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Monitoring activities for the preservation of an Etruscan hypogeum in unsaturated soil mass

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Abstract. A geotechnical monitoring campaign and a site investigation have been recently planned and undertaken aiming at the preservation and protection of the "*Palazzone*" Etruscan necropolis, an archaeological site dated back to Hellenistic period located 4 km from the city of Perugia, along the south-eastern margin of the hill where the town is settled. The site includes some beautiful and monumental cavities, among them, the *Volumni Hypogeum*. The majority of the graves are underground cavities excavated in partially saturated alluvial soil deposits. Their inspection reveals the geological features and the depositional structures. The groundwater table is located about 35 m below the ground surface. Due to the difficulties of soil-sampling inside the ancient cavities, only limited portions of the material were retrieved for conventional laboratory tests, although not enough for a geotechnical characterization. On the other hand, XRD analyses and MIP tests were performed. The obtained results allowed to recognize the relevant contribution of soil suction to the stability conditions of the lateral walls and the ceiling of the cavities, which is complementary to the weak cementation characterizing the soil mass. This important information supports the conservation strategy of the monument, which has as its primary tool the monitoring of environmental conditions, aimed at maintaining the unsaturated conditions of the soil mass.

1 Introduction

In the present study, a preliminary assessment of the environmental and geotechnical properties affecting the behaviour of the historic and monumental cavity of the *Volumni Hypogeum* sited in Perugia (Central Italy) has been performed. It has been shown [1] that one of the relevant parameters governing the stability of the monument is the suction of the soil mass, and therefore the need to maintain this condition over time is a priority for the conservation of the monument itself. Given the peculiarity of the problem at hand, the contribution of geotechnical engineering to the preservation of the site is considered fundamental and unavoidable. Due to the impossibility of in situ-testing and sampling from the cavity, the need of characterising the current state of the soil mass in terms of stress and suction levels requires indirect and non-destructive methods for the determination of the relevant geotechnical parameters.

The paper describes the methods already applied and those to be applied in the next future for the monitoring activity, finalised at effectively conserving the monument in the full respect of the integrity of sites and materials. The design and the development of a monitoring system for the protection and valorisation of the manufact presents a strong degree of innovation in the possibility of using networked systems, with high autonomy, designed with the use of low consumption and low cost components.

2 Geology of the site

The *Palazzone* necropolis is an Etruscan archaeological site discovered in 1840. The necropolis is mostly dated to Hellenistic period with only five tombs referrable to the Archaic period (second half of the 6th century B.C. - beginning of the 5th century B.C.) and it is located 4 km far from the city centre of Perugia, the capital city of the Umbria region in Central Italy. Perugia is set on the top of a hill, with maximum altitude of 493 m a.s.l., from which five ridges spread towards the Tiber River valley below. Along the slopes fluvial and lacustrine sediments outcrop (Pliocene and Pleistocene age). Due to the morphological and topographic characteristics of the location and the strategic position of the area, the Etruscan civilization chose the top of the hill for establish the first settlement. In the historic centre and nearby areas, several evidences of the Etruscan presence are still existing as ancient walls, artifacts and several necropolises. The morphological constraints that influenced urbanization in the Etruscan age are a direct consequence of the geological setting. However, in order to clearly understand the geology of the site, Perugia should be framed in a more general context, being the hill part of an extensive intermontane basin, the Tiberino Basin - TB (Fig. 1a; [2]), which is a semi-graben, bordered by normal fault systems, derived from the last extensional tectonics phase started in the Pliocene and still acting.

