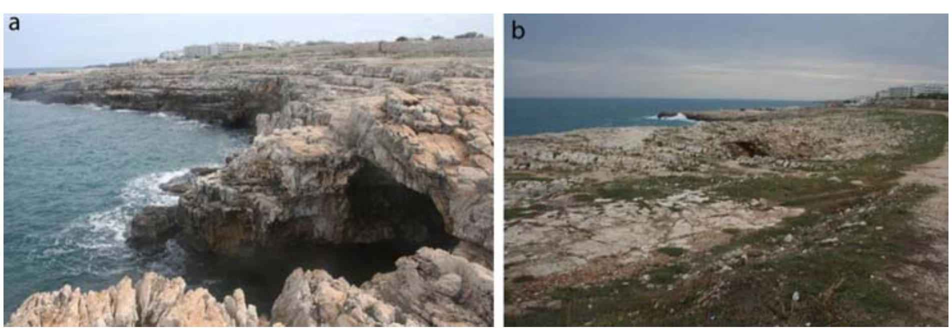

Figure 2. Views of Rondinella Cave entrances: (a) from the sea and (b) from inland. In both the pictures the town of Polignano a Mare is shown in the background.

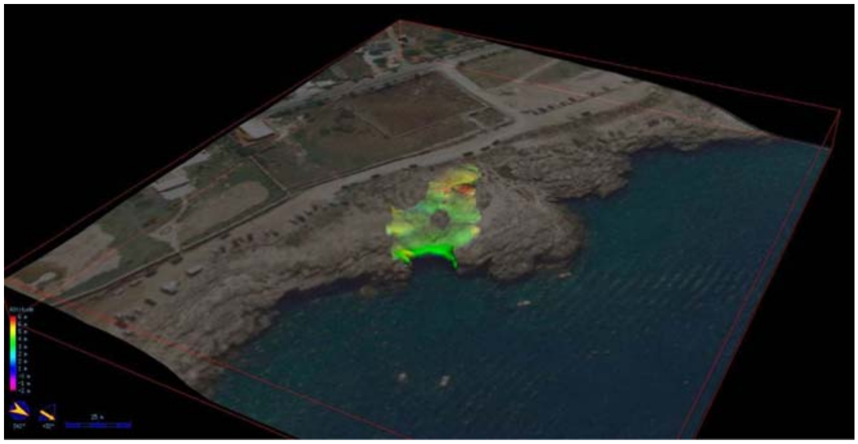

Figure 3. Perspective view of Rondinella Cave (Therion software elaboration). The orange-red area in the upper center of the cave is the sinkhole, the inland access to the cave system (see also Figure 2(b)).

As for the rest of the Murge area (the karst sub-region where Polignano a Mare is located) the Cretaceous bedrock has an overall sub-horizontal attitude (Parise, 2011) with average dipping toward the NE and local variations due to folds. The Plio-Pleistocene calcarenites crop out N of the cave, where the contact with the Cretaceous limestones is marked by a breccia with terra rossa matrix. Nearby the inland access to Rondinella Cave, the rock mass is strongly conditioned by the fold related to the collapse sinkhole (well visible at the right margin of Figure 2(a)). Moving away from the cave entrance, the bedding tends to sub-horizontal, with average dip of a few degrees toward E–NE. Several discontinuity sets are recognizable in the area, the main one being about perpendicular to the coast, whilst further joints are related to the stress release parallel to the coastline. These latter locally become of major importance in controlling the evolution of the present coastal morphology and are often the main set along which detachment occur, mostly in terms of falls or toppling failures (Andriani & Walsh, 2007).

The well-cemented calcareous breccia in terra rossa matrix crop out at the collapse sinkhole, but can also be found within the karst system, in erosional pockets located at variable heights of the cave roof. Rudnicki (1990) interpreted these deposits as related to paleo-karst phases started after the post-Cretaceous emersion, with later filling as a consequence of sea level changes. Eventually, Plio-Pleistocene deposits covered the older materials, and the subterranean hydraulic activity restarted after the last phase of land emersion. The karst system develops mostly in E–W direction (Figure 3). Within the cave, the main hypogean morphologies consist of highly karstified rock strata in the carbonate succession, showing development of multiple phreatic conduits and the solution breccias described by Rudnicki (1990). At least two levels are recognizable in the cave, with a difference in altitude on the order of about 3 m (Figure 4): the lower level follows the boundaries of the karst cave and consists of very narrow passages, which confirm the hypothesis of multiphase speleogenesis of the karst system.

Characterization of the rock mass at Rondinella Cave was carried out by means of a detailed structural survey in the karst system; notwithstanding the difficult conditions due to the cave environment, measurements were performed aimed at identifying the influence exerted by the discontinuity sets in the development of the underground openings. Once completed the field survey, the statistical elaboration of the data acquired, guided by the selection of the most representative sets as a function of their persistence and of the cave geometry, revealed the presence of four main discontinuity systems: the main ones are oriented NNE–SSW and N–S, whilst the NW–SE and WNW–ESE systems are subordinate. Based on the analysis of the structural data, it appears that the cave strongly developed along intrastratal partings, at the same time showing a structural control by tectonic discontinuities. As concerns bedding, even within the cave it is extremely variable as an effect of the deformation in the stratigraphy, related to the occurrence of the collapse sinkhole.

