Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)

Durability of calcarenitic hypogea in the underground cultural heritage of Palermo (Sicily)

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ABSTRACT: The paper deals with the stability conditions of hypogea, several hundred m^2 wide, dating from the Punic period to the XIX century, dug out of the calcarenitic table that makes up the bedrock of the Plain of Palermo in the Fossa della Garofala. This work concerns the influence that the shape of the hypogea and the characteristics of the lithotypes wields on the instability and decay phenomena taking place, by mean of laboratory tests on the calcarenite and parametric numerical models. The comparison between the numerical models and the actual instability phenomena validated the use of the empirical formula of Hoeck to the mechanical characterization of complex structured rock-mass in soft rock.

1 INTRODUCTION

Fossa della Garofala is the last part of the Conca d'Oro landscape, now totally immersed in the urban area, in which the geological and geomorphological values are compounded by cultural values that cover a span of history from the Punic period to the XIX century.

In a city where, as everywhere densely urbanized, it is almost impossible to read the features of the original environment, this area provides a rare synthesis of natural and anthropogenic environment of great cultural interest. Fossa della Garofala is a narrow valley carved by the stream Kemonia, not far from the nucleus of the Punic town of Palermo (Fig. 1).

Calcarenitic outcrops and the large supply of underground water since ancient times represented a resource for human activities, the first traces of which go back to proto age.

The systematic attendance of places was encouraged certainly by very striking undermining the foot of the slopes, which led to the formation of grottoes used as a shelter from since antiquity until the last war.

2 GEOLOGY AND MORPHOLOGY

Most of the calcarenitic bedrock of the Palermo Plain probably formed during the Sicilian Age in coastal and shallow sea environment; the last trasgressive cycle in the Palermo Plain is represented by the post-Tyrrhenian marine deposits found at an elevation of 21 m above sea level in the Papireto depression, near the Fossa della Garofala.

The neo-tectonic and climatic events that have occurred since the Pleistocene Epoch, from the alternating marine/continental phases to the final emersion are clearly visible on the rocky walls of the Fossa della Garofala. The valley profile, 1.8 km long, develops between 70 m and 30 m above sea level with a mean slope of 2%, which was carved out by the Kemonia creek on the calcarenitic table. The Kemonia flows between the two faults that are the boundaries of the Monreale graben, and reveals how tectonics exerted a strong control over the subterranean and superficial hydrography of the Plain of Palermo.

The calcarenitic body shows both the last marine sedimentation processes during interglacial periods both the erosion processes of the valleys during the continental phases, due to glaciations.

The most important aspect of the continentality phases is to be found in the valley's morphology. In fact, the deep incision of the valley, in respect of the Kemonia's small watershed, can be seen as the combined effect of the lowering of the sea level during glacial periods and the progressive neotectonic upgrowing of the ground at a rate of about 20 cm/1000y.

The valley's first erosion phenomena were triggered during the Middle Pleistocene when a sharp reduction in environmental temperature was coupled with intense tectonic lifting which caused the emergence of a vast area of the Plain. At the beginning of the Upper Pleistocene, the progressive heating of the climate caused another marine ingression that was, however, mitigated by slow tectonic lifting and a temporary interruption of erosion processes.

These latter started again with great intensity at the beginning of the Wurm glaciation, at which

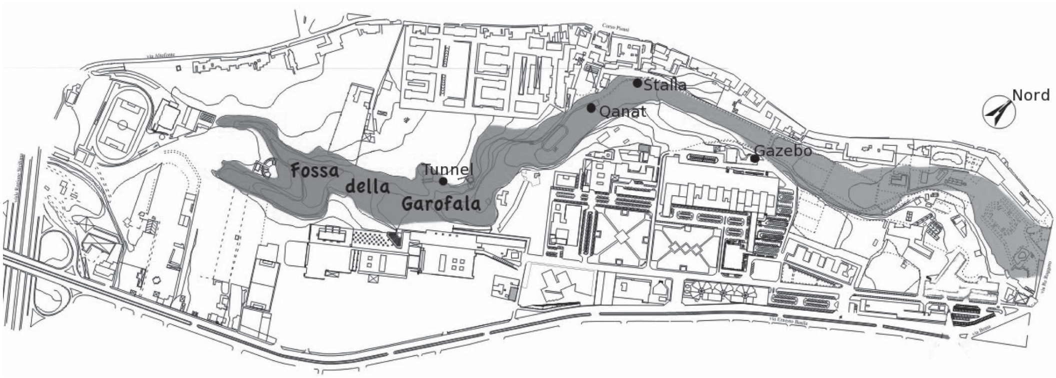


Figure 1. Map of the Fossa della Garofala.

