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Geo-Archaeological sites in the Campi Flegrei volcanic Complex: Historical, Geological, and Geotechnical Analysis for their preservation

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ABSTRACT: The Campi Flegrei volcanic complex provides a unique setting where archaeological remains coexist with active geological processes. Archaeological research has revealed that the current coastline lies far inland compared to the ancient shorelines, with submerged remains clearly showing the original extent of Roman settlements. Processes of ground lowering and raising have shaped a striking coastal landscape, where modern buildings stand on Roman ruins atop cliffs, with submerged structures extending into the sea. Frequent slope instabilities, mainly triggered by rainfall and seismic events, threaten both modern structures and valuable archaeological sites. This study investigates the mechanical behaviour of collapsible unsaturated pyroclastic deposits and tuff formations that influence cliff stability in the area. The textural and petrographic characterization of the unsaturated pyroclastic deposits was performed to clarify the origin of their collapse-prone behaviour. Laboratory analyses, including oedometer and direct shear tests on intact samples, demonstrate the collapsible nature of the Intracaldera Phlegraean Deposits (IPD) and quantify their collapse potential under wetting conditions. The results reveal a marked reduction in strength and volume stability upon saturation, confirming the key role of collapsible pyroclastic covers in triggering cliff failures and generating discontinuities within the rock mass. Finally, to assess cliff stability, a preliminary numerical modeling process was developed. Simulations show that failure mechanisms localize within the collapsible IPD layer, where safety factors approach critical values due to wetting. The results provide new insight into the geotechnical controls on slope stability in volcanic–archaeological contexts and supports strategies for preserving the geo-cultural heritage of the Campi Flegrei area.

KEYWORDS: Unsaturated pyroclastic soils and rocks, collapse potential, cliff instability, bradyseism, seismic condition

1 INTRODUCTION

1.1 Geo-Archaeological Framework of the Campi Flegrei Volcanic Complex

Many historical sites in Central-Southern Italy, including Rome, Naples, Pompeii, and Herculaneum, are built on or buried in pyroclastic deposits. In antiquity, these volcanic materials were widely used in construction due to their advantageous properties, such as the hydraulic behaviour of pozzolana. However, their geotechnical behavior remains only partially understood - particularly the processes of lithification and the variability of mechanical properties- which complicate sampling testing, and engineering assessment. The Campi Flegrei volcanic district, located within the Gulf of Pozzuoli on the western side of south-central Italy (Figure 1), has long been subject to instability phenomena affecting both natural slopes and archaeological sites. This densely populated volcanic complex covers approximately 12 km² and is among the most geologically active zones in Italy (Di Vito et al. 2016).

The Campi Flegrei caldera is a complex, polygenetic structure formed by two major explosive events: the Campanian Ignimbrite eruption (~39 ka BP) and the Neapolitan Yellow Tuff eruption (~15 ka BP). The two main events were followed by three phases of volcanic activity that produced numerous craters, many of which are still morphologically distinct today. The last eruption occurred in historical times (1538 AD), forming the Monte Nuovo tuff cone.

The Campi Flegrei is worldwide known for its bradyseismic phenomena, abrupt vertical ground movements of volcano-tectonic origin related to the inflating and deflating of the magmatic chambers, responsible for coastal landscape abrupt transformations, particularly during the Holocene (Mattei et al. 2024). The most recent bradyseismic crisis (1983–1985) caused an uplift of almost 2 meters, with visible consequences still observable in the harbour of Pozzuoli. Nowadays, the area is uplifting at an average rate of 20±3 mm/month (INGV- OV, Bollettino di Sorveglianza Campi Flegrei, June 2025). Etymologically, "Campi Flegrei" derives from the Greek fleguros ("burning"), a reference to intense volcanic activity. The region extends from Posillipo to Cuma (Figure 1), historically settled by colonists from Euboea and Chalcis. Underwater archaeological research has shown that the ancient coastline lay far seaward of its present position, revealing the original extent of Roman settlements now partly submerged. The fertility of the land made Pozzuoli a flourishing production and commercial center, where foreign merchants were active and grain ships from Egypt arrived regularly. Baia was known for its amenities, luxurious villas with their own piscinae, high-quality seafood, and splendid spas. The naval fleet was based in Miseno, a detachment of which sailed toward Herculaneum to assist the population, as attested by Pliny and the Roman liburna found on the beach of the ancient city. The phenomenon of bradyseism was already known to the ancients (ex aliis Simm. Ep. 1,8,1). The intensification of the processes of lowering and raising the ground level currently restore a very interesting coastal landscape, where modern buildings currently stand on Roman buildings located on cliffs overlooking the sea, occupied in the stretch in front by submerged structures. The presence of these biological traces, found up to +7 m MSL, reveals significant ground subsidence during the Middle Ages, followed by periods of notable uplift. One of the testimonies of the present and past volcano-tectonic activity is the well-known Serapis Temple in Pozzuoli, also known as Serapeo or Macellum.

