Investigations and stability analysis of San Marcellino cavities in the historical centre of Naples

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Abstract. The historical centre of the city of Naples is characterised by a network of underground anthropogenic cavities. Most of these cavities are stable and safe but sometimes for several reasons they are at least partially responsible of the occurrence of instability phenomena such as sinkholes and collapses. The opening of a sinkhole in the cloister of the Ancient Royal Boarding School (known as Educandato Reale of San Marcellino) led to fears of instability in the known underlying cavities. Therefore, a site investigation program was carried out to ascertain the causes of the event. The investigation concluded that the sinkhole was not related to the underneath cavities, located in tuff between 12 and 20 m beneath the main building. Nevertheless, due to the interest raised by the preliminary safety assessment, such a cavity system was selected within the MOSCAS project for further studies. The results of the site investigations and the stability of the cavities determined via FEM code Plaxis 2D are presented and discussed in this paper.

1. Introduction

Urban cavities that originate from human activity are excavated for several reasons (quarries, cisterns, crypts and catacombs); these cavities often form an intricate network of tunnels underneath urban centres, sometimes forming systems with several levels (Berti et al., 2002; Nisio et al., 2007).

The presence of anthropogenic cavities in the subsoil of urban centres can cause the collapse of the most superficial portions of the ground with the formation of surface collapses, creating a serious risk for urban buildings. In recent years, there has been an increase in the number of cases of sudden collapse, especially in urban centres, where cavities, sometimes combined with possible leaks in the hydraulic network, facilitate the triggering of these phenomena.

Within the framework of the MOSCAS research project (Models and tools for the characterization of underground cavities), safety levels of the cavities underneath the historic building of San Marcellino in the city centre of Napoli, Italy, was assessed. The interest for this case study was raised by the opening of a sinkhole in the cloister of the building in April 2012, that led to concern of possible instability in the known underlying cavities.

The main results of the stability analysis are briefly presented and discussed in the following.
2. Case study

Hundreds of cavities were excavated over centuries in the NYT (Neapolitan Yellow Tuff) that is present in the subsoil of the historic centre of the city of Napoli. Their stability is sometimes reason of concern. Among others, a system of cavities can be accessed from the basement of an historic building: the Educandato Reale at San Marcellino. It is a monumental building system in the ancient town that was originally erected as distinct monasteries in the VIII century. It comprises a two floors large cloister, composed of gardens and pedestrian boulevards (Figure 1a). Nowadays it hosts the University Museum of Paleontology and the International Scuola Superiore Meridionale of the Università di Napoli Federico II.

The building is located at the borders of the ancient Greek town (Neapolis) on a rise (a paleo-sea cliff) between 10 and 25 m of altitude a. s. l. The complex building system is founded at two different levels (Figure 1b), the lowermost of which is located at the south-east corner.

![Figure 1. San Marcellino complex: view from satellite (a) and photo showing the elevation difference between the lower and the upper cloisters (b).](image)

The geomorphology of the area is shown in figure 2, where is evident that the site was originally located on a paleosea cliff which bordered the so-called Pendino terrace, in turn crossed by several watercourses. As most part of the city of Napoli, ground conditions are characterized by fill material and pyroclastic soils (known as Serie Urbana Recente) layered on the roof of Neapolitan Yellow Tuff (NYT). NYT has long been used as construction material thanks to its good mechanical properties. Underground excavation for extracting tuff blocks led to complex cavity structures below the ground surface of the historical centre of Napoli, in addition to the pre-existing tunnels of the Greek-Roman Bolla aqueduct.

The excavation of cavities was not always made by following best practice; consequently, some of these cavities experienced instability phenomena, in some cases inducing severe damages to the buildings founded above.

In April 2012 a sinkhole occurred in the cloister of San Marcellino, some meters wide and 1.5 m deep. Due to the concern that the sinkhole could be the symptom of an instability phenomenon in the underlying cavities, a geological and geotechnical investigation was conducted.
The investigation finally concluded that the sinkhole was actually due to a leak of a water main, that produced a collapse in the shallower pyroclastic deposits, without any interference with the stability of the cavity located a few meters below. Nevertheless, the static condition of a few cavities located in NYT between 12 and 20 m beneath the main building has been analysed within the MOSCAS project. For this reason, additional geological and geotechnical survey were carried out.

The system of cavities below the building of San Marcellino is shown in Figure 3. From the basement of the building, that currently serves as a warehouse, stairs depart to access to a first level of cavities: the tunnels of the ancient aqueduct of Bolla. Their vault is mainly excavated in pyroclastic silty sand (pozzolana) and lined with tuff blocks. Their invert is excavated in the NYT. A further deeper cavity, entirely excavated in tuff, is found at the end of the stairs shaft. This cavity served originally as tuff borrow pit and it is nowadays used as seat for a deep accelerometric station. A laser scanner survey was carried out to produce a high-definition three-dimensional point cloud of the cavity system beneath the building.

