Geotechnical Engineering for the Preservation of Monuments and Historic Sites –
Bilotta, Flora, Lirer & Viggiani (eds)

The safety of an industrial archaeological heritage: The underground quarries in Marsala (Sicily)

M. Zimbardo, L. Ercoli & C. Cannone
University of Palermo, Italy

A. Nocilla
University of Brescia, Italy

ABSTRACT: The present paper analyses an underground and inactive quarry of calcarenite, which belong to a localised area called *Cave di calcarenite in Contrada Cuccidenna* that has been recognised as a typical example of industrial archaeological heritage. The study of this typical quarry is finalised to the preservation and safe fruition of this site, which represents the history of manufacturing technologies of rocky ashlars. Rock samples from the pillars have been collected and, at first, a petrographic characterisation has been performed. The strength parameters have been estimated by means of triaxial and isotropic compression tests. Through a finite element analysis, the mechanical characterization has been then used to assess the stability and safety conditions of the structure. The influence of several parameters has been considered: e.g. mesostructure of the rock mass, shape of the underground quarry and effects, in close areas, of human interventions.

1 INTRODUCTION

The *Calcarenite of Marsala* is widely outcropping in the western Sicily and it had been used in the historical and monumental buildings since the Punic age, at the beginning as elements of bearings walls and then, after the invention of the reinforced concrete, as masonry facing. An extensive quantity of shafts had been created because of these secular quarries, which are often localised under built-up areas, as under the Town of Marsala. As a consequence of the progressive increase of urban areas, numerous instabilities occurred both on the surface and in the underground quarries and the hazard condition increases consequently. The development of the underground cavities was therefore influenced by the quality of the rock: because of the extraction of the material with good mechanical properties, sometimes in the cavities the ceilings, the pillars and the bearing walls are made of the worse rock material. According to the local quarrymen (Rodolico, 1853), this lithotype can be classified in two main types: the *pietra forte* (strong stone), used for the public housing and monumental buildings, and the *pietra franca* (soft stone), which were avoided during quarrying. The variability of the me chanical characteristics of the material, which have conditioned the morphology of the underground extractions, has been clarified from the researches developed in the last years (Arces et al., 1998, 2000; Zimbardo, 2010). These studies have allowed the authors of the present paper to identify three different textural types, since the texture influences the mechanical properties of the material. In detail, these textural types are characterised by porosity of 50%, 40% and 60% respectively for the type A, B and C (Zimbardo et al., 2010). Successive studies have correlated the mechanical behaviour with the distribution and the type of pores and have leaded to a well-structured classification of Sicilian Calcarenite. From the point of view of its texture, this material has been separated in three classes according to the fabric: A (dense); B1e B2 (sponge), C (house of cards) and, according to this classification, the *Calcarenite of Marsala* belongs to B and C classes (Zimbardo et al., 2011).

The exploiting of the *Calcarenite of Marsala* begins in the VI^{c} b.C, when Phoenicians set up the town and surrounded it with a defensive wall and a moat. During the roman epoch the exploitation increased because of the enlargement of the town and her planning. Nowadays, after many years of intense exploitation, especially during the strong building industry demand of the 70s and the 80s, most of the quarries are abandoned and not in use. After the Second World War, open pit quarries have been most commonly used because of the better profits that arise from the lower costs of delivery and pile and the possibility to extract the whole thickness of the rock bank. Nevertheless the open pit quarries guarantee a better safety and healthiness working conditions. The extraction galleries show different shapes of typical sections: they can have a plane intrados or, rarely, a toppling flight steps. Rough pillars, based on quadrangular sections of 1 to 9 m^2, support the intrados in one level hypogeous cavities. The sections of these pillars can increase up to 50 m^2 and more for overlapping extraction rooms. Sometimes, for cavities placed side by side, the thin rock septum that separates them is committed to support the stability of the whole structure. Signs of the cutting equipment are evident on the quarry walls: vertical and horizontal cuts have been left by the cutting machine or, in the oldest quarries, by the axe used for the ashlar cut. Hence, it has been possible to recreate the cutting technique used during different historical periods: before the industrial age, ashlars were hand made, and with the passing of time, the extraction process has been mechanized. As a result, the working speed and the areas of exploitation increased. Consequently, the cavity dimensions have increased and the cover of some cavities has reduced to a thickness of few meters. It is worth mentioning that the exploitation of these quarries has been severe at all depths and that sometimes, when the quality of the rock bank allowed it, it has reached very high depth and it has stopped at the groundwater table. The present research regards the study of the *Cave di Calcarenite di Marsala in contrada Cuccidenna,* Figure 1a. The quarries in *Contrada Cuccidenna* summarize all the aspects of this manufacturing activities which have taken place from the beginning up to this day and age, in an amazing, large and complex sequence of open pit (Figure 1b) and underground areas (Figure 1c e Figure 1d).