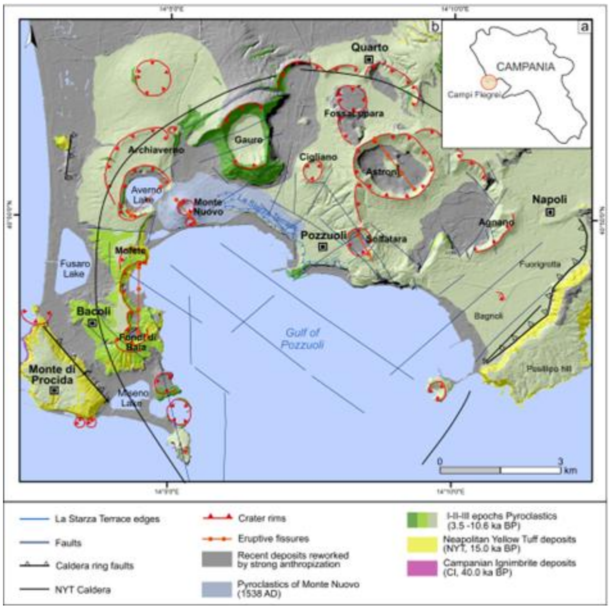

Figure 1. Geological map of the Campi Flegrei volcanic area (modified after Aucelli et al. 2020).

Built during the Flavian dynasty (69–96 AD), this remarkable site represents a key reference point for geological research, particularly for studies concerning sea-level fluctuations in volcanic regions. Indeed, the marble columns of the Macellum, perforated by Lithophaga mollusks (Figure 2), serve as natural sea-level indicators and vividly illustrate cycles of subsidence and uplift.

Figure 2. Marble columns of the Macellum, perforated by *Lithophaga* mollusks.

Historical drawings and photographs have allowed researchers to treat the Macellum as the earliest geodetic station in the Campi Flegrei network, documenting ground deformation since at least 1908. These long-term observations have guided subsequent studies, allowing geoscientists to reconstruct volcano-tectonic movements and landscape evolution throughout the Holocene (Morhange et al. 2006; Di Vito et al. 2016; Mattei et al. 2024).

1.2 Geotechnical aspects

The Campi Flegrei area is frequently affected by slope instability phenomena, primarily triggered by two main factors: intense rainfall and seismic events (Calcaterra et al. 2010). These phenomena typically affect pyroclastic deposits, both loose and lithified, derived from the stratigraphic succession of volcanic eruptions, the same depositional processes that buried Herculaneum during the AD 79 eruption.

Field and laboratory studies have shown that landslide triggering is closely associated with intense or prolonged rainfall, which reduces matric suction and, consequently, the shear strength of the soil (Scotto di Santolo, 2000; Scotto di Santolo et al. 2005; Aversa et al. 2013; Nocilla et al. 2015). Collapsible pyroclastic soils played a key role in cliff failures and in the formation of discontinuities within the rock mass (Evangelista et al. 2010).

The collapsible behaviour of granular soils is controlled by their open metastable structure (Rogers, 1995), which forms through capillary forces, clay–silt bonding, and weak cementing agents such as carbonates and oxides (Barden et al. 1973; Clemence & Finbarr, 1981). These mechanisms generate an apparent cohesion often referred to as *bulking*. Capillary and ion-electrostatic bonds are particularly sensitive to wetting (Osipov & Sokolov, 1994). Collapse is triggered when matric suction decreases during wetting (Fredlund & Gan,1995; Zimbardo et al. 2018), causing the destruction of these bonding mechanisms and abrupt structural collapse.

