Analysis of the Stability Conditions of the Grotte di Castellana (Apulia, Southern Italy)

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Abstract. The article describes the stability conditions of the rock mass of the summit part of the Grave in Grotte di Castellana (Puglia, southern Italy).

The geometric reconstruction, the geological, stratigraphic and mechanical characterization adopted for the safety status checks according to the NTC are illustrated, through 3D FEM modeling .

Direct (continuous core drilling) and indirect (seismic profiles and MASW) geognostic investigations were carried out. The surveys highlighted the presence of layers of variously fractured limestone rock with average RQD values equal to 55%. Rock samples were taken and subjected to laboratory tests for the recognition of physical and mechanical parameters (compression and traction). The quality of the rock mass was also assessed with Bieniawski (RMR), Burton (Q) and Hoeck & Marinos (GSI).

The reconstruction of all the geometric elements of the 3D CAD modeling was created starting from the point clouds, obtained from photographic survey and laser scanner, and used for the subsequent 3D FEM finite element modeling with the Midas FEA software.

Keywords: Castellana Caves · karst rocks · rock stability · 3D FEM modeling

1 Introduction

The karst complex of the Castellana Caves (Puglia, southern Italy) is an important tourist site: over 300,000 tourists visit each year. The Castellana Caves have been the subject of several publications [1, 2, 6], on the speleological, geological and stratigraphic characteristics of the site [3, 5]. For some representative sections, the safety conditions related to the stability of the rock mass have been analyzed in the past [4].

The following article proposes a structural model for the evaluation of deformations and safety factors through the FEM 3D finite element modeling of the rock mass that constitutes the karst complex of the Grave in the Castellana Caves (Fig. 1). For the first time, the geological, stratigraphic, mechanical characterization and the verification of the state of safety are illustrated by means of 3D FEM modeling. For the definition of rock mass, continuous core drilling and refraction seismic profiles were carried out with P waves and MASW.

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The static conditions showed wide safety margins.

2 Geological Frameworks

The geological scheme of the Grotte di Castellana area is represented by a powerful calcareous-dolomitic substrate of the Cretaceous age (Fig. 2).

The calcareous layers that make up the karst complex can be traced back to the Upper Cretaceous [5] and outcrop extensively throughout the area of the south-eastern Murge with an overall thickness, underground, of several hundred meters. This succession is made up of limestones, dolomitic limestones and dolomites, well stratified with the presence of rudists, intensely fractured and affected by karst dissolution phenomena.

In relation to the state of fracturing and karst formation, limestone in general can present very different aspects both laterally and in depth.

The arrangement of the calcareous-dolomitic rocks is given by layers with weak inclinations (0–10°) linked to the presence of mild wide-ranging folds. The calcareous rocks are affected not only by the frequent fracturing mentioned above, but also by the presence of direct faults, with a prevalent NW-SE direction, which overall displace the sub-stratum in blocks, lowered proceeding from the internal areas of the Murgia towards sea.

The area of the Grotte di Castellana is characterized on the surface by a trend with a rather flat morphology, with more accentuated local slopes due to the presence of the surface hydrographic network and by depressions of karst origin (sinkholes). The entrance to the Grave is an evident example of sinking of the roof of the karst cavity (sinkhole). The remaining part of the roof of the cavity is represented by layers of calcareous rock which reach a minimum thickness of just 3 m. The Grave develops a very large underground cavity about 60 m deep, 50 m wide and 150 m long.

The calcareous-dolomitic rocks of the Cretaceous age of the Murge, permeable due to cracking and karst phenomena, host an extensive underground water table, characterized by considerable potential and thickness. The groundwater surface in static conditions is generally found at a depth of 280 m from the ground level and therefore at an altitude of about 40 m above sea level.

3 Metodology

To create a structural model for the evaluation of deformations and safety factors, it was necessary to carry out an internal survey of the Grave and a topographic survey of various points of the external areas. This chapter documents, with some images, the reconstruction of all the geometric elements of the 3D CAD modeling created starting from the point clouds and used for the subsequent 3D finite element modeling.

