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Analysis of the behaviour of a carbonate rock mass due to tunneling in a karst setting

Biagio Palma[a], Anna Ruocco [a], Piernicola Lollino [b] and Mario Parise [b*]

[a] *IdroGeo S.r.l., Vico Equense, Italy*
[b]*National Research Council, IRPI, Bari, Italy*
[*]*Corresponding Author's E-mail: m.parise@ba.irpi.cnr.it*

ABSTRACT

Sorrento Peninsula is one of the most famous touristic resort of southern Italy. The high energy relief of the carbonate mountains, reaching over 1,100 m above sea level at a very short distance from the coastlines, along with the widespread development of karst processes, make the area extremely complex as regards the constructionof infrastructure lines. In the past, construction of railway and road tunnels was affected by serious problems due to instability phenomena, in part related to karst processes. In particular, the sector of Vico Equense is characterized by several collapse sinkholes, together with a number of further karst landforms.

In this paper we describe the activities performed during the construction of a tunnel for water disposal. The tunnel, entirely realized in carbonate rock masses, is some hundreds of meters long and shows at several locations karst natural caves, the main one of which was surveyed by means of laser scanner techniques. Such an approach made possible the remote sensing collection of discontinuity strikes and dips even along the chimney-like vertical caves. These data, combined with those derived from the classical geomechanical survey within the tunnel, allowed to characterize the rock mass and to evaluate the stability conditions in the different phases of the tunnel advancement. In the present paper, the geostructural and the geomechanical characterization of the rock mass are discussed, along with the analysis of the rock mass response to tunneling carried out by means of the discrete element method.

Keywords: Karst,Rock Mechanics,Carbonate rock mass, Tunnel

1. INTRODUCTION

Sorrento Peninsula (Campania region) is one of the most famous touristic areas of southern Italy. The high energy relief of the carbonate mountains, reaching over 1,100 m above sea level at a very short distance from the coastlines, and the widespread development of karst processes, make the area extremely complex as regards realization of infrastructures and communication routes. In the past, construction of railway and road tunnels encountered serious problems because of instability phenomena, in part related to karst processes (Budetta et al., 1996; Santo and Tuccimei, 1997). In particular, the area of Vico Equense is characterized by several collapse sinkholes, together with a number of further karst landforms.

The Sorrento Peninsula is a horst, oriented transversally to the southern Italian Apennine Chain, which separates the tectonic depressions of the Campania Plain to the north and the Gulf of Salerno to the south. The structure is a NW-dipping monocline ridge, consisting of thick Mesozoic dolomitic limestone sequences, superimposed by Miocene deposits preserved in small structural depressions, by Quaternary clastic deposits and by volcaniclastic materials deriving from the historical activity of the main volcanic districts (Vesuvian and Phlegrean Fields). The structural setting of the Peninsula is the consequence of several phases of tectonic uplift and erosion, started at the end of the Miocene. In particular, the present relief is the result of a Middle Pleistocene uplift that caused the rejuvenation of the main morphologic features of the area. During the last Glacial Würm, the ridge was also modeled by the combined action of mass wasting and karst processes. The structural framework is characterized by mostly sub-vertical faults, NW–SE and N–S trending (Patacca and Scandone, 1987). Subordinate systems, NW-SE and E-W trending, are also present. In most of the cases, the faults show strike slip components, locally with trans-tensional movements. The morphological setting of the area, characterized by the presence of ancient erosional surfaces and by steep fault scarps, is the result of the complex interaction between erosion, uplift and block faulting.

