Multiphase soil mechanics for landscape protection: from testing to modelling

Francesca Casini

Università degli Studi di Roma "Tor Vergata"

francesca.casini@uniroma2.it

Abstract: The stability of geotechnical structures is usually driven by the superficial layer of soils subject to cycles of drying and wetting and temperature variation. This shallow layer, interacting with atmosphere, is in unsaturated conditions due to the depth of water table and the change of water content with seasons. At least, the unsaturated soils are composed by three phases: the soil particles, the wetting phase and the non-wetting phase. To deal with this multiphase system the classical soil mechanics must be generalized accounting for the different phases and the interfaces between them.

The relevance of unsaturated soils mechanics was early recognized by the pioneering works of Croney (1952), Bishop et al (1960), Bishop and Blight (1963). The experimental data gathered during the late 1950s and 1960s had been used to define new effective stresses to describe the behaviour observed. After that period, the unsaturated soils has been categorized as "difficult soils" or "special soils" due also to the unsuccessful application of the proposed effective stresses (e.g. Jennings and Burland 1963).

To proper describe, the behaviour of unsaturated soils a fundamental step were given by the definition of two stress variables in the framework of state surfaces (Matyas and Radhakrishna 1968, Bishop and Blight 1963, Coleman 1962, Fredlund and Morgenstern 1977, Fredlund and Rajardho 1993). Based on those developments using the elasto-plasticity to overcome the limitation of the state surfaces, the first constitutive model (Barcelona Basic Model, BBM) has been formulated in 1990s. BBM is able to describe the main features of unsaturated soils, such as the collapse for saturation and the variation of strength with suction (Alonso et al. 1990). The model adopts the net stress and suction as independent variables to predict the behaviour of soils during drying and wetting cycles and mechanical loading. BBM defines a yielding locus in the plane mean net stress and suction, the Loading Collapse curve (LC), describing the evolution of preconsolidation stress with suction. The introduction of LC allows the model to predict the shrinkage deformation during wetting, known as "collapse for saturation". Further, BBM accounting for the increases in strength with suction, through the introduction of an apparent cohesion ruled by the parameter k.

The BBM placed the unsaturated soil mechanics closer to the mainstream of saturated soil mecheanics. The main shortcomings of the BBM were the following:

- The degree of saturation is not explicitly taken into account in the definition of the hardening law, only indirectly through the suction. It is missing the link between the Water Retention Curve (WRC) and the hardening variable;
- The parameter k predicting the increases in strength with suction is constant, while the experimental evidences exhibits a non linear increases of strength with suction.

From 1990s, a variety of hydro-mechanical constitutive models has been developed using the pairs net stress and suction or Bishop effective stress and suction as constitutive variables (e.g. Jommi and Di Prisco 1994; Wheeler 1996; Jommi 2000; Vaunat et al 2000; Wheeler et al 2003) and the elasto-plasticity framework. The adoption of Bishop effective stress and suction as constitutive variables overcome the mail limitations of BBM reported above, nevertheless the representation of stress path is not straightforward.

In the last two decades, different attempts have been made to explicitly include the microstructure and its evolution in the definition of constitutive models for unsaturated soils (e.g. Monroy et al 2012; Romero et al 2011; Casini et al 2012; Della Vecchia et al 2013; Vaunat and Casini 2017). This introduction allow the possibility to predict the behaviour of unsaturated soils depending on its initial pore size distribution and the prediction of the maximum of collapse for saturation depending on the magnitude of the stress applied. Based on those developments, different constitutive models have been implemented in Finite Element Code to simulate engineering application taking into account the multiphase composition of soils.

In this keynote, a brief review of the principal experimental evidences is first presented, followed by the definition of the stresses used to describe the behaviour observed. Later, a summary of the different classes of constitutive model is depicted. The role of the Water Retention Curve (WRC), linking the amount of water to the suction, is discussed with emphasis on its dependence on void ratio and microstructure. Further, an extension of the unsaturated soils mechanics to describe the behaviour of frozen soils is treated. Finally, different engineering application spanning from shallow landslides induced by rainfall to frost-heave soils are back-analysed using the framework of unsaturated soil mechanics.