2.1.1 Numerical analysis

Two-dimensional (2D) discrete element analyses have been performed with UDEC^{2D} in order to investigate the stability of the fractured limestone mass at Rondinella Cave, along the selected cross section shown in Figure 5. Although the cave geometry is typically three-dimensional (3D), the analyses described in this paper were aimed at assessing the capacity of a 2D model to properly assess the stability of the carbonate rock mass. The geometry of the whole model is rectangular (30×15 m) and is characterized by fixed horizontal displacements along the vertical boundaries, with fixed vertical displacements prescribed at

Figure 4. Northern margin of the main cavern at Rondinella Cave: note the depth difference between the pavement (where the caver to the left is standing) and the deeper level (from where the second caver, to the right, is coming out).

the bottom of the domain. Only the main discontinuity sets have been simulated in the model in order to reduce the computational effort. Therefore, the main joint sets which have been considered in the calculation are

- K1 ($\alpha = 82°$ with respect to the positive horizontal axis, spacing $= 2$ m)
- K2 ($\alpha = 115°$ with respect to the positive horizontal axis, spacing $= 2.4$ m)
- K3 ($\alpha = 45°$ with respect to the positive horizontal axis, spacing $= 0.8$ m)
- S ($\alpha = 0°$ with respect to the positive horizontal axis, spacing $= 2.0$ m); this set represents the bedding of the limestone succession.

Two different models have been taken into account, the first one being characterized by infinitely persistent joints (Figure 6(a)), which is aimed at simulating the worst conditions for stability, and the second model with non-persistent joints (Figure 6(b)).

A detailed *in situ* characterization has also been carried out aimed at assessing the shear strength properties of the joints. In particular, field roughness and joint wall compression strength measurements have respectively been performed by means of the Barton profilometer and the Schmidt hammer tests (Figure 7), following the ISRM suggested methods (ISRM, 1978; Ulusay & Hudson, 2007). According to the measurement results, Joint Roughness Coefficient (JRC) is found to be in the range 6–14 MPa, whereas Joint Wall Compressive Strength (JCS) results to vary between 60 and 80 MPa for weathered joints and JCS $= 100$–140 MPa for unweathered joints. As a consequence, the weathering degree of the limestone (e.g., the ratio between the JCS value for weathered joint and the JCS value for unweathered intact rock) is found to be about $JCS/JCS_{un} = 0.6$. The joints have been assumed

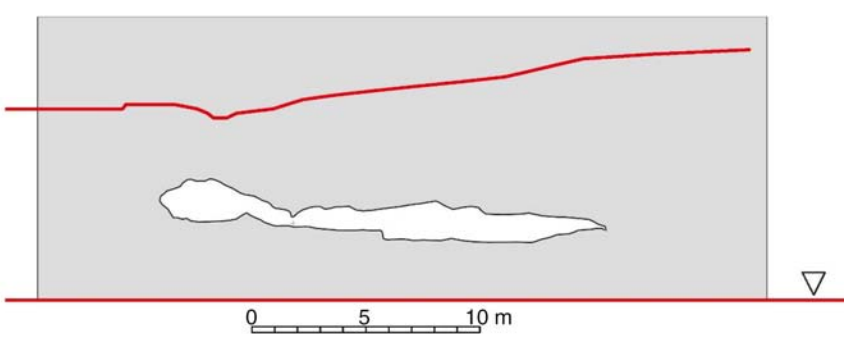

Figure 5. Transverse cross section of the Rondinella Cave used for the numerical analysis.

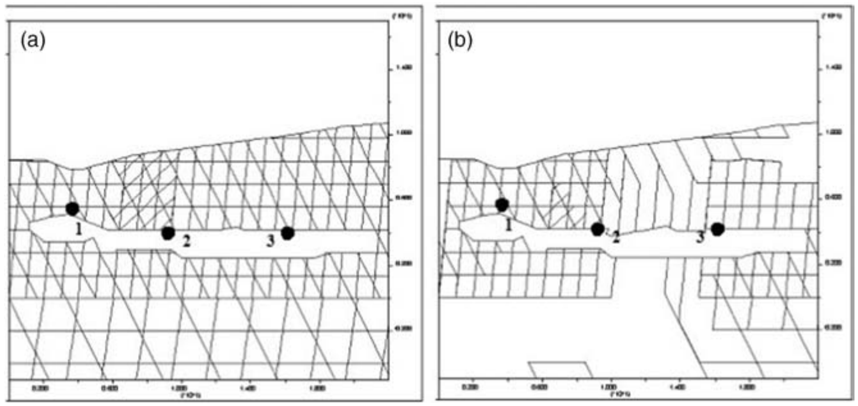

Figure 6. Block grid with infinitely persistent joints (a) and with non-persistent joints (b).

in the model to behave according to a Coulomb sliding law with null cohesion and friction angle value that has been defined based on the well-known Barton criterion (Barton & Choubey, 1977), by considering the minimum values of the aforementioned ranges of JRC and JCS and assuming a basic friction angle of $\phi_b = 35°$. The resulting peak friction angle of the joints has been found to be equal to $\phi = 50°$.

