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Proceedings of IV International Congress of Speleology in Artificial Cavities
Italy, Genoa, September 29th / October 1st



EDITORS

Stefano Saj, Carla Galeazzi

Michele Betti, Francesco Faccini, Paolo Madonia





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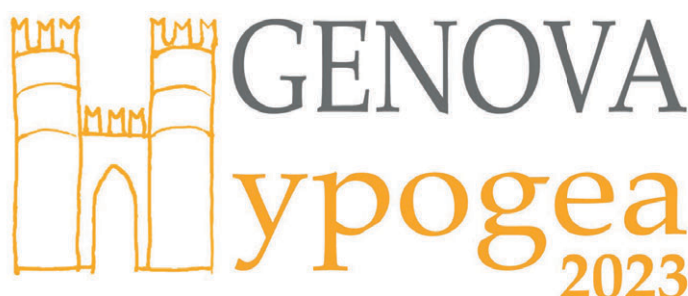


PROCEEDINGS OF IV INTERNATIONAL CONGRESS OF SPELEOLOGY IN ARTIFICIAL CAVITIES

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On the role of geo-structural features in the development of failure mechanisms affecting man-made underground cavities

Piernicola Lollino^{1,*}, Mario Parise¹

Abstract

The stability of man-made underground caves is progressively challenging throughout Italy due to the increase in urbanization processes as well as the gradual environmentally-driven degradation processes affecting caves excavated several decades ago and, later on, abandoned. In general, such processes interest the caves as a consequence of prolonged high-humidity conditions or, under more critical conditions, sudden inflow of a large amount of water due to pipeline leakages or rainfall infiltration. In the last years, a strong advancement in the 2-D and 3-D numerical modelling aimed at investigating the stability of underground caves within soft rock masses has been developed, and several scientific articles have been published in this perspective. In most of these works, the rock mass is simulated as continuous, consistently with the absence of relevant fractures or discontinuity sets, as largely observed within these geological settings. However, in some cases persistent discontinuities can affect the rock masses hosting the caves, and, accordingly, such geo-structural conditions need to be properly accounted for in assessing the safety of the underground environments. In this contribution, the role of joint inclination in the development of failure mechanisms within anthropogenic caves is firstly investigated by means of two-dimensional parametric finite element analyses of an ideal underground cave implementing discrete joints with different inclination. From a numerical point of view, the influence of discontinuities potentially existing in the calcarenite masses is explored by implementing joints as interfaces between continuous rock domains. In particular, numerical models with vertical and inclined joints are assumed and the corresponding results highlight the impact of the joint dip in the generation and enhancement of the failure mechanisms within the rock masses, as a function of the joint shear strength.

Keywords: artificial cavities, stability, failure, weathering, modeling.

Introduction

The potential failure of man-made underground caves, that were exploited and abandoned decades ago, is still nowadays frequently underestimated in land and urban planning policies, and has often serious consequences on the built-up environment. For artificial cavities within soft, porous rock masses, water infiltration from the ground surface or from pipeline leakages, water inflow into the caves, change in the ventilation conditions, and other factors, can be responsible for the degradation of the rock material properties over time, even in a relatively short time. Recent case studies regarding the failure of man-made underground cavities, which caused sinkholes affecting urbanized areas, are reported in previous works, as for example the sinkholes affecting calcarenite quarries in Southern Italy (Parise 2010, 2015; Vattano *et al.*, 2013), mining caves in Canada (Bétournay, 2009), the siltstone Longyou caverns in China (Li *et al.*, 2009), and the limestone mines in the Netherlands and Belgium (Van Den Eeckhaut *et al.*, 2007).

In the last years, numerical modelling has represented a highly efficient tool to investigate the stress-strain evolution of the rock mass around the cave, so that

the variations of equilibrium and the associated displacement field generated by a change in loading condition, or in boundary conditions, can be accurately simulated (Ferrero *et al.*, 2010; Parise & Lollino, 2011; Zhang *et al.*, 2016; Fazio *et al.*, 2017; Castellanza *et al.*, 2018; to mention a few). However, such numerical applications, which are basically performed with the finite element method (FEM), have mainly focused on intact rock conditions. As such, the rock mass is simulated as continuous, consistently with the absence of relevant fractures or discontinuity sets, as largely observed within these geological settings. However, in some cases persistent discontinuities can affect the rock masses hosting the caves, and, accordingly, such geo-structural conditions need to be properly accounted for in the safety assessment of the underground environments (Parise, 2012). Nowadays, the presence of joints within FEM analyses can be taken into account in a relatively easy way by employing interface or joint elements devised to represent discontinuities (Hammah *et al.*, 2008; De Silva *et al.*, 2022), although the main shortcoming existing in this application is represented by aperture and sliding possibility within the rock mass not being allowed, due to the continuity assumption made in the same methodology. In this

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Fig. 1 – Picture of a typical underground cave in soft calcarenite rocks.

perspective, an important opportunity is provided by discrete element methods (DEM; Lollino *et al.*, 2004) or the more recent hybrid finite element/discrete element methods (FEM-DEM; Munjiza, 2004; Lollino & Andriani, 2017; Lollino & Parise, 2023).