The relief was geo-referenced in such a way that it could be superimposable to that of the overlying area. Trattasi di rilievo di punti ausiliari, realizzato con strumentazione GPS GeoMax, mediante stazione con posizionamento cinematico, e più precisamente

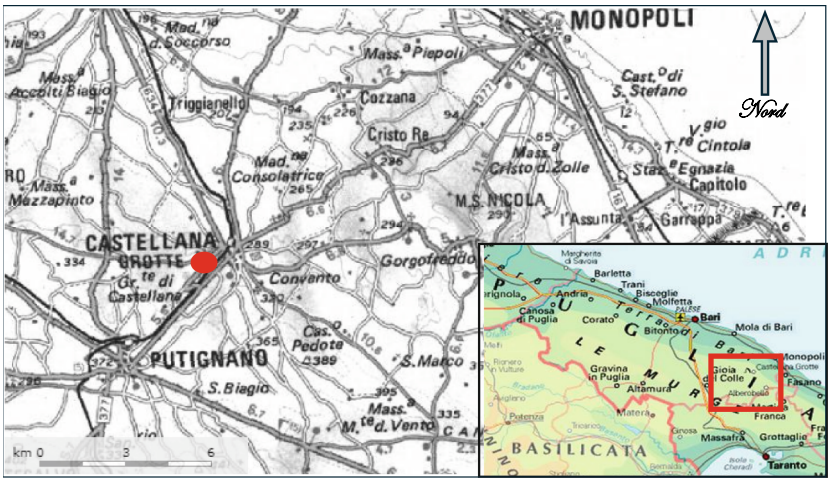

Fig. 1. Location of the karst complex of the Castellana Caves (Puglia, southern Italy)

le reti GNSS dinamiche sono stazioni GNSS statico: le reti GNSS statiche sono reti costituite da punti materializzati sul terreno e la tecnica impiegata è quella del RTK base-rover ovvero 2 ricevitori che registrano in maniera indipendente le osservazioni, il calcolo della posizione si effettua in post-processing. Il rilievo e stato geo-riferito in modo tale da poter essere sovrapponibile con quello del territorio sovrastante.

Due to the difficulty of reaching the places and the geological conformation of the cave, 3 small platforms were built to be able to arrange the necessary instrumentation for the survey.

The survey system was developed through the interpolation of two instrumental techniques: 3D laser scanning and photographic scanning (Fig. 3). The following instruments were used for the operations described above:

– Laser Scanner LEICAR DS3000;
– Macchina fotografica Canon EOS 6D Mark

The entire survey refers to a topographical support network previously prepared and created with a reference target to geo-reference the surface of the upper vault of the cave. All the tables necessary to understand the state of the places were then created. Furthermore, an interpolated three-dimensional model (mesh) with definition at 5 cm was developed for the plano-volumetric analysis of the entire area under examination. Subsequently, the upper part of the square was surveyed by developing a topographical grid and detecting some points in common with the surface of the underlying cave.

The following images illustrate the top and perspective views of the point cloud of the Grave area of interest (Fig. 4), the CAD model (Fig. 5) in which it is possible to observe the presence of the buildings, the upper layer of backfill and the underlying layer of limestones within which the cavity is modeled.



Fig. 2. **a)** The cave studied in this paper. **b)** Geomorphological map in which the dolines are in yellow, the impluvium lines in blue, the presumed faults in brown dotted lines, the red clay deposits in lightcyano and the Cretaceous limestones in green. The dashed blue line indicates the plan of the cave (Color figure online)

The geognostic investigations (Fig. 3) carried out concerned:

- 5 core boreholes at a depth of between 3 and 5 m with sampling;
- 2 points of geostructural measurements;
- two seismic profiles with P waves and Masw of 24 m;

- laboratory tests for physical and mechanical parameterization.

The stratigraphy of the boreholes has shown a perfect correspondence with the general stratigraphic framework of the territory. Below a short interval of soil there are layers of variously fractured limestone. The RQD values found are attributable on average to 55% which indicates a Mediocre quality of the rock mass according to the DEERE classification.

The MASW profiles both indicate $V_{s,eq}$ values higher than 800 m/s, indicating a soil category of type A as indicated by the NTC/2018.

The seismic profiles with P waves synthetically indicate two seismic events with average physical-elastic characteristics as indicated in the following Table 1.