Experimental evidences

Typical results under oedometric compression loading are reported in Figure 1a (after Casini 2008). The tests were performed on Jossigny silt under suction controlled conditions, the preconsolidation stress increases with suction while the compressibility coefficient decreases. When an unsaturated samples follow a wetting path can either swell or shrink, it depends on the initial conditions in terms of void ratio and degree of saturation, on the microstructure and on the vertical stress applied. Figure 2 summarizes a series of wetting tests performed on colluvium Brasilian soil (after Vilar *et al* 2006). The inundation of the samples have been performed under vertical stresses spanning from 50 to 400 kPa. It is interesting to note that the collapse for saturation (CP) exhibits a maximum and than decreases. CP evolution with vertical stress is reported in Figure 2b for two level of suction (60 and 200 kPa respectively).

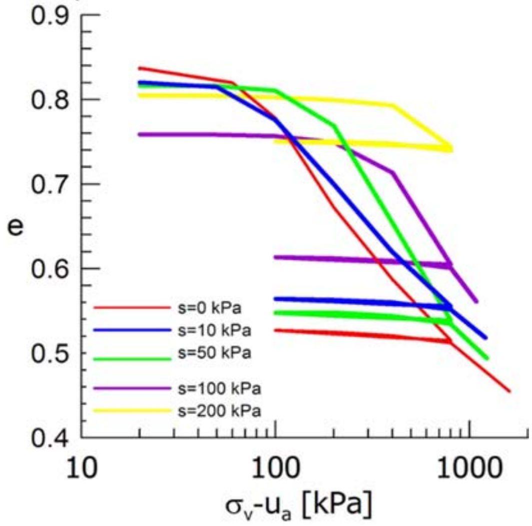

Figure 1 Oedometric tests at different suction level (after Casini 2008)

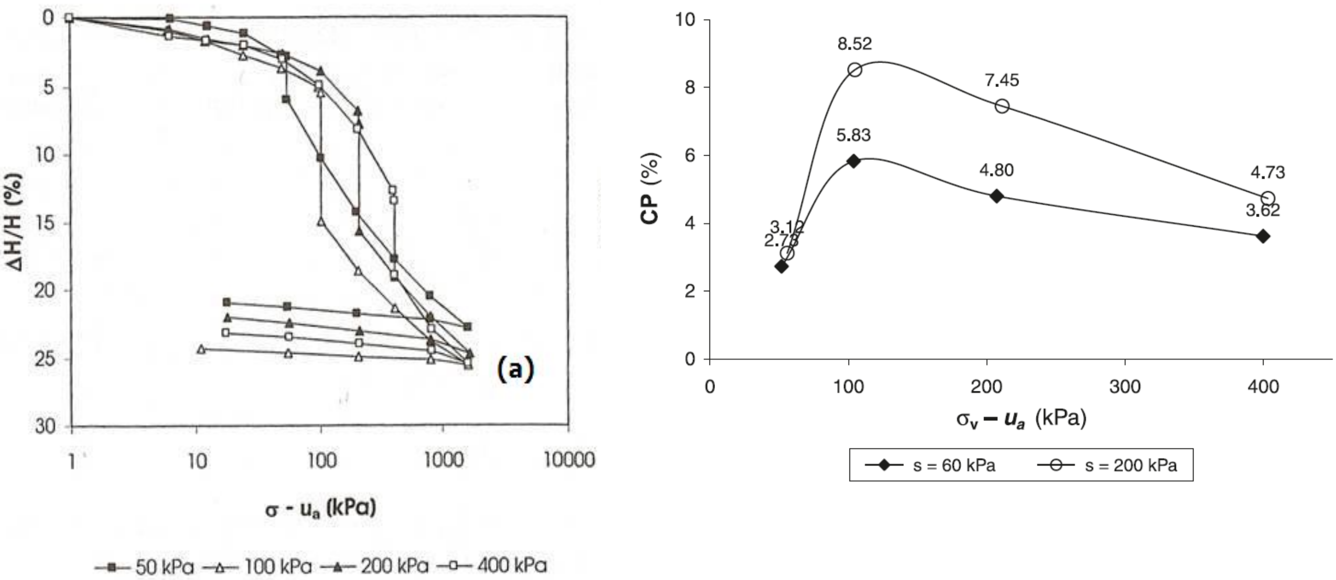

Figure 2 Axial deformation versus vertical net stress: a) inundation performed at different vertical stress; b) axial deformation during collapse (CP) versus net stress starting from two level of suction *(*after Vilar *et al 2006*).

