VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING –
Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale,
CNRIG2016

Simple shear tests on unsaturated soils

Sabatino Cuomo^{a,*}, Mariagiovanna Moscariello^a, Vito Foresta^a

^a*University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano (SA), Italy*

Abstract

Rainfall induces landslides in several geo-environmental contexts through a variety of triggering mechanisms. In shallow covers of unsaturated silts or loose sands, static liquefaction may occur upon shearing or wetting. The paper proposes simple shear and wetting tests performed on remoulded specimens of air-fall volcanic pyroclastic silty sands from Sarno site (Italy), where huge flowslides occurred. Simple shear wetting tests reproduce the initial stress conditions in the field as well as the stress path of the most common triggering mechanisms which take place during critical rainfalls. The tests are carried out through the Unsaturated Simple Shear apparatus designed at the University of Salerno. First, simple shear tests are performed in dry and saturated conditions and the results compared in terms of shear strength and volumetric response. Then, wetting tests – under constant vertical stress or constant shear stress – are performed. The experimental results are presented and the future research is outlined.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016

Keywords: Simple shear; wetting; failure; slope; landslide

1. Introduction

Shallow landslides are frequently triggered by rainfall in many geo-environmental contexts like Central America, New Zealand, Japan, Brazil and many other Countries. Soils of different grading and origin are involved in slope failures [1]. Typical examples are the shallow deposits of unsaturated pyroclastic soils [2,3] of Southern Italy, in a 3000 km² sized district where volcanic explosive activity of the Somma-Vesuvius volcano produced large amount of pyroclastic soils. Along steep slopes, pyroclastic soils are in unsaturated conditions and may experience static

* Corresponding author. Tel.: +39(0)89-964231; fax: +39(0)89-968732.

E-mail address: scuomo@unisa.it

liquefaction upon shearing or wetting [2]. This entails that flowslides may occur or, alternatively, shallow slides may evolve into destructive landslides of the flow-type.

Flow-like landslides are complex slope instability phenomena since they exhibit multiple stages and distinct kinematic characteristics throughout the whole process [3,4]. The failure stage is related to: rainfall infiltration from ground surface; water spring from bedrock; ponding at ground surface; or a combination of the previous factors. Those boundary conditions increase pore water pressures, with consequent reduction of shear strength, and formation of localized shear surface or a diffuse failure [1,2]. In the post-failure stage, the acceleration of failed mass relates to undrained (totally or partially) conditions able to produce high pore water pressures during the soil shearing [2]. Most of the previous laboratory investigations about failure and post-failure stages were performed through triaxial tests. In this paper, the Unsaturated Simple Shear Apparatus (USSA) – designed at the University of Salerno [5,6] – is used. The experimental results are presented and the future research possibilities are outlined.

2. Materials and Methods

2.1. Experimental devices

The Unsaturated Simple Shear Apparatus (Fig. 1) allows applying a vertical load to a soil specimen, and a “shearing mode” through the application of a controlled (i) horizontal force or (ii) horizontal displacement. A peculiarity of USSA is the shearing box consisting of a stack of twelve hollow disks which ensure zero lateral strain to the specimen. The disks are held together by two vertical screws doing the specimen assembly and removed before starting the shearing stage of the tests. The specimen housing has a circular inner cross section with a diameter equal to 51 mm. Cylindrical specimens 22 mm high are used. The specimen is sheared due to synchronized movement of two linear fluting grooves machined on the upper side of each disk, and two external holed metal straps fixed on bottom and top disks. The matric suction is measured or applied through the axis-translation-technique. Particularly, the suction is controlled at the bottom of the specimen, measuring the pore water pressure (suction) at the top. Being applicable both vertical load, shearing deformation and soil suction, the USSA is suitable to reproduce the in-situ conditions of a slope and the strain and stress paths induced by rainfall during the failure and post-failure mechanisms [1,2].

