Instability phenomena affecting the cultural heritage cave of Antro della Sibilla (Cuma, Italy)

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ABSTRACT: The present work aims at the analysis of localized instability phenomena affecting the archaeological site of the *Sibilla Antro*. The cave was excavated by Greek colonists in the formation of Neapolitan Yellow Tuff, a pyroclastic weak rock. This rock is naturally fractured and weakly stratified: for these reasons local instability phenomena occurred along the whole extent of the Antro, worsened by the deterioration of past remediation interventions by passive dowels in the 1980s. Based on a geomechanical field survey and a laboratory characterization of the rock material, a 2D numerical model of the most threatened section was implemented to assess the stress concentration points and the current stability conditions. A proposal is also made for possible low impact measures for safeguard and conservation purposes.

Keywords: weak rock, cultural heritage, instability, numerical analysis, Sibilla.

1 INTRODUCTION

This paper is the outcome of a collaboration between ISPRA (Geological Survey of Italy) and the Phlegraean Fields Archaeological Park, with the support of Sapienza University of Roma and University of Bologna. It aims at the analysis of localized instability phenomena affecting the archaeological site of *Sibilla Antro* and at the proposal of mitigation by low impact measures.

The anthropogenic rupestrian cave (Figure 1) is in the archaeological site of Cuma, which extends along the northern coast of Campania region, about 20 km north-west of Naples city. The cave was excavated by Greek colonists in the formation of Neapolitan Yellow Tuff, a pyroclastic weak rock with fragments of magmatic glass, lava scoriae and pumices.

The tunnel has a trapezoidal shape in the upper part (an anti-seismic stratagem used by the Greeks) and rectangular in the lower part, this latter being the result of the lowering of the walking surface during the Augustan period. In the same period several transversal openings were excavated with the aim of illuminating the tunnel, exchanging air of the environment and reaching the external terrace on which war machines were located. The whole structure is 131 meters long, 5 high and 2.5 wide (Figure 1).

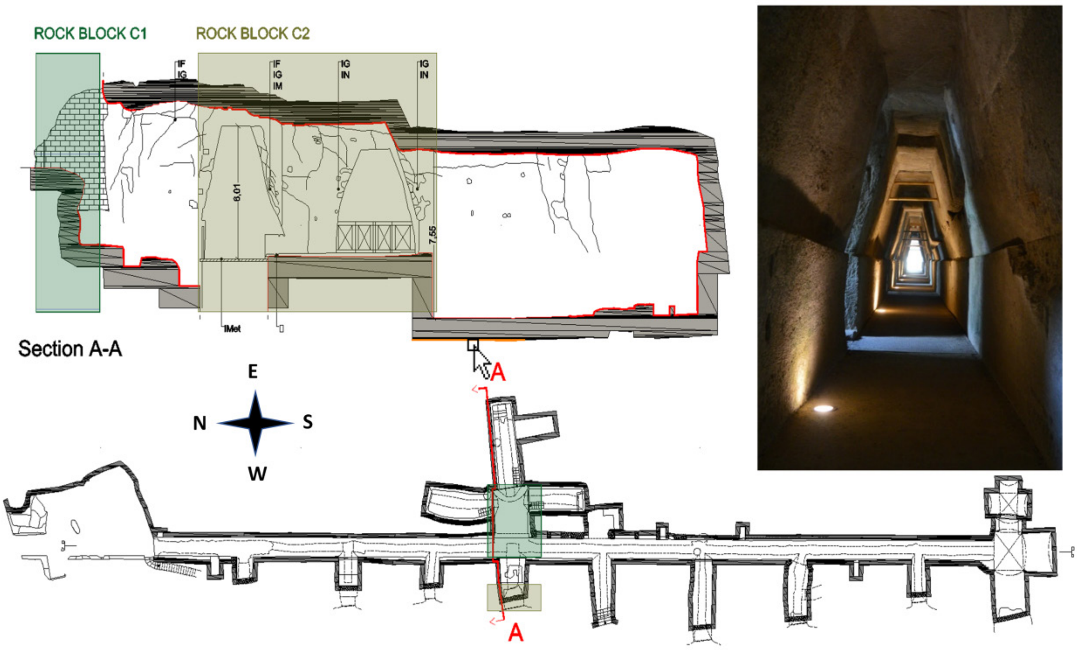

Figure 1. Internal view of the *Sibilla Antro* cave (on the right) and plan view and cross-section (on the left).