The strength of unsaturated soils increases with suction, the tests reported in Figure 3a were performed under suction controlled condition with a confining net stress $p\text{-}u_a$=400 kPa on Metramo silt (after Rampino et al 2000). Also the dilatancy increases with suction (Figure 3b) while the degree of saturation follow the volumetric behaviour, when the sample dilates the degree of saturation decreases (Figure 3c).

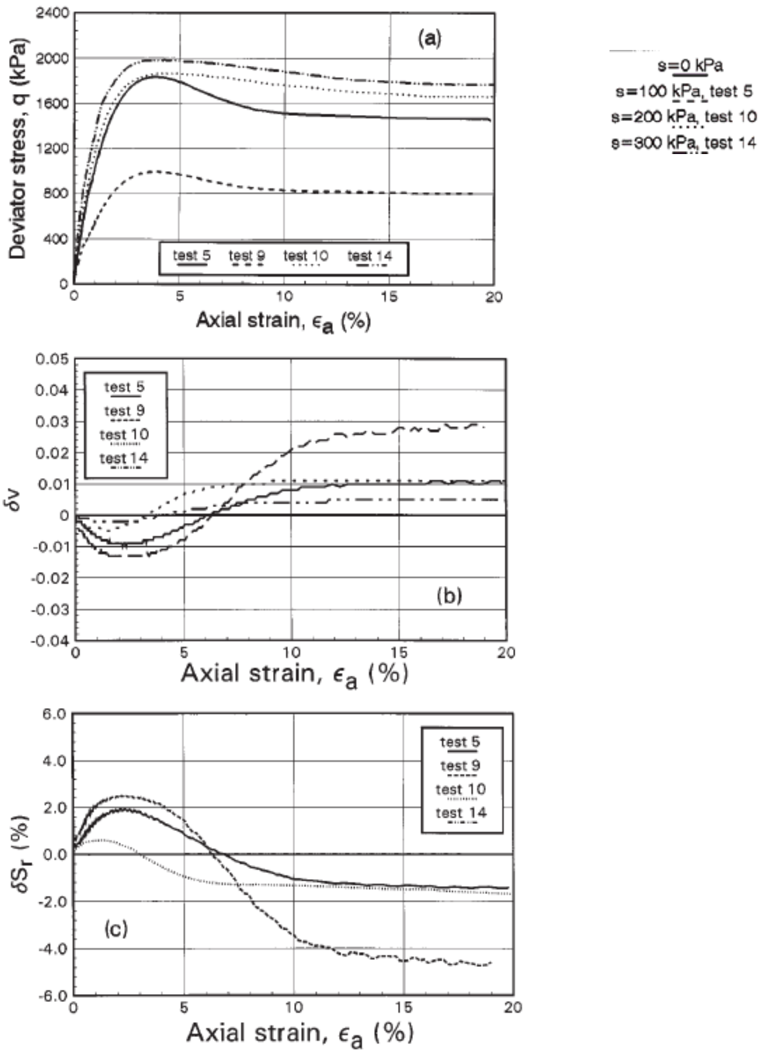

Figure 3- Axial compression loading phase of Metramo silt at different suction (after Rampino *et al* 2000)

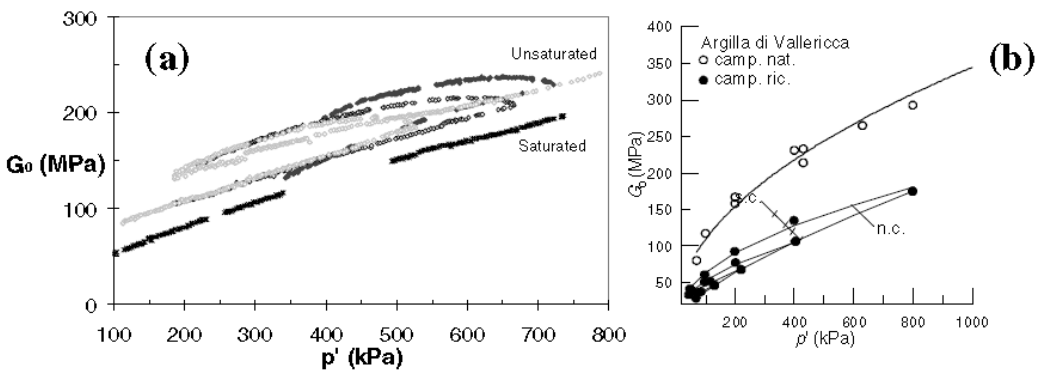

Figure 4- Small strain stiffness G_0 versus mean effective stress p': a) saturated – unsaturated samples of Po silt (after Vassallo *et al* 2006; Casini *et al* 2007); b) natural –reconstituted Vallericca clay (after Rampello *et al* 1995)