time both sea level and the depth of the valley were at their minimum. The erosion of the valley continued until five centuries ago as the Arab geographer Ibn Hawqual reports. Evidence of the Kemonia's geomorphologic history are the sub-vertical rocky walls of the valley that were cut by the flow of water, the shallow subsurface flow that feeds a rich riparian embankment and several grottoes that were.

3 CULTURAL HERITAGE

The first signs of human activity are of proto-historic age, as witnessed by the oven tomb found on the extreme southern edge of the Fossa and by another similar cavity, presumably of the same age, found a little further north on a big rocky outcrop.

The erosion at the base of the escarpments, which caused the formation of large grottoes, certainly encouraged the inhabitants to adapt these grottoes (Fig. 2a), a couple of metres high, about four metres deep and about ten metres long, to their own needs.

A curve tunnel branches off from inside one of these grottoes, that is partially enclosed by a wall, and penetrates deep into the rock, towards west (Fig. 2b).

To the north along the flanks of the valley, there are many deep hypogea.

Three of these hypogea are of particular importance. "Gazebo" hypogeum (Fig. 2c), so-called because the part in the open air houses a cast iron structure covering a circular tank. The shape of this tank could be compatible with an ancient system for retting plant fibres. Prince d'Aci used it as a fish tank, during the time of Prince d'Aumale it was reused as a covered dung pit (Biuso 1881).

The Gazebo hypogeum has a polygonal plain, about 400 m^2; it is enclosed on all sides by vertical rock walls, onto which five rectangular rooms open up. These rooms also have a rectangular plain or are L-shaped; the bottoms and walls waterproofed demonstrate that they were used as covered water tanks. There are two accesses to the hypogeum: an arch dug out of the rock and a curvilinear gallery, the cross section of which looks like the mouth of a furnace. Next to this is a very big hypogeum, that looks in plan like mesh, made up of a gallery from where other short galleries branch out. At the end of such galleries there is a shelf-like niche (Fig. 3b).

The hypogeum "Stalla" (Fig. 2e), so-called because it was last used as a stable (Biuso 1881), has only one room and is about 230 m^2 in size. The flat roof, that juts out for a width of about 8 m, is supported by pillars made of calcarenite ashlar blocks.

The same sort of stonework encloses the room, that is accessible through an ancient, pointed arch portal; it receives light through two windows of the same shape (Fig. 3a). There are traces of persistent water percolation on the walls: the back wall, shaped to fit a semi-circular niche (Fig. 2f) brings to mind the artificial Arab waterfalls of Arab-Norman buildings here the rock wall, is encrusted with carbonate concretions that indicate the presence of a now dried up spring. The shape of this hypogeum, with its semi-circular niche and its side tanks, makes you think it was used either for religious purposes or for retting papyrus fibres.

4 MACRO AND MICROTEXTURE OF THE ROCK

The rocky walls of the Fossa are made up of yellow bio-calcarenite, rich in macro-fossils concentrated in "nests" and sometimes in levels, konwn in the geotechnical literature as Nodular Calcarenite (CN), one of the main rock types, by extension