Pereira and Fredlund (2000), through triaxial testing, identified three deformation phases in metastable, partially saturated soils: a pre-collapse phase characterized by minor elastic volumetric changes at low degrees of saturation; a major collapse phase, marked by significant volume reduction due to the decrease in matric suction and the consequent collapse of the soil structure; and a post-collapse phase, in which, once suction reaches zero, only limited deformations occur, resulting from the secondary compression of the soil skeleton.

For collapsible soils, it is possible to identify the degree of saturation that determines the transition from brittle to ductile behavior (Aversa et al. 2013), as well as the influence of matric suction on peak strength, shear strength parameters, and yield stress. The volume changes during wetting can be quantified as a function of stress state and initial density.

A comprehensive understanding of both internal factors (e.g., particle bonding, soil structure) and external triggers (e.g., infiltration, capillary rise, rainfall, localized water flow) is essential for developing effective measures to prevent instability linked to bond collapse.

Jennings and Knight (1975) classified collapse severity using the Collapse Potential (CP), defined as Equation(1):

$$CP = \frac{\Delta H}{H_0} = \frac{\Delta e}{1 + e_0} \times 100 \qquad (1)$$

where ΔH is the sample's height change upon flooding, H_0 is the initial height of the specimen, Δe is the change in void ratio upon flooding and e_0 is the void ratio at the natural water content. They also proposed a standardized CP test, in which the specimen is flooded under a vertical stress of 200 kPa.

The results provide a basis for evaluating slope stability through numerical simulations, supported by laboratory investigations characterizing the mechanical behavior of soils, tuff, and recent pyroclastic deposits involved in instability processes.

2 LABORATORY INVESTIGATION

To assess the role of collapse due to wetting or destructuration in instability processes, compositional, textural, and mechanical analyses - including direct shear and oedometer tests- were conducted on intact samples in both unsaturated and saturated states. These investigations allowed characterization of soil microstructure and properties, refined through comparison with literature data. The following section provides an overview of the mechanical characteristics of key pyroclastic formations in the Campi Flegrei area. These include: (1) Unlithified Pyroclastic Deposits - subdivided in unlithified Neapolitan Yellow Tuff YTP (known as Pozzolana) and pyroclastic products of the volcanic activity of Campi Flegrei younger than 15.000 years (Intracaldera Phlegrean pyroclastic Deposits, (IPD) that overlie the YTP - (2) Lithified Neapolitan Yellow Tuff (NYT).

2.1 Unlithified Pyroclastic Deposits

To accurately characterize the geotechnical and mineralogical properties (bonding strength) of IPD soils, a multi-technique analytical approach was adopted. This included micro and macrostructure analysis as grain size analysis, density measurements, Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS), thermogravimetric analysis (TGA), and Raman spectroscopy. The main findings from these investigations provide an overview of the soil's physical and chemical characteristics.

Grain size analyses, presented in Figure 3 and compared with literature data (Picarelli et al. 2007), confirm the highly heterogeneous nature of the material, ranging from fine sandy silt to well-graded silty sand and sandy gravel. No consistent depth-related trend in grain size variation was observed.

The specific gravity G_s and the dry weight per unit of volume γ_d were determined. The value of G_s of the soil was equal to 25.3 and γ_d was between 12.4 and 18.6 kN m^{-3}.

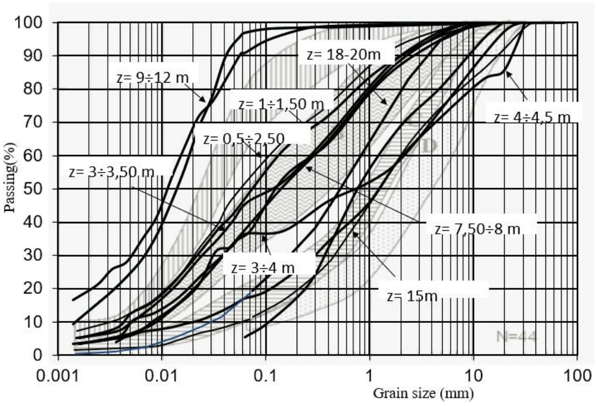

Figure 3. IPD: particle size distribution curves- black: present study; grey: literature data (modified from Picarelli et al. 2007).