Fig. 1. Schematic view of the Unsaturated Simple Shear Apparatus (USSA) (modified from Sorbino et al. [5]).

In the present paper, shearing and wetting tests were performed to reproduce the initial stresses and the wetting paths of the most common triggering mechanisms of rainfall-induced shallow landslides. In the first stage of these tests, the net vertical stress (σ) was constant and the shear stress (τ) increased at a constant time rate up to different ratios σ/τ . In the second stage, the net vertical stress and the shear stress were constant and the suction reduced through the injection of water into the specimens from the bottom. Other well-know devices like Volumetric Extractor (*VE*) and Richards Pressure Plate (*RPP*) were used to investigate the dependence of volumetric water content on matric suction 0 and former results obtained through Suction-controlled Direct Shear [7] and Suction-controlled Triaxial tests [7] were also referred to in this paper.

2.2. Investigated soil and experimental tests

The laboratory tests were performed on a non-plastic air-fall volcanic (pyroclastic) soil originated from the explosive activity of Vesuvius volcano. The specimens were prepared from the finest ashy soil of Campania region, namely “A” in Bilotta et al. [8], which typically is at the bedrock contact of the pyroclastic deposits.

This soil is very loose and has a metastable structure along steep slope [9,10]. The grain size distribution consists in 43.6 to 51.9% Sand, 43.9 to 54.03% Silt, 1.4 to 4.7% Clay. The soil specific gravity (G_s) is equal to 2.55; The specific volume (v) ranges from 3.595 (undisturbed) to 2.982 (remoulded) and the saturation degree (S_r) is between 74.8% (undisturbed) and 92.1% (remoulded) and the dry unit weight (γ_d) is 6.93 to 8.65 kN m⁻³ (respectively, undisturbed and remoulded). The average water content (w) is 51.9%, while the liquid limit (w_L) and plastic limit (w_P) are 53.8% and 49.3%, respectively (data from Bilotta et al., [11]).

The mechanical behavior of pyroclastic soils in saturated and unsaturated conditions was discussed in several works such as Bilotta et al. [8], Migliaro [12] and Lancellota et al. [10]. The shear strength was analyzed both for undisturbed and for remoulded specimens through suction controlled triaxial apparatus. Suction produces a significant increment of the shear strength of both undisturbed and remoulded soils, more evident for remoulded specimens, probably due their different internal structure. The strength parameters reported by Bilotta et al. [8] were: i) for undisturbed soils, effective cohesion (c) is nil and the friction angle (ϕ') equal to 34.7° in saturated conditions, while $c=9.6$ kPa and $\phi'=34.8^\circ$ at suction equal to 50 kPa; ii) for remoulded soils, $c=12.6$ kPa and $\phi'=35.9^\circ$ in saturated conditions, while $c=48.9$ kPa and $\phi'=35.5^\circ$ at suction equal to 50 kPa.

This paper discusses the results of the simple shear tests in Tab. 1, performed in saturated and unsaturated condition. Three tests (SSP0115, SSP0215 and SSP0315) on saturated remoulded specimens were performed in drained conditions: SSP0115 and SSP0315 at constant vertical load, and the SSP0315 at constant volume, i.e. varying the effective vertical stress during the test to keep the specimen height constant. One test was performed on unsaturated specimen (SS0213) at constant vertical load and at strain controlled conditions; another test (SSRPSG09) was performed decreasing the suction from 50 kPa up to failure to mimic one typical triggering mechanism of rainfall-induced landslides [13].

Table 1. List of the experimental tests.