The small strain stiffness G_0 increases with suction as shown in Figure 4a, indeed the values of G_0 versus *p*' measured under controlled suction conditions by resonant column tests (Vassallo *et al* 2006) shown a translation upwards. This behaviour is similar to those highlighted for saturated samples comparing natural and reconstituted of Vallericca clay samples in Rampello *et al* (1994).

Water Retention Curve

The Water Retention Curve (WRC) represents the volume of water retained in the soil as function of the suction $s = u_{nw} - u_w$ where u_{nw} is the pressure of the non-wetting phase (air above the water table) and u_w is the wetting phase (water). WRC is function of the void ratio (or porosity) of soil and exhibits hysteresis, as shown in Figure 5, whatever is the variable chosen to represents the amount of water in the soil ($e_w = V_w/V_s$; $S_r = e_w/e$; $w = e_w/G_s$; $\square_w = nS_r = e_w/1+e$).

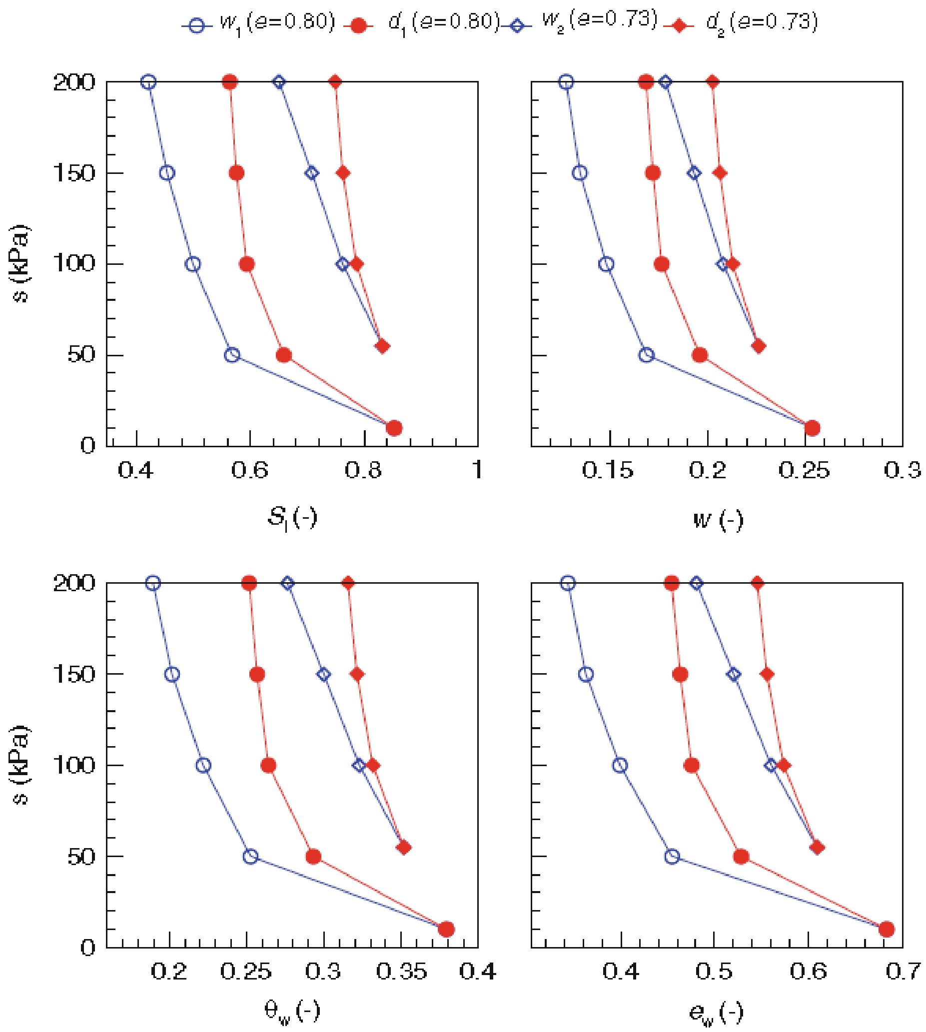

Figure 5 Water retention Curve of Jossigny silt under suction controlled conditions during wetting (blu curve) and drying (red curve) at two different values of void ratio e.