Figure 2. Geomorphological map of the urban area of Napoli and landscape evolution between 300 and 500 AD (modified after Ascione et al., 2020). The location of San Marcellino complex is highlighted with a red circle.

3. Stratigraphic and geotechnical model

The geotechnical model has been determined by the interpretation of the results of the geological investigation campaign that consisted of five boreholes (Figure 4a), eight SPT tests, four direct shear tests, four oedometric tests, a Down-Hole and a Multichannel Analysis of Surface Waves (MASW).

The S4 and S5 boreholes were carried out within the SNECS research project (Historic Center Social Network — in Italian, Social Network delle Entità dei Centri Storici – Petrosino et al., 2021) to design and sizing a low enthalpy geothermal plant, based on a closed-loop geothermal system and a heat pump (Massarotti et al., 2021).

The local stratigraphic characteristics of site are shown in figure 4b. Groundwater table is located at about 25 m b.g.l., that is a few meters below the cavity floor.
Figure 3. Geometrical asset of the cavities: a) 3D point cloud from laser scanner survey; b) photos of the building basement used as warehouse; c) photos of the stairs; d) photos of the ancient aqueduct tunnels; e) photos of the deeper cavity, originally a tuff borrow pit.

Figure 4. Boreholes (a); ground stratigraphy (b).

All the identified soil layers are made of coarse-grained materials; therefore in situ testing was generally preferred to determine their mechanical properties. Angles of shear resistance were determined according to Mitchell et al. (1978). Cohesion was assumed null for all the coarse-grained material. Soil stiffness was determined from the results of the Down-Hole tests; hence its value is referred to the small strain elastic behaviour. NYT was characterized from literature (Aversa and Evangelista, 1998;
Evangelista et al., 2002; Picarelli et al., 2007). A summary of the material parameters is provided in table 1.

| Layer                      | $\gamma_{nat}$ (kN/m$^3$) | $\sigma_c$ (MPa) | $c'$ (kPa) | $\phi'$ (°) | $\nu$ | $G$ (MPa) | $E'$ (MPa) |
|----------------------------|---------------------------|-----------------|------------|------------|------|-----------|-----------|
| Made ground                | 16.0                      | -               | 0.0        | 35.0       | 0.24 | 101       | 250       |
| Silty sand (pozzolana)     | 14.9                      | -               | 0.0        | 37.0       | 0.42 | 88        | 250       |
| Gravelly sand (pumices)    | 9.2                       | -               | 0.0        | 34.0       | 0.34 | 168       | 450       |
| Gravelly silty sand        | 16.2                      | -               | 0.0        | 33.0       | 0.34 | 168       | 450       |
| NYT                        | 16.0                      | 3.0             | 0.3        | 866.0      | 0.30 | 1500      | 1500      |

4. Stability analysis

The stability conditions of the deeper cavity (the tuff borrow pit) were preliminarily assessed by using the simplified analytical approach proposed by Evangelista et al. (2000) for roof stability of a rectangular cavity in tuff underlying a layer of soft ground. This assumes that cracks may develop at the cavity roof, propagating from the zones in tension, and a brittle failure may occur as shown in figure 5: the cavity roof separates in two blocks.

![Figure 5. Two-blocks roof failure mechanism (modified after Evangelista et al, 2000).](image)

By imposing the equilibrium to rotation, the critical length which gives rise to this mechanism can be calculated as:

$$L_{crit} = 1.225 \cdot t \cdot \left(\frac{\sigma_c}{\sigma_v}\right)^{0.5}$$

(1)

Where $\sigma_c$ is the compressive strength of tuff, $\sigma_v$ is the overburden stress acting on tuff, $t$ is the thickness of the cavity roof.

In this simple model the strength contribution of the overlying soil layer is neglected and the condition of stability of the cavity roof is determined by the ratio $L/t$, between the span of the cavity, $L$, and its thickness $t$.

By reversing Eq. (1), the minimum uniaxial compressive strength that is necessary for stability can be calculated as:

$$\sigma_{c,min} = 0.66 \cdot \sigma_v \cdot \left(\frac{L}{t}\right)^2$$

(2)

Hence, a safety factor $SF_{\sigma_c}$ can be defined as:
The weight of the building of San Marcellino, founded above the cavity, was estimated considering the structure geometry, its construction method and use. Hence, this weight was introduced in the calculations by applying at the top of the basement level a uniform vertical load equal to 48 kPa. This affects the value of $\sigma_v$ in Eq. 3.

