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Low-impact mitigation measures to contrast the instability processes affecting the Etruscan necropolis of Norchia

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ABSTRACT: This paper summarizes the geomorphological processes affecting one of the rock-cut tombs of the Etruscan necropolis of Norchia (Central Italy), its stability analysis and the assessment of preliminary mitigation strategies. The study was carried out through an interdisciplinary approach including: archaeological survey, geomorphological assessment and definition of prototype approaches for landslide risk mitigation plan of the whole rock-cut necropolis. The latter is considered a fundamental tool for the future tourist development of the site, safe from possible rock falls and slides. The investigation reveals the importance of engineering geology and geohazard assessment for the future conservation of rock-cut sites.

1 INTRODUCTION

This paper represents one of the outcomes of two different statements. The first one (starting since December 2019), between the *Soprintendenza Archeologica, Belle Arti e Paesaggio per l'area metropolitana di Roma, la provincia di Viterbo e l'Etruria Meridionale* and the Italian Institute for Environment Protection and Research (ISPRA, Geological Survey of Italy), was aimed at the analysis and assessment of stability conditions of the Etruscan necropolises distributed in the entire territory of competence.

The second cooperation, between ISPRA and University of Bologna (DICAM), was focused on the evaluation of stability conditions of the most threaten tombs of the whole Norchia Necropolis. The archaeological site of Norchia is an Etruscan settlement established along the ancient via Clodia, dating back to the Classical Hellenistic period (Ambrosini 2017).

After a short period of abandonment, during the Republican era, Norchia was populated back in the middle ages, alternating periods of splendor with periods of deep decadence.

The town was finally abandoned following a severe malaria epidemic in 1453. The peculiarity of the site, that makes it a unique example, is the nearby presence of a wide Etruscan necropolis. Dated between the end of the IV and middle of the II century B.C., it testifies rituals/habits/ceremonies of the Etruscan funerary religion.

The necropolis is more than 100 hectares wide, and includes rock-cut tombs of various types (façade, half-cube, false-cube and temple type) and dimensions (4–10 m high), showing a remarkable similarity with middle east and Asian tombs (e.g., the Nabatean rock cut city of Petra in Jordan and the tombs of Hegra in KSA).

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Norchia necropolis is one of the most significant examples of rock-cut tombs of the Hellenistic period, representing an important and rare illustration of rock architecture, one of the few preserved in Italy. In recent years, the in-creasing interest by archaeologists on Etruscan heritage in general and in particular on Norchia was mainly limited by issues of conservation and accessibility to the sites, this latter due to the presence of dense vegetation covering entirely the necropolis and to diffuse rock slope instability processes.

The above mentioned collaborative activities, between the University of Bologna, the Geological Survey of Italy (ISPRA) and local authorities, are aimed at the conservation and protection of Etruscan funerary monuments with the ultimate target of making the area accessible to the public in a complete state of safety from rock falls and slides.

The study described here refers in particular to a small tomb belonging to the Pile sector B (Figure 1), selected as pilot study to develop sustainable mitigation measures for the area at risk.

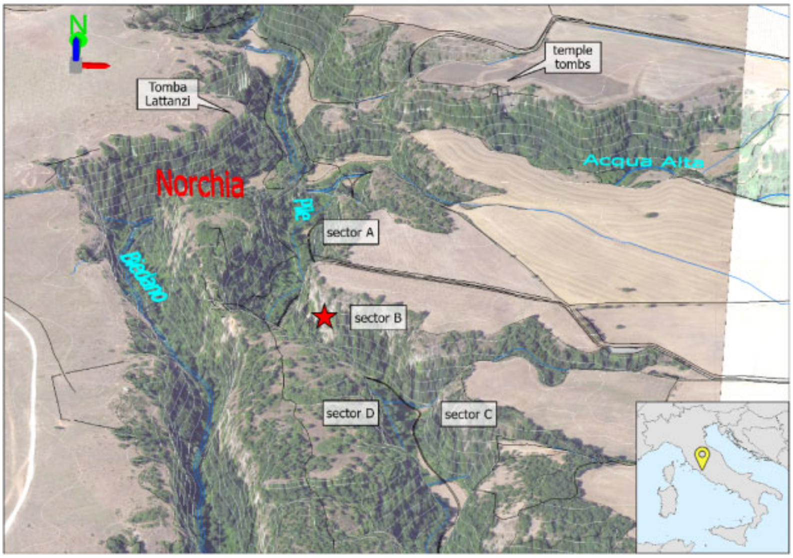

Figure 1. Norchia site and Necropolis sectors. The location of the selected tomb is marked with a red star.