These last figures show the different cutting techniques. Regarding the cutting technique, the material was removed gradually from the top down to the bottom, following horizontal and consequential planes.

Even more than 10 meters deep shafts guarantee the access to the galleries, the cross-ventilation and the way out for the extracted ashlars. The rock used to be cut laterally, in order to reach the higher quality material. Large rock pillars were left to support the structure that arises from the cutting and that consisted in big cavities, which could penetrate deeply into the rock mass, even hundred meters from the entrance shafts. The waste material was not removed: this end material, which generally represented the 30% of the entire excavated volume, was abandoned in piles in the areas that were already exploited, exactly along the gallery flanks.

The quarries in *Contrada Cuccidenna* are next to a deep artificial depression, confined by a versant created for the extractive activities. This slope

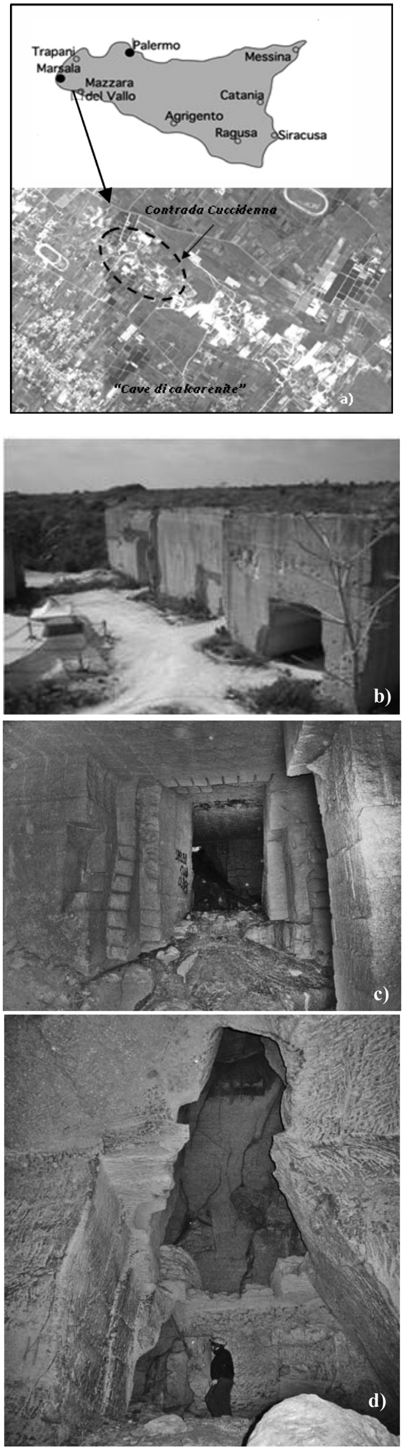

Figure 1. a) Map of "Cave di Calcarenite" b) open pit c) cutting machine signs in an underground d) axe signs in an underground cavity.

is characterized by a spontaneous and luxuriant vegetation, which occurred when the quarries were abandoned and the working activities ended. Nowadays, the deep depression is progressively filled by the waste material, which is partially coming from the closest cavities and partially coming from the close active quarries.

Regarding the site geometry, it is the result of the cutting progression. It consists in numerous crossing cavities, which are large from 6 m to 27 m and high from 8 m to 21 m.