Condition	Device	#	Test	e	$\sigma', \sigma - u_a$ (kPa)
Saturated	SS	SSP0115	CL	2.02	97
	SS	SSP0215	CV	2.03	48
	SS	SSP0315	CL	2.02	76
Unsaturated	DS	DS0213	CL*	1.66	100
	DS	DS0313	CL*	1.64	200
	DS	DS0413	CL*	1.69	300
	SS	SS0213	CL*	1.66	100
	SS	SSRPSG09	CL-wetting**	1.86	30

SS= Simple Shear, DS= Direct Shear; CL=Constant vertical Load; CV=Constant Volume; * suction 50 kPa; ** initial suction 50 kPa

3. Results and discussion

The mechanical behavior of unsaturated soils is strictly related to matric suction and water content, thus the Soil Water Retention Curve (*SWRC*) of remoulded pyroclastic soil was investigated through the Volumetric Extractor (*VE*) for suction up to 200 kPa, and Richards Pressure Plate (*RPP*) for suction from 200 kPa to 600 kPa. The experimental data (Fig. 2) were interpolated through Van Genuchten model:

$$\theta(s) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha s)^n\right]^m} \quad (1)$$

where θ_s and θ_r represent the saturated and residual water content, respectively; α , n and $m=1-1/n$ are shape parameters. The parameters were: $\theta_s=0.62$, $\theta_r=9.05 \cdot 10^{-7}$, $\alpha=0.02$ and $n=1.24$ for drying and $\theta_s=0.45$, $\theta_r=0.21$, $\alpha=0.50$ and $n=1.23$ for wetting. The model well interprets the experimental evidence with $R^2=0.951$ for drying and $R^2=0.994$ for wetting. The model coefficients are similar to those found for the curves labelled “Upper” (for drying) and “Lower” (for wetting) by Cuomo and Della Sala [14].

In saturated condition, simple shear tests were performed on remoulded specimens with initial void ratio from 2.018 to 2.028. The specimens were initially consolidated in k_0 -conditions at net vertical stress equal to 69.8, 75.0 and 100.0 kPa, respectively. Then shearing stages were performed at shear strain rate equal to 0.14 mm/h. All of the specimens showed a hardening behavior (Fig. 3a), and the shear strength envelope was obtained referring to the shear stress value at the maximum shear strain reached during the tests, with $\phi'=35.7^\circ$ and $c'=0$ kPa (Fig. 3a).

The mechanical behavior in unsaturated condition was analyzed through both direct shear tests and simple shear tests. Three direct shear tests (DS0213, DS0313 and DS0413) were performed at suction equal to 50 kPa, with a constant shear displacement rate (0.14 mm/h) in drained condition. The tests were carried out on three specimens with void ratio from 1.63 to 1.69, which were normally consolidated in k_0 conditions at 100, 200 and 300 kPa. All the tests exhibited a peak shear stress and then a moderate strain softening (Fig. 3b). One simple shear test (SS0213) was performed at controlled shear strain rate (0.015 h^{-1}), suction constant 50 kPa and net vertical stress 100 kPa. The direct shear tests (DS0213, DS0313 and DS0413) exhibited a softening behavior with the peak stresses reached at shear strain (γ) from 0.1 to 0.4. The difference between simple and direct shear test seems to match recent similar comparisons made for remoulded specimens in saturated condition [7]. The shear strength parameters obtained for unsaturated specimens at suction 50 kPa were $\phi'=33.6^\circ$ and $c=55.5$ kPa. The friction angle and the cohesion intercept obtained through direct shear tests were, respectively, smaller and larger than those from triaxial tests (Sect. 2.2). This is in agreement with the conclusions reported in Randolph and Wroth [16] and in Cuomo et al. [7] about shear strength parameters in saturated condition. Fig. 3c shows the failure envelopes obtained through the different devices for saturated and unsaturated specimens.

Fig. 2. Soil Water Retention Curve.

