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Research Paper

Modelling the mechanical behaviour of a natural unsaturated pyroclastic soil within Generalized Plasticity framework

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ABSTRACT

The paper deals with the mechanical behaviour of a natural volcanic silty soil sampled from steep slopes. This soil is very loose and unsaturated over most of the year due to climate conditions. Thus so-called wetting collapse and static liquefaction may occur during rainfall. Major issues are posed once the slides turn into flows with high destructive potential. However, the modelling of the constitutive behaviour is challenging and not yet available in the literature for this soil. A recent Generalized Plasticity Model was selected as it is capable to adequately take into account the effects of change in soil porosity, bonding related to the matric suction normalized versus soil porosity, and static liquefaction proneness. The model is calibrated for 37 saturated/unsaturated laboratory tests, and the performance of the model is assessed quantitatively. It is newly shown that the model – with one single set of constitutive parameters – is capable to well describe the soil mechanical response, in unsaturated and saturated conditions, experienced by the soil in different laboratory devices and along different stress paths. Those insights provide a theoretical framework for designing further laboratory tests, improving the understanding of this complex natural soil, and implementing better modelling of landslides of the flow-type.

1. Introduction

Natural volcanic air-fall soils show peculiar features, as well documented in recent literature [2,9,7,46,16]. Two specific mechanical responses are typical of those soils: (i) “static liquefaction” in saturated condition for undrained shearing, and (ii) so-called “volumetric collapse” in unsaturated conditions upon wetting.

Static liquefaction is typical of loose saturated sands [24,56,11] but similar behaviour was later observed also for silty sands or sandy silts [50,39]. More recent discussions pointed out that strain localisation is more important under plane-strain or 3D conditions compared to triaxial conditions [53,54]. These insights also underline that soil behaviour should be extensively investigated along different stress paths, and possibly for different conditions, e.g. saturated or partially saturated condition.

For unsaturated soil, the wetting-induced collapse consists in a decrease of total volume of a soil due to wetting at essentially unchanged total vertical stress. The occurrence and the magnitude of the collapse depends on several factors: (i) an open, potentially unstable soil structure [59]; (ii) a net total stress high enough to make the structure metastable; (iii) a bonding or cementing agent that stabilizes the soil in unsaturated condition [42]. Aimed to investigate this topic, Jennings and Knight [22] firstly proposed the “double oedometer” method, based on standard oedometer tests at natural water and saturation. However, no information related was achievable for the influence of wetting-drying cycles, later investigated for lightly compacted soils of Hong Kong [10] and compacted specimens of clay subjected to wetting-drying cycles soon after moulding [47]. The effect of triaxial state stress on the collapse occurrence was more recently investigated on collapsible lower Cromer till [1], poorly compacted sandy clay [26], compacted kaolin [55], powder clay [23] and clayey sand [52]. The quantitative simulation of the soil mechanical response requires the use of advanced constitutive models, capable to deal with the hydro-mechanical coupling in both saturated and unsaturated conditions. Several constitutive equations or models have been proposed to predict the behaviour of unsaturated soils. A fundamental contribution was provided by Alonso et al. [1], who proposed the so-called Basic Barcelona Model (BBM). In this model, the Critical State Theory [44] joined to the Classic Plasticity [21] is extended to unsaturated soils. BBM has been used so far to simulate the mechanical behaviour of moderate expansive

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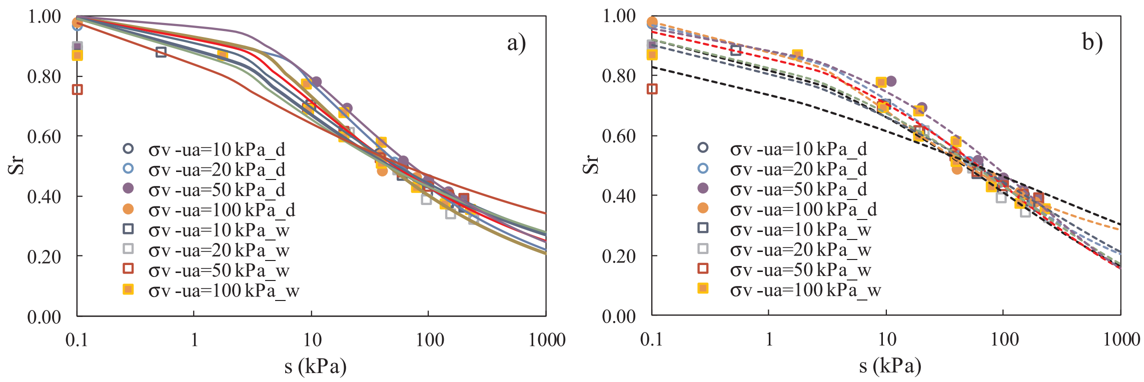

Fig. 1. Soil Water Retention Curve (SWRC) for different net vertical stress (σ_v-u_a) obtained through suction-controlled oedometer tests and interpolated through Van Genuchten model (a) and Fredlund and Xing model (b).

soils (like sands, silts, clayey sands, sandy clays or clays with a low plasticity). The stress variables of the BBM are the matric suction, the net stress (difference of total stress to the air pressure) and the specific volume, which is used as a state parameter. The model is capable to simulate: (i) the collapse or swelling, at different stress levels, due to a reduction of suction at constant net stress; (ii) the yielding of the soil due to the change of suction or net stress; (iii) the increase of the cohesion intercept due to an increase of suction. It is also worth mentioning the contributions of Wheeler and Sivakumar [55], who formulated an elasto-plastic-hardening model, starting from BBM model. An alternative approach is based on the Generalized Plasticity Theory [41,48,31], which will be used later on.