2 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

2.1 Geology of the area

The archaeological site was built on a highly articulated landscape closely related to the activity of the Phlegraean Fields, an active volcanic area - currently quiescent - which has affected a large part of the province of Naples since the upper Pleistocene (Lirer et al. 2011).

The detailed geological section adopted for the stability analysis (Figure 2) is characterized by the following formations: 1) the Neapolitan Yellow Tuff (NYT), 2) its weathered portion (NYT-W) and 3) a loose pyroclastic layer (PIR) (Di Vito et al. 1999). The cliff is supported by a man-made wall (4) constructed in Augustan age (I century BC).

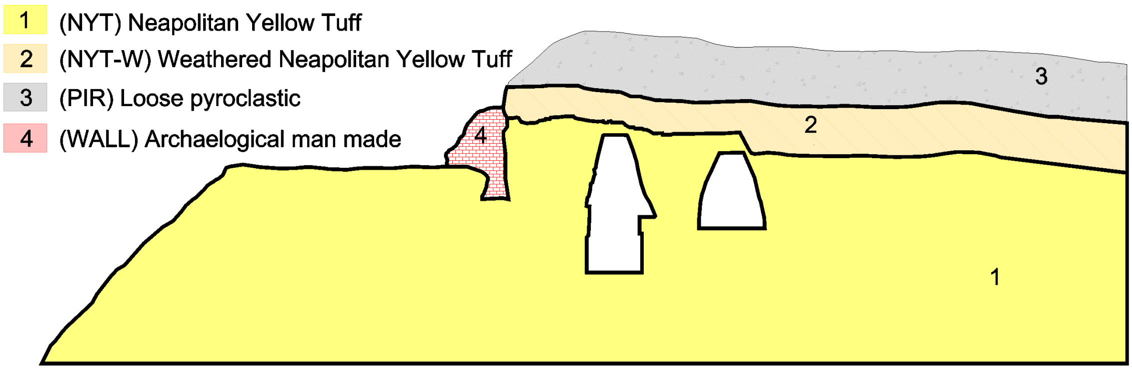

Figure 2. Detailed geological section adopted for the 2D numerical analysis.

2.2 Main instability processes affecting the site.

The NYT is affected by a widespread fracturing, due to the post-depositional cooling of the pyroclastic flow.

Although in tuff rocks consolidation joints are typically curvilinear in shape, three plane master joint systems are evident in the Sibilla Antro, two of them approximately perpendicular and ones parallel to the axis of the cavity, this latter probably due to stress release mechanisms of the external part of the tuffaceous mass.

The spacing of the perpendicular systems is 1 to 2 meters, whilst for the parallel one varies from some decimetres (in the outermost) to some meters in the inner part.

The high degree of fracturing is at the origin of instability phenomena, consisting of rock falls including sliding of rock wedges at the intersection of joint systems, toppling caused by the presence of the sub-vertical joints and detachments from the vault of the cavity in the upper part of NYT due the presence of the sub-horizontal strata. Further phenomena of instability were triggered by inappropriate reinforcement measures in the 1980s, widely present inside the cave. In fact, the swelling of the iron bar (due to oxidation) inserted into the tuff rock caused the formation of cracks and small detachments in correspondence with the angular corners between the tuff walls (Figure 3).

Figure 3. View of the cave and detail of natural joints and cracks caused by iron bar oxidation.

3 GEOMECHANICAL CHARACTERISATION

3.1 Laboratory testing

Few samples of fallen blocks were collected inside the cave at two nearby different locations (C1 and C2 in Figure 1). A total number of 37 specimens were prepared to investigate the physical and mechanical properties of the rock material (Diletto 2022). In particular, 11 specimens, having a diameter of approximately 38 mm, were used for the uniaxial compression test, while 20 specimens, with diameter of approximately 50 mm, were adopted for the Brazilian tensile test. Tests were conducted on both dry and saturated specimens and values of the uniaxial compression strength were adjusted to account for height/diameter ratio different from 2. The other 6 specimens were employed in triaxial compression tests, which however provided not reliable results and will not be considered in the following.

Before being destroyed in the mechanical tests, specimens were used to get information about the unit weight of volume in dry conditions (γ_{dry}), porosity (total n and open n_w), and P-wave velocity in dry conditions ($V_{P,\ dry}$), as summarised in Table 1. Unit weight of volume of the solid matrix (γ_s) was determined with a pycnometer on ground rock fragments. Inspection of Table 1 reveals the extremely high values of porosity associated to particularly low values of strength, further reduced by saturation, especially for samples collected at location C2.