The transition from unsaturated to saturated condition was analyzed through a wetting simple shear test performed on a remoulded specimen. The testing procedure was: 1) measurement of the initial suction; 2) application and equalization of suction (50 kPa); 3) application of net vertical stress (30 kPa); 4) increase of the shear stress at constant time rate (3.6 kPa h^{-1}) up to 34 kPa (shear strength in saturated conditions); 5) decrease of soil suction up to nil at constant rate of 0.5 kPa h^{-1} , under constant net vertical stress and shear stress. During the stages 4 and 5 some variables were monitored: shear strain (γ), suction value at the top of the specimen ($u_a - u_w$)_t, axial strain (ϵ_a), and cumulative amount of water exchanged by the specimen (Δw); other variables were computed: saturation degree (S_r), hydraulic gradient (J , definite positive for a downwards flux)

The stage 4 (increase of the shear stress) was carried out applying suction equal to 50 kPa at the bottom of the specimen and measuring the variation of the suction at the top. The difference of those suction values was about 5 kPa at the end of the stage, and was related to water outflow from the specimen water (Fig. 4a). The maximum of hydraulic gradient J was reached (Fig. 4a). And, the shear stress (τ) increment produced a shear strain smaller than 10%, axial strain (ϵ_a) about 5% and a moderate reduction of saturation degree (S_r), from 88.0% to 87.3%.

After the shear stage, the measured suction was again equalized at about 50 kPa, keeping constant the shear stress. The stage 5 consisted in the reduction of suction, causing water inflow (Fig. 4a) and the increase of saturation degree (Fig. 4b). The specimen underwent negligible shear strain and preserved its contractive behavior until suction was higher than 30 kPa. Later on, the suction at the top of the specimen dropped from 23 to 19 kPa in 1 hour, i.e. at a time rate about 8 times larger than the suction variation time rate applied at the bottom. The volumetric behavior became dilative, and the shear strain rate was about $2.3 \cdot 10^{-5} \text{ sec}^{-1}$. This corresponded to a small decrease of saturation degree (S_r) and also to a drop of J from -26 to -3 (Fig. 4b). At suction equal to 13 kPa, a rapid increment of shear and axial strains was observed in about 6 minutes (the shear strain rate was $7.1 \cdot 10^{-4} \text{ sec}^{-1}$). The difference between the suction measured at the top of specimen and the suction applied at the bottom was equal to about 5 kPa, while J reached the minimum value of -40. The failure corresponded to a dilative behavior and to large shear strains.

Fig. 3. Experimental results of Direct Shear and Simple Shear tests a) in saturated and unsaturated condition; b) failure envelopes for suction from 0 to 50 kPa obtained through Simple Shear (SS), Direct Shear (DS) and Triaxial (TX) apparatus.

4. Concluding remarks

Simple Shear (SS) tests were performed to investigate the mechanical behavior of a remoulded pyroclastic soil. The saturated shear strength parameters were consistent with those formerly achieved through Direct Shear (DS) and Triaxial (TX) tests. In unsaturated condition, the comparison between the shear strength parameters obtained through SS and DS tests well matches those of previous TX tests. However, this issue requires further experimental and theoretical investigation.

The mechanical behavior of soil upon wetting was also discussed with reference to a wetting test in simple shear

condition. The time evolution of suction, shear and axial strains and water exchange was measured for the specimen. The specimen exhibited a dilatative behavior upon wetting, with large shear strain. Further tests will be necessary to investigate different stress ratio and different rate of shear strain and suction reduction during the wetting stage.

Fig. 4. Experimental results of the shear stage with τ increasing (SH) and the saturation stage with τ constant (SAT): a) evolution in time of the monitored and computed variables; b) changes in relation to soil suction.