2 GEOGRAPHICAL AND GEOLOGICAL SETTING

The town of Norchia was located on a residual pyroclastic ridge, surrounded by steep slopes, at the junction of Pile and Acqua Alta streams with the Biedano river (Figure 1). Two layered pyroclastic deposits, red tuff from Vico volcanic apparatus at the top and grey tuff (Nenfro) from Vulsini volcanic apparatus below, overlay a Meso-Cenozoic flysch deposit (Figure 2). The tombs were excavated in the pyroclastic layers, according to the natural profile of tuff outcrops. Recent investigations have revealed that different threats affect the site: surface rock weathering, water percolation and infiltration, invasive vegetation and biological colonization, rock falls and rock slide from the cliff.

The site was affected by an intense erosive activity operated by the Biedano and the Pile streams, from South to North, and Acqua Alta stream, from West to East (Figure 2). The resulting plateau, given the soft consistency of the rocks, easily workable, made the place a strategic point for the settlement of the Etruscan town (Bear et al. 2009). Both the volcanic nature of the site and the tensional stress release due to the erosion of the river at the base of the slope created an important fractures system that affects the rock mass. The main families of discontinuities identified at the site are:

- sub-horizontal discontinuities due to the layering and gradation of deposits;
- vertical and sub-vertical fractures, orthogonal to the slope, caused by the cooling of volcanic rock;
- fractures with sub-vertical and inclined planes, parallel to the slope face, to be related to the stress release caused by the river erosion;
- fresh fractures spread from existing fractures caused mainly by plant roots.

These sets of discontinuity, together with the poor quality of the material (alternation of soft rocks), have produced over the centuries diffused phenomena of weathering and collapse, that have compromised the necropolis stability and accessibility.