Intact rock has been assumed to behave according to an elastic-perfectly plastic constitutive model, with a Mohr–Coulomb strength envelope and a tension cut-off. The shear strength parameters have been derived from the results of laboratory tests performed on rock samples belonging to the same formation (Calcare di Bari) that have been taken from a different study area, some kilometers far from Polignano a Mare. In particular, the laboratory tests indicate a value of the uniaxial compression strength ranging between 60 and 90 MPa, with a mean value of about $\sigma_c = 75$ MPa and a tensile strength, derived from indirect tensile tests, in the range 5–8 MPa. Based on these laboratory test results, the following shear strength parameters have been deduced: $c' = 1.1$ MPa, $\phi' = 35°$. A secant Young modulus ranging between 40 and 70 GPa has been also measured for this rock formation. For modeling purposes, the lower boundaries of the ranges of the property values have been considered.

The numerical procedure is composed, first, of a stress initialization based on the gravity loading method. Then, a plastic calculation has been performed according to the strength parameters described above.

The results of the plastic calculation stage in terms of vectors of block displacements are shown in Figure 8 for the model which assumes infinitely persistent joints and indicate a general instability of the whole cave roof. This seems to be in contrast with the current stable conditions of the rock mass which are presumably allowed by the out-of-plane arching effect. Figure 9 instead reports the displacement vectors for the model with non-persistent joints: a general stability condition of the cave roof is reported, with the local fall of a small block in the portion of the rock mass characterized by a higher fracturing degree. However, the stable conditions are confirmed by Figure 10 where the curves of vertical displacements of the three monitoring points indicated in Figure 6 against time-steps are shown: the tendency toward displacement values that are constant with time suggests stable conditions of the roof. The joints with zero normal stress for the same model are, on the other hand, reported in Figure 11, which shows the tendency to the stress relief of the cave roof and the opening of the horizontal bedding strata due to the gravitational forces of the upper portion of the rock mass.

Figure 7. Surveying the carbonate rock mass and the breccia deposits in the Rondinella Cave by means of Schmidt hammer (a and b) and Barton profilometer (c).

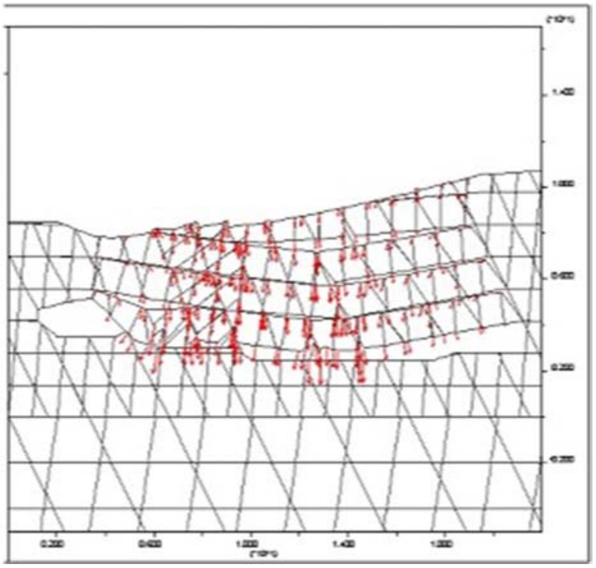

Figure 8. Rondinella Cave: vectors of block displacements for the model with infinitely persistent joints.

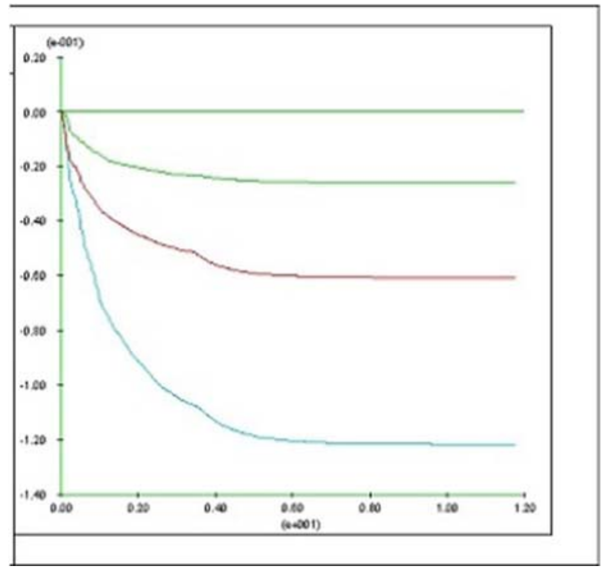

Figure 10. Rondinella Cave: curves of vertical displacements against timesteps of the monitoring points chosen in the numerical model (see Figure 6) for the case of non-persistent model. The asymptotic trend of the curves is an indicator of roof stability.

