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Sinkhole risk assessment in the metropolitan area of Napoli, Italy

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Abstract

The city of Naples and its neighboring is an example of urban area affected by frequent anthropogenic sinkholes. They occur where the mining of tuff at shallow depth left a wide and complex network of cavities. The collapse is usually triggered by the soaking of the overlying pyroclastic soils forwarded by the presence of leakage from aged aqueducts and sewerages. This note reports the first results of a multidisciplinary research activity aimed at enhance the knowledge of the triggering factors of these phenomena in urban contexts. The study focused on an area characterized by the presence of cavities dug in tuff, starting from the research and collection of their location and that of past collapse events. In particular, the paper presents the results of sinkhole occurrence assessment at both local and metropolitan scale. In the first case, in order to define the most likely triggering mechanisms a case study among the recent sinkholes was investigated. A detailed field survey of the phenomena permitted to define the stratigraphical and geometrical setting of the pre-existing cavity and collect soil and rock samples for the geotechnical characterization. The attained results permitted to identify the most relevant parameters that influence the susceptibility assessment in a study area at metropolitan scale.This study represents contribute to the definition of a procedure to study anthropogenic sinkhole in intensely urbanized areas and it represents a valuable support for future planning strategies of risk mitigation.

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Keywords: Anthropogenic sinkhole; Campanian grey tuff; cavity; sinkhole susceptibility

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1. Introduction

The origin and evolution of a sinkhole can be related to both natural and anthropic factors; Bates and Jackson [1] defines sinkhole as a circular depression in karst areas, however, when they are not associated to karst the definition of anthropogenic sinkholes can be more appropriated. Sinkholes constitute a relevant risk for the communities, because the phenomenon is suddenly triggered, and predictions cannot be easily assessed. They are observed in many countries and in different geological and geomorphological environments [2,3]. Several authors studied anthropogenic sinkholes occurred both in rural and mining areas [4] and highly urbanized contexts [5,6,7,8].

The territory of the city of Naples and its metropolitan area is one of the urbanised Italian areas most affected by sinkholes [9,10]. These phenomena involve tuff and loose pyroclastic soils and occur, where the mining in historical times left a complex system of underground cavities. In fact, the availability of soft rocks characterized by good mechanical properties located at few meters from ground, as the tuff, made it suitable for the building industries. An analogue network of cavities to those of Naples can be found in the hinterland areas, below the historical centres of the municipalities of Afragola, Arzano, Cardito, Casalnuovo, Casavatore, Casoria and Frattamaggiore, which, in turn, resulted the most affected by sinkholes in the last decade.

The research can be divided into two phases: 1) the definition and validation of the most common mode of failure for anthropogenic sinkhole, recently occurred in the inner sector of the Campanian Plain; 2) identification of a zonation criterion at the scale of the urban centre. The results present in this paper were based on the detailed stratigraphical and geometrical reconstruction of a pre-existing cavity and the collection of soil and rock samples for the geotechnical characterization of both the tuff and the pyroclastic soil. Conversely, the analysis of the occurred sinkholes permitted to define the main parameters which affect the sinkholes susceptibility.

2. Geological Settings

The city of Naples and its metropolitan area is located in the Campanian Plain, which is a wide and deep structural depression (graben) originated during the Plio-Pleistocene by the opening of the Tyrrhenian Sea. The graben is made of a carbonatic bedrock filled at the base with terrigenous Mio-Pliocenic successions, while the top is constituted by 200 m of interbedded pyroclastic, marine and alluvial deposits of Late Pleistocene Age [11,12,13].

The thick volcanic sequences are correlated to the volcanic activity of the three main Campanian volcanoes, i.e. Roccamonfina, Phlaegrean Fields and Somma-Vesuvius. The explosive activity of those volcanoes strongly conditioned the stratigraphic setting and the morphology of the Campanian Plain, which for the first 40-50 m is filled with pyroclastic fall and flow deposits.

The shallower deposits bury two relevant Ignimbrite Formations, the Campanian Ignimbrite (39000 years BP) and the Neapolitan Yellow Tuff (12000BP) [14,15]. The former widely cover the whole plain, while the latter mainly crop out in the city of Naples (Fig. 1).

For their good mechanical properties, i.e. high compression strength, low specific weight and shallow depth from ground level, they were involved since historical times in an extensive mining activity, from which a very dense network of cavities was inherited.

