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Multiphysics Laboratory Tests for Modelling Gravity-Driven Instabilities at Slope Scale

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Abstract

Ischia Island (Italy) experienced slope instabilities during the Holocene that occurred at different scales, from shallow mass movements up to large rock and debris avalanches. These events were strictly related to volcano-tectonic activity and the presence of a well-developed hydrothermal system and mobilized significant volumes of greenish alkali-trachytic tuffs (Mt. Epomeo Green Tuff, MEGT). Ongoing gravity-induced slope deformations in the Mt. Nuovo region also involve the MEGT over an area of 1.2 km2. In order to constrain geometry and mechanism of this phenomenon, and to highlight possible interactions between the thermo-baric field of the hydrothermal system and stress-strain conditions related to the Mt. Nuovo slope deformations, laboratory tests were carried out to assess and characterize the mechanical behaviour of the MEGT. Physical properties of the MEGT were first measured, including porosity, permeability, and elastic wave velocity. Mechanical characterization was then performed using a combination of uniaxial, tensile, and triaxial experiments on as-collected samples and samples thermally stressed in the laboratory. The obtained results reveal MEGT to have a high porosity and permeability, and that it deforms in a compactant (i.e. ductile) manner at very low confining pressure (i.e. depth). The triaxial tests allow us to derive failure envelopes for MEGT under dry and water-saturated conditions, defining the range of stress conditions for failure.

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Keywords: Slope stability; landslides; hydrothermal system; mechanical behaviour; numerical modelling

1. Introduction

Flank instabilities represent the most common indirect geo-hazard related to volcanic activities. Destabilization is usually produced by a combination of predisposing and triggering factors. Although magma emplacement or

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earthquake shaking are the most common triggers able to produce external transient forcing that could interact with inner pressures or accelerate deformations [1, 2], hydrothermal systems may also play a significant role, influencing slope stability in two ways: i) alteration can weaken or strengthen the materials involved as function of PT conditions and the chemical composition of fluids [3] and ii) transiently increasing the stress field within the slope [4, 5, 6]. Such collapses can in turn trigger subsequent hazardous events in a sort of "domino effect" leading to the occurrence of explosive eruptions, triggered by the sudden decompression of shallow magma reservoirs or hydrothermal systems [7, 8] or, in the case of marine volcanoes, destructive tsunami waves [9]. The case study of a gravity-induced slope deformation affecting the edge of Ischia resurgent caldera is presented here; to account for a well-constrained mechanical behavior of the involved lithologies, in view of future multiphysics numerical modelling, a suite of mechanical laboratory tests was carried out.

2. Geological Framework

Ischia Island represents the westernmost part of Phlegrean Volcanic District (Southern Italy) and hosts several Holocene slope instabilities that occurred at different scales, from shallow landslides triggered by meteo-climatic events, up to massive rock slope failures such as large rock and debris avalanches related to the volcano-tectonic dynamics of an asymmetric resurgent caldera. Such landslides and slope deformations generally involved trachytic pyroclastic flow deposits named Mt. Epomeo Green Tuff (MEGT) [10], emplaced during an intense explosive eruption dated 55 ka [11]. This asymmetric resurgence, controlled and driven by the intrusion of a shallow magmatic body, strongly modified the geological evolution of the island producing a stable hydrothermal system and influencing the local seismicity, as well as the gravitational processes of the steep resurgent block [12]. Recent studies pointed out the presence of significant recent slope failures and ongoing slope-scale deformations on the island of Ischia (e.g. [13, 14]) that could be related to internal forces of the volcanic system. These gravitational phenomena consist of large-scale mass movements including lahars, debris flows and large debris avalanches whose volumes ranged between 0.5 and 1.5 km^3 [14, and references therein]. Ongoing deformations still involve part of the western edge of the resurgent block located in the Mt. Nuovo area. This area, prone to failure, could mobilize a volume of about 180-190 million cubic meters [14] that could cover the town of Forio (Fig. 1). Importantly, Ischia Island also hosts a stable hydrothermal system [15] characterized by high heat flow (200-400 mW/m^2) and several thermal springs and gas vents (i.e. fumaroles) with surface temperatures up to 100°C. The internal circulation of this hydrothermal system could interact with the slope-system thereby modifying the thermo-baric and stress-strain field. This could, in turn, negatively affect the mechanical behaviour of the rock mass [16, 17] through material degradation [3, 18, 19, 20, 21] and therefore jeopardize the stability of the rock mass (e.g. [4, 5]).