Despite the approximation provided by the 2D plane-strain analysis which has been, here, used to simulate a problem characterized by 3D features, the analysis has revealed to be useful for detecting joint persistence as the major factor controlling the stability of the cave roof. Of course, the *in situ* 3D stress state, and in particular the stress level and the arch effect in the out-of-plane direction, provide safer conditions in terms of stability of the rock mass. Therefore, in such cases the 2D analysis should be considered as conservative, provided that all the other geometrical, structural, and mechanical features are well simulated.

2.2 Underground quarries at Cutrofiano

Underground quarrying is historically developed in many areas of southern Italy, including Apulia region, due to a

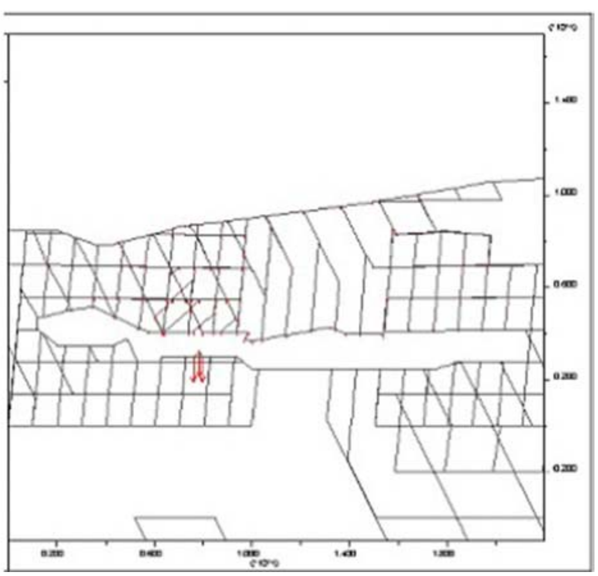

Figure 9. Rondinella Cave: vectors of block displacements for the model with non-persistent joints.

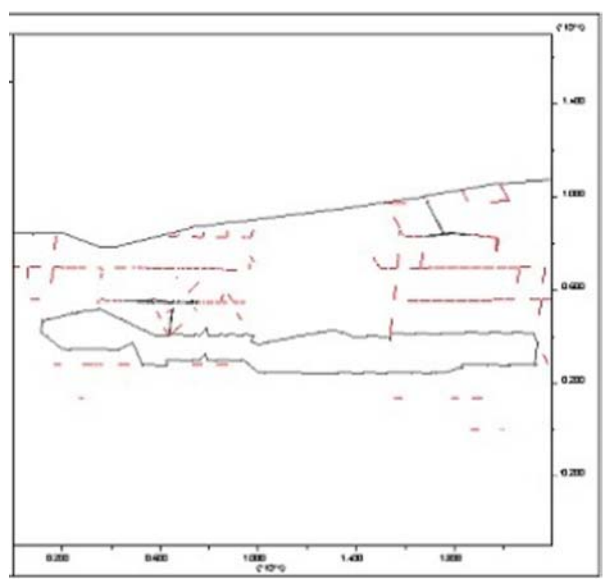

Figure 11. Rondinella Cave: joints with zero normal stress (open joints) for the non-persistent joint model.

number of reasons, the main ones being (1) the presence of rocks of good quality at moderate depth, not exposed at the surface; (2) the need to preserve surface lands to be used for agriculture (Parise, 2010b). Underground passages were therefore excavated (generally at shallow depths but locally reaching some tens of meters from the ground surface), mainly by digging vertical shafts for the entrance from the ground surface. Such works were undoubtedly a nice example of engineering ability at the time of excavation (typically, during the first decades of the nineteenth century), and nowadays represent, for those sites where the tunnels are still safe and sound, interesting examples of industrial archeology. In many cases, however, after a first phase of rational and careful exploitation of the underground quarries, a more confused phase of excavation followed, without any control in the development of the underground spaces. This brought about several events of instability, frequently induced by the degradation process of the rock material due to the environmental weathering. These events started underground as local instability processes but soon transferred their effects to the surface through upward propagation of falls from the quarry roof and direct opening of sinkholes above the tunnels. With time, the expansion of the urban area during the twentieth century, combined with the loss of memory of the underground features, led to the construction of buildings and infrastructures just above the quarries which were originally located at the outskirts of towns. Many towns in Apulia are today in these situations, and as a consequence a number of instability events have occurred through the years (Fiore & Parise, 2013; Parise, 2012; Pepe, Pentimone, Garziano, Martimucci, & Parise, 2013).

The area of Cutrofiano (Salento sub-region, southern Apulia; Figure 1) is one of the main quarrying districts of the region, with a long history of activity both at the surface and underground. The local geology shows the main rock used for construction purposes (a Pleistocene calcarenite) overlain by sands and clays. Underground quarrying of the calcarenite occurred through manual excavation of a number of 2.5- to 3-m-wide wells through the stratigraphic succession in order to reach the level of the calcarenite formation with the best properties. Once reached this level, the excavation proceeded horizontally, with a network of galleries in a regular room-and-pillar pattern. The overall network of underground galleries covers several tens of kilometers. The quarries represented for many years the main work for most of the Cutrofiano inhabitants, but, starting from the 1970s these activities slowly decreased until they were progressively abandoned, also becoming sites for illegal discharge of liquid and solid wastes.