SEM observations at low magnification (500×), coupled with EDS analyses, indicate that the soil exhibits a homogeneous composition dominated by silicon and aluminum. Potassium, sodium and magnesium are also abundant. Calcium is present and corresponds to carbonate phases identified through complementary mineralogical analyses. The EDS spectra also show detectable concentrations of iron and minor titanium, occurring as oxide phases. Overall, the sands consist predominantly of carbonate and aluminosilicate minerals, including augite, with a small but discernible fraction of clay minerals (Figure 4).

Figure 5 shows the conventional set of three thermoanalytical (TGA) curves: the percentage mass loss in the thermogravimetric (TG) curve, its first derivative (DTG), and the differential thermal analysis (DTA) curve. These curves revealed three major weight loss events. The first is associated with moisture loss, occurring between 30°C and 120°C. This is followed by a gradual weight loss without distinct peaks, which can reasonably be attributed to the presence of clay-based compounds, as indicated by the detection of silicon and aluminum in the EDS spectrum. Finally, a weight loss related to the decomposition of carbonates, primarily calcium carbonate, was observed. Raman spectroscopy conducted on the soil confirmed its composition and allowed the calcium carbonate content to be quantified at 8.82%.

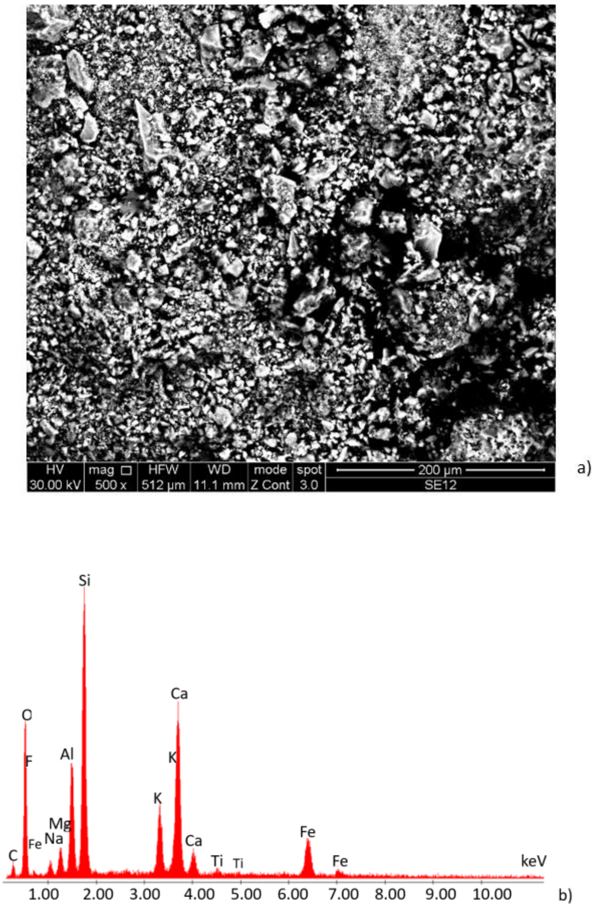

Figure 4. a) Scanning electron micrographs (SEM) b) EDS spectrum.

In order to investigate the Collapse Potential (CP), and compressibility characteristics of the soil, oedometer compression tests were performed on natural unsaturated soil samples subjected to saturation at vertical stress of 10 kPa, 20 kPa, and 200 kPa. In Figure 6 the void ratio is plotted against the applied vertical stress. Two distinct settlement phases can be identified: the first occurs under the natural moisture condition of the samples, while the second takes place after wetting with distilled water. A rapid settlement event between the two phases indicates collapse induced by wetting. In the same figure the experimental values of the void index variations (Δe) after cell flooding are shown.Unloading revealed that the compression process is largely irreversible due to structural collapse from loss of suction forces, which act similarly to weak cementation or grain interlocking (Kavvedas, 2000).

In this study, the evaluated Collapse Potential (CP) for the tested samples under a vertical stress of 200 kPa is 2.3%, corresponding to a moderate trouble collapse severity according to Jennings and Knight (1975).