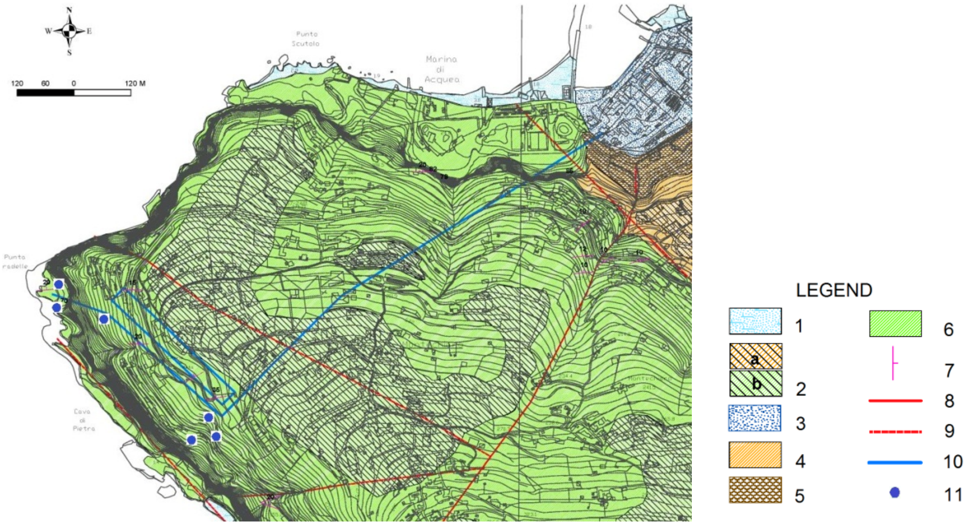

Figure 1. Geological map. Legend: 1) recent beach deposits. Holocene. 2) Indifferentiated pyroclastic deposits, resting over ignimbrite terraces (a) and low-gradient carbonate slopes (b). Holocene. 3) Alluvial fan deposits. Holocene. 4) Campanian Ignimbrite. Upper Pleistocene. 5) Ancient alluvial fan deposits. Upper Pleistocene. 6) Meta limestones. Cretaceous. 7) Strata bedding. 8) Fault. 9) Tectonic contact, dashed where presumed. 10) Trace of gallery. 11) Station for geostructural survey.

Historically, this part of Campania has been affected by many types of slope movements that caused catastrophic episodes, claiming casualties and producing severe damages. Among the most recent fatal events, it is worth to be reminded the January 1997 landslide at Pozzano, that caused four deaths, 22 injured people and a road closure for about two months (Calcaterra and Santo, 2004). Unfortunately, this was not the only episode, since, given the configuration of the peninsula, the main communication routes are located close to the seashore at the bottom of high relief slopes, and are therefore often affected and interrupted by landslide deposits.In the area, rock falls represent the most frequent typology of slope movement (Budetta and Santo, 1994; Palma et al., 2012). In addition to these phenomena, karst processes developed to create a complex network of fissures, conduits and voids, and their local concentration was crucial for the opening of hundreds of meters-long trenches at the surface and of collapse sinkholes (*sensu* Waltham et al., 2005) produced by massive fall of the overburden above karst caves. It comes out that the overall setting of the area has to deal with natural hazards of various typologies, but in any case related to karst.

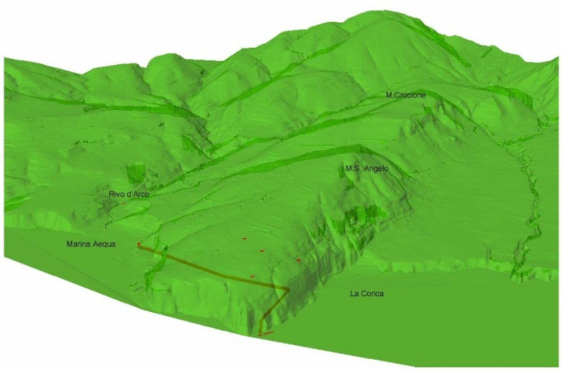

Figure 2. 3D-view of the Montechiaro ridge, showing the trace of existing and new-planned galleries.

Figure 3. Punta Gradelle seen from the sea, showing to the right the outlet of the existing gallery.