Notwithstanding the availability of comprehensive models, the mechanical behaviour of unsaturated volcanic air-fall soils is still limitedly addressed mostly because of the absence of extensive data-set of laboratory results. Other significant open issues are related to user-independent model calibration and quantitative assessment of model performance for complex constitutive models including many parameters.

The paper tries to fill this gap in the scientific literature modelling the mechanical behaviour of a complex natural soil: (i) in a wide range of states, from partially- to fully-saturated, in drained or undrained condition, and along different stress paths and confinement constraints including oedometric and triaxial; and (ii) using a comprehensive data-set. Thus, the paper provides an application of a model selected from the literature as it is capable to well reproduce important features of soil mechanical response. A procedure for model calibration is here proposed, and a systematic assessment of model performance is presented using a new-defined error function applicable also to other constitutive models.

The paper is organized as follows. It firstly presents the main peculiarities of a natural (air-fall volcanic) pyroclastic soil of Southern Italy, often involved in catastrophic landslides of the flow type [8,9,7], and the experimental laboratory testing programme developed in saturated and unsaturated soil conditions. Then, the Modified Pastor - Zienkiewicz constitutive model is presented [40,32,33], based on the fundamental concept of state and bonding parameter, which allows to accurately describing wide range of densities, confining pressure and suctions within a unitary framework, and through a unique set of constitutive parameters. Finally, calibration and performance of the constitutive model are discussed.

2. A vesuvian pyroclastic soil

The paper deals with an unsaturated air-fall volcanic (pyroclastic) soil of Southern Italy, originated from the explosive activity of the Somma-Vesuvius volcanic apparatus [8]. It is worth of note that: (i) the soil investigated resembles the behaviour of similar air-fall volcanic soils widespread all over the world (in almost 1% of Earth surface, [12], (ii) those soils are frequently involved in catastrophic landslides, (iii) there is still a lack of contributions regarding a comprehensive modelling of constitutive behaviour of such soils.

The soil investigated, classifiable as “class A” ashy soil according to Bilotta et al. [2], was involved in huge flow-like landslides occurred in May 1998, which caused many victims and damaged four towns at the toe of Pizzo d’Alvano massif. Since that time, slope failure and landslide propagation have been extensively studied [8,60]; among many others), while the soil constitutive behaviour has been oversimplified, as rigid perfectly-plastic, e.g. Cascini et al. [8], or elastic perfectly-plastic, e.g. Cascini et al. [9]. Whereas, more sophisticated and realistic constitutive models have been already used for other types of soils well reproducing slope failure, soil liquefaction and transformation from slide to flow (e.g. [7].

The soil grain size distribution consists in 43.6 to 51.9% Sand, 43.9 to 54.0% Silt, 1.4 to 4.7% Clay; soil specific gravity (G_s) is equal to 2.55; void ratio (e) ranges from 2.595 (undisturbed) to 1.982 (remoulded); the saturation degree (S_r) is comprised between 74.8% (undisturbed) and 92.1% (remoulded); the dry unit weight (γ_d) is 6.93 kN/m^3 to 8.65 kN/m^3 (respectively, undisturbed and remoulded). The average water content (w) is 51.9%, while the liquid limit (w_L) is 53.8% and the plastic limit (w_P) is 49.3% [3]. Due to the voids internal to the solid particles, this soil has a high porosity (0.53–0.74) and low soil unit weight (8.88–14.40 kN/m^3). Most of the studies investigated the role of matric suction, which is lowered by rainfall with dramatic consequences for slope stability. Thus, it is useful drawing some basic mechanical features.

The Soil Water Retention Curve (SWRC), relating the degree of saturation (S_r) to the matric suction (s), was obtained from drying and wetting tests (labelled as “d” and “w”, respectively in Fig. 1) conducted in Suction Controlled Oedometer tests [2,45] on undisturbed specimens at three different total net stresses (σ_v-u_a) equal to 10, 20 and 50 kPa. The experimental results (Fig. 1) show for SWRC a moderate variability, which is related to the inner nature of the air-fall soil under investigation. However, each experimental curve is well interpreted by Van Genuchten [51] model (with parameters: α equal to 0.19–1.02, n equal to 1.19–1.79, and m equal to 0.16–0.44) and Fredlund and Xing [18] model (with parameters: α equal to 23.59–448.38, m equal to 2.60–16.15 and n equal to 0.31–0.72):

$$S_r = S_{r0} + (1{-}S_{r0})\left[\frac{1}{1+(a{\cdot}s)^n}\right]^m \tag{1}$$

$$S_r = S_{r0} + (1{-}S_{r0})\left\{\frac{1}{\ln\left[e+(a{\cdot}s)^n\right]}\right\}^m \tag{2}$$

where S_{r0} is the residual saturation degree, s is the matric suction equal to u_a - u_w, u_a is the pore air pressure, u_w is the pore water pressure, a, m and n are parameters of the models, e is Euler's number.