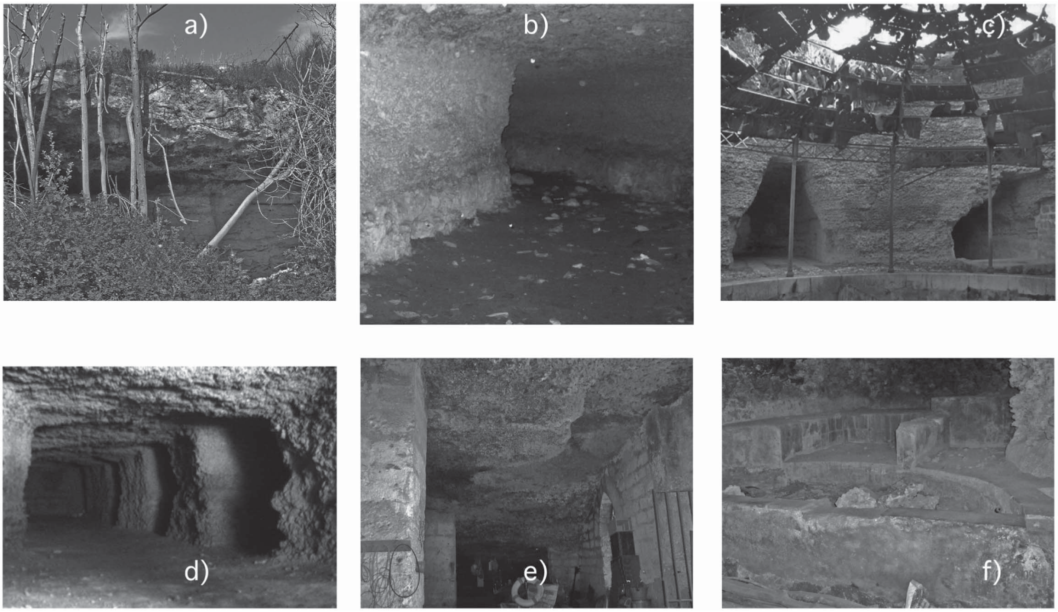


Figure 2. Hypogea in the Fossa della Garofala a) grotto; b) tunnel; c) Gazebo; d) "mesh" tunnels; e) Stalla; f) nichel.

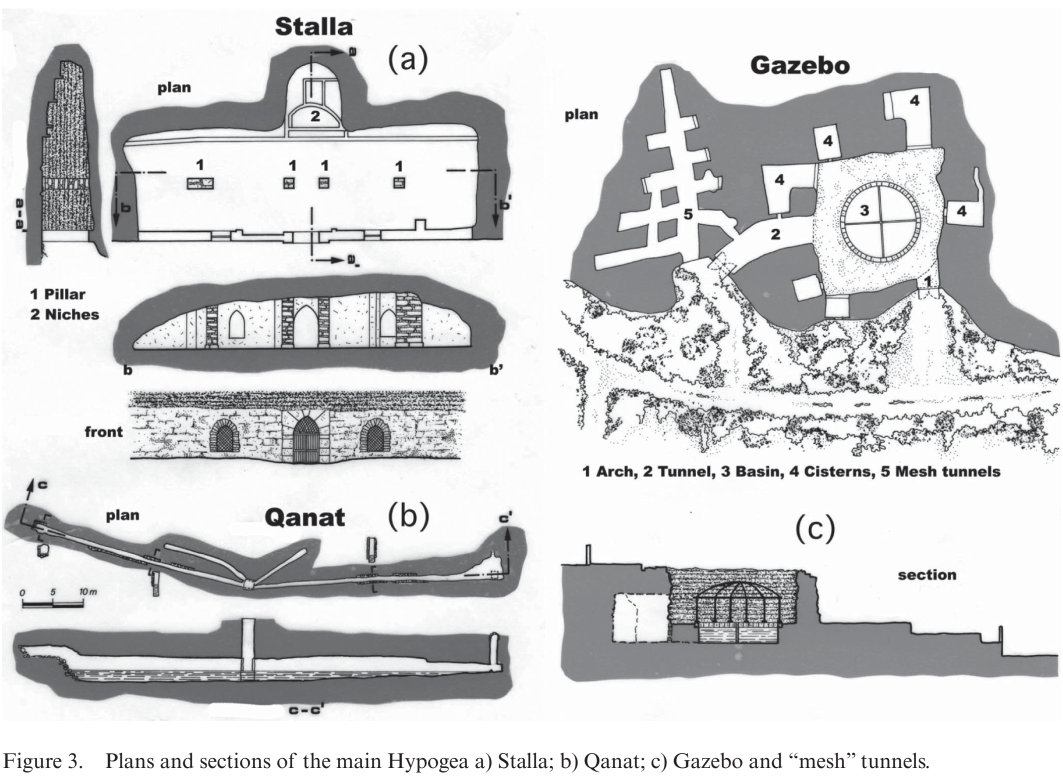


Figure 3. Plans and sections of the main Hypogea a) Stalla; b) Qanat; c) Gazebo and "mesh" tunnels.

and thickness, of calcarenitic Palermo formation (Nocilla et al. 2005).