The microstructure of the soil strongly affects the shape of water retention curve and the hydraulic properties as highlighted by different authors (e.g. Romero & Vaunat 2000; Romero et al 2011; Casini et al 2012; Della Vecchia et al 2015; Azizi et al 2019). Figure 6 shown the experimental results on Viadana silts aims at studying the effects of wetting and drying cycles on the WRC (Azizi et al 2019). The authors remark that fabric change take place even without significant volumetric strains, promoting an irreversible increase in the hydraulic conductivity and a reduction in the capacity to retain water compared to the as-compacted soil.

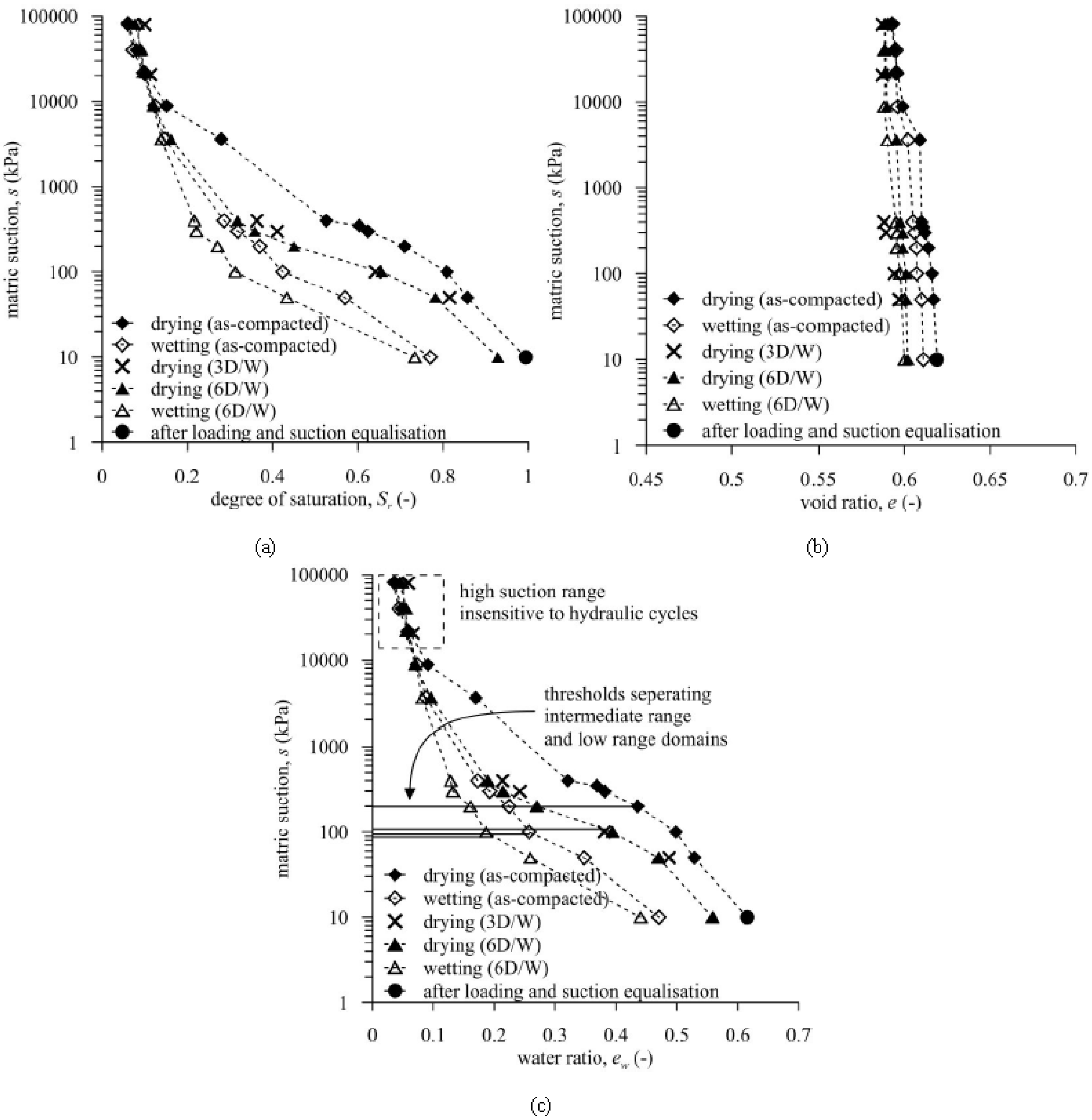

Figure 6. Effect of repeated hydraulic loads on the water retention behaviour: (a) Sr-log(s) (b) e-log(s) (c) e_w-log(s) (after Azizi *et al* 2019)

Stress variables and constitutive modelling in unsaturated soils

In saturated conditions, where two phase are considered solid particle and fluid, the Terzaghi effective stress represents the only stress governing the mechanical behavior of soils. In unsaturated conditions the choice of appropriate stress variable is still an intensive debated issue. With n-phase, we need "n-1" effective stresses to properly describe the behavior of a multiphase soil.

As pointed out in Jommi (2000): ''in fact, no single stress variable has ever been found which, substituted for effective stress, allows for a description of all the aspects of the mechanical behavior of a given soil in the unsaturated range''. A second variable is generally required to represent the stabilizing influence of suction on intergranular forces and the volumetric effects of its removal or weakening, by wetting (Gens et al 2006).