Table 1. Physical and mechanical properties of the NYT collected inside the Sibilla Antro (modified from Diletto 2022). (<*x*> = mean value, *sd* = standard deviation, *N* = number of data). The last four columns refer to the uniaxial compressive and tensile strength values in dry and saturated conditions.

		γ_{dry} [KN/m^3]	γ_s [KN/m^3]	n [%]	n_w [%]	$V_{P,dry}$ [km/s]	$\sigma_{c,dry}$ [MPa]	$\sigma_{c,sat}$ [MPa]	$\sigma_{t,dry}$ [MPa]	$\sigma_{t,sat}$ [MPa]
C1	<*x*>	12.6	17.4	50.9	47.65	2.1	4.9	4.8	0.8	0.6
	sd	0.56	0.45	3.10	2.97	0.08	0.99	0.41	0.09	0.13
	N	14	5	5	5	14	3	2	4	4
C2	<*x*>	12.5	17.2	51	47.54	2.0	5.0	3.5	0.9	0.6
	sd	1.12	0.19	1.61	1.32	0.24	1.30	1.23	0.26	0.10
	N	35	16	16	16	36	6	4	8	12

3.2 *In situ survey*

During the field surveys joint strength and geomechanical rock mass data were collected and analysed by using the scanline approach (ISRM 1978). As already anticipated, the geo-structural setting of the whole site is well described and defined by three main master joint families (K1, K2 and K3), the first two mainly sub-vertical and perpendicular to the axis cave (K1 = 80° dip and 360 dip direction; K2 = 60° dip and 320 dip direction) and the third one (less inclined) and parallel to the axis (K3 = 64° dip and 185° dip direction). These three main families intersect the sub-horizontal depositional pyroclastic flow joints (S). The joint roughness was estimated using the Barton comb, obtaining an average value of JRC equal to 12. Due to the characteristics of the material (soft rock) and its degree of alteration, the strength of the Antro rock walls was evaluated degrading of 20% the uniaxial compressive strength of the material in saturated conditions (average value of the two locations C1 and C2 equal to 4.1 MPa), thus obtaining a JCS value equal to 3.3 MPa. As regards the residual friction angle φ_r, a final value equal to 36° was obtained by decreasing of 20% the value of the friction angle (45°) obtained from tilt tests carried out using dry blocks. A final estimation of the GSI qualitative index equal to 75 was obtained.

4 2D NUMERICAL MODELLING

The numerical analysis was carried out with the finite element software Plaxis 2D referring the cross-section schematized in Figure 2, located in one of the most critical areas of the Sibilla Antro.

The numerical analyses included the following stages: 1) incremental activation of the gravity in the initial estimated configuration of the hill using an elasto-plastic law for the NYT and NYT-W layers, while the PIR layer, which is not directly involved in the stability issues of the Antro, was considered as linear elastic, 2) slope erosion due to geo-morphological processes, 3) excavation of the Sibilla Antro and concurrent construction of the retaining wall, 4) stability analysis with the c-φ reduction procedure to assess the global factor of safety.

For the NYT and NYT-W layers the Jointed Rock constitutive model was adopted. In place of Plaxis native model, the user version characterised by an isotropic elasticity and an additional Mohr-Coulomb strength criterion for the rock material was preferred (Brinkgreve et al. 2022). For NYT a single ubiquitous horizontal low-strength direction was introduced to account for the presence of the almost horizontal pyroclastic flow joints, while for NYT-W two weak directions were considered: a horizontal one and a vertical one. The vertical joints affecting the NYT layer, whose exact position around the two openings in the section was known (see section A-A in