The walls have a carious aspect to be referred to the presence of strongly cemented and welded nodules, while the inter-nodular spaces are filled with the same incoherent arenaceous material, that has often been removed by floating processes.

Two different levels can be recognised in terms of macro-structure: the lower one has sub-horizontal stratification, highlighted by selective erosion phenomena which gives it a strato-nodular layered texture. Localised structures, caused by currents, are concentrated near the contact with the upper one. This latter shows a chaotic distribution of the pseudo-nodules which indicates more variable deposition conditions (Fig. 4).

The selective erosion that has affected the calcarenitic deposit after emergence resulted in a progressive differentiation of levels with different degrees of cementation.

The nodules, centimeter in size, consist of sandstone clasts linked by sparitic cementation. They form a continuous but irregular level that assumes shapes and forms like animal figures, called "kindchen".

The banks with a nodular structure are frequently defined at the base and at the roof by thin layers of rock with texture more uniform and cementation more continuous; on the surfaces of these layers a thin coating of loose sand is present (Fig. 5).

Thin sections show that the rock is a biocalcarenite containing fragments of red algae, foraminifera and fragments of mollusc shells.

The rare lithic clasts are carbonate and sometime quartz. The particle size varies within the different depositional levels from very fine to medium-fine.

The grains are welded by a thin sparitic patina in the porous areas, spare calcite fills almost completely the intergranular voids in the nodules.

In the single layer, the nodules are "welded" together in points or in reduced areas of contact; similar "welding", less frequent and however with non-uniform distribution, can be seen, sometimes, in a vertical direction between nodules of adjacent layers.

Water seepage through the rock mass, particularly intense during the wet season, induces dissolution processes of the thin patina of sparite that wraps the grains; the weakly cemented areolae disaggregate: so that even unnoticeable flows cause the progressive removal of silt and fine sand, enhancing nodular structure of the rock.

The frame of the nodules within the banks, made therefore to the scale of decimeters, has been expressed in terms of packing density (PD) (Kahn 1956). Measurements provides average values of 50% (Fig. 6).

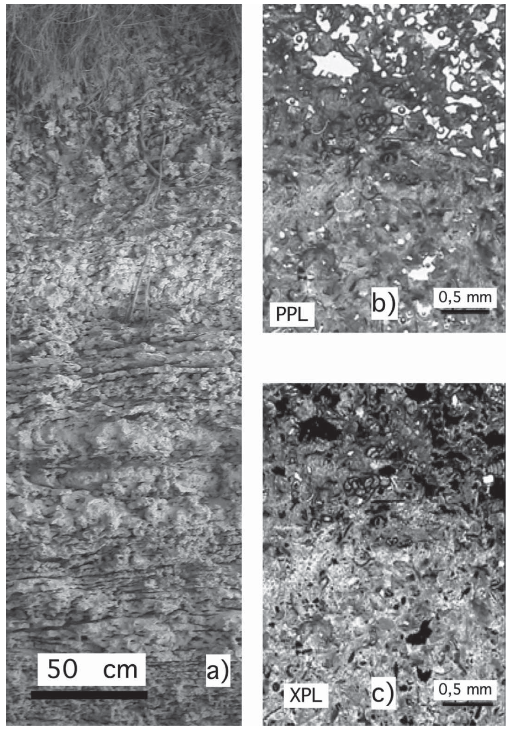


Figure 4. Structure of the rock-mass: a) microtexture of the calcarenite: b) thin section in plane polarized light c) thin section in crossed polarized light.

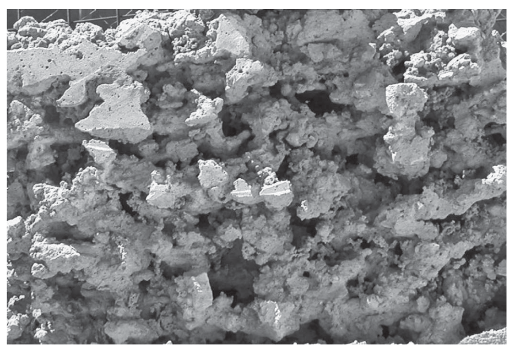


Figure 5. Locked nodules.