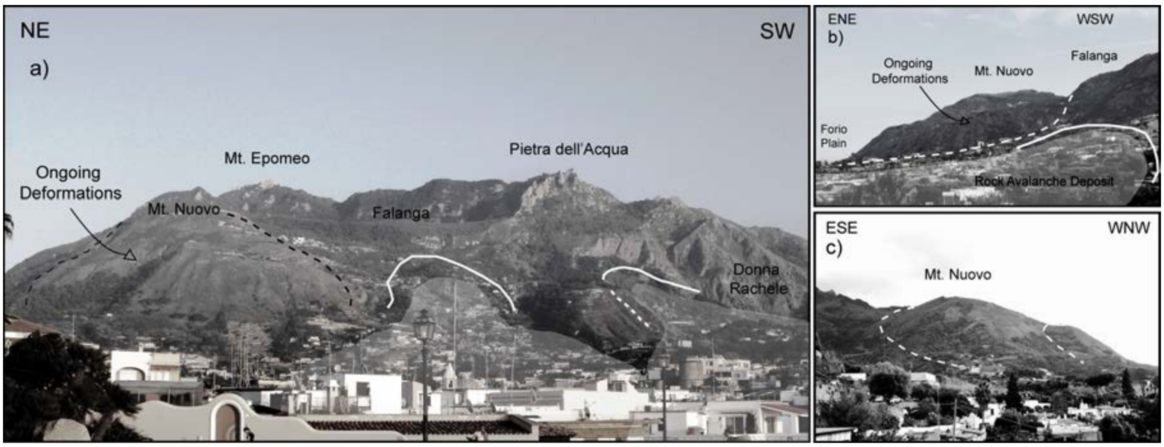

Fig. 1. (a) Panoramic view of the Mt. Epomeo relief from the Forio plain; the Mt. Nuovo area, involved in the ongoing gravitational deformation is clearly visible on the left side of the picture; (b) NW-SE view of the deformed block and of the apical zone of one of the documented rock avalanches [14]; (c) ESE-WNW view of ongoing deformation with secondary landslide terrace and counterslopes.

3. Multiphysics laboratory characterization

In order to investigate the possible thermo-mechanical interaction between the Ischia hydrothermal system and the development or evolution of shallow and deep gravity-driven slope deformation, laboratory tests were carried out to assess and characterize the mechanical response of the MEGT to various environmental conditions (i.e. lithostatic pressure, thermal stress, water-saturation). To this end cylindrical samples were prepared by dry-coring, to avoid washout of the fine fraction. We then performed a systematic laboratory study that probed the physical (porosity, elastic wave velocity, permeability) and mechanical properties of the MEGT (using a combination of uniaxial, tensile, and triaxial experiments) according to ISRM standard [22]. All the measurements and experiments were performed at the Géophysique Expérimentale laboratory at the Institut de Physique du Globe de Strasbourg (IPG Strasbourg).

3.1. Rock Physical Characterization

The rock physical properties of the MEGT were first measured (porosity, permeability, elastic wave velocity) on samples nominally 40 mm in length (L) and 20 mm in diameter (D) [22]. The data show that porosity spans between 36 and 52% (Fig. 2a) and permeability varies between 5×10^{-14} and 2.5×10^{-13} m^2 (Fig. 2b). We find that permeability varies by about an order of magnitude over this range of porosity, but not in a systematic manner (Fig. 2). Values of porosity and permeability were measured using a helium pycnometer (AccuPyc II 1340 Micromeritics®) and a steady-state gas (nitrogen) permeameter, respectively [23]. Permeability was measured under a confining pressure of 1 MPa.