In such a context, we present in this paper the outcomes of studies carried out to complete a sewage disposal plant at Punta Gradelle locality: in particular, the work consisted in the excavation of a new tunnel (300 m long and 15 m wide; Fig. 4), where the disposal plant will be located, and some enlargements for the already existing Seiano gallery. The new tunnel is designed in NW-SE direction through the Montechiaro ridge, a monocline dipping toward the N-NE, and bounded by the sea to the west (Figs. 2 and 3). The present morphological configuration is in some way also derived by anthropogenic activities, since several open quarries have been opened in the carbonate rock faces.

Figure 4. Phases of advancement of the gallery front.

2. GEOMECHANICAL CHARACTERIZATION OF THE ROCK MASS

A detailed geological-structural survey aimed at the identification of the main rock mass features wascarried out both underground and along the slope surface. It is well known that rock geomechanics problems quite often need to face practical difficulties in investigating the rock mass itself due to accessibility to the sites and the data collection represents generallya very delicate and crucial part of the geomechanical analysis. In the specific case here examined, practical problems of measurements had therefore to be solved in order to reduce as much as possible the erroneous representation of the joint pattern, that derive from measurements performed only at the more accessible sites (Terzaghi, 1965; LaPointe and Hudson, 1985; Dershowitz and Einstein, 1988). For these reasons, we also used speleological and alpine techniques along the slope surface, thus performing a systematic survey through horizontal and vertical scanlines covering the most significant sectors.

Macroscopic and mesoscopic structural analysis were carried out to detectthe main joint sets and the prevailing directions of the kinematic indicators. The survey was focused to the identification and the interpretation of the most important features required for a complete characterization of the rock mass (Hoek and Bray, 1981; Hudson and Priest, 1983): type of discontinuity, orientation, spacing, aperture, infilling, persistence, weathering, etc. Given the nature of the limestone, a particular attention was focused on weathering effects, which result from the combination of physical alteration and chemical solution (Fookes and Hawkins, 1988). The surveys were carried out according to the standards defined by the International Society of Rock Mechanics (ISRM, 1978), and the collected data were graphically represented in Lambert-Schmidt equatorial projection.

At the six measurement stations, horizontal and vertical scanlines have been established, thus totalizing 12 scanlines. Further, more than 50 survey forms were produced during advancement of the tunnel, in order to characterize the rock mass discontinuities. Beside the bedding, five main discontinuity setshave been recognized, as listed in Table 1. The statistical analysis of the collected data show that most of the discontinuities are highly inclined to vertical, except for the bedding (Fig. 5). Verticality of the planes is in particular evident for the system K1 which, given the excavation direction of the gallery, is that one greatly unfavorable to the advancement (Bieniawski, 1979). Spacing is variable between 15 and 30 cm, which corresponds to classes of "close" to "moderate spacing" according to the ISRM guidelines. This parameter is of great importance for the geomechanical characterization, since it controls the development of release tension cracks.

Table 1. Average attitude of the main identified discontinuity systems

FAMILY	STRIKE	DIP
K1	224	81
K2	171	85
K3	132	83
K4	266	82
K5	051	61
S	017	16

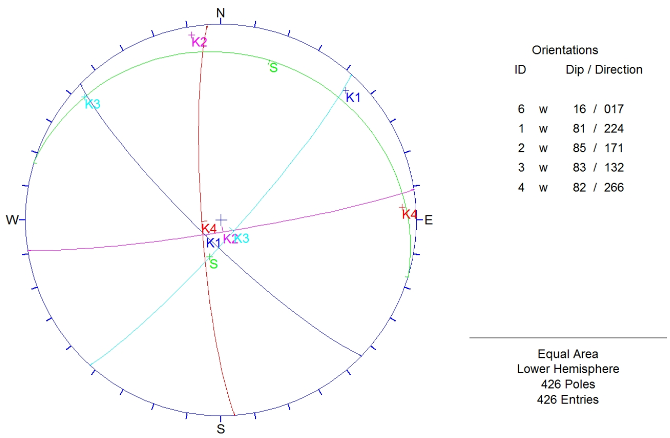

Figure 5. Overall plots of structural data.