Table 1. Physical-elastic characteristics

layer	thickness (m)	average speed (m/s)	volumetric weight (kN/m^3)	Young modulus (kg/cm^2)
1	1.0	440	20	15000–17000
2	5.0	1340	22	35000–55000

Table 2. Geometric characteristics of discontinuities

	dip	inclination
K1	65°	85°
K2	220°	85°
K3	300°	85°

The structural survey of the rock mass was carried out following the Bieniawski and Romana classifications which allow to satisfy the questions requested and the problems that arise. Two survey points were taken into consideration at the entrance to the grave.

The summary of the average positions of the main families of discontinuities obtained to which is added that of the sub-horizontal stratification with inclinations always lower than 5° indicates the following orientations and dips (Table 2):

The rock mass was classified according to Bieniawski (1989). The RMR Value is equal to 65 corresponding to a GOOD cluster (Table 3).

In the past [4], a stability analysis (two-dimensional finite element) was carried out on different stretches of the Castellana Caves than the one proposed in this work.

In relation to the importance of the site, linked to the presence of inhabited buildings and public roads and visitors, in addition to the uncertainties connected with the procedures adopted in the definition of the stratigraphy, the loads and the geotechnical parameters adopted, the minimum value to be guaranteed of a safety factor $Fs \geq 1.25$ was set. Regarding actions, there are two types of loads, building loads and road loads. Below are illustrated the methods and regulatory references for their definition and application in the cases in question.

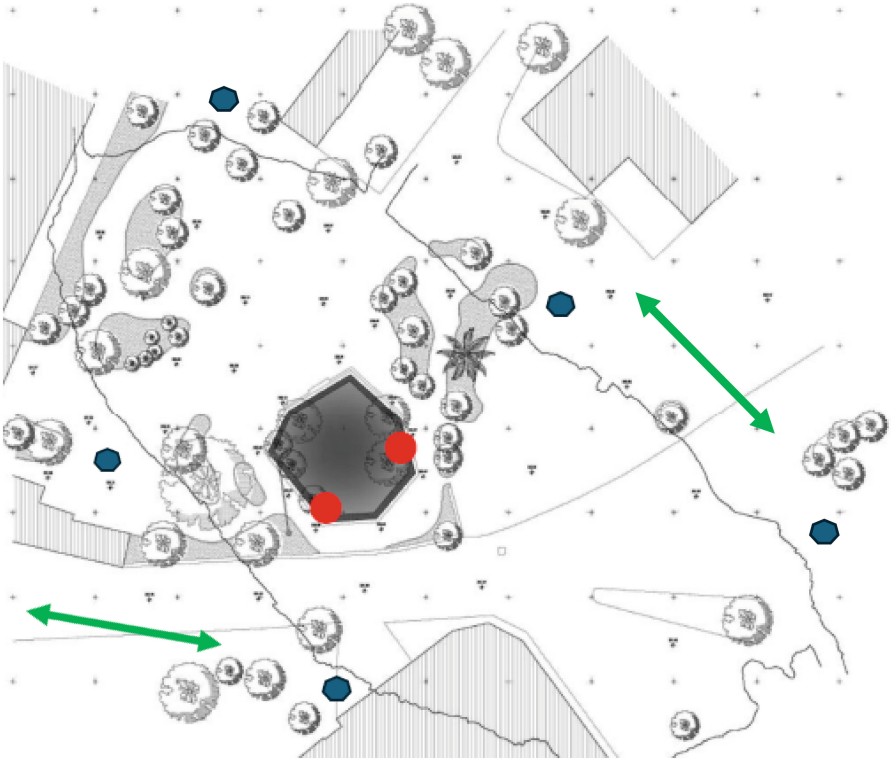

Fig. 3. Location of geognostic investigations: in red the geostructural measurements, in blue the boreholes, in green the profiles with P waves and MASW (Color figure online)

Since the dimensions of the buildings were possible to define from the surveys, it was decided to define the characteristic value of these loads depending on the plant dimension and height of the buildings reproducing solids with a certain specific weight (gamma). The solid of each building was reconstructed as a parallelepiped from point clouds and the load was therefore dependent on the plan geometries and proportional to the height of the parallelepipeds. To define the gamma, preliminary evaluations were made on 1, 2 or more floors typical buildings, finally, cautiously a value of 5 kPa per meter of building height (or 5 kN/m^3) was considered. To be amplified by 1.5 or 1.3, as a permanent load.