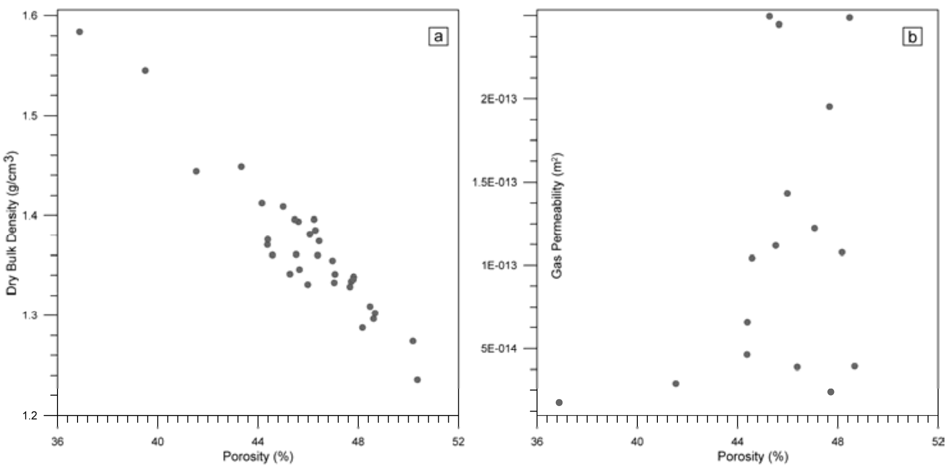

Fig. 2. (a) Porosity as a function of dry bulk density; (b) Permeability as a function of porosity.

3.2. Mechanical Characterization

3.2.1. Uniaxial experiments

Uniaxial Compressive Strength tests (UCS; $\sigma_1>\sigma_2=\sigma_3=0$) were performed on dry and water-saturated samples at a constant strain rate of 10^{-5} s^{-1} up to failure. The water-saturated samples were vacuumed-saturated in distilled water and then deformed inside a water bath, and the dry samples were vacuum-dried in an oven at a temperature of 40°C for at least 24 hours. UCS tests were performed on three different porosity classes (i.e. 40–44%; 44–48%; 48–52 %). The data highlight a clear decreasing trend for both uniaxial compressive strength and elastic moduli with increasing porosity (Fig. 3a). We find that an increase in porosity reduces the UCS (Fig. 3a). Strength is reduced from about 6.5 MPa to about 3 MPa as porosity is increased from 40–44% to 48–52%, respectively (Fig. 3a).