3. Main features of cavities and sinkholes in the study area

In Figure 1, a typical collapse sinkhole of the Campanian plain is shown. Figure 1b shows the plan view of the system of cavities, while Figure 1c shows the stratigraphic contact between the Tuff and the loose pyroclastic cover. The failure is triggered to the leak from a water or sewer pipelines, which may induce slow saturation of pyroclastic soils at the roof of the cavity, with an overall increase of weight and a reduction of the shear strength due to the decreasing of matric suction [18]. The weakest spot is usually the well of access or “occhio di monte”, which represents a preferential flow path for the water that infiltrating increases the thrusting forces on the wall of the well, leading to failure of the soil for active state or a collapse of the soil initially unsaturated. This mode of collapse leads, along with stresses increase due to the presence of water, to the brittle failure of the vault of the cavity generally already in precarious equilibrium conditions.

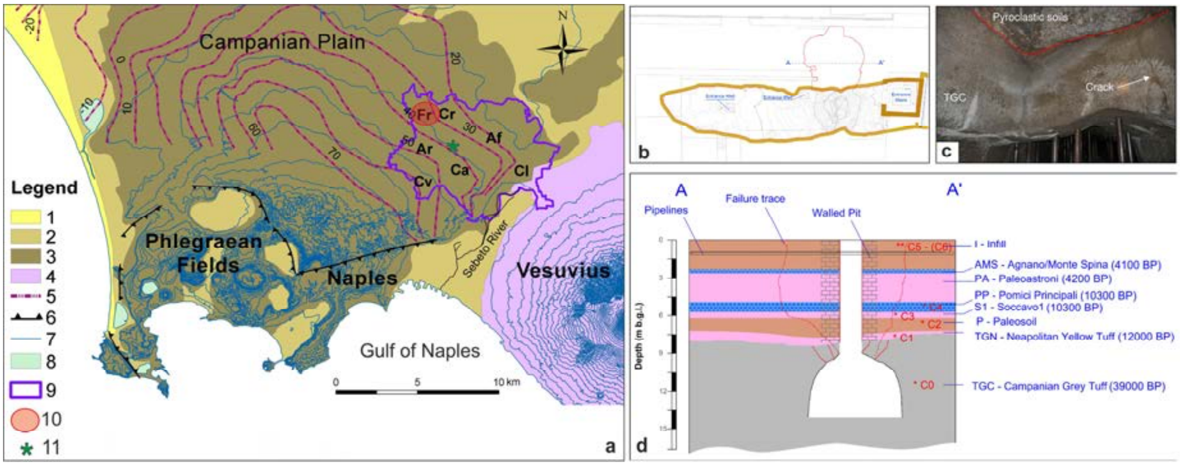

Fig. 1. a) Simplified geological map of Naples and its metropolitan area. [modified after 16]. Legend: 1) coastal deposits (Holocene); 2) alluvial and colluvial deposits (Holocene); 3) pyroclastic deposits and tuffs of Phlegraean Fields (Upper Pleistocene - Holocene); 4) pyroclastic deposits and lavas of Somma-Vesuvius (Upper Pleistocene – Holocene); 5) contours of the top of Campanian Ignimbrite (meters above sea level); 6) Campanian Ignimbrite caldera; 7) contour elevation (25 m); 8) lakes; 9) main municipalities affected by historical sinkholes (Af = Afragola, Ar = Arzano, Ca = Casoria, Cr = Cardito, Cl = Casalnuovo, Cv = Casavatore, Fr = Frattamaggiore); 10) case study at metropolitan scale; 11) case study at local scale. b)Plan view of the Anthropogenic sinkhole occurred in the study area.;c) Detail of the stratigraphic contact between the Tuff and the pyroclastic soils of the case study; d) Geological and geotechnical model of the case study at local scale.