2 ROCK MASS MESOSTRUCTURAL CHARACTERIZATION

The rock formation *Calcarenite di Marsala*, which formed in the lower Pleistocene, crops out in the south-west quadrants of the province of Trapani along a band directed NW-SE upon an area of 300 km^2. This rock formation can even reach thickness of about hundred meters.

The rock banks used for commercial purposes, reach the dimension of more than 10 meters in the middle-northern area. On the contrary the rock banks became extremely thin towards south.

The lithological and particle size characteristics of the rock formation *Calcarenite di Marsala* are extremely variable. This variability, in both direction vertical and horizontal, reflects the multitude of involved depositional mechanisms (Arces et al.,1998) and it is characterised sometimes by sandy, sandy-silty lenses or levels that can be interposed among the cemented levels of *Calcarenite*.

The rock mass mesostructure, which has been detected both at the surface and in the underground, is featured by discontinuities that are normal to the layers. These joints have an high or very high persistence (>10 m) and a wide or moderate spacing (5–7 m). Three families of discontinuities characterised the mesostructure of this rock formation as shown in Figure 2 in which modal values of the dip and the dip direction are given.

If a big scale observation is made, the discontinuities appear lightly waved. On the contrary, at small scale, the joint surfaces appear substantially plane. It is worth noting that the presence of discontinuities does not influence the stability, with the exception of the case in which the natural discontinuity is next to a cut wall. Since the upper cavities are 10–15 m large, the rock mass can be considered as a homogeneous and continuous medium characterised by the mechanical and physical features of the intact rock.

The cavity ceiling is always next to the ground level, which lies 3–4 m above for the youngest quarries and about 10 m above for the oldest ones.

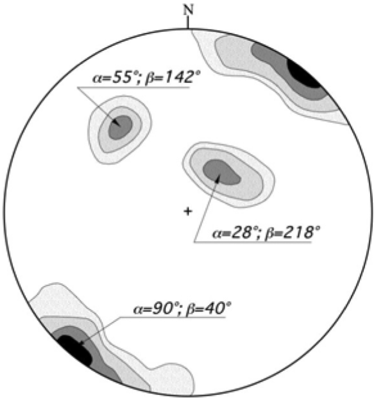

Figure 2. Isodensity diagram of the rock mass.

3 PETROGRAPHIC AND GEOTECHNICAL CHARACTERISATION OF THE INTACT ROCK

For the experimental programme, in the hypogeous cavities, 12 ashlars have been extracted (20 cm large, 18 cm high and 40 cm long). Despite the extreme variability of the texture in the *Calcarenite di Marsala*, in the considered site the rock is very uniform.

To correlate the textural characteristics with the mechanical behaviour, 8 thin sections have been observed in transmitted light by means of a petrographic microscope.

The rock is a biocalcarenite characterized by a uniform composition. The bioclasts are here presented in decreasing order of present percentage: fragments of rhodolithes, fragments of mollusc shells and foraminifera. Briozoa, entrochi and anellida are sporadically present. Lithoclasts, made of fragments of carbonate rocks and monocrystalline or polycrystalline grains of quartz silt, are present at very low percentage.

The particle size distribution of the grains is well graded: the particle size varies between 0.1 mm to 8 mm and the modal value is about 0.8 mm. Sphericity is good for all the bioclasts and lithoclasts except for the fragments of mollusc shells that are flat and elongeted. Roundness is high in the most cases. The grain contacts are, with the same frequency, of tangential or of flattened type. In rare cases, the flat grains show an oriented fabric.

A very thin film (about 10–50 μm thick) of calcite cement wraps totally the grains, as shown in Figure 3. The crystals are microsparitic in size (7–50 μm is the thickness of the cement coating) and appear usually placed side by side in a single level.