The present paper is aimed at proposing a preliminary investigation on the role of structural features, as discrete joints or proper joint sets, in the equilibrium state of artificial cavities by means of finite element analyses carried out on an ideal underground cave implementing discontinuities within the rock mass domain. To this purpose, an overview of the geological background and typical structural features of the region under study is firstly outlined. Then, a parametric analysis made up of different two-dimensional numerical models characterized by different joint inclination angle values is proposed, and some interesting insights in the failure mechanism of underground caves are highlighted.

Geological background and typical structural features

Apulia, the south-eastern heel of the Italian boot, widely presents outcrops of calcarenite rocks of different ages, from Miocene to upper Pleistocene, that have been affected by excavation, given the soft, or very soft, nature of the rock, making them easy to work, but at the same time guaranteeing sufficient strength to support excavations (Fiore *et al.*, 2018). The different calcarenites may be highly variable in terms of their petrographic and structural features, and this has effects on the mechanical response of the rock, leading to a possible high degree of hetero-

geneity at different sites. In particular, the increase in water, eventually up to approaching the saturation point, is among the main factors potentially bringing the calcarenites close to general failure.

Overall, the physical properties of the rock masses allowed to develop many different typologies of artificial cavities, from civilian settlements to underground aqueducts and cisterns, to olive mills up to quarries (figure 1). In most of the cases, calcarenites can be ascribed to a continuous rock mass, due to the very scarce presence of fractures and joints, that are typically concentrated close to the cavity entrances, or nearby the open slopes, as an effect of stress release. However, in some conditions the calcarenite rock mass may locally present joints that appear to control the likely failures, both as isolated joints and sets or families. In such a situation, the role played by these discontinuities cannot be neglected and should therefore be included in the modelling analysis.

Numerical analyses

In order to investigate the role of structural features in the equilibrium of the rock mass forming the cavity roof, a two-dimensional finite element model of an ideal underground cave characterized by a single joint set, with variable inclination angle and shear strength properties, has been developed. The model sizes are 50 m x 30 m, with an inner rectangular region subjected to excavation representing the cavity, 10 m wide and 6 m high, with roof thickness equal to 6 m. Conventional boundary conditions typically used in static analyses, with null horizontal and vertical displacement imposed along the model bottom and null horizontal displacement prescribed along the vertical boundaries, have been applied to the model. Free displacements have been imposed at the top boundary representing the ground surface. According to the model geometry described, the external boundaries result to be sufficiently far from the process zone, i.e. the area around the cavity, so that the risk of numerical boundary effects is significantly reduced. The adopted discretization mesh is represented in figure 2, which shows a coarser mesh in the domain areas far from the process zone, and a significantly finer mesh in the area around the cavity, where high strain levels are supposed to be expected. Therefore, the mesh proposed represents a reasonable compromise between significantly enhanced computational accuracy and relatively short computational time. A single joint set, with variable joint inclination, persistence and shear strength, has been simulated in the different analyses to explore the role of discontinuities in the equilibrium conditions of the rock mass. Rock properties representative of the typical mechanical behavior of the soft calcarenite outcropping in Apulia, where such anthropogenic cavities have been excavated, as described in previous studies performed by the authors (Perrotti *et al.*, 2018), have been imple-