As concerns persistence, defined as the length of the discontinuity traces as measured at the exposed surface, the values are concentrated in the classes from "very low" to "medium", and, subordinately, in "very high". The frequency histogram showing the persistance data highlights the differences among the different discontinuity sets, with the families K1 and K3 being the most significant, whilst the others appear to terminate against them.

Aperture is mostly in the range 0,5-1,0 mm, corresponding to "moderately open" and "open" classes in the ISRM guidelines. Further, open cracks belonging to K1 system have been recognized during the survey. Filling is generally absent, and cohesive where present, or, subordinately, it consists of residual materials from the solution of carbonate rocks.

A detailed 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, following the ISRM standards (1978). According to the measurement results, JRC is found to be in the range 4 – 9, whereas JCS results to vary between 36 and 70 MPa. Since the JCS value of the unweathered joint is equal to JCS_{un} = 79 MPa, the weathering degree is in the range

JCS/JCS_{un} = 0,45 - 0,88. Based on the well-known Barton criterion (Barton and Choubey 1977) and assuming a basic friction angle of ϕ_b = 35°, the peak friction angle of the joints results to be in the range 35° – 45°.

Karst features have been identified during the surveys, both at the ground surfaceand along the advancement of the tunnel. As regards the latter, the most significant was a 23-mt high karst chimney, that was the object of specific cave explorations, and was analyzed by means of laser scanner techniques (Figs. 6and 7).

Figure 6. Views of the karst chimney encountered during excavation.

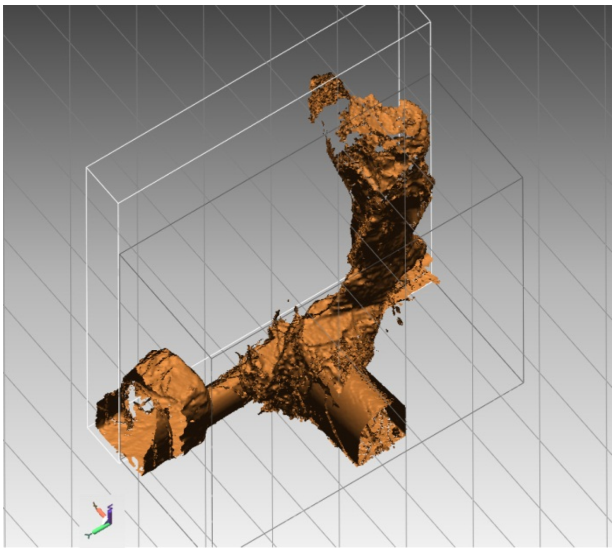

Figure 7. Laser scanner surveying of the karst chimney.

3. NUMERICAL ANALYSIS

Discrete element analyses have been performed with $UDEC^{2D}$ (ItascaCG, 2004) in order to investigate the behaviour of the fractured rock mass when subjected to the excavation of both the existingand the more recent disposal plant (Fig. 8). The geometry of the whole model is rectangular (140 × 140 m) and is characterised by fixed horizontal displacements along the vertical boundaries, withfixed vertical displacements prescribed at the bottom of the domain. At the top of the grid a vertical pressurecorresponding to the average overburden above the examined domain has been imposed. Only the main discontinuity sets have been simulated in the model in order to reduce the computational effort:

- K1 (α = 90° respect to the positive horizontal axis, spacing = 1.8 m)
- K2 (α = -40° respect to the positive horizontal axis, spacing = 6 m)
- S (α = -30° respect to the positive horizontal axis, spacing = 0.7 m), this representing the bedding strata of the mass.

All the sets have been assumed to be characterised by infinite joint persistence in order to simulate the worst conditions for stability. Higher spacings have been assumed in the far-field part of the domain in order to reduce the computational effort.