If compared to the total volume of grains and pores, cement is of low amount, except for a thin

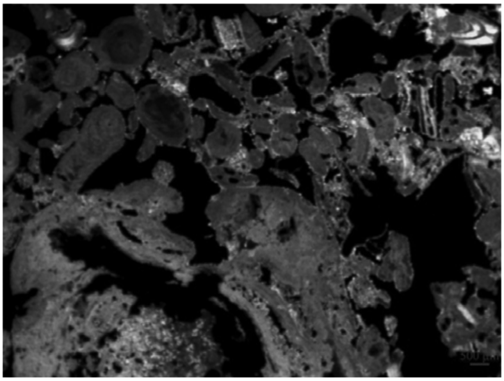

Figure 3. Thin section of the Marsala lithotype.

section referring to a fault surfaces, characterized by micritic cement, which almost fill the interparticle voids. On the contrary all other samples show a low amount of cementation: interparticle and intraparticle porosity is open. As for void volume, the porosity has been evaluated by means of optical comparing tables, and it is about 40–45%. Pores size varies between 0.8 to 0.12 mm.

According to Zimbardo et al. (2011), the pores have been classified as *macropores* when their size is a multiple of the modal size of the grains, *mesopores* when they have about the same size of the modal size of the grains, and *micropores* when the size is lower than the modal size of the grains or like the smallest grains.

Mesopores and micropores are uniformly distributed, macropores are less in volume than the formers and are present in restricted areas. The rock can be described as sponge fabric (lithotype B2, Zimbardo et al., 2011).

The void index is variable between 0.84 and 1.01, the dry unit weight is between 13.4 kN/m^3 and 14.9 kN/m^3 and a modal value of 14.2 kN/m^3 can be estimated. The slaking test results show values of the durability index I_d between 0.83–0.92. These values highlight the strong cementation bond, despite the low percentage of cement and the high porosity.

Regarding the mechanical properties of the rock, the uniaxial rock strength has been investigated for saturated and dry samples and values between 1.2 MPa and 4 MPa have been detected. Although high values have been determined for dry samples, the rock is always classified as a rock with very low strength.

In Figure 4 the Miller diagram shows that the test values are in the average ratio of the tangent elastic moduli. The tangent elastic modulus at the 50% of the ultimate strength is between 300 MPa e 1500 MPa.

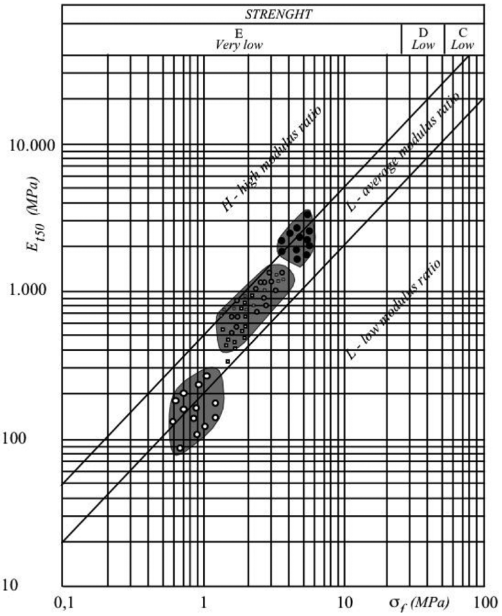

Figure 4. Miller diagram: Uniaxial tangent stiffness at 50% ultimate strength versus uniaxial strength.

These values are intermediate between those typical for lithotype C and lithotype B1, and are similar to values estimated on rock samples coming from close quarries.

The yielding stress obtained by means of isotropic compression tests (Figure 5) is 3 MPa. It is possible to notice that the material mechanical behaviour is typical of strong bonding since the yielding is on the right of the Normal Compression Line (NCL) (Coop & Cuccovillo, 1997).

With the yielding, an elevate decrease of volume occurs and the material becomes progressively denser. As shown in Figure 6, the same behaviour has been observed during triaxial tests and, elaborating the test results, the shear strength parameters at failure (c′ = 0.23 MPa, ϕ′ = 35°) have been estimated.

According to all tests carried out, both isotropic and triaxial compression, a unique yielding surface has been drawn in Figure 7.