Road loads were considered as a variable load from traffic. The adopted regulatory reference is that of bridges, with the cautious value of 9 kPa of the first lane. In the following images are reported the FEM models (Fig. 3) in which it is possible to observe the buildings and, in evidence, the road loads.

The weight of the superficial soil layer present above the limestone layer, equal to about 1m, was modeled as a distributed load on the entire area, equal to 18 kN. Since it represents the weight of the soil, no factorizations were applied.

Since almost all buildings are higher than 6 m, the reference load was to be that of two-storey buildings, i.e. 5 kPa per metre of building height (i.e. 5 kN/m^3).

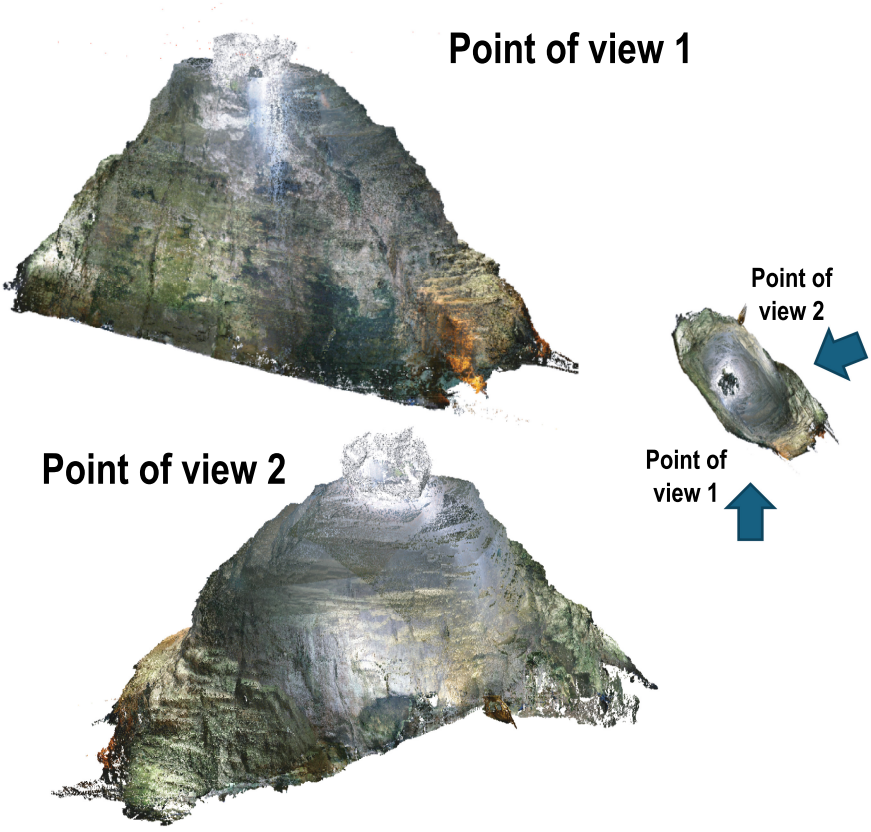

Fig. 4. Perspective views of the point cloud.

4 Mechanical Characterization

The mechanical characterization of the rock mass plays a fundamental role in the correct evaluation of safety conditions. Therefore, it is also essential to evaluate the uncertainties related to the variability of the results. In the study in question, and in the analysis of the results of laboratory tests (compression, tension) for mechanical characterization, a statistical approach was applied, as illustrated below.

The characteristic value of a parameter of a soil or rock must be chosen based on a cautious evaluation of the value that influences the occurrence of the limit state. The ultimate limit state of collapse is associated with a high level of deformation of the soil with the exceeding of the maximum mobilizable resistance. The serviceability limit state to a moderate level of deformation of the soil without exceeding the maximum mobilizable resistance. For the characteristic value of a geotechnical parameter, finally, it should be understood as a reasoned and cautious estimate of the value of the parameter in the limit state considered (Fig. 6).