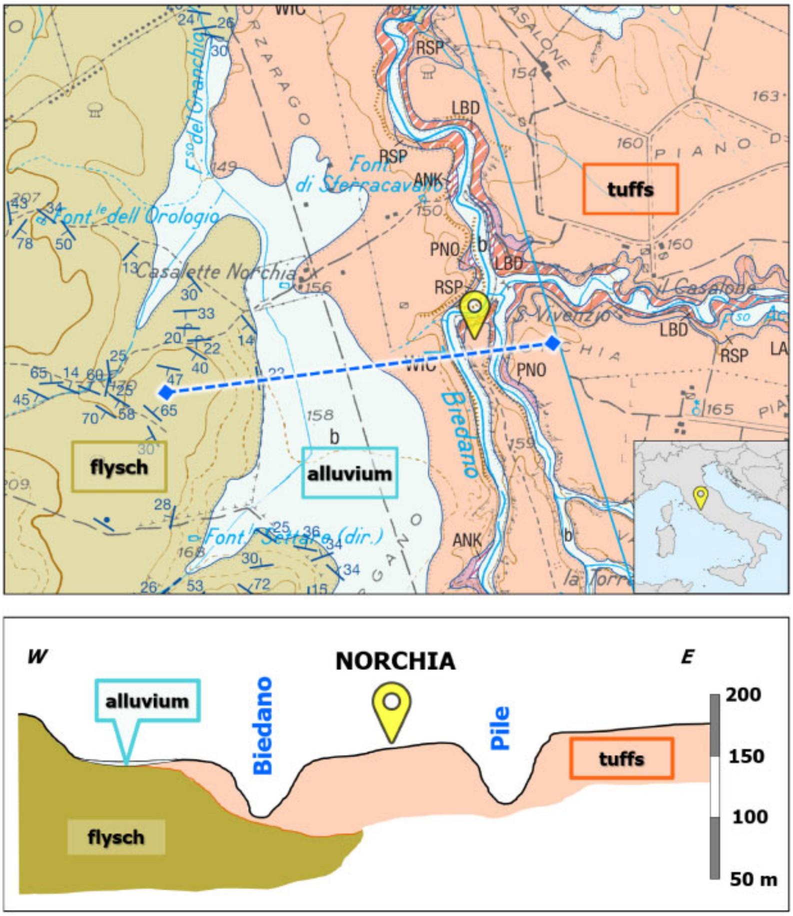

Figure 2. Geologic setting (up) and cross section (down) of the area, from Carta Geologica d'Italia, scale 1:50'000, Sheet 354 (ISPRA, Geologic Survey of Italy).

Figure 3 illustrates the appearance of the necropolis about 30 years ago after an important intervention of reclamation of the vegetation (left) and an hypothetical historical reconstruction (right). As anticipated, the paper focuses specifically on a small tomb belonging to the sector of the Pile B stream (Figures 1 and 4). Previous studies on the rock material outcropping in the necropolis carved in the slope, pointed out that this sector is split into two main levels (Ciccioli et al. 2010). The selected tomb is located in the upper level at the stratigraphic contact between the red black scoriae tuff and the ignimbrite of Nenfro (Figure 4, left).

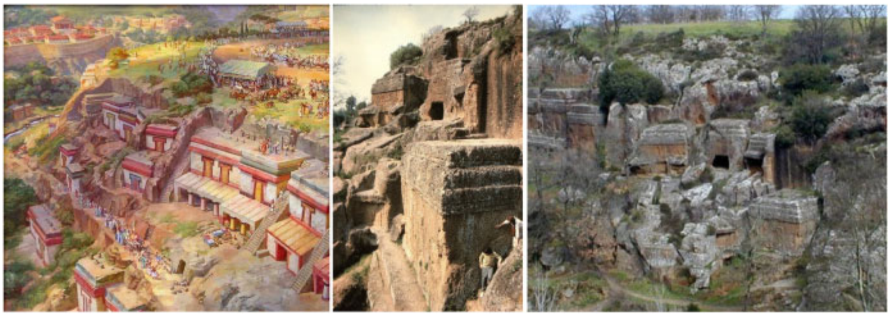

Figure 3. Recent picture (right and centre) of the necropolis in the Pile sector B (Ambrosini, 2017) and an historical hypothetical reconstruction (left) (ANTICAE VIAE, 2020).

Figure 4. Frontal and lateral view of the tomb selected as a prototype example of analysis and mitigation measures.

3 LABORATORY CHARACTERIZATION OF ROCK MATERIALS

Three different rock blocks were collected during the field surveys of October and December 2019, nearby the selected tomb.

The blocks are mainly differentiated in two lithologies. In particular, making reference to Ciccioli et al. (2010), the red tuff with black scoriae was referred to lithology A and the black tuff with black scoriae (also called grey tuff, or ignimbrite of Nenfro) was referred to lithology B. Among the sampled blocks, two of them belong to lithology A. They are irregularly shaped, o-range/reddish in color (indicating the presence of oxidized iron), with the presence of well-defined leucite crystals inside, and with inclusions of blackish material (lava) and pumice stone.

One block belongs to lithology B. It shows a grayish matrix that contains clasts of different shape and material. The difference in color, with respect to the other two blocks, indicates the lack of oxidized iron in its mineralogical composition (Perini et al. 2007).

Figure 5. Tuff outcrop of two different lithology (left) and the collected samples (two from lithology A and one from lithology B).

The appearance of this block and the different altitude at which it was taken suggest also a different pyroclastic flow deposit and a different alteration, due to the different atmospheric conditions to which it was affected. Due to the extremely weak nature of the material, combined with the presence of clasts with a greater resistance than the soft matrix, it was not possible to realize cylindrical specimens of standard size for this block, but only parallelepiped specimens (Figure 6).