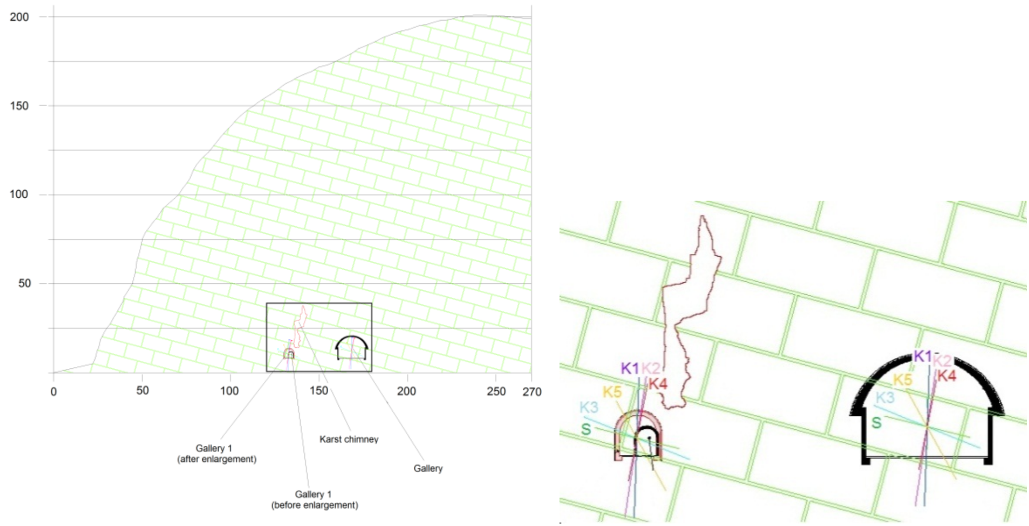

Figure 8. Cross section considered for the analysis, and close-up view with indication of the discontinuity sets.

Joints have been assumed to behave according to a Coulomb law with null cohesion and friction angle with values equal to ϕ = 35°, 40° and 45°. Intact rock has been assumed to behave according to an elastic-perfectly plastic constitutive model, with a Mohr-Coulomb strength envelope having the following parameters:c' = 5 MPa, ϕ' = 42°, σ_t = 8 MPa, in accordance with the results of uniaxial compressive tests performed on intact rock. In particular, mean uniaxial compression strength results to be 80 MPa, whereas tensile strength has been assumed to be 1/10 of the compression strength.

The initial stress state has been assigned by means of a gravity loading procedure. Afterwards, the excavation of the old disposal tunnel has been firstly simulated (Analysis A), followed by the excavation of the new tunnel (Analysis B). In the present analyses, both the tunnels have been simulated as unlined in order to investigate the response of the rock mass when subjected to the unloading induced by the excavation and the capacity of the rock mass of sustaining the different decompression stages.

a) Analysis A - newtunnel

The results in terms of block displacement vectors induced by the excavation of the newtunnel (to the extreme right in Fig. 8) are shown in Figure 9for three different joint friction angles (ϕ = 35°, 40° and 45°). The figure indicates that with the assumption ofa friction angle equal to ϕ =35° the rock mass experiences a large decompression in the portion above the cave for a thickness of about7-8 m,thatresultsto be highly asymmetric due to the effect of the inclination of the bedding planes. Only instability of single blocks along the roof boundary of the tunnelis instead observed in the case of friction angle equal to 45°. The different response of the rock mass is also clarified by Figure 10, where the contours of horizontal displacements are shown. Thefigure indicates that in the first case (ϕ = 35°) the decompression zone is much larger than the other two cases and that, as a consequence, the pressure on the lining is expected to be presumably higher on the left (SW) side due to the aforementioned asymmetric loading. The same results are confirmed by Figure11, where the joints subjected to zero normal stress is reported, indicating that in the first case (ϕ =35°) a large number of bedding joints are subjected to opening due to decompression, together with vertical joints located close to the vertical boundary of the tunnel.