5 MECHANICAL CHARACTERIZATION

The mechanical characterization has been carried on both on single nodules both on strato-nodular samples. The weight per unit of volume of the rock varies between 17 e 22 kN/m^3, depending to the ratio, in the range 45%–60%, between the volume of the nodules and the total volume.

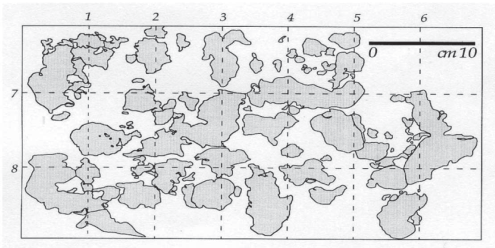


Figure 6. Measurement of packing density (PD) of the nodules.

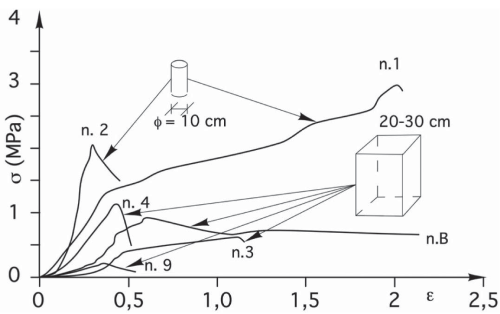


Figure 7. Uniaxial compression tests.

The strength of nodules has been obtained by point load tests, that give values of the uniaxial strength between 1 and 30 MPa ($\sigma_{fmean} \approx 10$ MPa).

The strength of the nodular bank was instead measured by uniaxial compression tests (Fig. 7) on cylindrical samples (10 cm diameter) and on roughly cubic blocks, with side ranging from 20 to 30 cm, shaped by mean of a bandsaw. Unlike the nodules, the uniaxial compression tests on the aggregate made of welded nodules and interlocked sands give values of σ_f considerably lower, ranging from 0.2 to 3 MPa; tests evidence a large scale effect.

This effect significantly influences the tangent modulus, that ranges between 50 and 1200 MPa.

The results of uniaxial compression tests (Fig.8) show that the values differ even an order of magnitude.

Consequently, at the scale of the rock-mass, the rock is classified as "very poor".

The heavily different mechanical behaviour of the strato nodular samples in respect to a single nodule causes the difficulty of reaching a reliable geotechnical modeling of the rock-mass.

As shear strength parameters were adopted the following values (Zimbardo 2009):

$c' = 500$ kN/m^2; $\varphi' = 33°$.

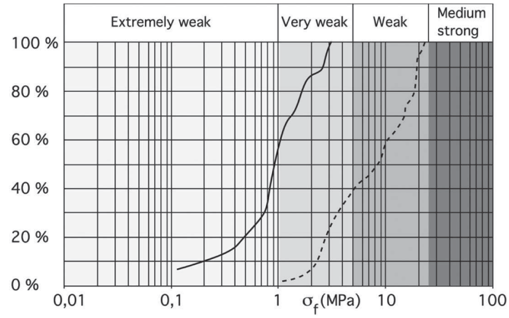


Figure 8. σ_f values distribution curve obtained by mean of uniaxial compressive tests on strato nodular samples and by mean of point load tests on the nodules.

In consideration of the scale effect and of the deformation characteristics, we have used too, the empirical method of Hoek, evaluating the GSI index.

The classification introduced by Hoek (1994), for very poor rock-mass made of sparsely interconnected elements (angular or sub angular) with surfaces of the individual elements little or very altered, indicates GSI values between 15 and 30.

The empirical formula relating the deformability modulus to GSI index, proposed by Hoek & Diederichs (2006) provides the following range of values:

$10 \div 86$ MPa

which may be considered acceptable according to the results of tests on samples of higher dimension.

6 DESCRIPTION OF THE INSTABILITY PHENOMENA

In the grottoes and in the hypogea, collapse occur from tunnel roofs and new fractures appear on the walls rock that separate the cavities.

At the bottom of the covered tanks in fact it's possible to see a growing accumulation of blocks and sand coming from the roof of the cavity, where fresh falls of slabs are evident (Figs 9a, b).

The most significant collapse occurred after the 2002 earthquake, these collapse in fact have caused a dangerous reducing of the roof thickness.