4 NUMERICAL ANALYSIS FOR SAFETY ASSESSMENT

In Figure 8 the geometrical model used for the stability and safety analysis is shown for the quarry site in study in *Contrada Cuccidenna*. The geometrical model consists in a section with cavities next to the depression created for the open pit quarries.

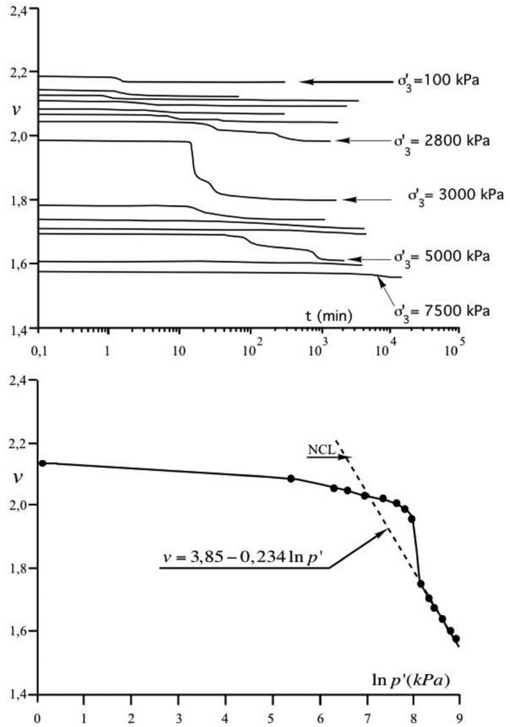

Figure 5. Specific volume changes during isotropic compression for test A1.

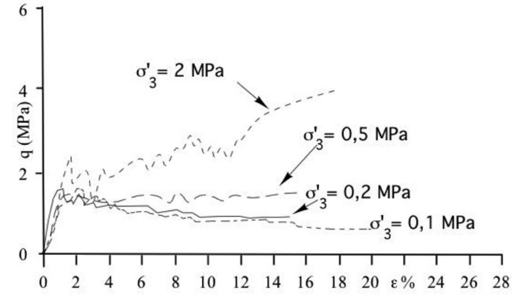

Figure 6. Drained triaxial tests.

The cavity dimensions have been determined directly in situ by means of a laser distance meter. After the geometrical definition of the model, the numerical analysis has been carried out in a plane deformation state using a finite element program where triangular elements with 15 junctions and 12 Gauss points have been considered.

Considering domains of different extensions (between 80 m and 102 m) it has been demonstrated that the stresses are substantially uninfluenced by the domain length, therefore the lowest extension has been chosen, since the displacement was zero for the boundary point (Fig. 8 point A) at the ground level on the right. Because of the high values of discontinuities spacing (>5–7 m), Mohr Coulomb has been adopted as failure criterion to consider in the numerical analysis.

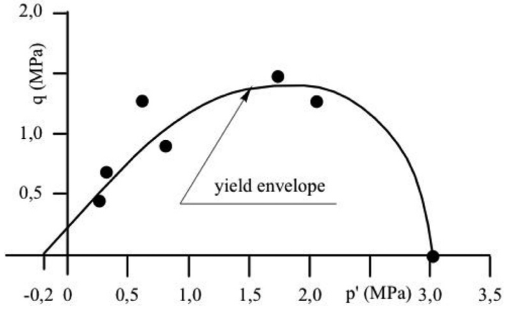

Figure 7. Yielding surface. Data from triaxial and isotropic tests.

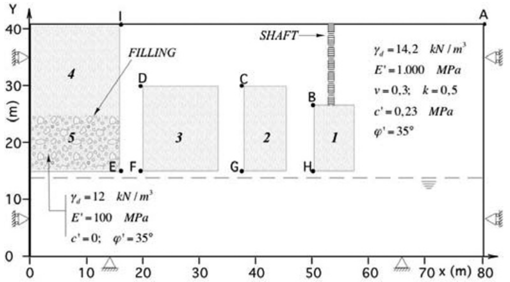

Figure 8. Geometrical definition of the model.