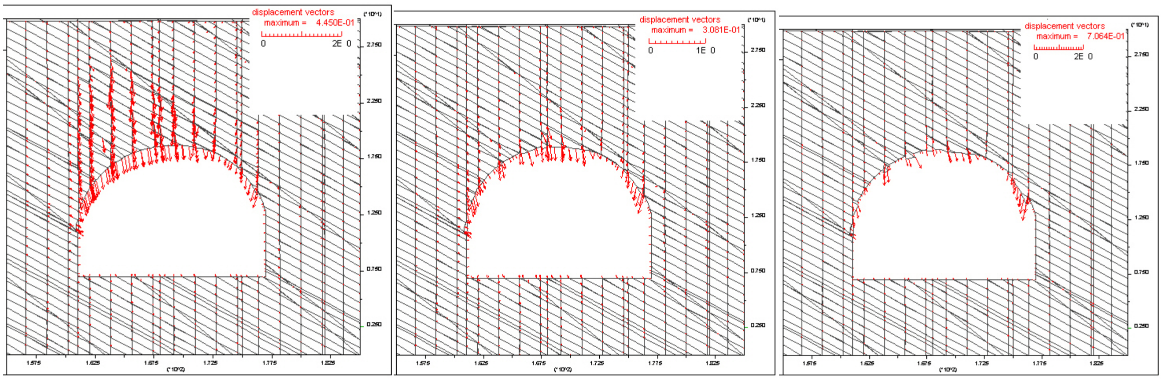

Figure 9. Block displacement vectors for different joint friction angles (ϕ = 35°, 40° and 45°).

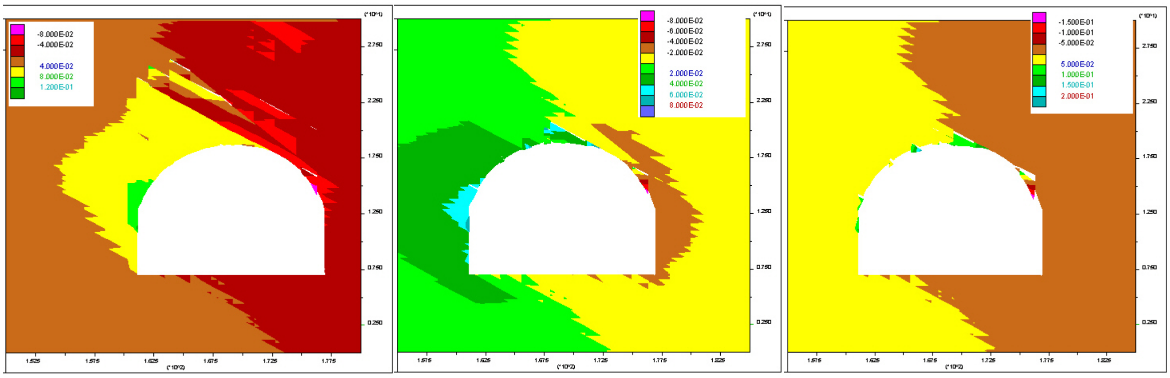

Figure 10. Contours of horizontal displacements for three different values of joint friction angles (ϕ = 35°, 40° and 45°).