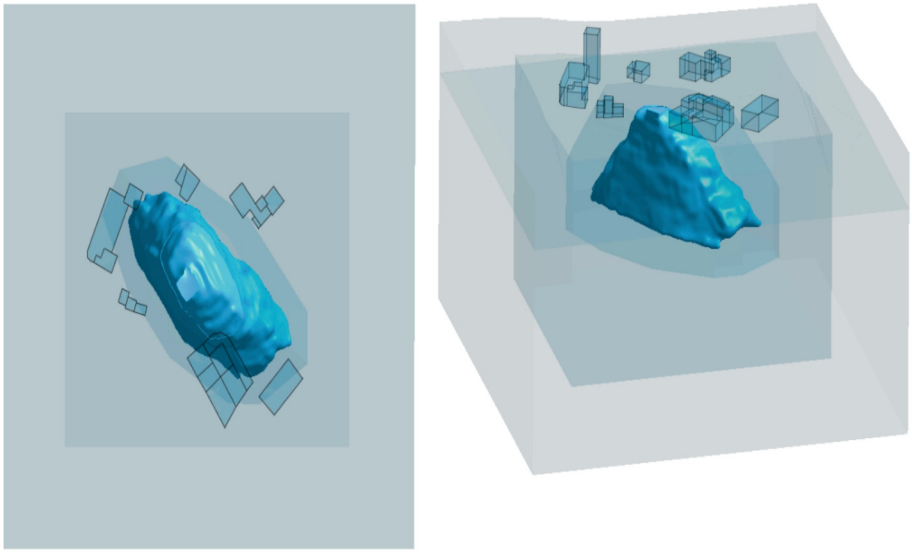

Fig. 5. Perspective views of the 3D CAD modeling including the solid around the entrance of the cave and the buildings above.

Table 3. Rock mass classification according to Bieniawski (Bieniawski 1989s)

RMR corrected	100 ÷ 81	80 ÷ 61	60 ÷ 41	40 ÷ 21	<20
Class	I	II	III	IV	V
description	Excellent	Good	Fair	Poor r	Very Poor
cohesion (kPa)	>400	300 ÷ 400	200 ÷ 300	100 ÷ 200	<100
friction angle (°)	>45	35÷ 45	25 ÷ 35	15 ÷ 25	<15

The summary of the statistical analysis carried out on the compression and tension tests for the determination of the characteristic parameters of the intact rock is reported.

The following tables (Tables 4 and 5) report the synthesis of the statistical analysis carried out on the compression and tensile tests for the determination of the characteristic parameters of the rock, the parameters and graphs of the Hoeck-Brwon constitutive model for the intact slope and for the mass (GSI = 60) and the corresponding linearization using the M-C model for the mechanical characterization to be adopted in the stability checks (Compensated resistances).

The characteristic value of the specific weight was determined as the average value of all the laboratory tests, equal to 24.6 kN/m^3. Similarly, stiffness has been adopted as the average value of the intact rock, as unlike resistance parameters, it has little impact on stability analyses. The same applies to the Poisson coefficient and from an analysis of the tests, the value of 0.31 was chosen. In the following table, the summary of the characteristic and design parameters to be adopted for global stability analysis

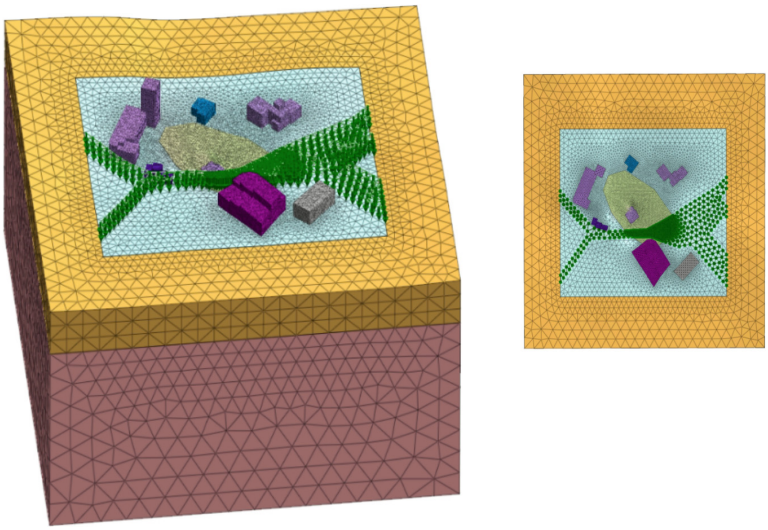

Fig. 6. FEM model. Perspective view and plan. Highlight buildings and road loads

is reported. As already described in previous chapters, it is reminded that the design parameters reported in the tables refer to static conditions.

