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A microstructural insight into compacted clayey soils and their hydraulic properties

Enrique Romero *

Department of Geotechnical Engineering and Geosciences, Universitat Politècnica de Catalunya, Barcelona Spain

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ABSTRACT

A review of the literature is initially presented to bring into light the important microstructural effects on the hydraulic properties of different compacted clayey soils. Experimental data coming from microstructural and macroscopic studies on different compacted clayey soils with dominant multi-modal pore size distribution are analysed to provide a comprehensive picture of different phenomenological features of hydraulic soil behaviour. The data come from clayey soils compacted on the dry side (i.e., with an intrinsic and permanent aggregated structure) or alternatively with dominant coarse fraction (i.e., sand–bentonite mixture with shielding skeleton and well-developed inter-grain porosity), which undergo important microstructural changes on wetting and drying. A microstructural model, already developed to take into account microstructural aspects on water retention curves, is used to plot in the Proctor plane the microstructure set up by compaction and its evolution along hydraulic paths. The model is also used to explain the evolution of hydraulic properties (water and air permeability, water retention) along wetting and drying paths on an artificially prepared mixture of sand and bentonite with dominant granular fraction. The bentonite strongly reacts to changes in water content and allows studying the transition from a granular soil with large pores between sand grains to a low-permeability material on wetting. The key point of this simple model is the introduction of the dependence of the microvoid volume (admitting saturated aggregates) on water content, following an equivalent behavioural response to the macroscopic shrinkage curve.

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1. Introduction and background

Microstructural experimental studies have recently re-emerged as an important tool to improve understanding of phenomenological behavioural features of compacted soils (compressibility, water retention properties, and water permeability), setting out hypotheses for micro and macrostructural interactions and in building up multi-structural constitutive models (see for instance: Alonso et al., 1999; Loret and Khalili, 2000; Sánchez et al., 2005; Alonso et al., 2010; Romero et al., 2011; Della Vecchia et al., 2013). Nevertheless, it is important to remark that this re-emergence is based on a long research tradition on compacted soils with pioneering works carried out in the 1960s and early 70s (to quote but a few of them: Seed and Chan, 1959; Mitchell et al., 1965; Barden and Sides, 1970; Diamond, 1970; Sridharan et al., 1971). Since then, works were systematically undertaken to study microstructural features and their effects on different properties of fine grained soils, such as shear strength and tensile strength properties (see for instance: Ahmed et al., 1974; Marsland et al., 1990; Vaunat et al., 2007; Zeh and Witt, 2007; Kochmanová and Tanaka, 2011; Merchán et al., 2011), as well as on hydraulic properties (Garcia-Bengochea et al., 1979; Benson and Daniel, 1990; Prapaharan et al., 1991; Huang et al., 1998; Romero et al., 1999; Vanapalli et al., 1999; Watabe et al., 2000; Simms and Yanful, 2002; Chapuis et al., 2006; Frydman and Baker, 2009; Jamei et al., 2011; Li et al., 2011) and on soil compressibility characteristics (Sivakumar and Wheeler, 2000; Katti and Shanmugasundaram, 2001; Santucci de Magistris and Tatsuoka, 2004; Delage et al., 2006; Ferber et al., 2008; Tarantino and De Col, 2008; Koliji et al., 2009). There is a resurgence of interest in these subjects due to the use of novel microstructural experimental techniques with better resolution and interpretation tools to analyse the arrangement and distribution of particles and aggregates. These studies include descriptions of particle/aggregate size and morphology, their assemblages and orientations, inter-particle contact orientations and contact force directions, as well as on pore type, distribution and connectivity. Much attention has been also paid to the distribution of pore sizes in different soils and their changes along mechanical and hydraulic paths (to cite but a few of them: Delage and Lefebvre, 1984; Coulon and Bruand, 1989; Griffiths and Joshi, 1989; Al-Mukhtar et al., 1996; Penumadu and Dean, 2000; Sivakumar and Wheeler, 2000; Simms and Yanful, 2002; Cuisinier and Laloui, 2004; Simms and Yanful, 2005; Koliji et al., 2006; Delage, 2006; Thom et al., 2007; Romero and Simms, 2008; Li and Zhang, 2009; Mascarenha et al., 2010; Monroy et al., 2010; Koliji et al., 2010; Cuisinier et al., 2011; Casini et al., 2012; Villar et al., 2012).