The Pleistocene calcarenite succession covers a thickness of about 15–20 m. Within this formation, four levels may be discriminated: the first is represented by a well-cemented yellowish calcarenite, 2–3 m thick, locally known as *mazzaro*; this is followed by cemented white-yellow calcarenites, 4–5 m thick, and by a level of fine-grained white calcarenites, in thickness ranging from 7 to 12 m. Eventually, slightly loose, fine to middle-grained whitish calcarenites close the succession, with a thickness of 2–3 m. The two central levels show the best technical characteristics (Andriani & Walsh, 2003) and have been historically the object of the underground quarrying activity at Cutrofiano. The local geological-structural setting has an overall attitude of the strata toward the SW, so that the best calcarenites are to be found underground at depth ranging from some 7 m nearby the town to over 50 m a few kilometers farther south. The galleries of the Cutrofiano underground quarries are 5–6 m wide on average and high from 6–6.50 to 8 m (maximum value observed 10 m). Within the wide network of underground passages, several types of instabilities have been observed, from both the vaults and the walls of the galleries. In vault, detachments occur as massive falls of significant volumes of rock mass involving thickness of 2–2.5 m. The resulting morphologies are in the shape of arches, typically involving the gallery for its complete extension, putting in light (and sometimes involving) the *mazzaro* level. Along the vertical walls, large rock detachments, extending laterally up to 2–3 m, have been instead observed during the field surveys.

After abandonment of the quarries, several sinkholes occurred in the area: the first events for which documentation have been found occurred during the 1950s, and produced a number of depressions and wetlands south of the town, as an effect of the exposure of the perched water table sustained by the clays (Parise, 2012). The last sinkhole events were, on the other hand, registered on 15 July 2008, and on March, May, and October, 2010, ranging in size from a few meters up to 25 m in diameter (Fiore & Parise, 2013). Initially, the link between underground quarry and sinkhole events was not fully investigated due to difficulties in entering the subterranean systems. In the last 10 years, caving surveys were carried out to map the quarry development and identify the areas affected by instability phenomena (Figure 12(a),(b)). These often correspond at the surface to sites where subsidence had already occurred, producing the formation of wetlands due to emergence of the perched water table (Figure 12(c)) or originating sinkholes (Figure12(d)). In addition to those already occurred, a particular attention was addressed to other incipient signs of instability, such as swelling of the walls, protrusion of wedges, spalling, deformations, and cracks opening. These may represent in fact premonitory signs of instability, as observed in many sites worldwide, and can be used in order to understand the mechanical behavior of the rock mass and the degradation processes occurring within the caves (Parise & Lollino, 2011; Szwedzicki, 2001).

Figure 12. Instabilities in the underground quarries (a and b) and examples of sinkhole at Cutrofiano (c and d).

Based upon detailed field surveys carried out within the quarries, and covering about 30 km of explored and mapped underground passages, an ideal finite element model has been implemented in order to assess the main factors controlling the instability processes at Cutrofiano. In particular, the main objective of the numerical analysis was the investigation of the role of gradual degradation of the mechanical properties of the rock mass surrounding the cave boundaries as a consequence of wetting/drying cycles, thermal loading, chemical weathering, and other environmental processes active in the caves. As such, these weathering processes are supposed to be the cause for a slow decay of the rock strength properties within the most shallow rock strata surrounding the caves, which is responsible for the development of local and global failure mechanisms. Then, the role of the proximity of two adjacent caves to enhance the development of the failure process, compared to the single cave model, has been also assessed.

The geotechnical properties of the rock and soil materials involved are given in Table 1. To simulate the behavior of the materials involved an elastic perfectly plastic constitutive law with a Mohr–Coulomb shear failure criterion, non-associated flow ($\psi = 0°$), and tension cut-off has been assumed in the analyses.

The numerical procedure includes four analysis stages. A gravity-loading stress initialization stage has been first simulated, followed by a plastic calculation stage with the implementation of the unweathered rock properties. Later on, the excavation of the underground caves has been simulated. Finally, the process of degradation of the properties for the rock strata surrounding the caves has been implemented with the strategy described below.

The numerical model adopted shows an overall thickness of the deposits overlying the calcarenites of 20 m, with a sand layer in the first 6 m and clay below (Figure 13). The clay is underlain by the 3-m thick well-cemented *mazzaro* layer and then by the softer calcarenite that extends to the bottom of the model. In the model the cave is of rectangular shape, 6 m large and 7.2 m high, these being the typical mean sizes of the quarries as measured in the field. The simulation of the gradual decay

Table 1. Geotechnical properties adopted for the finite element model at the Cutrofiano underground quarries.