Table 4. Summary of statistical analysis carried out on compression and tensile tests for determining characteristic parameters of intact rock.

		σc	E	**σt**
average	[MPa]	50.39	43803	9.24
Dev. standard	[MPa]	19.64	18767	2.96
Coeff. of variation	[–]	0.39	0.43	0.32
minimum	[MPa]	20.18	18605	4.00
Number of tests	[–]	13	13	13
Xk, medium	**[MPa]**	**40.68**		**7.78**
Xk, medium/average	[–]	0.81		0.84

Table 5. Summary of characteristic parameters

c	[kPa]	800
φ	[°]	49.3
Resist. To traction	[kPa]	300

Table 6. Summary of the results of the stability analysis

Condition	Status	FS
Static	Current	2.55

The results of the finite element model analysis to assess the level of safety in the current state of the rock mass are shown below.

Safety conditions are defined based on the global stability safety factor, which is calculated as the ratio between resisting stress and mobilized stress. In the numerical models, to calculate this ratio, the resistance parameters (in this example, the angle of friction and cohesion) are progressively reduced, identifying the reduction factor for which there is a loss of equilibrium in the system, that is, the one that starts under collapse conditions. This condition corresponds to the non-convergence of the numerical model. The reduction factor that determines collapse represents, therefore, the safety factor, as it corresponds to the ratio between the mobilized resistance parameters and the ultimate resistance parameters.

Graphically, this reduction is like what is done by the regulations with the factoring of the characteristic parameters, in static conditions, to determine the design parameters, as illustrated in the following figure. It is highlighted that the constitutive model for rocks adopted is bilinear, consisting of two linear segments: the Mohr-Coulomb line segment, linearization of the Hoeck-Brown constitutive model used for the characterization of rocks, and a vertical segment that limits the tensile strength. Therefore, the reduction of resistance parameters regards the angle, the cohesion of the Mohr-Coulomb line and the tensile strength.

To identify the most critical areas, the most plasticized areas have been analyzed, which indicates the areas where potential "failures" occur in the mass according to collapse kinematics determined by the reduction of resistance parameters as previously illustrated (Fig. 7).

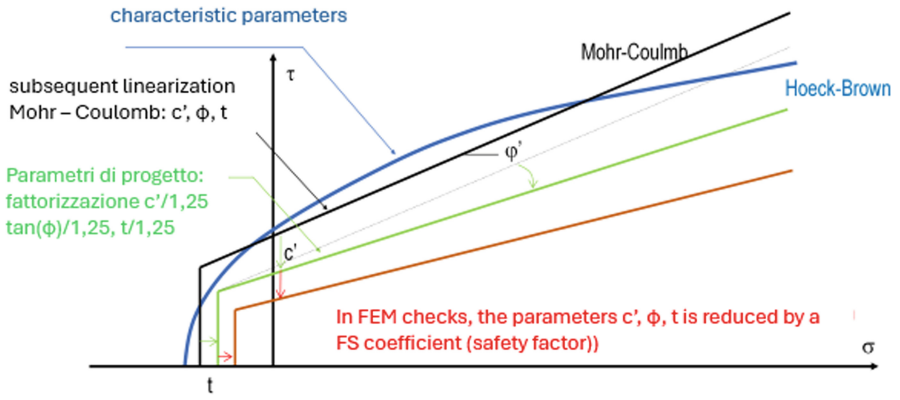

Fig. 7. Graphical illustration of the calculation of the safety factor of the bilinear constitute model adopted for calcarenite in FEM modelling

Plastic deformations in the intact rock begin for values of the order of 0.001. In the rock mass, due to a lower resistance, although in the presence of a lower stiffness, we expect that they occur for values of the order of 0.001–0.0003.

This analysis was carried out to define a criterion with which to identify the potentially most critical zones, that is, those that are most responsible for the potential collapse kinematics.

The results of the stability analysis in static conditions are reported (Table 6).

Based on a safety factor of 2.5, the current situation is considered safe. In the following figures, the results of the analyses carried out are illustrated. From the total displacements, the potential kinematics in the collapse limit conditions in the area around the edge emerges. Plasticization, on the other hand, indicates the most critical areas, the main cause of the limit conditions.

5 Result and Discussion

In the last year about 300.000 persons are visited the Grotte di Castellana: the static conditions showed wide safety margins, with factors greater than 2.5. This result is of great importance for the future management of the karst site.