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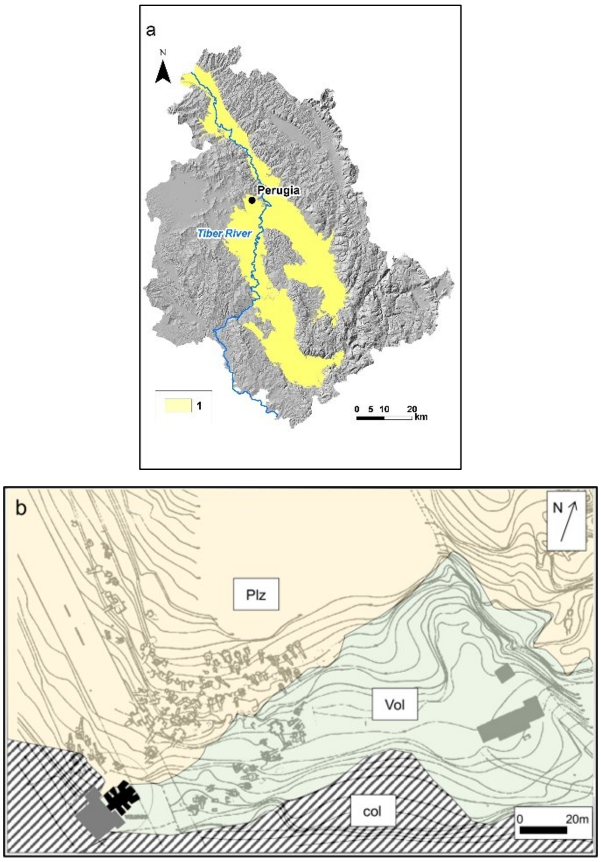

Fig. 1. a) Location map of the Perugia city in the Umbria region (Central Italy), 1: Tiber Basin; b) geological map of the Palazzone necropolis, Plz: Palazzone Unit, Vol: Volumni Unit, col: colluvial deposits. The polygon highlighted in black colour is the *Volumni Hypogeum*.

The basin is filled by a continental sequence, corresponding to a paleo-environment where rivers, lakes and swamps alternate in space and time [3].

Continental sequences such as TB are characterized by high lateral and vertical heterogeneity. Given the non-conservative nature of these deposits, undisturbed outcrops are not frequent. Moreover, in a predominantly mountainous region such as Umbria, the fluvial and lacustrine deposits have the lowest slope values and, as a result, these areas are intensely anthropized, making it even more difficult to find not urbanized or cultivated zones where natural outcrops can be observed.

The *Palazzone* necropolis is located on the fluvial and lacustrine sediments too. Almost 200 hypogean tombs (Fig 1b) dug into the ground and without coatings that can hide the natural soil offer a view on this geological complex. For this reason, the *Palazzone* necropolis is not only a site of undoubted archaeological importance but is also a precious window on the geological setting of the hill of Perugia and more generally of the TB.

In the necropolis the most relevant tomb is the *Volumni Hypogeum* (second half of the second century). The tomb (Figures 2, 3) reproduces the shape of a roman house with ten rooms. Thanks to the spatial arrangement of the different rooms, it is possible to observe the sedimentary structures from different orientations and fully understand the depositional paleoenvironment and the flow directions that have deposited the sediments [4]. In detail, the entire sedimentary sequence outcropping in the necropolis is between ~210 m a.s.l. on the floor of the *Volumni Hypogeum* and ~238 m on the last tombs on the top of the slope. A detailed survey activity allowed to define two lithostratigraphic units: Volumni (Vol) and Palazzone (Plz) units both dated to Lower Pleistocene and discordant along the contact (Fig. 1b, [5]). These units are attributable to a braided river environment with a fining upward sequence. In the hypogeum, only the Vol outcrops. This unit confirms a depositional environment related to a fluvial system with well-defined channels. Limited to the entrance staircase of the *Volumni Hypogeum*, the transition to the Plz unit can be observed. The Plz has a more complex and dynamic depositional organization with mixed-fill channels, first gravelly/sandy, then clearly sandy. The dip direction of the two units is always towards the SSE/SSW direction [6].

In the cavity, at the bottom of the rooms, conglomerates prevail, while sands are predominant on the roof and upper part of the walls. This distribution was probably exploited for digging the base of the hypogeum, whereas the conglomerates are present and exhibit better geotechnical properties; the sands on the upper portion were suitable, because easily sculpted, to make the friezes and embellishments of the tomb. The paleocurrents in the Vol unit show a general direction towards south; this data can be interpreted with a source of sediment from the north, similar to the one that could have settled most of the deposits of the Perugia hill.