	γ (kN/m^3)	E' (kPa)	ν'	c' (kPa)	ϕ' (°)	σ_t (kPa)	σ_c (kPa)
Sand	18	90,000	0.3	0	28	0	–
Clay	20	50,000	0.25	15	20	0	–
Mazzaro	17.5	180,000	0.3	360	33	300	2400
Soft calcarenite	15.5	100,000	0.3	180	30	160	1400

Notes: Key to symbols: γ, unit weight; E', Young modulus; ν', Poisson ratio; c', cohesion; φ', friction angle; σ_t, tensile strength; σ_c, unconfined compressive strength.

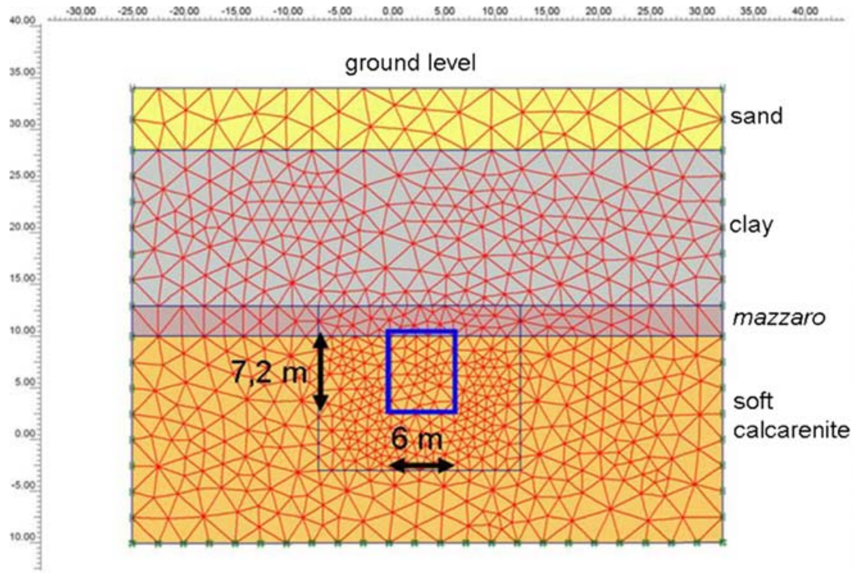

Figure 13. Geological model used for the finite element analysis at Cutrofiano. The typical size and shape of the underground quarry is indicated by the solid line rectangle.

of the mechanical properties of the soft calcarenite along the side boundaries of the quarry, as well as of the *mazzaro* layer at the roof, has been carried out by means of the gradual reduction of both rock cohesion and tensile strength along the layers shown in Figure 14 according to the degrees of degradation as summarized in Table 2. In particular, the degree of degradation has been imposed to be at the maximum along the cave boundaries and to reduce toward the inner portions of the mass. As a consequence of this progressive strength reduction, at stage 4 plastic zones are calculated, starting from the corners of the cave and developing through the inner rock mass up to the formation of a local failure mechanism along the boundaries (Figure 15). The shear zones also follow the same aforementioned trend, with high inclination angle from the corners of the cave (Figure 16). These results are in agreement with the inclined fissures and apertures developing from the corners of the vertical walls, as observed within the underground quarries.

A process of rock degradation at the roof of the cave, which is formed of the stiffer calcarenite (*mazzaro*), as an effect of water percolation from the ground surface, instead produces plastic zones and vertical displacements indicating a local failure mechanism which forms a dome shape vault (Figure 17). Eventually, the effects of the increase in the cave size, both in width and in height, due to repeated local instabilities, as described above, have been analyzed in order to assess the conditions under which general failure of the rock mass above the cave occurs. Therefore, the cave has first been progressively enlarged to a width equal to $B_{max} = 8$ m, whereas the height has been increased to a maximum value of $H_{max} = 9.5$ m. This height increase induces a reduction of the thickness of the *mazzaro* level overlying the cave to $s = 0.5$ m. Such modifications, along with the thinning of the *mazzaro* level above the quarry, determine the development of a general chimney-type failure mechanism that can

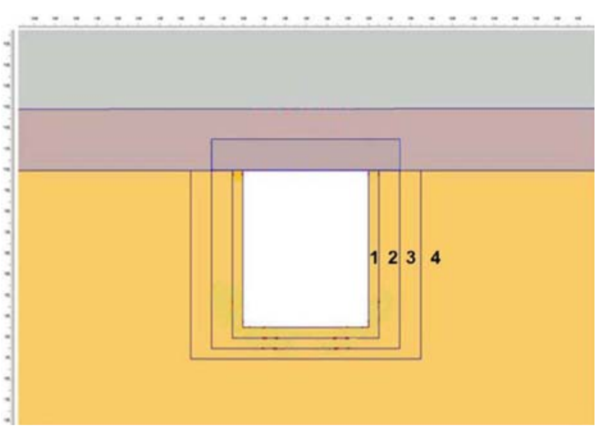

Figure 14. Detail of the model geometry with indications of the rock layers subjected to progressive strength reduction (see Table 2).