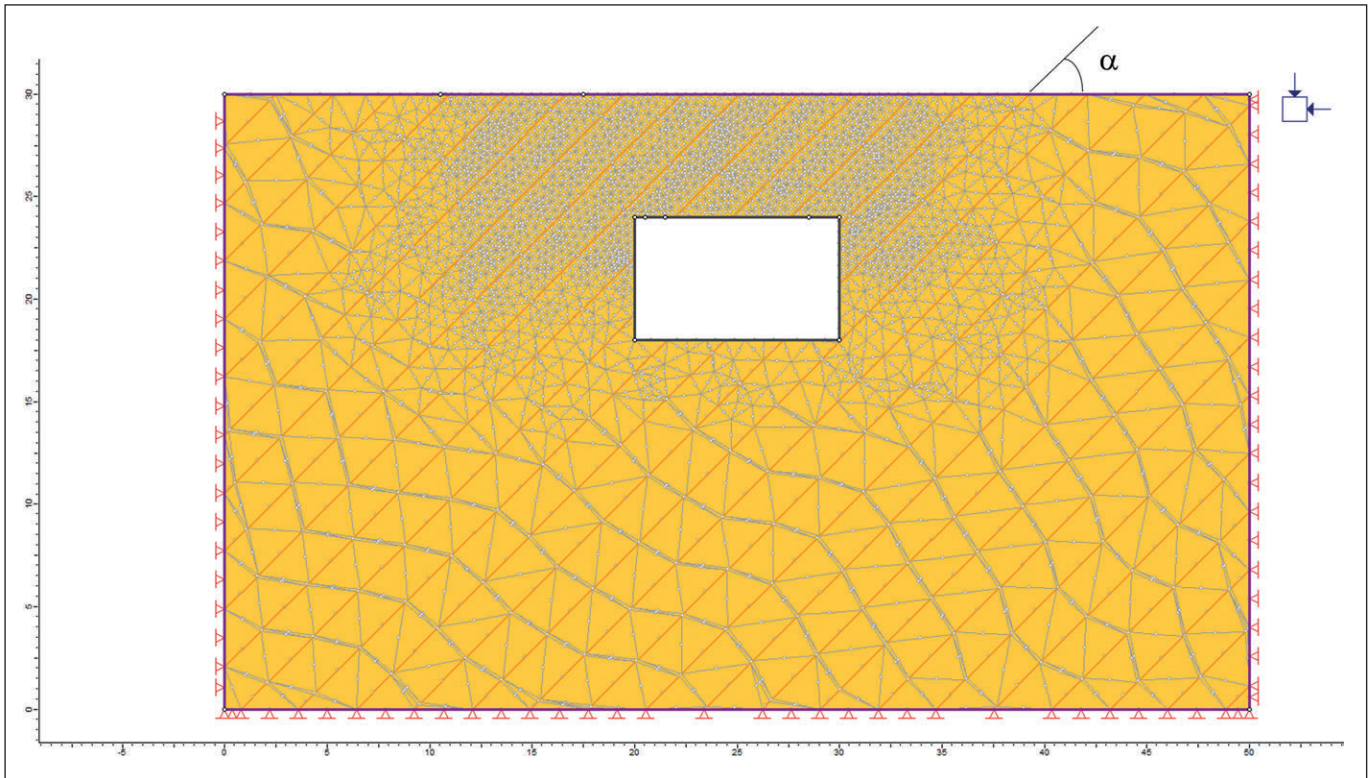


Fig. 2 – Numerical domain and discretization mesh adopted.

Property	γ (kN/m ³)	E (MPa)	ν	c' (kPa)	ϕ (°)	σ_t (kPa)
Value	17	200	0.3	200	30	200

Table 1 – Material properties adopted for the calcarenite rock.

mented for the rock matrix. To simulate the rock mass behaviour, an elastic-perfectly plastic model, with a Mohr-Coulomb failure criterion, has been assumed. The rock material properties are summarized in Table 1.

For the rock joints, a shear strength, characterized by null cohesion and tensile strength, as well as variable friction angle values, has been chosen in the analyses. As such, the shear strength is represented uniquely by the friction angle, whereas the elastic normal and shear stiffness values of the joints have been assumed to be, respectively, equal to:

$J_{kn} = 100000 \text{ MPa/m}$,

$j_{ks} = 10000 \text{ MPa/m}$.

An initial stress state resulting from geostatic vertical stresses and horizontal stresses derived from a $k_0 = 1$ assumption, i.e. $\sigma_h = \sigma_v$, has been simulated in the analyses.

In order to investigate the role of joint inclination with respect to the horizontal direction (α value in fig. 2),

different values of the same parameter have been assumed in the models, ranging from vertical joints ($\alpha = 90^\circ$) to inclination angle of $\alpha = 65^\circ$, 45° , 30° and 20° . A joint spacing equal to $s = 2 \text{ m}$ has been kept as fixed in all analyses here described, whereas an infinite persistence has been also assumed. For the different models implementing variable joint inclination, different values of the joint shear strength have been assumed in order to detect the strength values mobilized at failure conditions. In particular, friction angle values ranging from $\phi' = 32^\circ$, which corresponds to highly smooth surface joints (i.e. no roughness and no dilation), to $\phi' = 55^\circ$, corresponding to significantly rough joints (i.e. large dilation), have been taken into account.

Model instability has been defined when a clear failure mechanism, characterized by a well-defined concentration of plastic shear strains or plastic zones as well as by increased displacement in the area delimited by the plastic zones, is detected and, also, numerical convergence of the analysis is not reached.

Results and discussion

A preliminary model, with no joints (i.e. intact rock mass) has been carried out and the results indicate stable conditions of the cavity roof.

The numerical results corresponding to the model with vertical joints indicate a strong influence of the joint shear strength in the equilibrium conditions of the cavity roof. In particular, when joint friction angle values larger than $\phi' = 38^\circ$ are adopted, the model does not show any sign of instability. With $\phi' = 36^\circ$, the model is in a marginal stability state, characterized by a straining mechanism that involves an area corresponding to the whole cavity roof, thus resembling the typical mechanism of collapse sinkhole (Gutierrez *et al.*, 2014; Parise 2019, 2022). However, under these assumptions, the model is still stable from a numerical point of view, i.e. numerical convergence is still ensured. When a lower value of the joint friction angle is taken into account ($\phi' < 35^\circ$), the model reaches numerical instability, with a typical chimney failure mechanism delimited by the joints aligned with the vertical boundaries of the cavity (fig. 3). In particular, figure 3a shows the contours of the calculated plastic shear strains, which indicate concentrated plastic zones at the upper and lower extremes of the joints, whereas the cumulated total displacements, showing significant downward displacement values concentrated within the overall cavity roof, are reported in figure 3b.

Therefore, the above described model results to be highly sensitive to the joint shear strength parameter, since the equilibrium conditions of the cave roof change from stable to unstable, according to limited variations in the same parameter.