A lithostatic initial stress state has been considered and a value of 0.5, for the lateral coefficient of earth pressure at rest, has been considered. In the Figure 8, the mechanical parameters obtained by the experimental tests and used in the model are shown. Simulations corresponding to the geometrical configurations of cavities during the different historical periods have been performed. In the same figure, it is possible to observe the cutting sequence estimated on the base of statements of quarrymen descendants and their historical reconstruction has been highlighted with a progressive numeration.

Hence, at the beginning, the stress states has been referred to the quarry state with the realisation of the cavity n°1 only. Developing the analysis, the realisation of successive cavities and the final partial filling of the open pit quarries with the waste material have been taken into consideration, as shown in the Figure 8.

Hence, the presence of only one cavity has been considered in the first cycle of numerical analysis. Dimensions have been assigned to the cavity, which is 7 m large, 11 m high and accessible through a shaft 13 m deep (Fig. 8 phase 1). The cavity has been realised by means of an excavation that stopped at about 1–2 m from the groundwater table. A maximum deviatoric stress of 690 kPa has been reached in correspondence to the edges of the cavity (points B and H of Fig. 8).

During the second phase (phase 2), a septum 5 m thick separates the first cavity and the second. The excavation of the second cavity started at a deepness from the ground level of about 9 m and it stopped at the same deepness of the previous cavity.

The second hypogeous cavity is 7 m large and 15 m high and, even in this case, a maximum deviatoric stress of 720 kPa has been reached in correspondence to the base edge of the cavity (point G of Fig. 8). At the same time, deviatoric stresses in proximity of points H and B have scarcely increased.

As for the third cavity (phase 3) that is 13 m large and 15 m high, the walking floor and the distance from the ground level are at the same depth as the previous cavities. In this cavity, a maximum deviatoric stress of 890 kPa has been reached in correspondence to the edges of the cavity (points D and F). At the same time, the stress state in proximity of the close cavities did not increased. On the contrary, deviatoric stresses in all septa between two close cavities (1–2 and 2–3) have increased up to a maximum value of vertical stresses so that the ratio between the uniaxial resistance and these vertical stresses (σ_c/σ_v) is always more than 3.5 (Evangelista et al., 2000).

Once the excavation in the underground quarries has been ended, the extraction has been proceeded in open pit quarries: a depression with sub-vertical walls has been created in successive steps of excavations, which moves deeply towards the ground water table and crossing somewhere the cavities walls (phase 4 of the numerical analysis).

As much as the open pit excavation proceeds, the deviatoric stresses increase and concentrate both at the open air in proximity of the base of the septum which separates the open pit wall with the third cavity and both in the underground in correspondence of its ceiling.

In these two areas, a high deviatoric stress of 1280 kPa has been reached. On the contrary, in correspondence to the base edge of the cavity, the vertical stress increased so that a reduction of the ratio σ_c/σ_v occurs and a value of 2 is reached. Meantime, an increment of deviatoric stresses between the biggest cavities ceiling and the ground level occurs.

At this phase, the cavity covering starts to be exposed to a deviatoric stress range of 200–400 kPa.

In the ceilings, particularly in the third cavity, this ratio between the mobilized shear strength and the ultimate one can increase up to a value of 0.7 but the stability is still assured. The safety condition, described by this ratio, is confirmed by the stress paths, which developed during excavations.

The septum between the open pit quarry and the third cavity shows localised plasticized areas that indicate that the ultimate shear strength has been reached (Fig. 9).

Indeed the shear strength contours show values of 1 for the ratio between the mobilized shear strength and the ultimate one in correspondence to the bottom of the third cavity and the open pit wall (D stress path in Fig. 10). For all the other points and in every excavation phase, stress paths confirm the safety conditions, as shown in Figure 10 where stress paths for points E, D and F are presented.