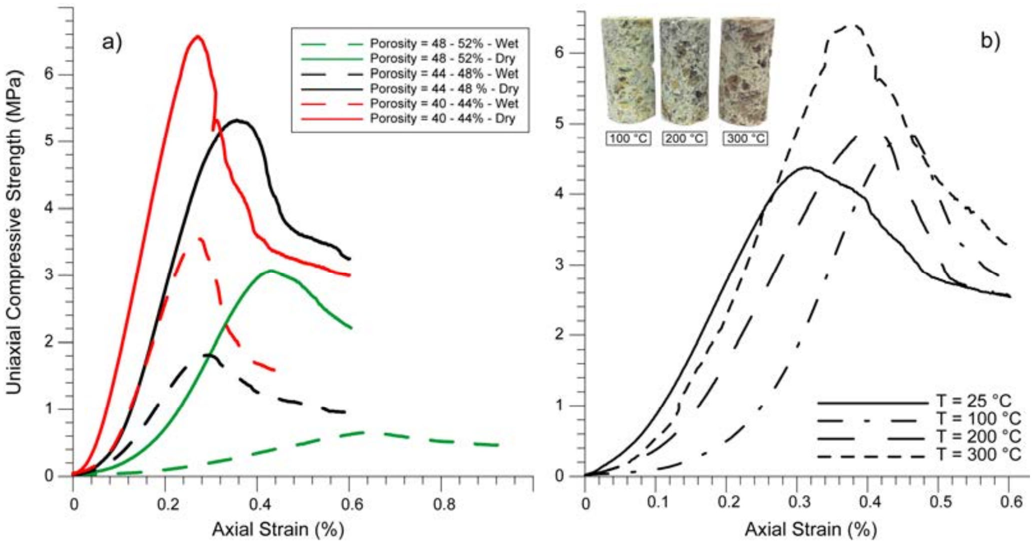

Fig. 3. (a) Uniaxial stress-strain curves for dry (solid lines) and wet (dashed lines) MEGT samples containing different porosities; (b) Influence of thermal stressing on uniaxial compressive strength of selected porosity samples in a range of temperature between 25 and 300°C.

A weakening effect due to water saturation was also observed for all three tested porosity classes (Fig. 3a), as previously observed in porous sandstones, limestones [24, 25], and volcanic rocks [26].

Due to the prevalence of secondary authigenic mineralization (phillipsite ± chabazite, interstratified illite/smectite, Fe-rich illite and low amount of analcime) [14, 27], UCS tests were also performed on thermally stressed samples over a range of temperatures up to 300°C (Fig. 3b), the maximum expected temperature within the hydrothermal system. The thermally stressed samples were heated to the target temperature at a rate of 1°C/min and left for two hours at the target temperature before being cooled back to room temperature at the same rate. The tests on thermally stressed samples were performed in order to assess possible degradation and reduction in strength and stiffness as observed in similar porous tuff due to the dehydration of zeolites (Neapolitan Yellow Tuff, NYT) by [18]. Zeolites are aluminosilicates with an open porous structure capable of storing water that can be released upon exposure to a couple of hundred degrees. Such minerals are also responsible for the typical greenish colour of the rocks, which outcrops all over the island. The samples tested were selected based on their essentially equal porosity (maximum variation lower than 0.2%) to minimize the effects of porosity that could potentially mask the thermal contribution. The obtained results do not show significant loss of mass during heating, and clear strength losses are absent or not appreciable (Fig. 3b).

3.2.2. Triaxial experiments

High-porosity tuffs (30–50%) have previously been shown to switch to inelastic compaction at very low effective pressures ($Peff=Pc-\alpha Pp$, where Pc and Pp are the confining and pore pressure, respectively, and α is the poroelastic constant assumed herein to be equal to 1), corresponding to shallow depths (few hundred meters) [19, 28]. Based on these data, it is reasonable to assume that a change in the mechanical behaviour and the failure mode of rock mass might influence the strain response of the volcanic flank, driving slope deformation or even instabilities and collapse. To better understand the factors that can influence the deformation of the edge of Ischia's resurgent caldera, a series of triaxial tests on cylindrical samples (L/D = 2) were cored from representative MEGT rock samples. Triaxial tests ($\sigma_1>\sigma_2=\sigma_3$) were performed by conventional triaxial apparatus on dry and water-saturated samples at a constant strain rate 10^{-5} s^{-1} under drained conditions, following [22] ISRM standards. In the wet experiments a pore pressure (Pp) of 10 MPa was chosen. Prior to deformation, the samples were kept at the target effective pressure for at least 12 h to ensure microstructural equilibrium. The triaxial tests were performed on selected samples with porosity of 46 ± 1%, in both dry and wet conditions, under a range of effective pressures (Peff) between 0.5 and 5 MPa, conditions relevant for the gravity-driven slope deformation.

Hydrostatic experiments were also performed on a MEGT sample (Fig. 4b) containing a mean connected porosity by imposing an isotropic stress (i.e. $\sigma_1=\sigma_2=\sigma_3$). In this experiment (performed under wet conditions), the porosity of the sample was monitored as the confining pressure was increased in small increments. All of the triaxial tests were carried out at room temperature. Further details about the triaxial experimental apparatus can be found in [29]. Results of the triaxial tests performed on MEGT samples are shown in Fig. 4.