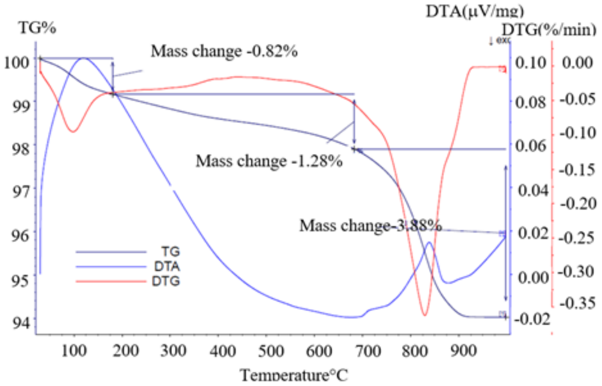

Figure 5. Thermogravimetric analysis (TGA) curves.

Figure 6 also includes the results from similar tests performed on YTP Pozzolana soil samples (Picarelli et al. 2007), for which CP values reach up to 5%, indicating a higher collapse severity. The CP value could be used as a reference for evaluating the susceptibility to instability phenomena in the Campi Flegrei area.

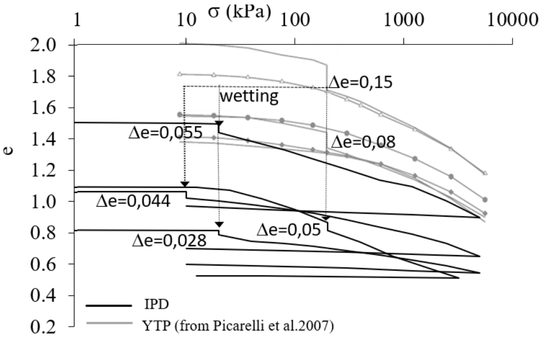

Figure 6. Results of oedometer compression tests on unsaturated sample with wetting phase

Figure 7 shows the reduction in void ratio (Δe) due to wetting as a function of initial void ratio (e_0). The diagram also reports the initial (S_i) and final (S_f) degrees of saturation, highlighting that the samples remained unsaturated despite cell flooding. It can be observed that the reduction in void ratio increases with increasing initial void ratio and, for the IPD soils, with increasing initial degree of saturation.

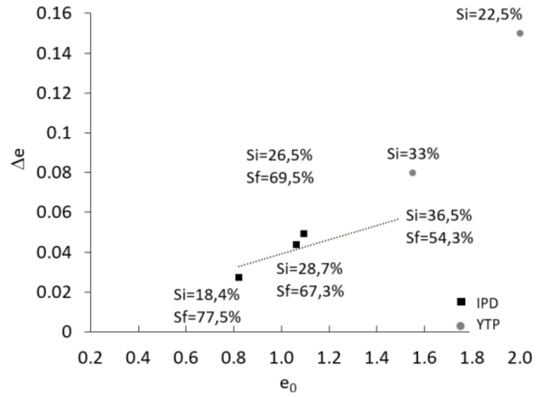

Figure 7. Quick variation of void index (Δe) for different values of initial void ratio (e_0).

Collapsible behavior of soil was also identified from direct shear test results. The experimental program included two distinct test procedures: (a) shear tests on natural samples subjected to wetting during shearing at peak strength, intended to investigate the effects of saturation occurring close to failure; and (b) direct shear tests on specimens saturated during the consolidation stage, used for comparative purposes as illustrated in Figure 8. A drop in shear stress, at the wetting phase, highlights a structural collapse. This response is more pronounced on Pozzolana (YTP) soil. Specimens sheared in unsaturated conditions initially tend to exhibit either dilative or contractive behavior depending on the applied normal stress.

However, once saturation is introduced, all samples display volumetric contraction accompanied by a sharp reduction in strength, clearly indicative of a collapse mechanism.