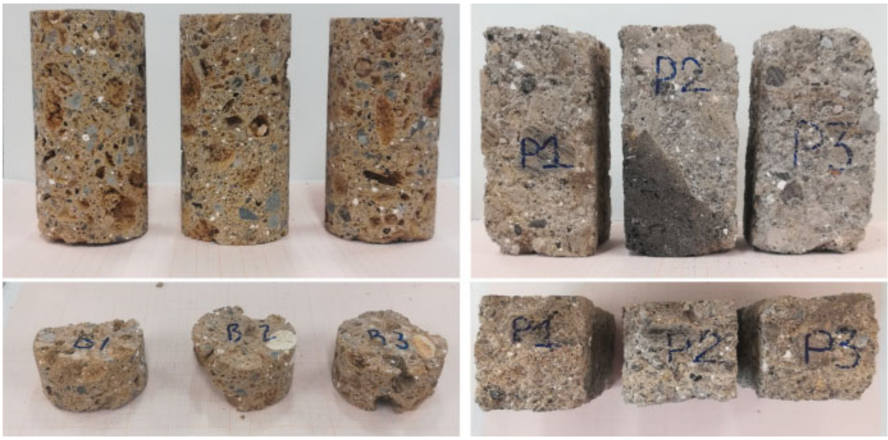

Figure 6. Specimens for the laboratory tests. Cylindrical specimen belonging to lithology A (left) and parallelepipeds to B (right).

Table 1 summarizes the main physical and mechanical properties determined by laboratory tests. For the red tuff with black scoriae (lithology A) uniaxial compressive tests and Brazialian indirect tensile tests were carried out both on dry and saturated specimens. The dynamic elastic modulus (Edyn) was derived by the P wave velocity (VP), measured by ultrasonic test.

Inspection of Table 1 reveals that:

- the porosity (n) varies between 50% (A lithology) and 60% (B lithology);

Table 1. Summary of the physical and mechanical characterization of the investigated rock materials. The uniaxial compressive tests of grey tuff specimens were carried out using parallelepiped specimens.

Lithology	red tuff with black scoriae	red tuff with black scoriae	grey tuff
condition	*dry*	*saturated*	*dry*
γ (kN/m^3)	11.74	15.18	10.27
n (%)	50.85	/	61.35
σ_c (MPa)	2.65	1.43	1.33
σ_t (MPa)	0.48	0.18	/
V_P (km/s)	1.3	1.22	/

- the uniaxial compressive strength (σ_c) and the tensile strength (σ_t) are extremely low, especially for the B lithology (Deere and Miller, 1966);
- saturation induces a relevant decrease in strengths.

4 IN SITU CARACTHERISATION

4.1 *Topographic survey*

In order to reconstruct the detailed geometry of the site and to perform the appropriate stability analyses, the possibility to acquire a 3D model has been considered, both from the ground (TLS, Terrestrial Laser Scanning) and from remote by UAV. Unfortunately, none of the above mentioned surveys was possible to implement, due to the dense vegetation for TLS and to the no-fly-zone for drone due to the nearby military area.