References

- [1] L. Cascini, S. Cuomo, M. Pastor, G. Sorbino, Modelling of rainfall-induced shallow landslides of the flow-type. *ASCE's Journal of Geotechnical and Geoenvironmental Engineering* 1 (2010) 85-98.
- [2] L. Cascini, S. Cuomo, M. Pastor, C. Sacco, Modelling the post-failure stage of rainfall-induced landslides of the flow-type. *Canadian Geotechnical Journal* 50(9) (2013) 924-934 doi: 10.1139/cgj-2012-0375.
- [3] L. Cascini, G. Sorbino, S. Cuomo, S. Ferlisi, Seasonal effects of rainfall on the shallow pyroclastic deposits of the Campania region (southern Italy). *Landslides* 11(5) (2014) 779-792 doi: 10.1007/s10346-013-0395-3.
- [4] S. Cuomo S, M. Pastor, L. Cascini, G.C. Castorino, Inter-play of rheology and entrainment in debris avalanches: a numerical study. *Canadian Geotechnical Journal*, 1-15 (2014) doi: 10.1139/cgj-2013-0387.
- [5] G. Sorbino, G. Migliaro, V. Foresta, Laboratory investigations on static liquefaction potential of pyroclastic soils involved in rainfall-induced landslides of the flow-type. *Unsaturated Soils - Alonso & Gens (eds)*, 2011.
- [6] S. Cuomo, V. Foresta, G. Sorbino, Remarks on a new simple shear apparatus for saturated and unsaturated soil testing". (2016) Submitted for publication.
- [7] S. Cuomo, M. Moscarriello, V. Foresta, Shear strength of a Vesuvian pyroclastic soil measured in different testing devices. *Proceedings of Workshop on Volcanic Rocks and Soils, Ischia (Italy)*, 24-25 September 2015. ISBN: 978-1-138-02886-9 (2016) pp. 231 - 236.
- [8] E. Bilotta, L. Cascini, V. Foresta, G. Sorbino, Geotechnical characterization of pyroclastic soils involved in huge flowslides. *Geotechnical and Geological Engineering* 23 (2005) 365-402. doi :10.1007/S10706-004-1607-3.
- [9] G. Sorbino, G. Migliaro, V. Foresta, Laboratory investigations on static liquefaction potential of pyroclastic soils involved in rainfall-induced landslides of the flow-type. *Un-saturated Soils- Alonso&Gens (eds)*, 2011.
- [10] R. Lancellotta, C. Di Prisco, D. Costanzo, S. Foti, G. Sorbino, G. Buscarnera, R.M. Cosentini, V. Foresta, Caratterizzazione e modellazione geotecnica. In: *Criteri di zonazione della suscettibilità e della pericolosità da frane innescate da eventi estremi (piogge e sisma) / Leonardo Cascini*. Compositeservice srl, Padova, pp. 266-319. ISBN 9788890687334 (in Italian), 2012.
- [11] E. Bilotta, V. Foresta, G. Migliaro, The influence of suction on stiffness, viscosity and collapse of some volcanic ashy soils. In *Unsaturated Soils: Advances in Geo-Engineering*, Toll et al. eds, 2008.
- [12] G. Migliaro, Il legame costitutivo dei terreni piroclastici per la modellazione di scavi in ambiente urbanizzato ed in-fluenza della parziale saturazione. PhD Thesis, Università degli studi di Salerno (Italy), 305 pages, (2008).
- [13] S. Cuomo, M. Moscarriello, V. Foresta, Wetting simple shear tests on pyroclastic soils involved in shallow landslides. *Proceedings of 12th International Symposium on Landslides (ISL) Napoli (Italy)* 12-19 June 2016 (accepted for publication), 2016.
- [14] S. Cuomo, M. Della Sala, Rainfall-induced infiltration, runoff and failure in steep unsaturated shallow soil deposits. *Engineering Geology* 162 (2013) 118-127. DOI: 10.1016/j.enggeo.2013.05.010
- [15] M. Budhu, On comparing simple shear and triaxial test results. *J. Geotech. Engrg.* 110 (1984) 1809–1814. DOI: 1984.110:1809–1814, 1984.
- [16] M.F. Randolph, C.P. Wroth, Application of the failure state in undrained simple shear to the shaft capacity of driven piles. *Géotechnique* 31(1) (1981) 143–157.