Particularly, most of these studies have become pertinent to compacted clayey soils due to their dominant and intrinsic multi-modal pore size distribution PSD (i.e., aggregated type) created on preparation – besides the natural particle aggregations – , and whose

* Departamento de Ingeniería del Terreno, c/Jordi Girona 1-3, Campus Nord, Edificio D-2, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain. Fax: +34 93 4017251.
E-mail address: enrique.romero-morales@upc.edu.

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behaviour is complicated by the presence of both air and water that also affect the evolution of this multi-modal pore network from a multi-phase interaction viewpoint. These studies have illustrated that the microstructure of a given compacted soil is not unique (samples compacted on the dry or wet side of optimum), and strongly depends on the preparation method used (dynamic or static compaction) and the stress paths followed to reach a given point in the compaction plot. A classic example affecting hydraulic properties is the variation in water permeability of a clayey soil at different compaction water contents. A saturated soil compacted wet of optimum exhibits lower permeability than the same saturated soil compacted to the same dry density at dry of optimum. Watabe et al. (2000) showed this important sensitivity of the water permeability to the compaction degree of saturation on compacted glacial till at constant void ratio, in which a reduction of about two orders of magnitude was observed when comparing water permeability values between initial degrees of saturation of 0.50 and 0.90. The difference has been attributed to the quantity and size of clay aggregates brought about by compaction at different levels of water content; i.e., the initial microstructure set up during soil preparation, which controls subsequent soil behaviour (Garcia-Bengochea et al., 1979; Benson and Daniel, 1990; Delage et al., 1996). Nevertheless, this as-compacted microstructure should not be considered permanent since it evolves with the stress paths followed, as will be shown along the present paper.

Another example dealing with permeability features, is the important differences encountered between the intrinsic permeabilities measured in low-porosity compacted clayey soils at different saturation states and when different permeants are used. Much higher values are observed at dry conditions when the permeability to air is measured – several orders of magnitude larger than the value under water saturated conditions and at the same void ratio – , as observed in Fig. 1 for compacted and predominantly divalent bentonite (refer to Villar and Lloret, 2001; Villar et al., 2005 for further details). The gap of several orders of magnitude cannot be explained only in terms of the higher gas mobility due to Klinkenberg gas slippage effect (see for instance, Geankoplis, 1983). A dependence of intrinsic permeability on water content (or degree of saturation) should be introduced, as suggested by Olivella and Gens (2000), to take into account the changes in microstructure when the clay is wetted. As observed, microstructural effects are pertinent to the design and service life of a wide range of geotechnical applications, ranging from earthwork constructions (earth dams, river and canal dikes, railway and road embankments) to waste isolation systems (engineered barriers).

On the basis of experimental data on compacted clayey soils, in which mercury intrusion porosimetry MIP is given special attention to describe the pore network and its size distribution (Romero and Simms, 2008), the paper shows the important effects of the initial microstructure and its evolution along suction paths. The Proctor compaction plot has been used to present the initial microstructural features set up during compaction. The data come from clayey soils compacted on the dry side (i.e., with an intrinsic and permanent aggregated structure) or alternatively with dominant coarse fraction (i.e., with shielding skeleton and well-developed inter-grain porosity). The soils range from a clayey silt typically used in earthwork constructions to bentonite and sand/bentonite mixtures used in engineered barrier systems. To explain and emphasise the evolving nature of the microstructural effects on hydraulic properties, an artificially prepared mixture of sand and bentonite with dominant granular fraction (80% on dry mass basis) has been used. The bentonite strongly reacts to changes in water content and allows studying the transition from a granular soil with large pores between sand grains to a low-permeability material on wetting, when the inter-grain porosity is filled with expanded bentonite.