Fig. 2. a) The *Volumni Hypogeum*; b) Volumni Unit with conglomerates and sands in channels on the wall n. 4 (B-C), see also Figure 3.

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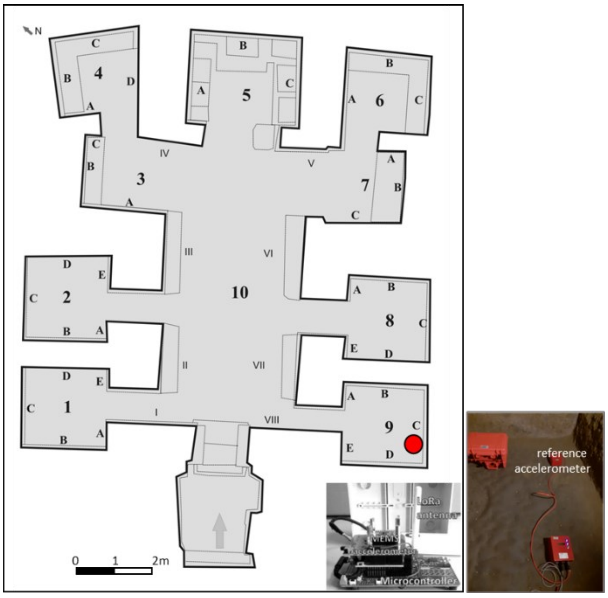

Fig. 3. Plan view of the *Volumni Hypogeum*. The red symbol indicates the location of the in-house and reference accelerometer sensors.

In the more recent Plz unit, the paleocurrents indicate the same flow direction as the Tiber River, thus revealing the evolution of the hydrographic network similar to the present one.

3 Monitoring system

The *Palazzone* Necropolis is one of the most relevant types of evidence of the Etruscan civilization in central Italy. Moreover, the geological characteristics of the deposits allow to understand the palaeoenvironment of the Perugian hillside dating back at least ~ 2,5 million years. The importance of this archeologic site, its valorisation and the need to guarantee its preservation and conservation is therefore noticeable. At the street level, near the building wall, approximately 10 m from the position where the sensor node was placed, a railroad track is present, with a level crossing and a road for vehicular traffic. At the *Volumni Hypogeum* site, the near-vertical walls and ceilings of the cavity do not seem to suggest evidence of instability, reasonably due to the concurrent effect of grain cementation and suction induced by partially-saturated conditions. In a previous study [1], simplified 2-D stress/strain FEM (Finite Element Method) analyses, taking into account the unsaturated conditions of the soil mass, were carried out in order to get a preliminary insight of the stability conditions of the area. According to these analyses, the most vulnerable elements of the cavity were found to be the roof top and the lateral walls, possibly prone to soil instability if the soil suction was reduced to 50 kPa.

Given the uniqueness and peculiarity of the cavity, monitoring is fundamental for any vulnerability assessment. A customized electronic monitoring system was used for in-situ measurement of the vibrational stresses and specific environmental quantities The monitoring system, developed in-house at the University of Perugia, consists of several measurement devices that can be disseminated in the environment and share data using Internet of Things (IoT) technologies.

3.1 IoT low-cost accelerometer sensors

The core of the monitoring system is a low-cost sensing device, equipped with a tri-axial accelerometer, a long range wireless IoT data transmission capability, a GPS module, and a microcontroller handling the timing, control, and data storage functionalities. The sensing device was characterized in [7] by laboratory tests and preliminary field tests inside the cavity, providing results in agreement with a commercial reference accelerometer. Following such preliminary test, further in-situ vibration measurements were performed using a commercial sensor, the SS-05 triaxial velocimeter by Sara Electronic Instruments [8]. The measurements were performed at two different locations within the site: at ground level and inside the underground cavity, directly below the location of the ground-level measurement. The goal of these measurements was to study the response of the soil surrounding the cavity to vibrational stresses, relatively to the geotechnical properties of the materials. The measurements were performed during the passage of trains along the railway, which is in close proximity to the *Volumni Hypogeum*. The train passage induces noticeable vibrational stresses on the cavity, thus allowing to effectively study its properties. The results of the measurement campaign, performed in June 2021, are shown in Figure 4.