The analyses with inclined joints revealed relevant outcomes in terms of cave failure mechanism as well as shear strength threshold values for cave stability. In particular, when a large joint inclination angle is assumed ($\alpha = 65^\circ$), the model results to be stable for joint friction angle larger than $\phi' = 44^\circ$. For lower values of the same parameter, a general failure, as well as a lack of numerical convergence, are calculated in the analysis. Therefore, the threshold friction angle value for stability is calculated to be approximately equal to $\phi' = 44^\circ$. In figures 4a and 4b, in order to give evidence of the failure mechanism, the yielded zones and the total displacement contours calculated in the analysis assuming $\phi' = 42^\circ$ are plotted, respectively. Both figures highlight a clear tendency to develop a straining mechanism involving the whole cavity roof (i.e. up to the ground surface), which is confined by the highly-inclined joints.

When a joint inclination angle equal to $\alpha = 45^\circ$ is assumed, the model results to be stable (i.e. numerical convergence is reached) for joint friction angle larger than $\phi' = 47^\circ$. For lower values of the same parameter, the tendency to develop triangular-shaped local failures along the upper boundary of the cavity, which are delimited by the inclined joints and new plastic zones developing within the intact rock, is simulated in the analysis. In figures

5a and 5b, the plastic shear strains and the total displacement contours calculated in the analysis assuming $\phi' = 45^\circ$ are plotted, respectively, as representative of the typical failure mechanism occurring in this model. Both figures clearly show the local failure developed along the cavity roof, although some straining effects are also calculated even in the upper area, i.e. up to the ground surface.

In the case of a joint inclination angle equal to $\alpha = 30^\circ$, the model results to be stable (i.e. numerical convergence is reached) for joint friction angle larger than $\phi' = 50^\circ$. For lower values of the same parameter, a triangular-shaped local failure, which is formed by the inclined joints and new yielded zones that develop within the intact rock, tends to develop along the upper boundary of the cavity. In figures 6a and 6b, the plastic zones and the total displacement contours calculated in the analysis assuming $\phi' = 49^\circ$ are plotted, respectively.

The previous failure mechanism is strongly enhanced in the analysis with $\alpha = 20^\circ$ joint inclination angle (fig. 7), for which a threshold joint friction angle for stability equal to $\phi' = 50^\circ$ has been obtained. In this case, the local failure along the cavity roof is clearly identified, but a straining mechanism involving the whole roof thickness up to the ground surface is generated as a consequence of the loosening effect of the local failure.

A plot summarizing the threshold joint friction angle values for stability against the joint inclination angle within the different numerical models has been reported in figure 8. It indicates a clear trend of reduction in the threshold value for stability of the friction angle, from values larger than 50° to 35° , with joint inclination angle values increasing from $\alpha = 20^\circ$ to $\alpha = 90^\circ$. These results indicate that, for highly inclined joints, rock mass instability can be triggered even with low friction angle values of the joints, whereas for low-inclined joints cavity failure can be triggered only with very large friction angle values. These outcomes strongly highlight the need of a proper geological and structural characterization of the rock masses, that appears to greatly influence the possibility of reaching failure conditions.

The numerical results above described also show that a clear change in the failure mechanism arises when the joint inclination changes, since with highly-inclined joints the tendency to proper sinkholes (chimney-shaped mechanisms) dominates (Berest, 2017), whereas with low-inclined joints local triangular-shaped failures take place along the upper boundary of the cavity. In this latter case, the possibility to propagate upward, until reaching the ground surface and producing a collapse sinkhole, seems to be lower.

Models implementing non-persistent joint sets have been also developed and the corresponding results indicate a strong influence of the joint persistence in the equilibrium state of the rock mass. In particular, in the case of non-persistent joints, the presence of rock bridges significantly reduces the tendency to instability of the rock mass above the cavity.