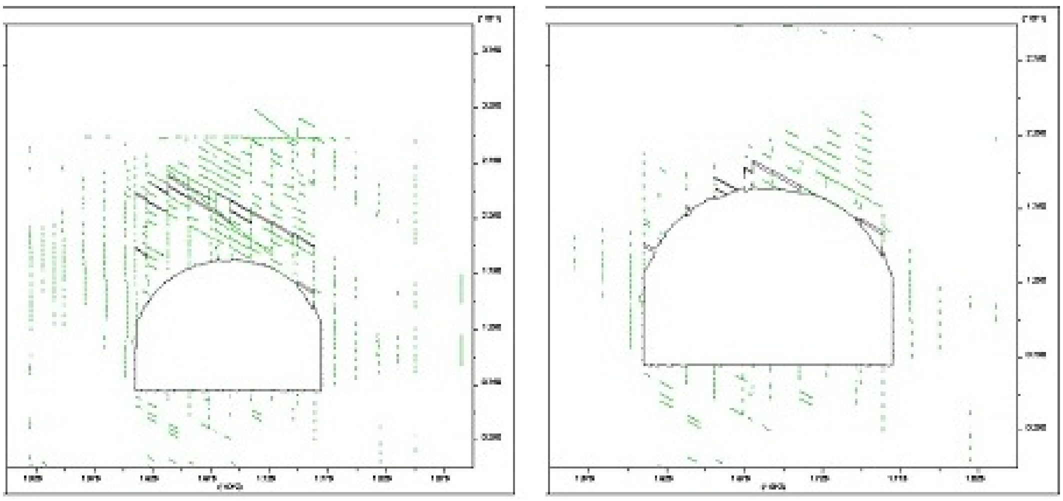

Figure 11. Joints subjected to zero normal stress for joint friction angle ϕ = 35° and 45°.

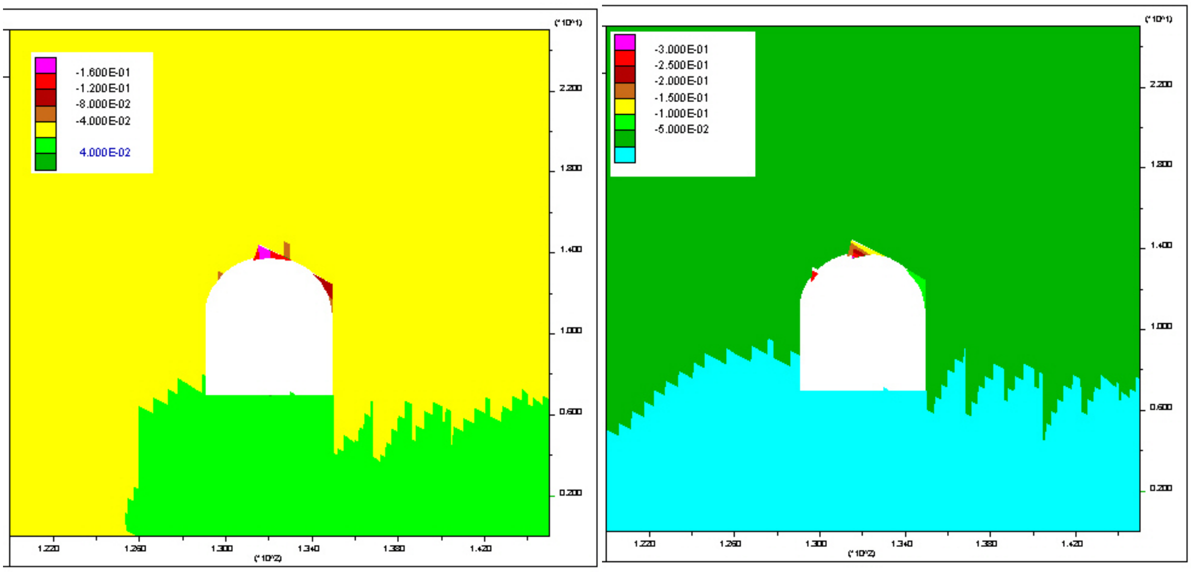

Figure 12. Contours of vertical displacements for joint friction angles ϕ = 35° and ϕ = 45°.