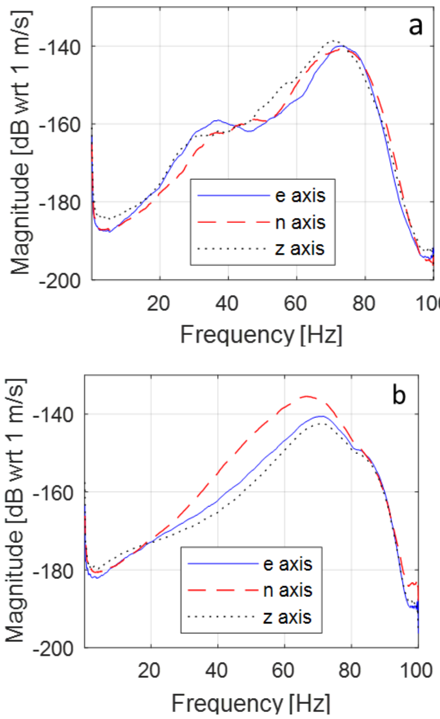

Fig. 4. Spectra of the velocity signals measured during train passage at ground level (a) and in the cavity (b), along the east axis (denoted as "e"), north axis (denoted as "n"), and vertical axis (denoted as "z"). The magnitude is shown in dB, calculated with respect to 1 m/s.

By comparing the spectra of the velocity signals at ground level and inside the cavity, it is possible to notice that they are different, thus indicating that the soil properties affect the vibrational response of the cavity. The measured vibrations exhibit a peak value of approximately 50 µm/s, which is in any case well below the maximum threshold of about 3 mm/s for historic buildings defined by the Italian regulation UNI 9916, as proven also by using the commercial software VIBER [9].

To further study the difference between ground-level and cavity-level data, the horizontal-to-vertical-spectral-ratio (HVSR) was computed from the experimental velocity data, according to the Nakamura method [10], resulting in Figure 5. From this figure, a peak in the cavity HVSR can be observed at a frequency of 40 Hz, which is not present in the ground-level HVSR. This information can be used to study the dynamic properties of the soil layers and their interaction with the structures surrounding the cavity [11].

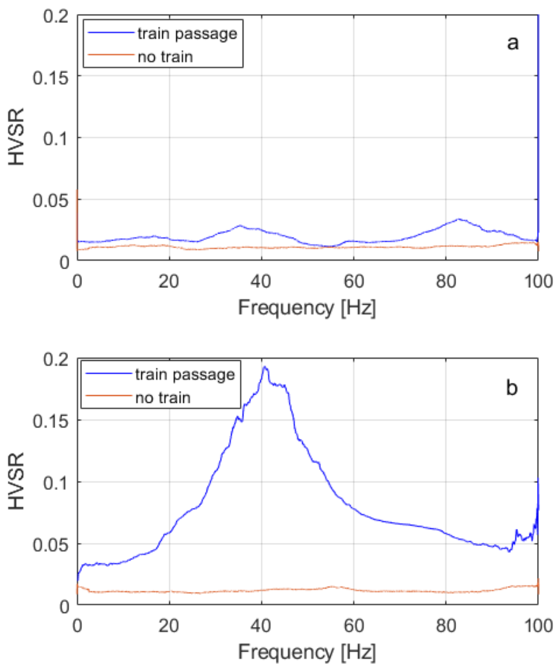

Fig. 5. HVSR computed from the velocimeter measurements: (a) at ground level, and (b) in the cavity.

3.2 Development of sensing devices for multiple physical quantity measurement

To extend the capabilities of the developed monitoring system described in § 3.1 and allow for monitoring environmental quantities, a temperature and a humidity sensor were added to the sensing device. In particular, the DHT22 module, a commercial off-the-shelf inexpensive component, was used.

This component is characterized by a compact size (16 mm x 13 mm) [12], which makes it suitable for integration in the developed sensing device. Furthermore, it is capable of measuring ambient temperature from -40°C to 80°C with a nominal accuracy of ±0.5°C, and relative humidity (RH) from 0% to 100% with a nominal accuracy of ±3%. It provides measured data via a digital Inter-Integrated-Circuit (I^2C) serial protocol.