The cavities are usually located within 10 m from the ground level and they are dug in the lithic portion of the Campanian Grey Tuff (TGC). In the study case the gallery is about 10 m long, the width is about 7.3 m, the height is 5 m. The vault of the tuff layer is about 1 m thick and it is overlied by 9 m of a pyroclastic succession mainly made of sandy ashes, with some relevant layer of pumices. In Figure 1d, the local stratigraphy and the location of the disturbed and undisturbed soil samples collected is shown.Starting from the ground level the stratigraphic setting is made of nearly 2 m of Infill, constituted by reworked ashes and paleosoils, a 30 cm thick layer of pumices coming from the AMS eruption (4100BP), which overlie a 2,5 m thick succession of ashes, pumices and lithics of the Paleoastroni eruption (4200BP). At the mean depth of 5 m from ground level a relevant 80 cm thick layers of pumices in ashy matrix is found (PP, 10300BP), which overlie a silty ashes succession nearly 2.5 m thick (S1, P). Finally, a thin layer of ash coming from the most distal *facies* of the TGN rests at the top of the lithic *facies* of the TGC.The groundwater level is far below the bed of the TGC, while the pyroclastic soils are usually in unsaturated conditions.

4. Case study at local scale

The laboratory investigations were carried out on cylindrical specimens collected from some blocks of TGC fallen in the study cavity. The testing program is reported in Table 1.

Table 2 reports the average physical properties of the collected samples. The compression wave velocity (V_P) was firstly measured before the other tests through ultrasonic pulse probes, in order to indirectly evaluate the homogeneity of the samples and the relationship with the degree of saturation. The unconfined compression strength, UCS, decreases with water content and with the increase of porosity. This strength reduction is in agreement with that observed on fine Neapolitan yellow tuff [17,18] and Campanian grey tuff [19].

The tensile strength, σ_T, of the rock was measured indirectly through the bending test according to UNI EN 196-1. The shear strength parameters (c' and φ') were derived from the results of isotropic triaxial tests carried out on dried specimens and on saturated ones at the laboratory of the Federico II University. The results of these tests were reported in Figure 2 in the plane of effective principal stresses. It shows that the envelope accordingly follow the Mohr Coulomb failure criterion with the minimum values generally in saturated conditions.

Table 1. Testing program.

Test type	σ'c (kPa)	N. of samples	Specimen condition
UNIAX	0	5	wet & dry water content
TENSIL	0	5	dry water content
TX-CID	150-300-700/800	4	Saturated and dry samples

Table 2. Mean physical and mechanical properties of the samples.

Gs	γ	γd	n	Sr	V_P	UCS min - max	σ_T mean ± Dev.St.	φ' mean	c' min - max
(-)	kN/m^3	kN/m^3	%	%	m/s	MPa	MPa	°	kPa
2.39	13.4	11.4	51	31	2010	1.13 – 3.37	0.61±0.371	30	400 - 600

The behavior of the materials was then compared with that reported in the literature for other pyroclastic weak rocks [20,21]. The shear strength resulted inferior to the other tuffs mainly in terms of cohesion, while the behavior was fragile at dry condition and ductile with contractive volumetric strains in saturated conditions in the tested range of confinement. A typical cavity, as the one depicted in Figs. 1b-d, was assumed as case study. Simplified analyses were performed, with reference to the mechanisms of local or general failure of the roof, following the methods proposed by Evangelista et al. [22]. The critical vault span, L_c, which would lead to the general collapse of the roof, was calculated through the equation:

$$L_c = 1.225 \cdot t \cdot \left(\frac{UCS}{\sigma_v} \right)^{0.5} \tag{1}$$

where t is the thickness of the roof, σ_v is the vertical stress at the depth of the roof before digging.

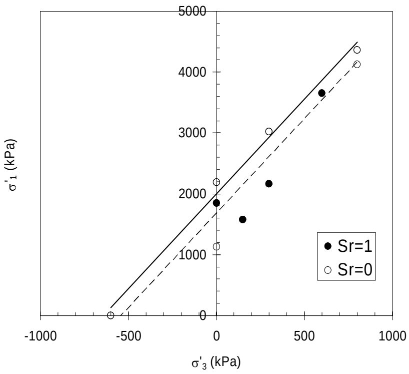

Fig. 2. Envelope of TGC peak strength.