The geometric reconstruction, geological, stratigraphic and mechanical characterization adopted for the verification of the state of safety are illustrated. For the definition of the rock mass, continuous core drilling and seismic profiles (with P waves and MASW) were carried out.

For the first time the reconstruction of all the geometric elements of the 3D CAD modeling was carried out starting from the point clouds (from laser scanner analysis) and used for the subsequent FEM 3D finite element modeling.

For first time with the classification of the rock mass with Beniawski and through the FEM analysis are describes the stability conditions of the rock mass of the Grotte di Castellana's Grave (Puglia, southern Italy): the results obtained are well comparable (Figs. 8 and 9).

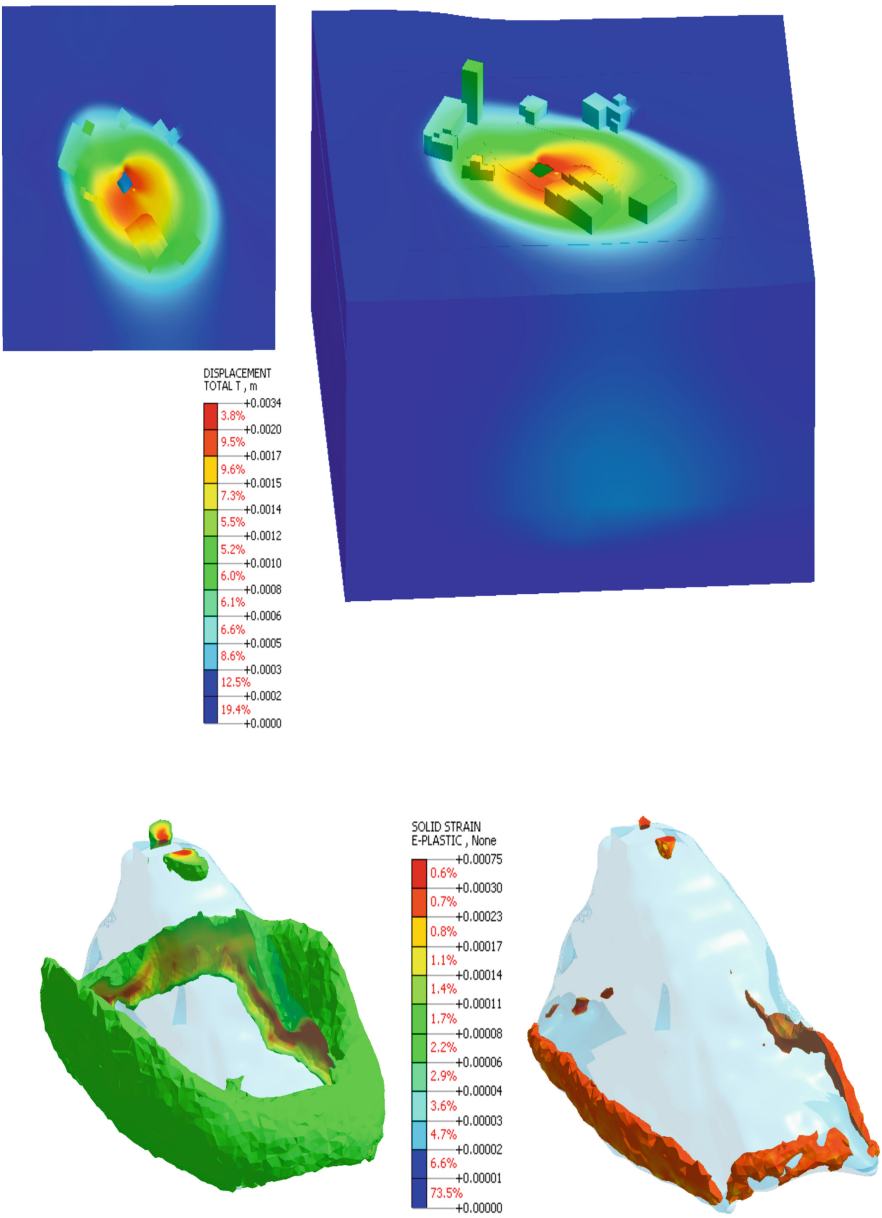

Fig. 8. Static conditions in the current state (FS of 2.55), at the top collapse kinematics (total displacements), at the bottom left plastic deformations > 0.001 and > 0.003 on the right.