Two perpendicular sections of the cavity were analysed, shown in figure 6 on the plan view of the cavity system beneath the building. Both sections are located in the main room of the cavity. They are oriented along the directions of the transverse walls (1) and of the main façade (2) of the main building of San Marcellino, that is founded above the cavity. A constant thickness, $t$, was assumed for the roof of the two sections, hence the value $L/t$ was computed as 3.7 (section 1) and 6.9 (section 2).

Considering the parameters in table 1 the following values of safety factor $SF_{\sigma_c}$ were computed according to Eq. (3): $SF_{\sigma_c} = 1.4$ for Section 1 and $SF_{\sigma_c} = 0.4$ for Section 2.

Such a simplified calculation had raised concern on the stability of the cavity. Therefore, numerical analyses were needed to investigate the problem with better accuracy.

Plane strain analyses were performed by means of a fem code (Plaxis 2D), neglecting conservatively any effect arising from the three-dimensional stress distribution (D’Agostino et al. 2010). The mechanical behaviours of the soil layers and the tuff were described with a simple elastic-perfectly plastic constitutive model, with a Mohr-Coulomb failure criterium, using the material parameters shown in table 1. The numerical domain was extended horizontally 25 m on both sides of the cavity central axis and vertically from the ground level up to 25 m below, that is enough to avoid any boundary effects on the soil volume around the cavity. The finite elements model was made of triangular elements with 15 nodes, hence the Section 1-1 contains 15833 nodes and 1960 elements, whereas the Section 2-2 contains 19181 nodes and 2378 elements.

Since groundwater table was located a few meters below the cavity floor, pore water pressures were neglected in the analyses.

![Figure 6. View of the two analysed sections.](image)

The current state of stress around the cavity has been calculated by simulating a staged construction, by supposing that the cavity was excavated in parts, by dividing its final section in three horizontal layers that were removed in sequence, starting from the top to the bottom.

Following this stage, the stability conditions have been assessed using a common numerical procedure that consists in progressively reducing the original shear strength of the materials.

The safety factor $SF$ is defined according to the following equation:

$$SF = \frac{c'}{c'_{\text{red}}} = \frac{\tan \phi'}{\tan \phi'_{\text{red}}}$$

(4)
In Eq (4) $c'_{red}$ and $\phi'_{red}$ are the reduced shear strength parameters. The safety factor of the cavity, SF, is identified on a curve plotting SF($c'_{red}$, $\phi'_{red}$) as a function of the displacement of an appropriately selected node, where the calculated SF($c'_{red}$, $\phi'_{red}$) keeps constant in subsequent steps.

Safety factor $SF = 3.32$ was calculated for section 1 and $SF = 1.78$ for section 2.

Although the two safety factors defined in Eq. (3) and Eq. (4), $SF_{\sigma_c}$ and $SF$, are not directly comparable, since by reducing both $c'$ and $\phi'$ by $SF$, $\sigma_c$ would be reduced more than $SF_{\sigma_c}$, this study shows that the safety margin estimated by the numerical analysis is larger than that computed by the simplified equilibrium in figure 5 since, differently from Evangelista et al. (2000), the strength contribution of the upper soil layers is taken into account (as also shown by Sannino, 2020).

The numerical calculation allowed also identifying stress concentration in correspondence of singularities in the profile of the transverse section and a large volume of tuff at the cavity roof where very low horizontal stresses may indicate the onset of cracking (figure 7). Actually, this volume corresponds in section 2 to a clear evidence of an ancient block fall from the roof of the cavity (figure 8).

**Figure 7.** Numerical results for section 1-1 a) Deviatoric stress; b) Minimum principal stress (tensile is positive).

**Figure 8.** Numerical results for section 1-1 a) Deviatoric stress; b) Minimum principal stress (tensile is positive).

5. Conclusions
A large part of the historical city centre of Napoli is characterized by loose pyroclastic soils overlying a bedrock made by Neapolitan Yellow Tuff. This latter material has been quarried over the centuries and widely used as a building material. Several tunnels for water supply were also excavated since Greek and Roman ages, thus creating a widespread network inside NYT.

Within the framework of the MOSCAS research project, the safety level of one of these cavities, located underneath the historic building of San Marcellino has been assessed.

A complete site investigation was carried out, consisting of a 3D laser scanner survey of the cavity system and of several boreholes from the ground surface, with the sampling of a number of soil specimens for laboratory testing, and a geophysical survey with a combined use of a Down Hole and a MASW.
Finite element numerical analyses were carried out to investigate the stability of the cavity beneath the main building, that caused concern for its proximity to the building foundations and the limited thickness of the tuff layer above its roof.

The stresses within the rock masses following a simulated opening of the cavity were calculated. A procedure of progressive reduction of the strength parameters of the soil layers above and of tuff, allowed to assess that the cavity is stable in its current geometrical configuration.

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