Table 2. Degree of reduction of cohesion and tensile strength of the soft calcarenite during the different stages of simulation of rock degradation for the layers shown in Figure 14.

Stage of analysis	Layer 1	Layer 2	Layer 3	Layer 4
1	100	100	100	100
2	90	100	100	100
3	70	90	100	100
4	50	70	90	100

Notes: A degree of 100% corresponds to unweathered rock.

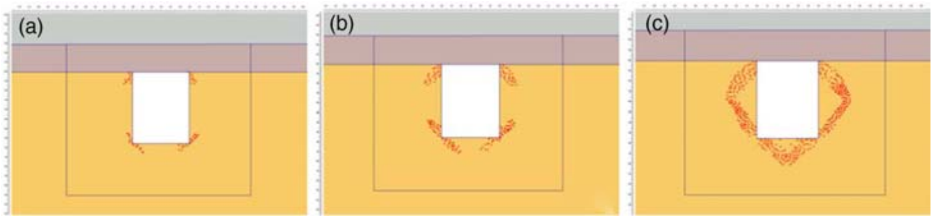

Figure 15. Plastic points due to progressive reduction of the cohesion of the soft calcarenite along the vertical side boundaries of the quarry: (a) $c' = 180\,\mathrm{kPa}$, (b) $c' = 140\,\mathrm{kPa}$, (c) $c' = 100\,\mathrm{kPa}$.

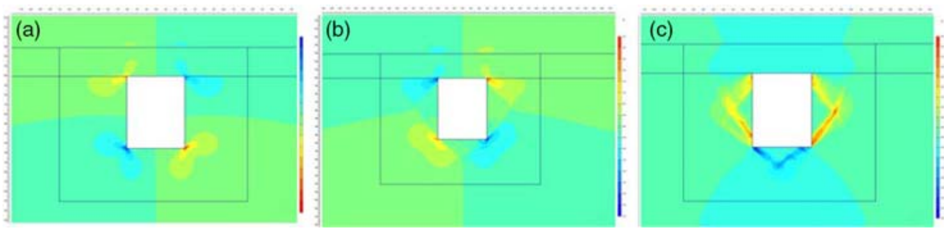

Figure 16. Shear strains due to progressive reduction of the cohesion of the soft calcarenite along the vertical side boundaries of the quarry: (a) $c' = 180\,\mathrm{kPa}$, (b) $c' = 140\,\mathrm{kPa}$, (c) $c' = 100\,\mathrm{kPa}$.

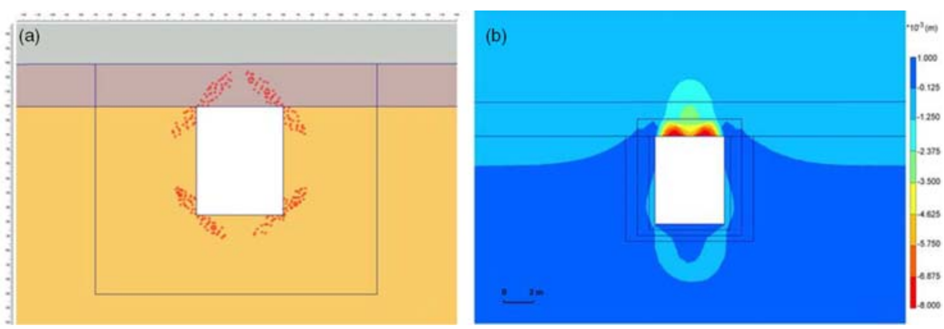

Figure 17. Plastic points (a) and vertical displacements (b) due to progressive reduction of the cohesion of the *mazzaro* at the cave vault.

produce sinkhole effects at the surface, shown in Figure 18 in terms of shear strains (a) and cumulated vertical displacements (b), both reaching the ground surface.

Finally, the effect of the interaction of two close rooms at low distance (7 m) has been also investigated, this being a very frequent condition existing in the Cutrofiano underground quarry systems. The analysis shows the initiation of local failure mechanisms along both the inner vertical walls already with the assumption of a reduction to 90% of the unweathered rock properties. Figure 19(a),(b) indicates, respectively, the plastic zones and the shear strain contours resulting from this stage of the analysis. A complete local failure process is instead reached when a reduction to 70% of the unweathered rock properties is implemented in the model. Figure 20(a) shows the complete propagation of inclined shear zones in the rock volume between the two caves, and the contours of cumulated vertical displacements reported in Figure 20(b) indicate that the highest displacements develop in the same area. It comes out that with such a close distance of two adjacent cave rooms a strength degradation less than that required for the development of the failure mechanism in the case of a single room is needed. Therefore, this result highligths the influence of the interaction of close subterranean rooms to enhance and accelerate the process of development of local collapses.