The brittle stress–strain curves are typical of those for rock in compression, since they present an initially concave trend (produced by elastically closing pre-existing microcracks) followed by a pseudo-linear elastic trend. Finally, a third convex stage where irreversible deformation occurred above the onset of dilatancy until the peak stress is reached. Dilatant deformation (i.e. brittle) was associated with shear fracture formation and strain softening. Conversely, compactant deformation (i.e. macroscopically ductile) did not result in strain softening and differential stress increased with increasing strain.

The transition from a dilatant to a compactant failure mode occurred in the MEGT at effective pressures between 1 and 2 MPa (Fig. 4c-4d), corresponding to a depth lower than 200 m, i.e. depth relevant for the Mt. Nuovo slope. The hydrostatic test completes the failure envelope of MEGT and shows that inelastic compaction can occur in the absence of a differential stress at an effective stress of 11 MPa (Fig. 4b). However, such pressure values are too high to be relevant for the stability of the Mt. Nuovo slope.

The failure envelope delineates the stress conditions under which the tested materials will fail, representing a critical state line that divides admissible and inadmissible states of stress (under and above the envelope, respectively). Failure envelopes for MEGT in dry and wet conditions are summarized in P-Q space in Fig. 4a, where P is the effective mean stress ($P=\sigma_1 + 2\sigma_3)/3\text{-}Pp$) and Q is the differential stress ($Q=\sigma_1\text{-}\sigma_3$).

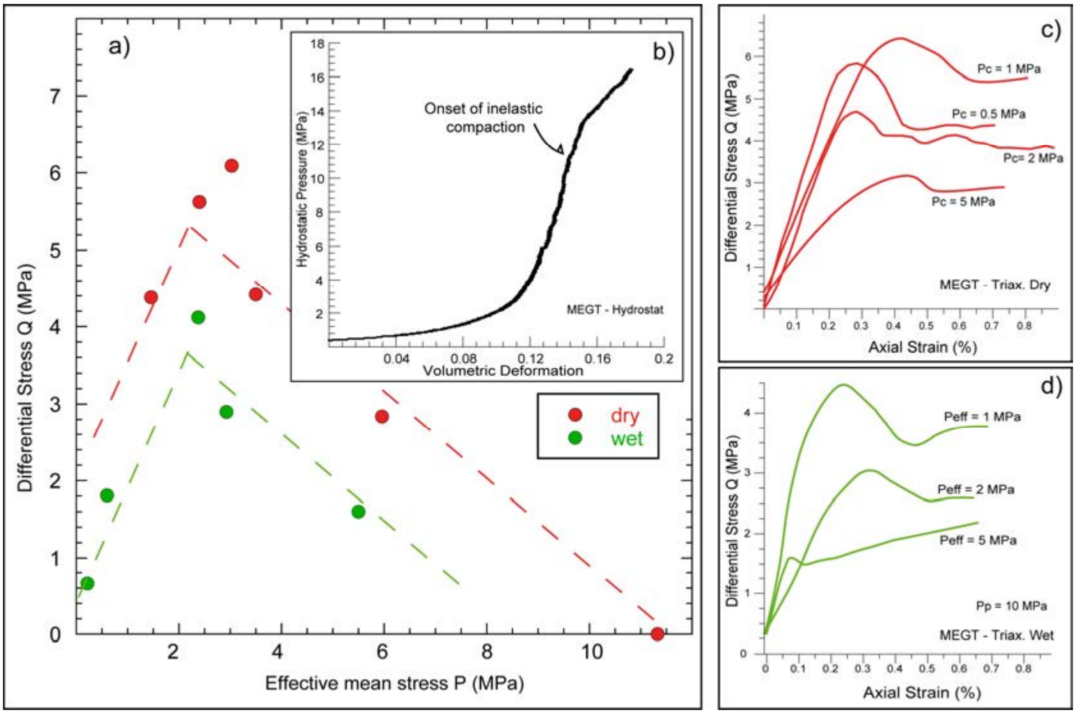

Fig. 4. Summary of triaxial and hydrostatic tests (b) performed on MEGT under dry (c) and wet (d) conditions. *P-Q* failure envelopes (a) for both dry (red dots and lines) and wet (green dots and lines) cases are shown.