The DHT22 module was connected to the microcontroller board in the realized sensing device, which was programmed to read temperature and RH data every 3s. The correct operation of the environmental quantities measurement was validated by comparing the data from the sensing device with those from a reference instrument, a RS1260 thermo-igrometer, under laboratory conditions at about 26°C and 55% RH. The difference with respect to the reference instrument was 0.1°C temperature and 2% RH. Therefore, the extended-capability sensing device is now suitable for a wide range of applications, including environmental monitoring at the considered site.

4 Geotechnical characterization

The difficulties of soil-sampling at the Necropolis of *Palazzone* and inside the *Volumni Hypogeum* are clearly linked to the preciousness of the site and the nature of the soil layers - mainly coarse-grained materials - constituting the roof and the upper portion of the walls of the cavity. For this reason, non-invasive testing techniques must be used; in this case, only very small portions of materials belonging to the Vol unit were retrieved from the vertical wall, at 1.5 m of height from the ground floor of the first room located on the right side when descending into the Hypogeum through the access stairs (see Fig. 3). The material was obtained in a loose state by hand scratching the cavity walls with great care, without any cutting tool. Determination of grain size distribution and water content were performed.

Fig. 6. Room n.9 (see location in Fig. 3): details of the soil surface.

4.1 Microstructure and physical properties

To get a preliminary understanding of the microstructural and chemo-mineralogical features of the materials in which the Hypogeum is excavated, X-Ray Diffraction (XRD), Thermogravimetric Analyses (TGA) and Mercury Intrusion Porosimeter (MIP) tests were performed. Figure 7 shows the results of the XRD analysis indicating the presence of muscovite, anorthite, quartz, as well as gypsum and calcium carbonate, whose large amount is furtherly proved by the TGA results (Fig. 8). The presence of calcium carbonate, in addition to a certain degree of cementation and significant soil suction levels in the soil mass surrounding the cavity presumably yield to soil shear strength parameters large enough to guarantee the observed stability of the walls and the ceiling of the cavity. The maintenance of partially saturated soil conditions is therefore crucial.

Preliminarily, the retention properties of the soils were recently estimated by comparing the results of the MIP tests carried out on soil samples belonging to the same geological unit and retrieved at the outskirts of the investigated area, close to the Hypogeum, with those predicted by the Arya & Paris model [13, 6]. Figure 9 shows the pore size distribution of the same material in terms of frequency of pore entrance diameters. A monomodal distribution of pores is observed, with modal size ranging between 1 and 2 μm.

The predicted soil-water retention curve is shown in Figure 10. Based on the available geological and hydrogeological data, it can be argued that groundwater table is located about 35 m below the ground surface, i.e. ~ 25 m underneath the hypogeum floor. As such, plausible suction values in the soils constituting the walls and the ceiling may possibly be estimated at about 200 kPa. For this suction level, a saturation degree of 60% in the soil mass can be assumed from the retention curve, which is consistent with the physical properties of the soil mass.

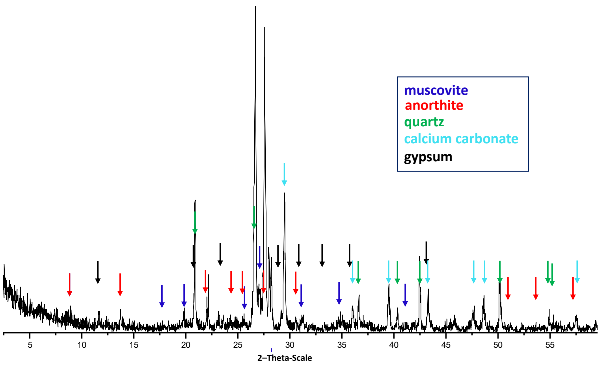

Fig. 7. Vol soil unit: X-ray diffraction pattern

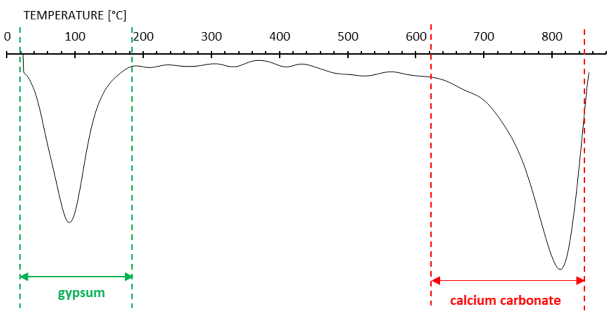

Fig. 8. Vol soil unit: results from TGA analyses.