The most common choice of two variables to describe the behavior of unsaturated soils are:

- net stress $\sigma_{ijnet}=\sigma_{ij}-u_{nw}\delta_{ij}$ and suction $s=u_{nw}-u_w$ (*e.g.* Fredlund & Morgenstern 1977; Alonso *et al* 1990);
- generalised stress approach $\sigma'_{ij}=\sigma_{ij}-u_{nw}\delta_{ij}+\chi(u_{nw}-u_w)\delta_{ij}$ (Bishop 1959) and suction $s=u_{nw}-u_w$; (e.g. Jommi 2000, Tamagnini 2004; Casini 2012; Della Vecchia *et al* 2015; Rotisciani *et al* 2015, 2016).

A summary of the possible choice in unsaturated conditions is reported in Tarantino *et al* (2000), Gens *et al* (2006); Nuth and Laloui (2008) and Sheng (2011).

The definition of two stress variables, net or generalized, are not able alone to explain the collapse for saturation during wetting. In addition, we must define a yielding curve (Loading-Collapse) which increases with suction (e.g. Alonso et al 1990) or with degree of saturation (e.g. Jommi 2000) as function of the net or generalized mean stress. In Figure 7 is an idealized scheme of the path followed by a sample during wetting in the e-σ'_v plane and (1-χ)- σ'_v planes (after Casini 2012).

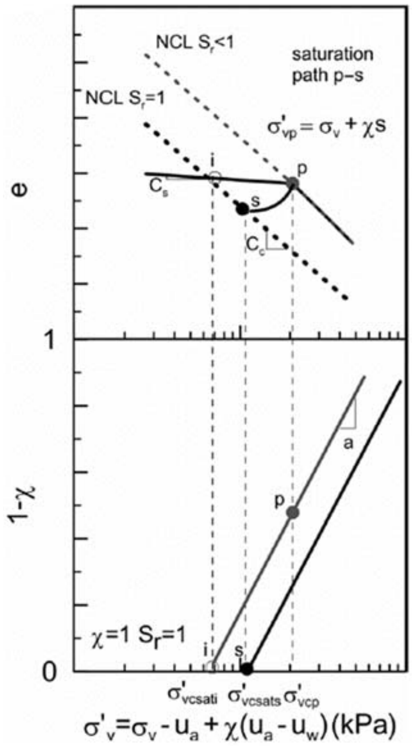

Figure 7 Stress path followed by a point p to saturation s. Point I represents the saturated preconsolidation vertical stress of point p (after Casini 2012).