3.2.3. Tensile experiments

To completely evaluate the failure envelope (i.e. critical state line) in both the compressive and tensile fields (here assumed conventionally as positive and negative, respectively), indirect tensile tests were conducted using the Brazil-disc technique [22]. Five disc-shaped specimens were loaded diametrically in compression to produce a maximum tensile stress at their center. Indirect tensile strengths were then calculated using standard rock mechanics relationships [22]. Indirect tensile strengths calculated for the MEGT were about 1±0.2 MPa, similar to values reported for similarly porous tuffs [18] in Table 1.

4. Discussion

The derived physical and mechanical properties, here summarized in Table 1, are in agreement with similar tuffs from the Neapolitan area (Italy) [18, 29] that show high values of porosity and permeability can influence hydrothermal circulation, as well as fluid migration and degassing. The observed mechanical effect due to porosity increase or water-weakening justify how a high-porosity horizon in the slope might fail at very low differential stress. Therefore, locally more porous layers in the heterogeneous MEGT could act as weak zones that localize deformation promoting and controlling the overall slope stability. In addition, water-saturation can significantly affect strength and deformability of material involved in the gravity driven slope deformation, resulting in a weakening effect able to drive instabilities of rock masses.

The impact of water on strength can be quantified by the ratio UCS_{wet}/UCS_{dry} as defined by [28]. We find UCS_{wet}/UCS_{dry} values between 35 and 20% for the MEGT, values not dissimilar to those found previously for a variety of tuffs [28] (Fig. 5a). It follows that fluid circulation within the hydrothermal system may play a key role in governing rock mass strength and therefore slope stability.

Table 1. Summary of the physical and mechanical properties derived for MEGT. A comparison with tuffs from Neapolitan area of Italy (i.e. Neapolitan Yellow Tuff -NYT- and Grey Campanian Ignimbrite -WGI-) is proposed [18, 29].

Parameters	MEGT	NYT	WGI
Dry bulk density (g/cm^3)	1.36	1.27	1.33
Mean connected porosity (%)	45.5	43.8	48.5
Permeability (m^2)	1E-13$^{\#}$	1.2E−15*	1E−13*
Dry P-wave velocity (km/s)	2.59	2.29	2.31
Dry S-wave velocity (km/s)	-	1.25	1.28
Unconfined compressive strength (MPa)	5.32	3.47	9.23
Young modulus (GPa)	2.62	-	-
Indirect tensile strength (MPa)	0.99	1.00	1.62

$^{\#}$ Gas Permeability; *Water Permeability

Uniaxial tests on thermally stressed samples showed a negligible effects of temperature on mechanical behaviour of zeolitized tuff, contrary to what observed by [18] in NYT as low as 100°C (Fig. 5b). Due to the relatively low temperature range tested, and the microstructural heterogeneity of the material, such effects are likely prevented or masked. Nevertheless, temperature effects on rock mass rheology and time dependent deformation cannot be neglected. The mechanical characterization performed on MEGT through triaxial testing (Fig. 4) highlights that the dilatant (brittle) to compactant (ductile) transition occurs at a very shallow depth, corresponding to an effective stress level between 1 and 2 MPa. This transition therefore occurs at a depth relevant for the Mt. Nuovo slope, and could influence gravity-induced strain deformation. Compactive failure, unlike dilatant behaviour, requires a progressively lower differential stress for inelastic strain accumulation as depth (and pressure) increases (Fig. 4). For this reason, inelastic compaction may occur at shallow depth and be the mechanism responsible for driving the present-day slope deformation. The parameter values derived from these laboratory tests (Table 1) will be directly exploited through a specific engineering-geological model that includes mechanical zonation where stress levels and temperature intervals are distinguished according to the experimental outputs.