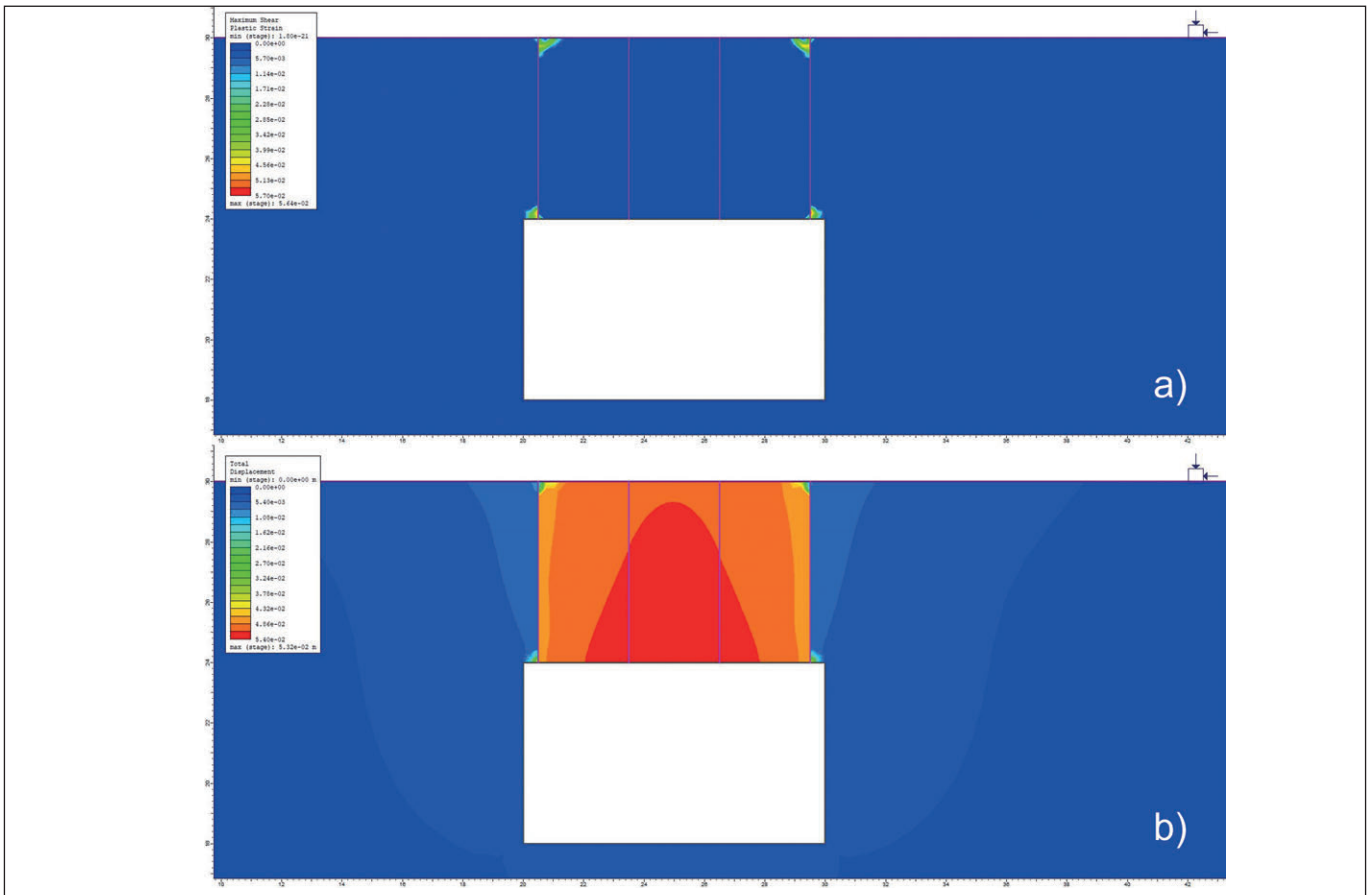


Fig. 3 – Numerical results with vertical joints: a) contours of plastic shear strains; b) cumulated displacements.