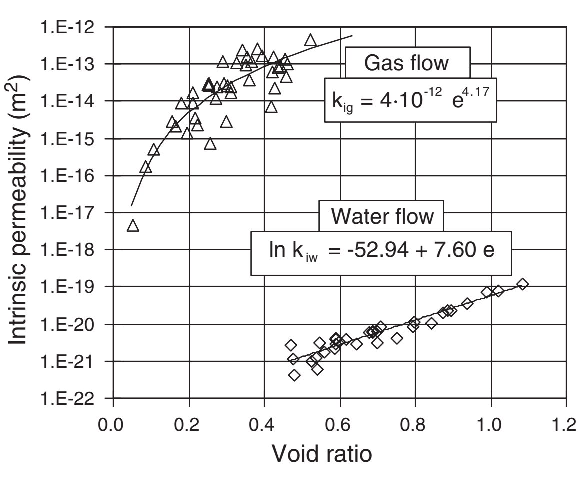

Fig. 1. Intrinsic permeability of compacted bentonite as a function of void ratio obtained from saturated water flow and air flow tests (Villar and Lloret, 2001).

To describe the microstructure set up on compaction and its evolution, two main types of pores are considered: inter-aggregate pores (macrovoids between soil aggregates or shielding grains) and intra-aggregate pores (microvoids inside clay aggregates). This separation should not be considered merely in terms of pore sizes, since it is mainly associated with specific behavioural features (Delage et al., 1996; Romero et al., 1999; Lloret et al., 2003). The intra-aggregate porosity displays non-constricted porosity with no bottle neck effects; water adsorption storage mechanism not affected by porosity variations and restricted capacity to liquid flow. On the other hand, the inter-aggregate porosity displays an interconnected porosity and a water storage mechanism affected by void ratio changes (Romero et al., 2011). It is known that MIP is not able to penetrate all the pores of these compacted clayey materials, which usually display maximum pore sizes below 500 μm (maximum value detected by MIP). The non-intruded volume of intra-aggregate porosity (below 6 nm) is corrected by considering macroscopic measurements of the actual void ratio (see for instance, Lloret et al., 2003).

The effects of microstructural changes have been interpreted with a simple physically-based model that introduces the dependence of the microvoid volume (admitting saturated aggregates) on water content and emulates the behavioural response of the macroscopic shrinkage curve. The model has already been used to study microstructural features on water retention properties of compacted clayey soils with bimodal pore size distribution (Romero et al., 2011; Della Vecchia et al., 2013).

2. Studying the evolution of the pore size density function along stress paths

Changes in inter-aggregate porosity are dominant during loading at constant water content on the dry side, as shown in Fig. 2 for different statically compacted clayey soils. The figure presents the initial and final pore size density PSD functions, as well as the initial and final void ratios e, and degrees of saturation e_w/e, during compression at constant water ratio e_w (i.e., volume of water to volume of solids, $e_w = w\rho_s$, where w is water content and ρ_s density of solids). The figure also indicates the maximum vertical stresses (σ''_{vmax}) applied on static compaction under oedometer conditions. The soils studied, which were all freeze-dried before MIP determination, correspond to illitic–kaolinitic clay (Figure 2a), clayey silt (Figure 2b) and sand–bentonite mixture with a dominant sandy shielding skeleton (Figure 2c), whose main geotechnical properties are summarised in Table 1 with row references 5, 3 and 9, respectively. The as-compacted samples of illitic–kaolinitic clay and clayey silt are characterised by bimodal PSD distributions. The as-compacted sand–bentonite mixture displays one large pore mode at inter-grain scale (macrovoids between shielding sand grains) and two pore modes at clay-aggregation scale (microvoids with pore sizes smaller than 30 μm). The larger inter-grain mode forming the shielding

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