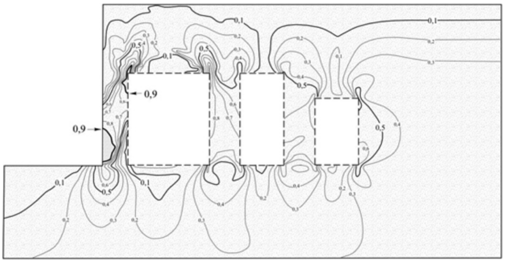

Figure 9. Shear strength contours: Phase 4.

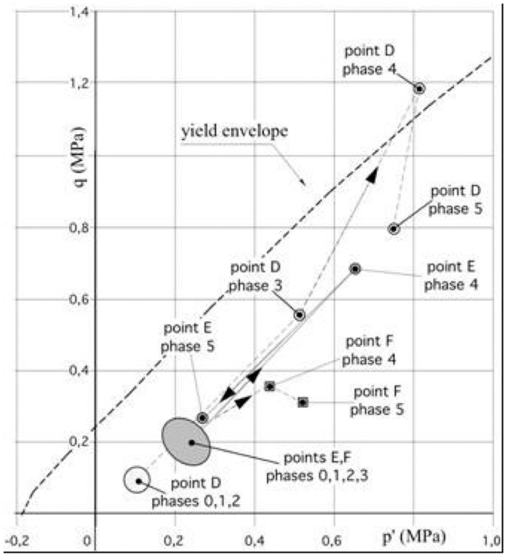

Figure 10. Stress paths and yield envelope.

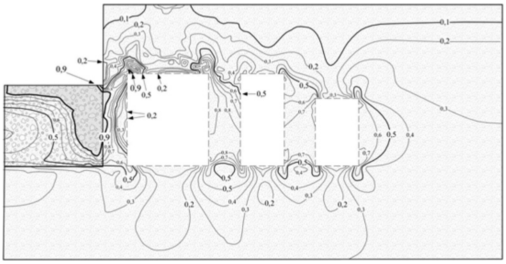

Figure 11. Shear strength contours: Phase 5.

When the open pit is realized, a redistribution of stresses follows and, in correspondence of points D, E and F of the new pillar between the open pit with the third cavity, an increment of the effective mean stress p′ occurs because of the reduction of the section on which the cover weight is applied.

In the same diagram, the yielding envelope is drawn. This curve highlights the passage from the purely elastic behaviour to the elastoplastic behaviour. The D stress path reaches and cross the yielding surface and the plasticization condition occurs. However the ultimate strength stress is not reached, all stress paths point out the possibility for different areas to reach elevate strains which are linked to destructuration processes that can occur in the material. Even if the ratio between the uniaxial strength and the vertical stresses (σ_c/σ_v) is far from 1, the previous results indicate a risk condition, due to the rheologycal behaviour of the *Calcarenite,* that is not negligible for the third cavity.

The last phase of the numerical analysis (phase 5), corresponds to the partial filling of the open pit quarries with the waste material. As shown in Figure 11, stress contours show an improvement of safety conditions, especially in the underground cavities. Also stress paths highlight the described improvement and in Figure 10 it is possible to notice the coming back of the stress paths (see ending points).

As a consequence of the filling procedure, also the end material can be subjected to a stress state close to the plasticization: the material is often throws without an adequate constipation and strains occur in correspondence of the external basements.

5 CONCLUSIONS

The possibility to extract a wide quantity of material in a very high speed is a consequence of progresses in the used technologies, which have allowed the passage from manual methodologies of extraction to industrial techniques. Cavities realised with manual techniques show heights, extension and septum thickness and ceiling thickness that guarantee an high value of the safety factor, which decreased severely when big cavities have been realised by the industrial cutting equipment (steam and after electrical). As a consequence of the enlargement of the cavities, the ceiling thickness has reduced substantially down to values of few meters. Above these cavities, buildings and civil structures have been realised and the safety conditions decreased consequentially.

The better safety and healthiness working conditions have promoted open pit quarries, which used to be realised deep in the ground down to the water table. This procedure creates wide pits in the calcarenite bank, which can be sometimes next to hypogeous cavities.

In the *Cave di Contrada Cuccidenna*, the plasticization of some areas occurs as a consequence of excavations and the safety condition get worse.