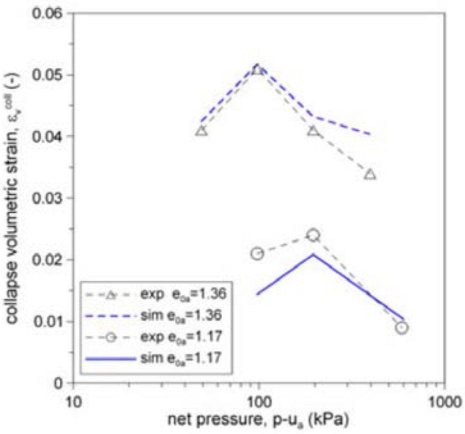

Figure 8 Collapse strain dependence on initial density and applied stress for compacted Pearl clay (after Della Vecchia *et al* 2015)

Further the introduction of microstructure evolution in the WRC and the anisotropy (after Romero & Jommi 2008) in the mechanical model led the possibility to predict also the maximum of the collapse for saturation as shown in Della Vecchia *et al* (2013) and reported in Figure 8.

The final part of the keynote is devoted to an extension of the BBM framework (Nishimura *et al* 2009) able to describe the behavior of artificially frozen soils (Casini *et al* 2016; Mole *et al* 2017) and to the use of the unsaturated framework to predicts the triggering mechanisms of shallow landslides (Sitarenios *et al* under review).

References

Alonso E.E., Gens A., Josa A. (1990) A constitutive model for partially saturated soils. Géotechnique 40:405–430

Azizi, A., Musso, G., Jommi, C. (2019) Effects of repeated hydraulic loads on microstructure and hydraulic behaviour of a compacted clayey silt. Can Geotech J (in print).

Bishop, A.W., Alpan, I., Blight, G.E., Donald, I.B. (1960) Factors controlling the strength of partly saturated cohesive soils. In: Research conference on shear strength of cohesive soils, Boulder, ASCE, pp 503–532

Bishop, A.W., Blight, G.E. (1963) Some aspects of effective stress in saturated and partly saturated soils. Géotechnique 13:177–197

Casini, F. (2008). Effetti del grado di saturazione sul comportamento meccanico di un limo. PhD thesis, Università degli Studi di Roma La Sapienza, Italy

Casini, F. (2012) Deformation induced by wetting: a simple model. Canadian Geotechnical Journal 49: 954–960

Casini, F., Gens, A., Olivella, S., Viggiani, G. (2016). Artificial ground freezing of a volcanic ash: laboratory tests and modelling. *Environmental Geotechnics* 3 (3): 141-154.

Casini, F., Vassallo, R., Mancuso, C., and Desideri, A. (2007). Interpretation of the Behaviour of Compacted Soils Using Cam-Clay Extended to Unsaturated Conditions. In: Theoretical and Numerical Unsaturated Soil Mechanics, Springer Proceedings in Physics, 113(1): 29-36.

Casini, F., Vaunat, J., Romero, E., Desideri A. (2012). Consequences on water retention 32 properties of double porosity features in a compacted silt. Acta Geotechnica. 7: 139–150.

Coleman, J.D. (1962) Stress strain relations for partly saturated soil. Correspondence. Géotechnique 12:348–350

Croney, D. (1952) The movement and distribution of water in soils. Géotechnique 3:1–16

Della Vecchia, G., Jommi, C. and Romero E. (2013). A fully coupled elastic–plastic hydromechanical model for compacted soils accounting for clay activity. International Journal for Numerical and Analytical Methods in Geomechanics, 37 (5): 503–535.

Fredlund, D.G., Morgenstern, N.R. (1977) Stress state variables and unsaturated soils. J Geotech Eng Div ASCE 103:447–466

Fredlund, D.G., Rahardjo, H. (1993) Soil mechanics for unsaturated soils. Wiley, New York

Gallipoli, D., Wheeler, S., Karstunen, M. (2003) Modelling the variation of degree of saturation in a deformable unsaturated soil. Géotechnique 53(1):105–112

Gens, A. (2010). Soil-enviroment interactions in geotechnical engineering. Géotechnique 60(1): 3-74.

Gens, A., Sánchez, M., and Sheng, D. (2006). On constitutive modelling of unsaturated soils. Acta Geotechnica, 1 545 (3): 137–147.