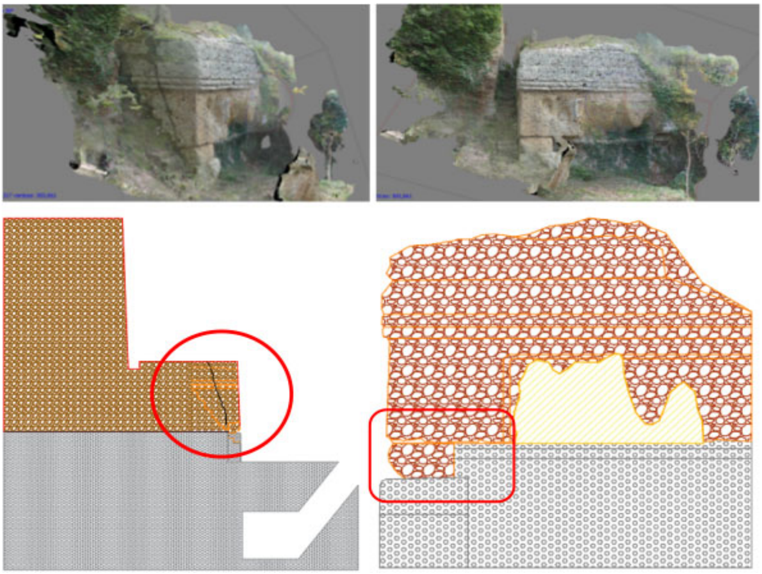

Figure 7. 3D digital-photo reconstruction (upper), lateral and front view (down) of the selected tomb. Red circle highlights the presence of fracture.

In order to overcome this problem a prototype example, well representative of the architectural style of the necropolis, was selected to reconstruct the detailed geometry (Figure 4). It is a partially underground tomb (Figure 4, left), with a collapsed rock block obstructing the entrance to the burial chamber detached from the tomb itself, where the façade exhibits a yellow color (Figure 7).

Externally the tomb has a massive body typical of the "dado" style, but some architectural elements typical of the temple tombs are also present. Part of the massive body is excavated directly into the rock mass, while the remaining part is overhanging and stand on two lateral pillars, made up of blocks belonging to the tuff of the B lithology. At the time of the inspection it was observed that one of the two supports has failed (Figure 7), while the remaining one is affected by a well open fracture (triggered by the plants roots), that extends in the rock-mass behind the tomb façade and that determine a wedge of rock potentially unstable (Figure 7, right).

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The topographic reconstruction of the tomb was made by a 3D digital photogrammetry, processing of photos taken during the various field surveys. More specifically, a digital photo-grammetry technique and image processing were implemented. The adopted software (Agisoft Metashape©) allows, starting from images related to the same subject captured from different perspectives, to create a point cloud 3D model as well as precise geometric sections in *dwg* and dxf format (Figure 7).

By using 34 photos of the selected tomb, it was possible to extract a point-cloud of about 40000 control points (corresponding points in the individual photos) derived from the alignment of the images provided by the program.

4.2 *Structural setting of the selected tomb*

Field investigation was also carried out to collect information on the rock-mass at site scale. Essentially, they consisted in the survey of the characteristics of the discontinuities, including their spacing, orientation and roughness. The already mentioned fracture responsible for the potential sliding involving the tomb, was referred to a dip of 68° and a dip direction of 245°, while the slope face has dip of 88°, with the same dip direction. A volume of 10.58 m3 was estimated for possible unstable block, by integrating the information derived from the fracture orientation and the geometrical reconstruction of the tomb.

5 STABILITY ANALYSIS AND PRELIMINARY CONSOLIDATION MEASURES

The stability analysis was carried out with the limit equilibrium method, assuming an a priori slide mechanism and introducing appropriate hypotheses on the acting forces (Boldini et al. 2017). In particular, given the unit weight of volume of the rock material, the unstable block was estimated to have a weight of 124.15 kN.

The block is currently stable partly due to the presence of rock bridges along the fracture and partly due to the support foot still present. These two contributions tend to reduce over time, due to physical degradation and to progressive failure.

The analysis was carried out in the worst scenario, not considering them. In addition to the weight force, pseudo static forces were considered to account for potential local seismic actions:

$$K_h = \pm (K_h \times W) \tag{1}$$

$$K_v = \pm (K_v \times W) \tag{2}$$

in which:

$$K_h = \beta_s x \frac{a_g}{g} x S \tag{3}$$

$$K_v = \pm 0.5 X k_h \tag{4}$$

ag is the maximum horizontal acceleration at the bedrock (Stucchi et al. 2004), here assumed equal to 0.137g, while S = SS ST is a parameter that takes into account respectively the type of soil (SS = 1.2 for weak rock material) and the amplification due to the topography of the studied area (ST = 1.4 or slopes with inclination greater than 15°). βS is the reduction coefficient of the maximum acceleration expected at the site (βS = 0.24). The safety factor (FS) is expressed as the ratio between the total shear resistance Tr, including the contribution made available by the presence of the passive bars, and the total shear stress (T) acting along the shear surface:

$$F_s = \frac{T_r}{T} \quad (5)$$

The proposed system for consolidation includes steel bars Feb44k with improved adhesion of 24 mm diameter and 3 m length. The characteristic tensile yield strength of the steel is fy = 430 MPa, corresponding to an axial yield strength Ny = 194 kN. A downward inclination of 5° was adopted to facilitate the injection of cement mixture.