3. Conclusions

Evaluation of rock mass stability in natural and man-made caves has a crucial importance in many built-up areas and communication routes of Apulia, since propagation to the surface of the failures occurring underground often results in heavy damage and losses to society. The issue must be properly faced, by means of an inter-disciplinary approach involving different professionals, in the perspective to cover all the necessary fields of knowledge: these include, but are not limited to, cave exploration and survey,

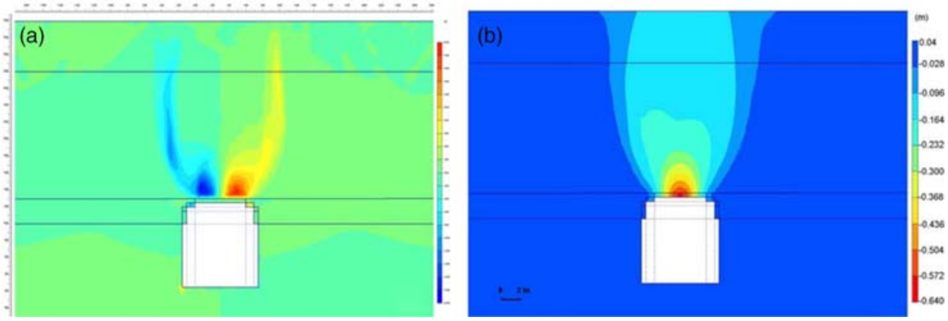

Figure 18. Shear strains (a) and vertical displacements (b) due to increased size of the quarry.

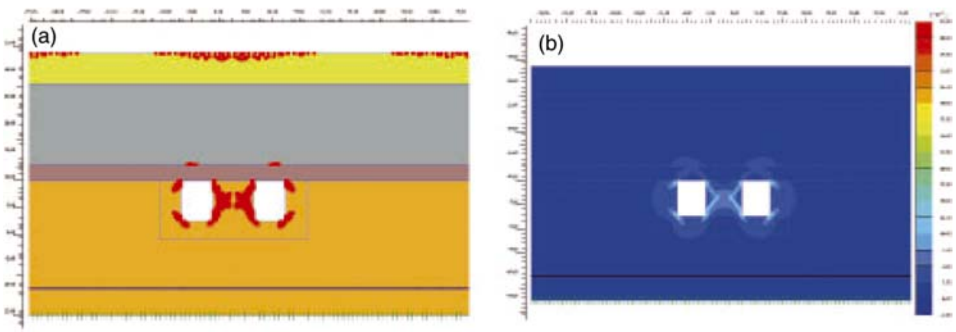

Figure 19. Model with two quarry rooms with a distance of 7 m. Plastic points (a) and shear strain contours (b) calculated for a reduction to 90% of the unweathered rock properties.

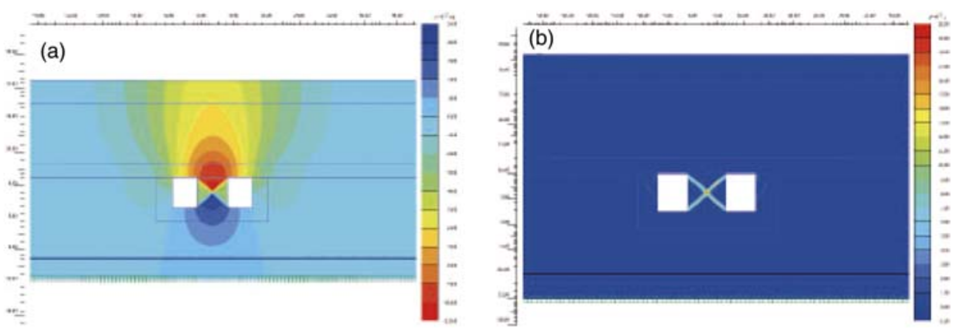

Figure 20. Model with two quarry rooms at a distance of 7 m. Contours of cumulated vertical displacements (a) and shear strain contours (b) calculated for a reduction to 70% of the unweathered rock properties.

geomechanical characterization of the rock mass, evaluation of the weathering acting on the rock mass, identification of the rock type failures, and implementation of numerical analyses. The two case studies presented in this article were aimed at showing the potentialities and drawbacks of some available numerical approaches to the study of similar boundary value problems. For the first case, represented by a natural cave within a jointed rock mass, the role played by persistence of vertical joints has been observed to be relevant. For the case of a man-made cave in a continuous calcarenite rock mass, on the other hand, the influence of environmental weathering of rock and the resulting strength degradation resulted to have a major role in the development of local failures, and in their propagation upward, until producing the global failure of the roof overlying the cavity. The influence of the close distance between two adjacent cave rooms for the enhancement of the failure rock processes has been also highlighted. Although the analysis being 2D, the overall methodology described in this paper seems to be capable of revealing the main features of the failure mechanisms of the rock masses as well as the factors controlling the same processes. However, the study has also confirmed the need to proceed toward the use of 3D numerical analysis in order to overcome the limitations associated with oversimplification related to analyses performed in 2D.

A crucial point is, in any case, the need to base any model, whether 2D or 3D, on real data deriving from field survey, that is, to build and implement models based upon detailed knowledge of the factors controlling the underground processes. These data are, as a matter of fact, indispensable for a correct understanding of the failure mechanisms occurring within the caves and the proper design of the model to be used for the numerical analyses.

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