Jennings, J.E.B., Burland J.B. (1962) Limitations to the use of effective stresses in partly saturated soils. Géotechnique 12:125–144

Jommi, C. (2000) Remarks on the constitutive modelling of unsaturated soils. In Experimental Evidence and Theoretical Approaches in Unsaturated Soils. Proceedings of the International Workshop on Unsaturated Soils, Trento. Edited by A. Tarantino and C. Mancuso. Balkema, Rotterdam. pp, 139–153

Matyas, E.L., Radhakrishna, H.S. (1968) Volume change characteristics of partially saturated soils. Géotechnique 18:432–448

Molé, V., Casini, F., Viggiani, G.M.B. (2017). Il congelamento artificiale dei terreni eseguito nei pressi di un palo di fondazione. XXVI Convegno Nazionale di Geotecnica - La geotecnica nella conservazione e tutela del patrimonio costruito

Monroy, R., Zdravkovic, L., Ridley, A. (2010) Evolution of microstructure in compacted London clay during wetting and loading. Géotechnique 60(2):105–119

Nishimura, S., Gens, A., Olivella, S. & Jardine, R.J. (2009). THM-coupled finite element analysis of frozen soil: formulation and application. *Géotechnique* 59 (3) : 159-171.

Nuth, M., Laloui, L. (2008) Advances in modelling hysteretic water retention curve in deformable soils. Comput Geotech 35:835–844

Nuth, M., Laloui, L. (2008) Effective stress concept in unsaturated soils: Clarification and validation of a unified framework. Comput Geotech 32:771–801

Rampello, S., Silvestri, F., Viggiani, G. (1994) The dependence of small strain stiff-ness on stress state and history for fined grained soils: the example of Vallericca clay. In Proceeding of the First International Symposium on Pre-failure Defomation of Geomaterials, Sapporo, pp 273-278

Rampino, C, Mancuso, C., Vinale, F. (2000) Experimental behaviour and modelling of an unsaturated compacted soil. Canadian Geotechnical Journal 37: 748–763

Romero, E. and Jommi, C. (2008). An insight into the role of hydraulic history on the volume changes of anisotropic layey soils. Water Resources Research, 44.

Romero, E., Della Vecchia, G., Jommi, C. (2011) An insight into the water retention properties of compacted clayey soils. Géotechnique 61(4):313–328

Romero, E., Vaunat, J. (2000) Retention curves of deformable clays. In: Proceedings of international workshop on unsaturated soils: experimental evidence and theoretical approaches, Balkema, Trento, pp 91–106

Rotisciani, G. M., Casini, F., Desideri, A., Sciarra, G. (2016) Hydro-mechanical behavior of an embankment during inundation. Canadian Geotechnical Journal, 10.1139/cgj-2016-0174

Rotisciani, G. M., Sciarra, G., Casini, F., and Desideri, A. (2015) Hydro-mechanical response of collapsible soils under different infiltration events. Int. Journal for Numerical and Analytical Methods in Geomechanics, 39 (11), 1212–1234.

Sheng, D. (2011). Review of fundamental principles in modelling unsaturated soil behavior. Computers and Geotechnics 38(6):757-776

Sitarenios, P., Casini, F., Askarinejad, A., Springman, S.M. (under review). Hydro-mechanical analysis of a surficial landslide triggered by artificial rainfall: the Ruedlingen field experiment. Géotechnique (under review).

Tamagnini, R. (2004) An extended Cam-clay model for unsaturated soils with hydraulic hysteresis. Géotechnique, 54(3): 223–228.

Tarantino, A., Mongiovi, L., Bosco, G. (2000) An experimental investigation on the isotropic stress variables for unsaturated soils. Géotechnique 50:275–282

Vassallo, R., Mancuso, C., Vinale F. (2007). Effects of net stress and suction his-tory on the small strain stiffness of a compacted clayey silt. Canadian Geotechnical Journal, 44(4): 447-462.

Vaunat J, Romero E, Jommi C (2000) An elastoplastic hydromechanical model for unsaturated soils. In: Proceedings of international workshop on unsaturated soils: experimental evidence and theoretical approaches, Balkema, Trento, pp 121–138

Vaunat, J., Casini, F. (2017) A procedure for the direct determination of Bishop's χ parameter from changes in pore size distribution. Géotechnique 67(7): 631-636.

Vilar, M.O., Rodrigues, R.A. (2011) Collapse behavior of soil in a Brazilian region affected by a rising water table. Canadian Geotechnical Journal 48(2): 226-233.

Wheeler, S.J. (1996) Inclusion of specific water volume within an elastoplastic model for unsaturated soil. Can Geotech J 33:42–57

Wheeler, S.J., Sharma, R.S., Buisson, M.S.R. (2003) Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils. Géotechnique 53:41–54