Further instability might occur because of the degradation phenomena of the exposed rock or because the ground water table can be very close to the foot of the quarry structure. Indeed, in this case, extremely intense rainfall events can increase the level of the ground water table and a saturation of the lower Calcarenite levels might occur.

If a fruition of the area is planned, both of the above phenomena need to be carefully studied and solved.

At the moment, the partial filling of the open pit quarries with the waste material, in the *Cave di Contrada Cuccidenna*, improves the safety conditions and limited possible destructuration phenomena which might occur at the ceiling edges and at the septum walls or, rarely, at their basement. As a consequence of an inadequate constipation of the filling waste material, differential settlements might occur and endanger the access to the internal and the external areas of the quarry.

The touristic enjoyment of this amusing industrial archaeological heritage is possible and desirable on condition that, besides the necessary studies of instability phenomena, the stability operation project is done after an accurate monitoring of the deformation and stress state processes, particularly for the septa next to the open pit excavations.

ACKNOWLEDGMENT

The authors are grateful to Mr. L. Foderà, owner of the *Cave in Contrada Cuccidenna*, who allowed the access to the area and the rock sampling for the mechanical characterization. The authors would also like to express their gratitude to the speleologist Mr. T. Giordano for his contribution to the sampling and detection of hypogeous cavities. A thank goes to Professors C. Gullo for his comments on cutting historical techniques and historical data. The authors are indebted to *Soprintendenza BB.CC.AA.* of Trapani for the thematic historical charts supply.

A special thank goes to Professors N. Nocilla for his advice in the interpretation of the data.

REFERENCES

Arces, M., Nocilla, N., Aversa, S., Lo Cicero, G. 1998. Geological and geotechnical features of the "Calcarenite di Marsala". *Proc. 2nd Int. Symp. on "Hard Soils—Soft Rocks", Naples, 12–14 Oct. 1998*. Balkema, Rotterdam, 1, 15–25.

Arces, M., Aversa, S., Nocilla, N., Lo Cicero G. 2000. The Pleistocene "Calcareniti di Marsala: Geotechnical and Sedimentological Characterisation". *Memorie Società Geologica Italiana, 55.*

Coop, M.R. & Cuccovillo, T. 1997. Yielding and pre-failure deformation of structured sands. Géotechnique, 47(3), 491–508.

Corkumb, B.T. 1997. Three Dimensional triangulated boundary element meshing of undergroun excavations and visualization of analysis data. *Thesis of Doctor of Philosophy. Department of Civil Engineering, University of Toronto.*

Evangelista, A, Feola, A, Flora, A, Lirer, S., Maiorano, M.R.S. 2000. Numerical analysis of roof failure mechanism of cavities in a soft rock. *Geoeng, Melbourne.*

Evangelista, A, Flora, A, Lirer, S., De Sanctis, F., Lombardi G. 2002. Studi e interventi per la tutela di una patrimonio sotterraneo: l'esempio delle cavità di Napoli. *XXI Convegno Nazionale di Geotecnica L'Aquila.*

Kavvadas, M.J. 2000. Modelling the soil behaviour—Selection of soil parameters. The Geotechnics of Hard Soils-Soft Rocks—Balkema, Rotterdam.

Rodolico, F. 1953. Le pietre delle città d'Italia. F. Le Monnier.

Zimbardo, M. 2010. Comportamento meccanico di rocce tenere: le calcareniti di Palermo e Marsala, Thesis of Doctor of Philosophy. Department of Civil Engineering, Università degli Studi di Napoli Federico II.

Zimbardo, M., Nocilla, N., Ercoli, L. 2011. Petrographic and textural characteristics and mechanical behaviour of Sicilian calcarenites. *Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering* (*goetechnics of hard soils/soft rocks*). A. Anagnostopoulos al. (Eds.)

Zimbardo, M., Nocilla, N., Evangelista, A., Ramondini, M., Scotto di Santolo, A. 2010. Destructuration of typical sicilian calcarenites. *Bullettin of Engineering Geology and the Environment,* Ed. Springer.