On rock diaphragm and sidewalls, irregular fractures very persistent, that divide the rock-mass in large blocks with a predominant vertical development, are present.

A thick natural vegetation (Celtis australis, Ailantus altissima, Rhamnus alaternus) in recent decades has grown to the crowning of the sub vertical walls that surround the hypogea or which are

Figure 9. Rock mass decay phenomena: a) fall of slabs b) development of cracks c) fall due to the pull out of the roots.

the sides of the valley. Both to the wedge effect of the roots, both the effect "sail" that the wind exerts on the foliage (Brown & Sheu 1975), (Nocilla 1999), caused significant collapse especially on the vertical walls of the valley (Fig. 9c).

7 ANALYSIS OF INSTABILITY PHENOMENA

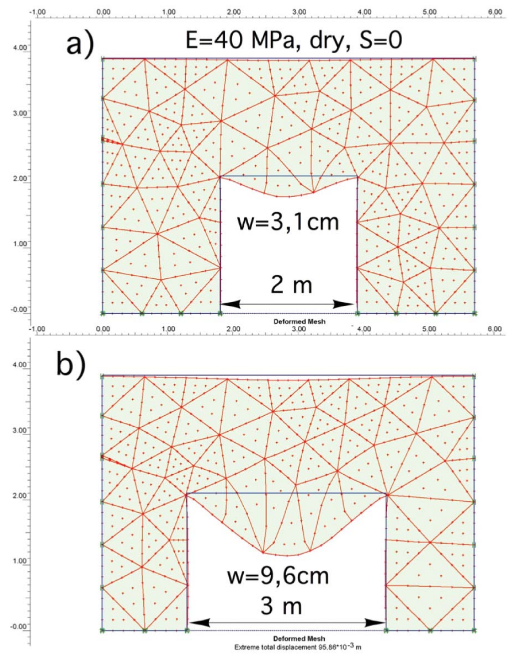
The study of onset conditions of the instability phenomena was analyzed using a finite element program that allows stress-strain analysis at different, even in parametric terms, boundary conditions.

The analyses performed by varying the Poisson's coefficient between 0.2 and 0.4 show a modest influence of this parameter.

The following analyses were developed varying the E modulus value between 40 MPa, that is the mean value suggested by the elaboration proposed by Hoek, and 1000 MPa, that is close both to the maximum value determined by laboratory tests, both to the values given in the literature on the basis of back-analysis of vertical displacements of buildings in the Palermo calcarenite (Valore 1999).

The deformation values in the roof obtained assuming the minimum E value are comparable with those deduced from the measurements with the laser scanner; these latter, infact, evidence the misshapen of the roof in respect to original planarity of the strata.

For example, referring to a cavity 2 m large, for E = 40 MPa, in dry conditions the maximum vertical displacement of the roof is equal to 3.1 cm (Fig.10a), and it assumes values of 3.5 cm in presence of saturated soil. In the case of a larger span (3 m), e.g the "L-shaped" tank (Fig. 9a), the increasing of the deformation is noticeable: in dry condition it reaches the value 9,5 cm, in saturated condition 10,6 cm (Fig. 10b). The numerical analyses for the saturated condition are carried out in terms of effective stress. In this condition (S = 1) the phreatic level has been assumed at the ground level.



Figur 10. Displacements: E = 40 MPa, dry condition a) span 2 m, b) span 3 m.

For E = 1000 MPa the displacement in the roof is 0,12–0,14 cm respectively in dry and wet conditions(Fig. 11a). The same low values (0,38–0,42 cm respectively in dry and wet conditions) are obtained also considering the larger cavity (Fig.11b).

For the nodular calcarenite, the deformability characteristics of the rock-mass are, hence, properly indicated by the empirical formula of Hoek, and they are also close to the results obtained by laboratory tests on samples of larger size.

Shear stresses which would justify the failure events can only be obtained by considering larger spans or the pressure due to root systems.