The safety factor was calculated for the different values of t and according to the depth of the TGC as the ratio between the existing extraction width, L, and the critical span, L_c, evaluated by eq. (1). The minimum and maximum value of the uniaxial compressive strength $\sigma_{UCS,}$ coming from the experimental results were adopted. For a thickness of 1 m of TGC, critical length resulted from 3.9 m to 6.7 with a safety factor (SF) equal to 0.53 to 0.91. In this case, the widths of the gallery are less or about equal to the critical ones. It is clear that the evaluation is conservative. This last assumption was demonstrated by means of extensive parametric studies carried out in 2D plane strain condition with Finite Difference and Finite Element analyses, reported by Evangelista et al. [20]. However, this evaluation is at the same time unsafe, because it can assess the general failure of the roof, but it cannot exclude local failure mechanisms such as block or slab falls, related to the discontinuity network and to the crack propagation due to the brittle behaviour of the tuff [21].This approach was then inserted together with other parameters as input for the evaluation of the susceptibility at the triggering of sinkhole in a selected municipality of the Campanian Plain.

5. Case study at metropolitan scale

The analysis of the sinkholes occurred in the study area showed that the main predisposing factor to the occurrence of sinkholes is the presence of a network of pre-existing cavities in the tuff formation of the Campanian Ignimbrite (TGC) at small depth below ground level. The collapse frequently occurred along the abandoned or not maintained wells of access. The availability of underground waters (i.e. sewers, aqueducts and their intersections) is a relevant factor, as punctual or systematic water loss can slowly saturate the ground at the roof of the cavity, affecting its stability. A cascading effect can be triggered, as small leaks prompt small chasms which in turn, if poorly controlled and arranged can cause new breakage of the network, bigger failures and finally the collapse.

A procedure for a first level of zonation of the susceptibility to sinkhole is attempted. It identifies the areas characterized by high susceptibility, where focus additional investigations. The method was conceived as a sum of scores attributed to the following parameters:

- Presence of a underground cavity;
- Progressive depth of the Tuff and Increase of the Pyroclastic cover;
- Progressive distance from sewer network;
- Progressive distance from aqueduct pipelines;
- Safety factor according to section 5.

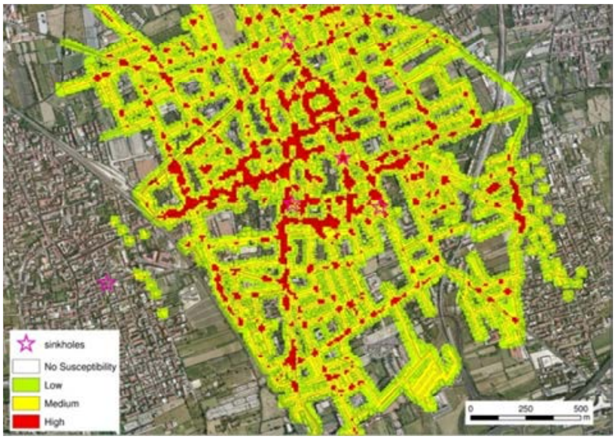

Fig. 3. Sinkhole susceptibility map for the municipality of Frattamaggiore.

The highest values of susceptibility correspond to the areas where all above-mentioned factors occur and are usually located in the historical core of the town. Conversely, lowest and null values are attributed where no sinkhole and cavities are present and a reduced presence of water networks is associated. Average values of susceptibility are finally found where no data on historical sinkholes are present, but predisposing conditions (cavity, surface water networks) for the triggering exist. In Figure 3 an application for the municipality of Frattamaggiore is shown.

Conclusions

The Campanian plain and the hinterland of Naples are an example of urban area affected by frequent anthropogenic sinkholes. The cavities are usually located within 10 m from the ground level and they are dug in the lithic portion of the Campanian Grey Tuff (TGC), where the vault is usually 1 m thick layer of tuff overlied by pyroclastic soils and the failure is usually triggered by the leak from a water or sewer pipelines. The performed geotechnical laboratory investigations permitted to characterize the unconfined compression strength, the tensile strength and the shear strength parameters. The envelope of failure data follows the Mohr Coulomb criterion with value of cohesion lesser than other Campanian tuffs. These results together with the presence of a network of underground cavities, the depth of the tuff, the distance from sewer network and aqueduct pipelines, were adopted to provide a method to define the sinkholes susceptibility at the scale of the municipality. The method was conceived as a sum of scores and identifies the areas characterized by high susceptibility, where focus additional investigations.This study attempted to contribute to the definition of a procedure for the study of anthropogenic sinkhole in intensely urbanized areas and it represents a valuable support for future planning strategies of risk mitigation.

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