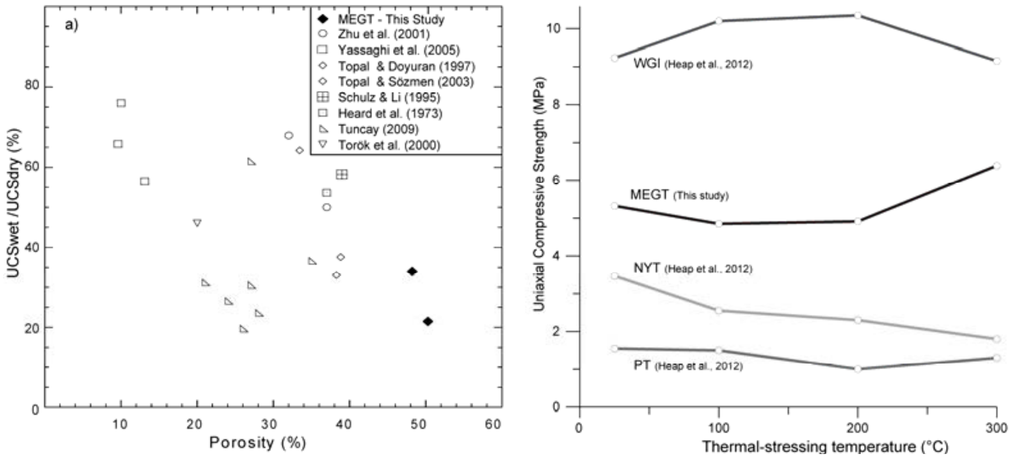

Fig. 5 (a) UCS_{wet}/UCS_{dry} as a function of porosity, modified after [28 and references therein; (b) Comparison of thermal stressing effect on strength [18]; NYT only shows a systematic decrease with temperature. MEGT (this study), similar to WGI and PT [18], appears unaffected by thermal stressing.

The final aim of such a modelling will be a comprehensive and more accurate slope stability analysis, required to assess the risk related to possible paroxysms evolving toward catastrophic slope failures. Based on the here performed laboratory characterization a thermo-mechanical 2D numerical modelling will be designed for the Mt. Nuovo slope using a multiphysics approach that includes conductive-convective heat transfer, fluid flow in a fractured porous medium, and time-dependent rheology.

5. Conclusions

Mt. Nuovo at Ischia Island hosts at the same time a huge gravitational slope deformation and a stable hydrothermal system able to interact with evolution of the slope by influencing the mechanical response of involved rock mass. The mechanical tests performed on porous tuff involved in the gravitational process highlight a switch in failure mode at shallow depth, which could be the driving mechanics of slope deformation. Effects of porosity and water content clearly results in a weakening of the involved material, which seems unaffected by dehydration effects that could negatively compromise its stability. The obtained results allow us to constrain the role of predisposing factors on mechanical behaviour of MEGT, providing the basis for a thermo-mechanical 2D numerical modelling designed to quantify the thermo-baric conditions of the hydrothermal system capable of promoting the ongoing landslide process towards a general collapse which, as outlined above, could be responsible for tsunami generation in a domino-effect scenario. Moreover, effects due to pseudostatic, cyclic or dynamic external actions (i.e. tides, bradyseism, earthquake shaking) will be modelled, as they can interact with the landslide-involved mass, modifying the stress-strain field of the slope and so interacting with the deeper hydrothermal and volcanic systems. This numerical modelling will be performed accounting for possible relations between changes in geothermal system conditions (predisposing feature) and destabilizing actions (triggers) that can be responsible for catastrophic failures could induce a multi-hazard scenario affecting the densely-populated Neapolitan area.

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