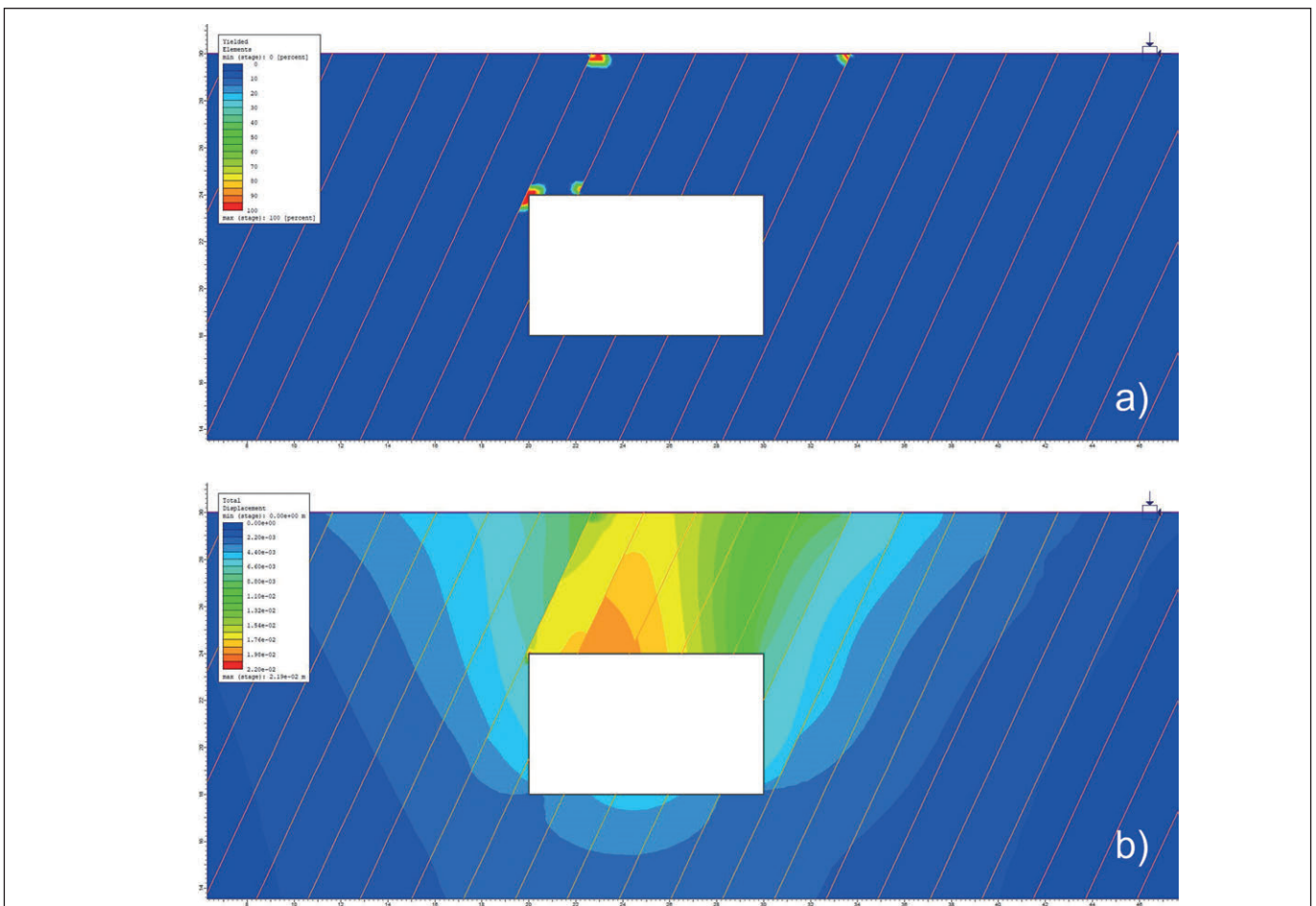


Fig. 4 – Numerical results with $\alpha = 65^\circ$ inclined joints: a) plastic zones; b) cumulated displacements.

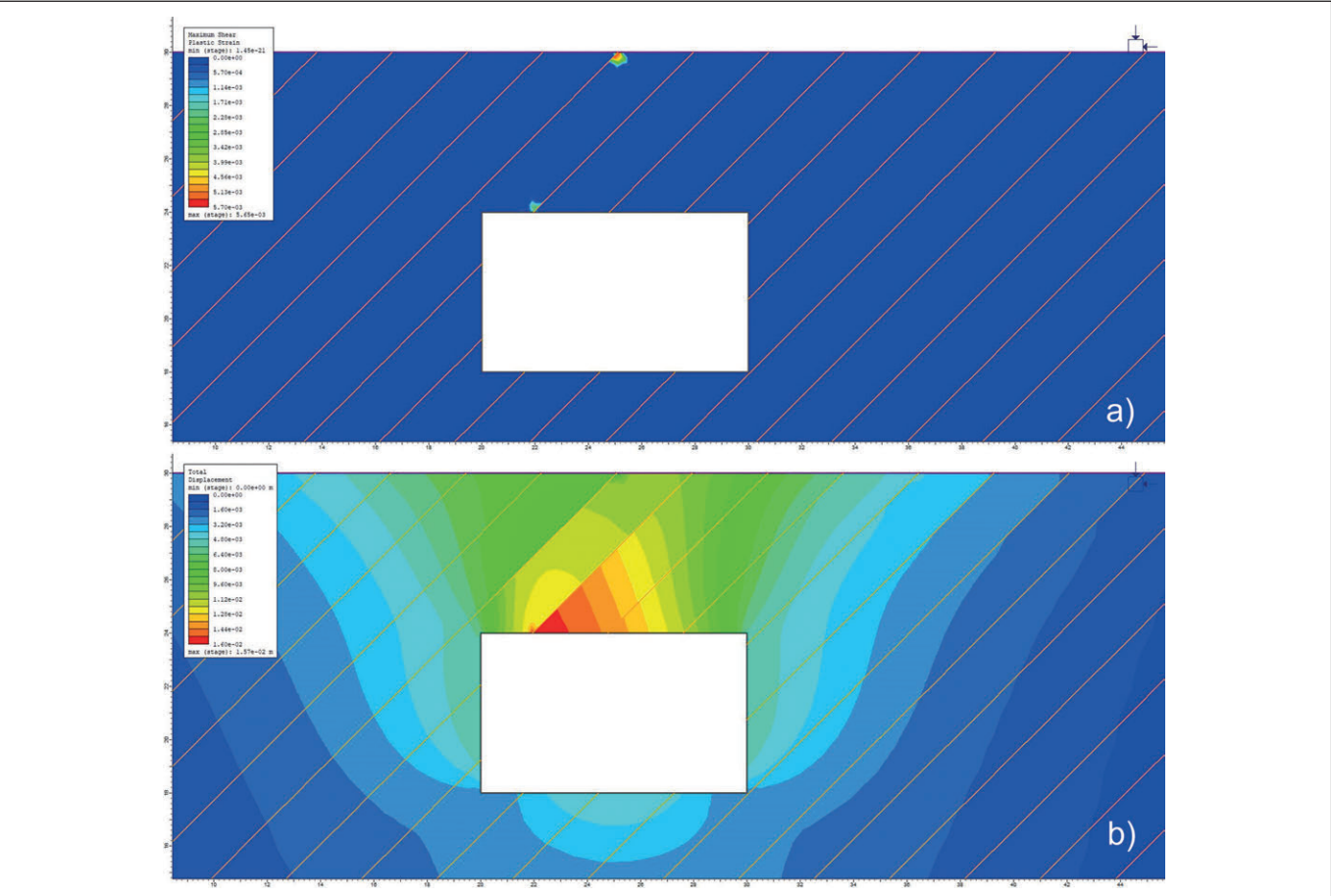


Fig. 5 – Numerical results with $\alpha = 45^\circ$ inclined joints: a) contours of plastic shear strains; b) cumulated displacements.