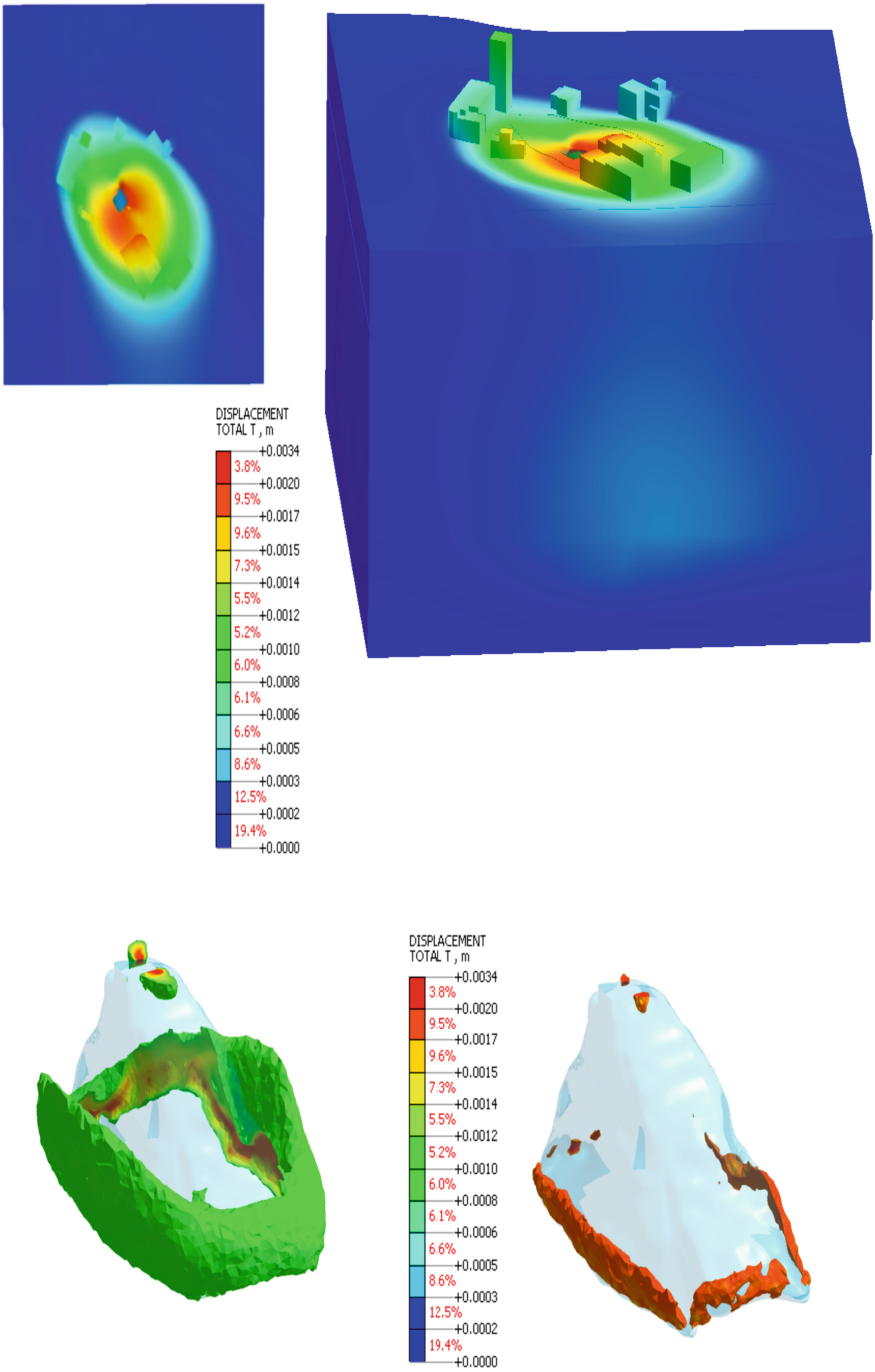

Fig. 9. Static conditions with intervention (FS of 2.55), at the top collapse kinematics (total displacements), at the bottom left plastic deformations > 0.001 and > 0.003 on the right.

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