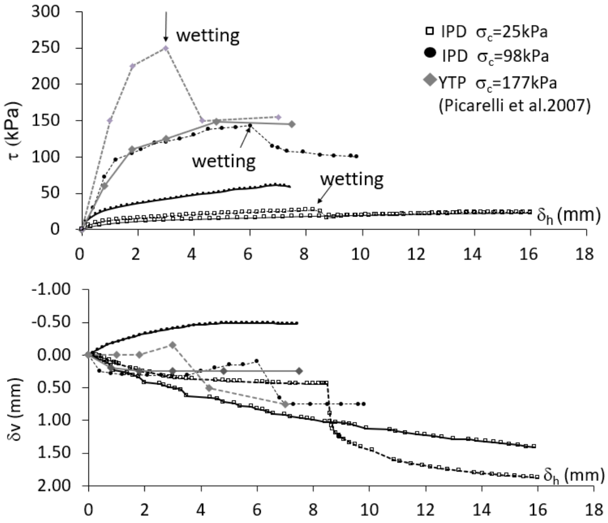

Figure 8. Shear tests on saturated samples (continuous line), samples wetted at peak (dashed line): a) shear stress (τ) vs. horizontal displacement (δ_h) b) vertical displacement (δ_v) vs. horizontal displacement (δ_h)

2.2 *Neapolitan Yellow Tuff NYT*

In the Campi Flegrei area, the Neapolitan Yellow Tuff (NYT) is widely distributed and emerges along both natural sea-facing cliffs and inland slopes (Figure 9). The NYT is characterized by a porous structure, with porosity values typically ranging between 30% and 50%, which significantly influence its mechanical behavior and durability. The uniaxial compressive strength (UCS) of NYT is highly variable, commonly ranging from 1 MPa to over 15 MPa depending on factors such as moisture content, weathering degree, dry unit weight, and stratigraphic position.

According to Nocilla et al. (2009), the NYT is classified as a Hard Soils–Soft Rocks (HSSR). Depending on the stress conditions, it exhibits different mechanical behaviors. Under triaxial compression, NYT specimens show a rock-like elastic behavior at low confining pressures, characterized by limited deformation. As the isotropic confining pressure increases, the behavior progressively transitions toward a soil-like (pulverulent) response, accompanied by significant volumetric deformations. It is possible to identify a specific stress value, yielding stress, at which the material transitions between elastic and elasto-plastic deformation regimes. In the rock-like phase, stresses are supported by both cementation and grain-to-grain contact. When cement strength is exceeded, destructuration process reduces interparticle bonding, shifting stress transmission toward grain contacts and causing a transition from rock-like to soil-like behavior, with significant changes in mechanical properties (Leroueil and Vaughan, 1990).

Experimental results indicate that the friction angle of NYT typically ranges between 25° and 35°, while cohesion values vary from 0.5 to 3.0 MPa. These variations are mainly attributed to the heterogeneous structure of the tuff (Aversa et al. 2013; Picarelli et al.2007).

Figure 9. Posillipo cliff, Naples.

3 NUMERICAL ANALYSES

Many cliffs in the Campi Flegrei area are partially saturated, requiring numerical modeling of unsaturated soil behavior for safety assessment. Mechanical behavior, influenced by matric suction and degree of saturation, affects shear strength and stiffness. Analyses used an elastic–perfectly plastic Mohr–Coulomb model with Bishop's stress to account for the strength increase induced by suction, while hydraulic behavior was described using the Van Genuchten (1980) soil water retention curve, calibrated with suction-controlled tests on pyroclastic soils (Picarelli et al. 2007) and initial condition based on matric suction monitoring (Scotto di Santolo et al. 2005).

The finite element model (Figure 11a) represents a typical sea-facing cliff in the Campi Flegrei area and was analyzed under plane strain using 15-node triangular elements in Plaxis 2D (Bentley, 2022). Base nodes were fixed in both directions, vertical boundaries allowed only horizontal movement, and the model width was sufficient to prevent boundary effects on the slope's mechanical response.

Numerical analyses under static conditions, aimed at reproducing the current stress state and assessing the corresponding safety conditions, were conducted by first initializing the model's stress state through the instantaneous activation of self-weight, along with the generation of pore water pressures and suction.

Subsequently, a steady-state seepage analysis was performed by applying the total hydraulic head on the vertical left boundary to simulate pore pressure distribution in the partially saturated soil mass. After defined the effective stress field, accounting for suction-induced shear strength, c–φ reduction analyses were carried out.

The parameters of the numerical model, Table 1, were calibrated based on the results of the tests reported in section 2.

Table 1. Parameters assumed in the model.

Soil	IPD	YTP	NYT	Unit
γ	18.6	14	14	kN/m^3
φ'	34	28	28	°
c'	2	250	500	kPa
ψ	0	0	0	°
E	240	187.6	276	MPa
ν	0.3	0.3	0.3	-

Figure 11b illustrates the failure mechanism in terms of deviatoric strain increments, obtained through static analysis, incorporating the suction field determined in the previous phase.