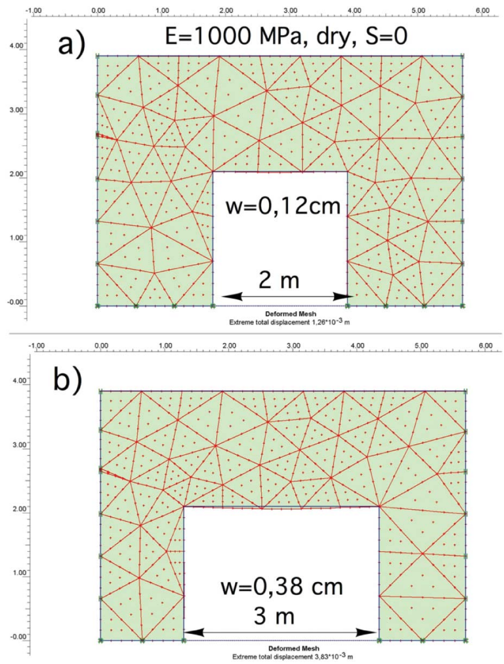


Figure 11. Displacements: E = 1000 MPa, dry condition a) span 2 m, b) span 3 m.

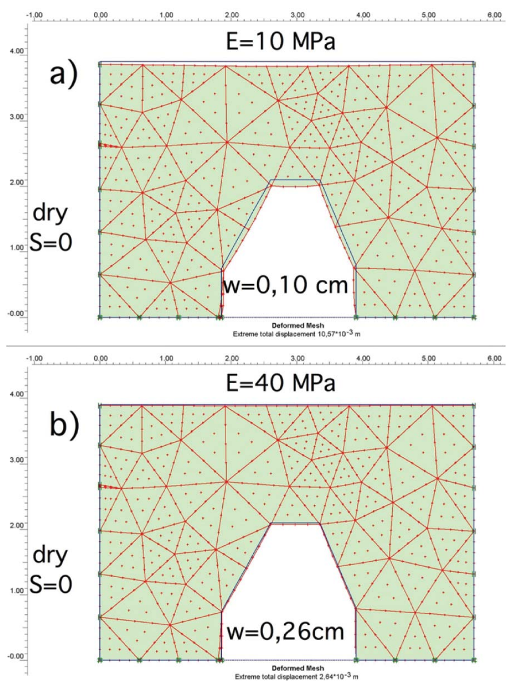


Figure 12. Displacements: a) E = 10 MPa, b) E = 40 MPa

As it is not known the intensity of the stress induced by the roots, the pressures were considered as uniformly distributed on the single layer surface and with the maximum value of 1 kPa: roof shear stresses of 0.2 MPa–0.4 MPa are achieved; these values are close to failure condition.

Some further analysis, assuming cusped shape (2–3 m large) provide deformations characterized by negligible vertical displacements, both in the case of E = 40 MPa, both for very high values of deformability (E = 10 MPa), that could be assumed merely in the case of a complete decay of rock mechanical charactericstics (Figs 12a, b).

The analysis and the surveys indicate the possibility of:

– detachment of slabs from the roof, making even more small thickness of the vault (e.g. slab fallen in the underground tank to the left of the access tunnel to "Gazebo");
– enlargement of fractures at first hidden or a little open, as in the small tank on the right side and in the rock architrave of "the arch entrance";
– neoformation of persistent fractures, such as in rock walls and in the arch of the entrance.

On the contrary no cracks neither slab falls are present on the vaults of the curved tunnel in plan, that in section have "cuspide shape", that is a typical shape used in Sicily from very ancient time (VI century B.C.) in the exploitation of weak rock masses (e.g. Hear of Dyonisus in Syracuse).

8 CONCLUSIONS

The structure of the rock mass, characterized by irregularly alternated nodular calcarenite banks and continuous layers of weakly cemented sands, plays an important role on the stability. In fact the rock-mass is like a sequence of flat subhorizontal plates.

In the interlayers it is possible the development of significant action of the roots of such magnitude as to give rise stresses and strains that lead damage failure.

The variability of the micro and macro texture characteristics of the rock generates an extremely complex structure, whose mechanical characterization was achieved in laboratory with uniaxial compression tests. For the characterization of the rock-mass it was necessary to refer to the Hoek empirical method.

The modeling has given values of deformation of the roof comparable with the deformed shapes of non collapsed vaults measured with a laser scanner.

The analysis also highlighted the influence of the saturation conditions of rock and subsequent filtration processes. These processes not only lead an increment of the deformation in the roofs, but also lead the constant and continuous decay of the mechanical characteristics due to the corrosion of the weld between the nodules and due to the progressive removal of the grains of silt from the internodular voids and from sandy laminations.

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