The resulting force applied by the single bar was estimated according to the approach outlined in Ribacchi et al. (2018). More in detail, the displacement vector was assumed parallel to the fracture (null dilatancy). As final results a Fs equal to 3.43 was obtained considering two bars, which is higher than the 1.375 value, prescribed for non-natural slopes by the Italian technical code.

The possible sliding mechanism at the bar-cement interface and rock-cement can be considered as satisfied when the length of the bar over the fracture is more than 40 times the diameter of the bar. The foundation length assumed for the interventions was 1.80 m, adequate against this collapse mechanism (British Standard 1989).

To better integrate the interventions and decrease the visual impact, the head of the passive bars will be conveniently hidden from view by using same rock resulting from drilling activities (Figure 8).

Figure 8. Rock core drilled used for mitigation (left), bar insertion (center) and bolt sealing (right).

Before the hole is drilled, a continuous bore of 15 cm will be carried out to preserve the core itself. Once the reinforcement is installed, the rock core drilled will be reinserted into the hole and cemented with a mortar with local aggregates, to hide the plate and mitigate the visual impact of the intervention.

The stability analysis stated the necessity of two passive bars. Nevertheless, in order to ensure a correct and homogeneous distribution of the forces involved (avoiding excessive stresses concentrations with possible local breakages) it was decided to adopt the configuration of the bars showed in Figure 9.

6 CONCLUSIONS

The study summarized relevant on-site activities and laboratory tests aimed at characterizing the instability processes affecting on tomb in Pile sector B of Norchia necropolis. These activities allowed to design a reinforcement intervention, aimed at safeguarding the cultural heritage and at

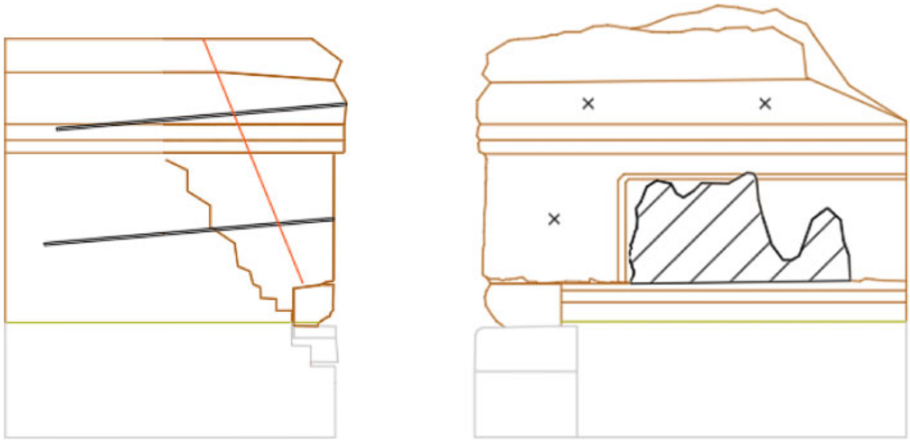

Figure 9. Configuration of the passive bar reinforcement: prospectus (left) and cross section (right).

securing the archaeological site to the future opening for tourist. More in general, they present an operational standard and prototype approach potentially exportable to other cases from a theoretical and methodological point of view. The physical and mechanical characterization of the main tuff lithologies of the site was carried out for the first time, thus providing a useful database for further studies and for future archaeological campaigns. The present study promotes the extensive use of topographical and geomatics survey techniques, even at low cost and of expeditious type. In the future, it will be necessary to carry out reclamation of the area from the vegetation. A long term action will provide a management plain of sustainable mitigation measures tailored for all the possible instability processes in accordance with a multi-annual maintenance and monitoring plan.

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