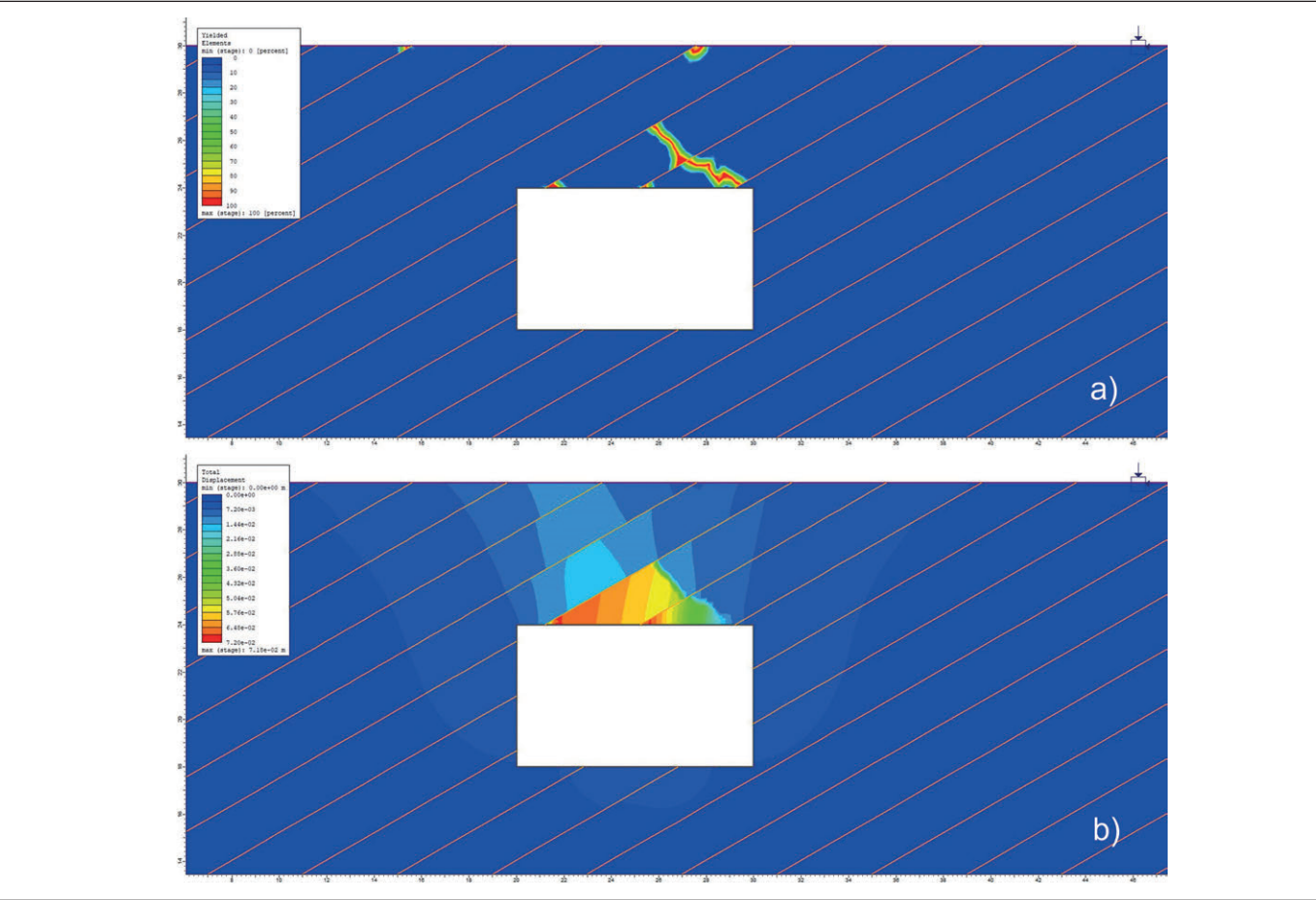


Fig. 6 – Numerical results with $\alpha = 30^\circ$ inclined joints: a) plastic zones; b) cumulated displacements.