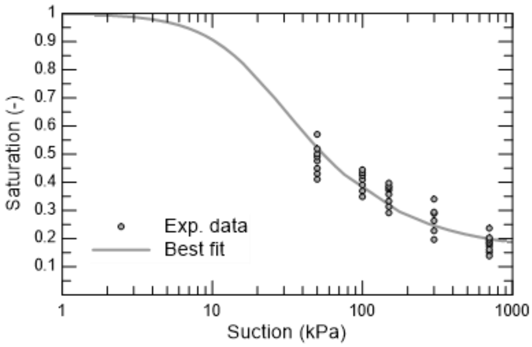

Figure 10. Experimental retention curve (Exp. data) and prediction using the Van Genuchten model.

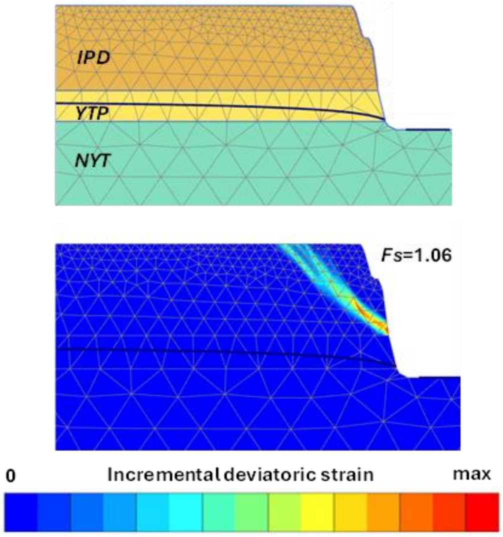

Figure 11. Fem model (a) and Failure mechanism under static condition (b).

It is evident that the failure mechanism is confined within the IPD layer, with a low factor of safety; full saturation from intense rainfall could reduce soil strength and trigger collapse. This scenario highlights the need for further investigation, which will be addressed in future studies.

Finally, pseudo-static analyses were carried out to evaluate the critical acceleration (a_c) associated with the onset of a collapse mechanism in the cliff. This was achieved through pushover analyses, progressively increasing the horizontal component of the body forces until the collapse mechanism was triggered. The resulting mechanism coincides with that identified under static conditions, and the corresponding critical acceleration is approximately 0.1 g. This relatively low value, comparable to that expected for the examined site according to the NTC18 code for the Life Safety Limit State (SLV), highlights the need, for a comprehensive safety assessment of the system, to further investigate its seismic performance by evaluating the displacements induced by a spectrum-compatible seismic inputs.

4 CONCLUSIONS

The Campi Flegrei volcanic complex exhibits a distinctive interplay of geological, archaeological, and environmental factors, presenting significant challenges for both slope stability and heritage conservation. This study characterized key formations, especially the collapsible Intracaldera Phlegraean Deposits (IPD) and the Neapolitan Yellow Tuff (NYT) - which are critical for understanding and modeling slope instability in the area. Laboratory analyses confirmed the collapsible nature of unlithified pyroclastic deposits, showing significant reductions in volume and shear strength upon wetting, while the Neapolitan Yellow Tuff (NYT) exhibited a transition from rock-like to soil-like behavior under varying stress states, influenced by its porous structure and destructuration processes. Numerical modelling, based on unsaturated soil mechanics, reliably simulated stress and suction conditions, showing that failure is concentrated in collapsible layers with near-critical safety factors. Further reduction in suction due to heavy or prolonged rainfall could trigger complex slope failures, including debris or mudflows.

Matrix suction plays a key role in slope stability, highlighting the need to account for unsaturated soil behaviour in analyses of pyroclastic deposits, particularly on very steep slopes. The CP value could then be used as a reference for evaluating susceptibility to instability, especially in geologically active and archaeologically sensitive areas such as Campi Flegrei. Future work will include parametric studies of rainfall infiltration scenarios and evaluations of potential microstructural stabilization treatments to reduce soil collapsibility. This multidisciplinary approach supports both landslide risk mitigation and the long-term preservation of a geologically and culturally unique landscape.

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