Figure 1), were accounted for using single interfaces, having the same strength parameters characterizing the horizontal strata. For the NYT material the corresponding Mohr-Coulomb strength values were based on the linearization of Barton strength criterion in the 0 – 80 kPa interval (the latter number corresponding the maximum stress at the foot of the excavation), while NYT-W strength parameters were obtained by linearizing a Barton criterion with reduced JCS and JRC values (by 20% and 2 points, respectively) in the 0 – 60 kPa interval, in view of its shallower position. Finally, for the rock material a Mohr-Coulomb strength criterion with a friction angle of 28°, a cohesion of 900 kPa and a tension cut-off of 450 kPa was introduced, in agreement with the results of the uniaxial compressive tests of this campaign and laboratory data obtained by Scotto di Santolo et al. (2015) on the same material including also triaxial tests. The tensile strength along discontinuities was set equal to zero for NYT-W, while a near-zero value of 0.5 kPa was assigned to horizontal weak planes and single vertical discontinuities within NYT; the dilatancy angle was set equal to zero in all cases. In absence of direct determinations, the Young's modulus and Poisson's coefficient of tuff were derived from literature data on the same formation and site (Heap et al. 2014 and Heap et al. 2019). For the PIR layer an equivalent elastic modulus of 0.2 GPa (considerably lower than that of the tuff layers) and a Poisson coefficient of 0.2 were considered. The wall was made with local tuff blocks and therefore the same properties of NYT layer were assumed.

Table 2. Values of the physical-mechanical parameters adopted in the numerical simulation.

Parameter		**NYT**	**NYT-W**	**PIR**	**WALL**
γ	[kN/m^3]	12.6	12.6	12.0	12.6
E	[GPa]	1.6	1.6	0.2	1.6
ν	[-]	0.3	0.3	0.2	0.2
$c_{material}$	[kPa]	900	900	-	-
$\varphi_{material}$	[°]	28	28	-	-
$\sigma_{t,material}$	[kPa]	450	450		
c_{joint}	[kPa]	10	5	-	-
φ_{joint}	[°]	54	51	-	-
$\sigma_{t,joint}$	[kPa]	0.5	0		
ψ	[°]	0	0	-	-

Figure 5 shows the distribution of total displacements and plastic points at the end of stage 3. Inspection of the figure reveals that tensile strength is reached at the roof of the two rooms and at the corners of their cross-sections. The sub-vertical joints are characterized by both shear and tensile strength plastic points, especially those near the two cavities. These results are in good agreement with the observed localized damage zones identified during the in-situ survey. The stability analysis carried out at stage 4 resulted in a factor of safety of 1.54, thus indicating that the site is currently characterised by stable conditions at the global level, also considering the particularly demanding 2D schematisation of the numerical model.

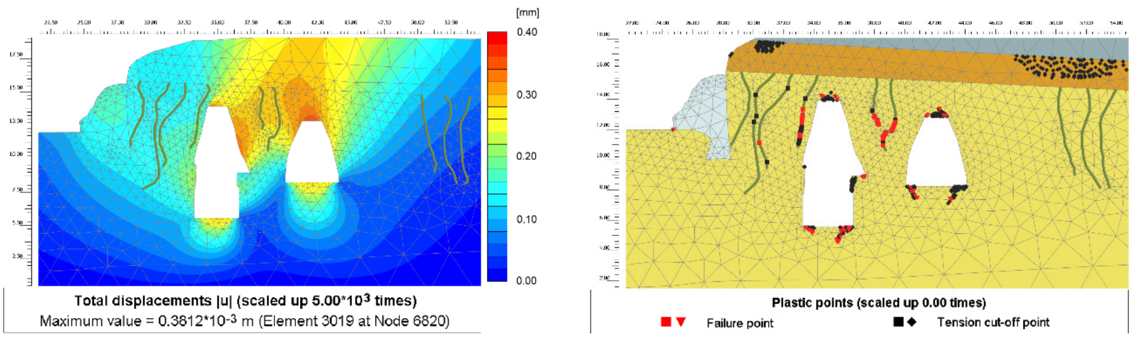

Figure 5. Results of the 2D numerical simulation (stage 3): total displacement (left) and plastic points (right).

5 CONCLUSIONS

The paper summarises the preliminary activities carried out to understand the instability processes affecting and threatening the *Sibilla Antro* in the archaeological park of Phlegrean Fields at Cuma.

The study allowed the definition of a preliminary plan of low-impact countermeasures for the partial reopening of the site for tourism purposes (e.g. Boldini et al. 2018 and Spizzichino et al. 2022). The numerical analysis excluded the generalised collapse of the hypogeum, thus supporting the use of short-term reinforcements (passive dowels) to repair small instable blocks affecting the excavation corners and vaults.

A topographic monitoring system is currently being under implementation: it is made by a total station and micro prisms, installed in the portions potentially affected by future phenomena, and accompanied by a wireless system of deformation sensors.

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