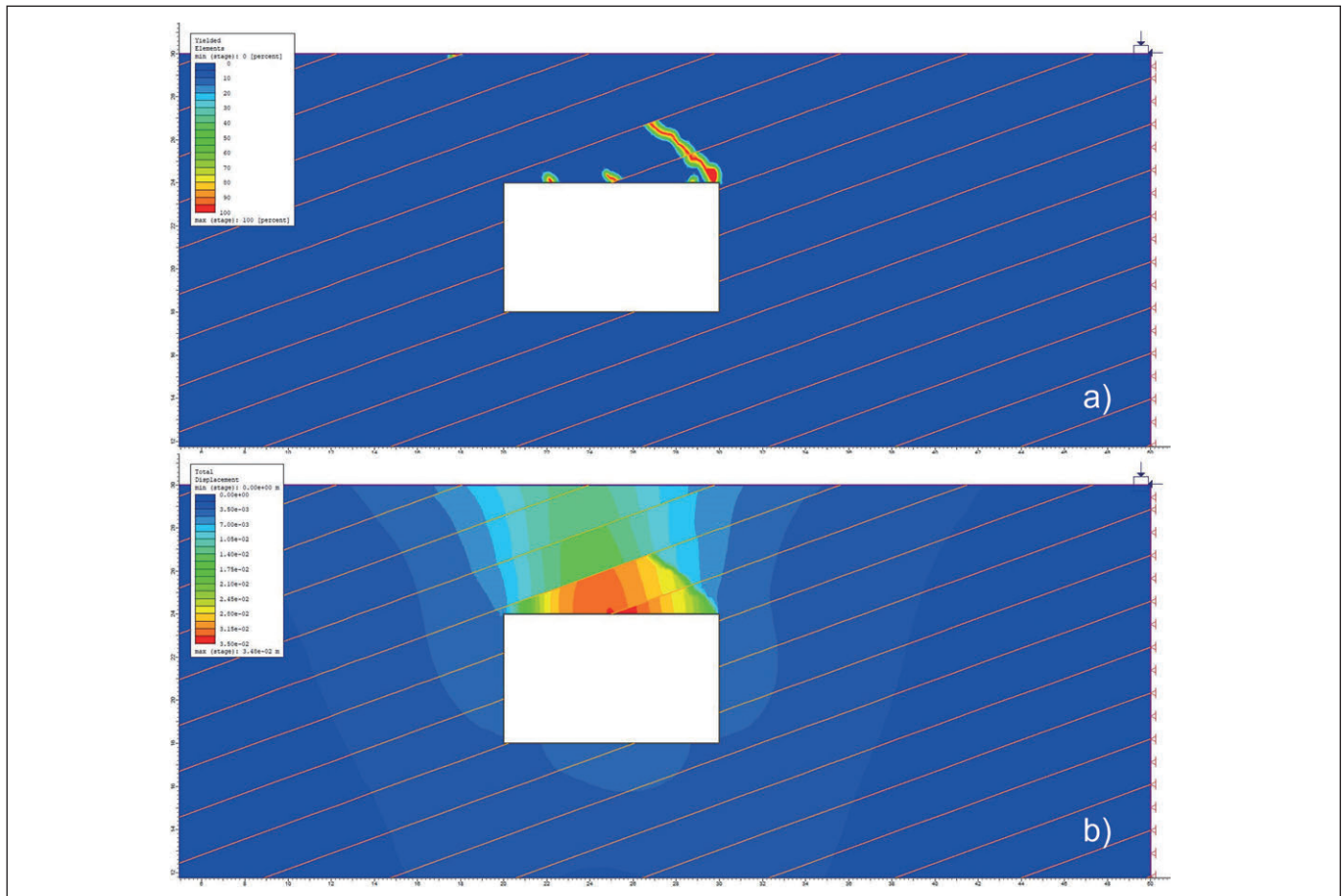


Fig. 7 – Numerical results with $\alpha = 20^\circ$ inclined joints: failure mechanism.

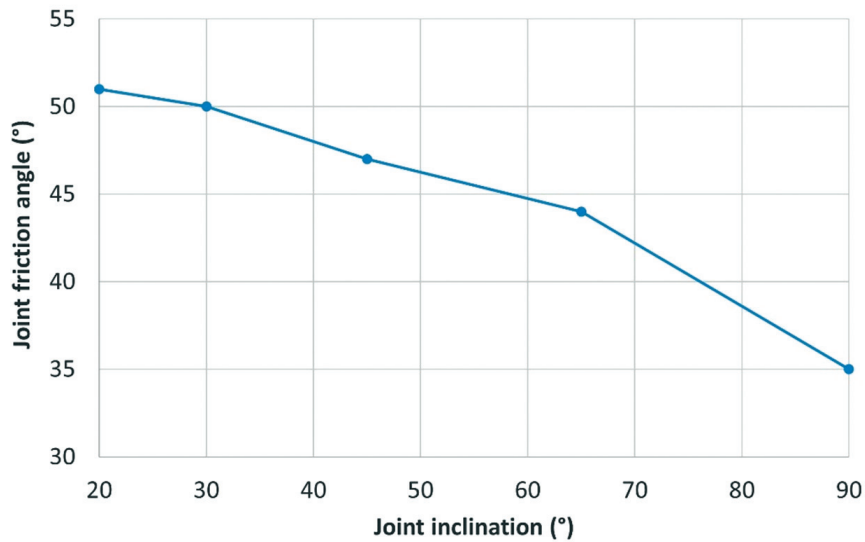


Fig. 8 – Plot of threshold joint friction angle values for stability against joint inclination angle.

Concluding remarks

This paper has investigated the role of joint sets, with large spacings, within the vaults of anthropogenic caves in soft calcarenite rock masses. To this purpose, numerical models with vertical and inclined joints have been assumed and the corresponding results highlight the impact of the joint dip in the generation and enhancement of the failure mechanisms within the rock masses, as a function of the joint shear strength. The analyses are still on going, taking advantage of the large amount of data regarding artificial cavities in calcarenites of Apulia, and will further proceed in delineating the other factors that, together with the physical properties and the geo-structural features, may contribute to the development of underground failure mechanisms.

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