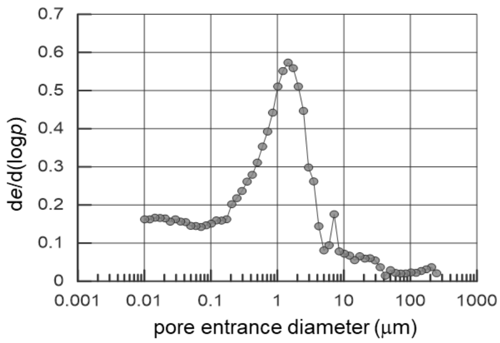

Fig. 9. Vol soil unit: frequency of pore entrance diameters from MIP tests (adapted from [1]).

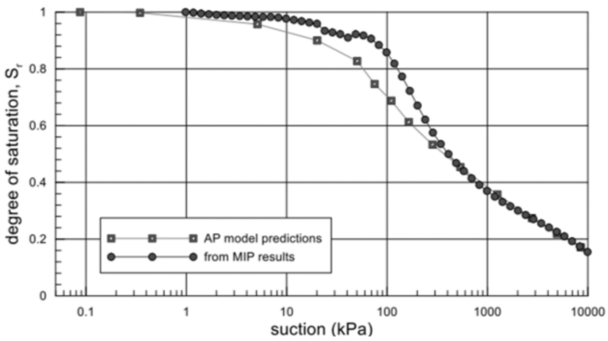

Fig. 10. Soil water retention curve estimated from Arya & Paris [13] model predictions and pore size distribution from MIP tests (adapted from [6]).

4.2 Monitoring plan and in situ investigation program for the site preservation

Even if it is not always perceived, the underground context - the so-called "fourth dimension" - can disclose a new perspective of a city. The artificial cavities have different values, such as historic, architectural or archaeological ones. Under certain conditions, these places have valuable geological data too. In such cases, the effort to enhance and preserve this heritage should be even stronger. The Necropolis of *Palazzone* and the *Volumni Hypogeum* have been classified as archaeo-geosites [3], i.e. sites where both archaeological and geological values are present. However, the geomechanical properties of the excavation sites and the proximity of infrastructures, such as roads and railways, represent a risk factor. The potential of the necropolis in terms of tourist and educational offer is high; this premise makes it necessary to create a conservation and safety program, in particular for the most valuable tombs, such as the hypogeum and those that could show evidence of possible instability.

Therefore, a 3D geoelectrical survey of the area above the hypogeum is further planned. Geophysical surveying techniques have proved to be highly useful as they supply fast, non-invasive and detailed evaluation of some physical quantities in large buried volumes to be investigated. In particular, the well-known dependence of electrical resistivity values on the soil water content suggests the geoelectrical method as one of the most suitable for studying the suction level as a function of electrical resistivity in the field [14, 15]. Piegari and Di

Maio [15] showed how this non-invasive method can be implemented for monitoring spatial variations of soil suction by using soil resistivity data derived from in situ electrical resistivity tomography surveys. They proposed the combined use of one of the most common empirical quantitative relationships among porosity, electrical resistivity and degree of saturation of soils, i.e. the Archie's law [16] and the van Genuchten's water retention model [17] for predicting matric suction values by using resistivity data.

The suction regime in the soil mass is considered an essential factor in the preservation of the hypogeum. The proposed investigation will allow us to define the suction level of the soil mass through a three-dimensional measurement of electrical resistivity, providing a reference state for interventions to be implemented for the conservation of the hypogeum aimed at maintaining the suction regime in the soil mass.

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