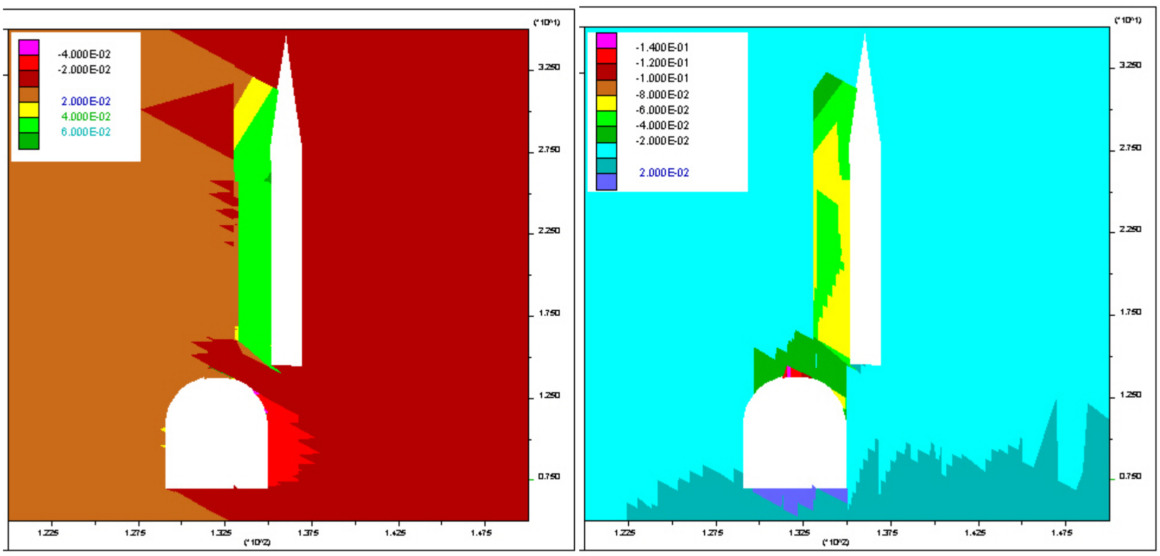

Figure 13. Contours of horizontal (left) and vertical displacements (right) due to the interaction between the oldtunnel and the karst chimney.

b) Analysis B - oldtunnel

No difference is instead observed when the enlargementof the oldtunnel (to the left in Fig. 8) is simulated with the assumptions of different friction angles. For all the three cases, only the instability of shallow portions of the cave roof is simulated and the decompression zone of the rock mass is very limited (Figure 12), this should presumably being the consequence of the smaller size of this tunnel respect to the fracturing state of the rock mass.

No interaction is observed in the model between the strain fields produced bythe two tunnels.

c) Analysis C - oldtunnel, interaction with karst chimney

The interaction between the enlargement of the oldtunnel and the karst chimney mentioned in section 2has also been verified by means of numerical analysis, although the Authors being aware of the inexistence of proper plane-strain conditions in the case of the karst chimney. The results in terms of contours of horizontal and vertical displacement show that a decompression of the portion of the rock mass between the tunnel and the chimney is generated due to the construction of the tunnel (Figure 13), even though this is expected to be limited just to the area of the chimney.

4. CONCLUDING REMARKS

It is already well known in the scientific literature how the carbonate massifs of Campania may be affected by instability processes that are often related to karst. In particular, the effects of dissolution in widening the joints, and increasing the karst voids and conduits, thus significantly contributing to reduction of the cohesive strength, has been demonstratedin several occasions. From rock failures of various typologies, to occurrence of sinkholes and subsidence at the ground surface, these effects may be very severe, especially when dealing with underground engineering works. This is true not only in Campania, but also for many other regions in southern Italy (Delle Rose et al., 2003; Del Prete et al., 2010; Iovine et al., 2010).

In the present paper, a detailed geostructural and geomechanical characterization of the calcareous rock mass at Punta Gradelle (Sorrento Peninsula, Southern Italy) is discussed and the results of the discrete element analysis aimed at assessing the rock mass response to tunneling are presented.The paper highlights the need for detailed geostructural analyses in such fractured rock mass contexts, which are also affected by karst processes and generally produce strongly anisotropic responses to tunnelling and excavation (Zhou and Beck, 2011).

This represents a diffuse problem for several regionsin Southern Italydue to the widespread presence of such geostructural environments. In this case, the geomechanical analysis has been oriented to the assessment of the most likely range of parameters characterizing the shear strength of the joints to be used in the numerical analysis. The results of the discrete element numerical calculations confirm the strong influence of the structural control on the rock mass response to the excavation, which is shown to be highly anisotropic, mostly for a large-size tunnel. Even though it is very difficult to evaluate the effective role played by karst in promoting rock failures (Parise, 2008), karst is shown to be responsible for the enhancement of the anisotropic response of the rock mass and the generation of strain fields or proper rock failures during excavation that do not occur without karst voidsand conduits.

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