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Microstructural changes of an undisturbed, reconstituted and compacted high plasticity clay subjected to wetting and drying

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ABSTRACT

The behaviour of soil, and in particular compacted clay fill, can have significant implications on the safe and reliable operation of man-made infrastructure. The mechanical behaviour of soil (e.g. volume change and shear strength) is widely recognised as being associated with the microstructural arrangement (fabric/structure). In the case of high plasticity clays, despite the large amount of research carried out, soil microstructure and its evolution along mechanical and hydraulic paths are still not well understood. This makes incorporation of microstructural analysis difficult in engineering practice and highlights the need for further research. A comprehensive microstructural analysis of Maryland clay, a high plasticity residual soil, based on mercury intrusion porosimetry tests, is presented in this paper. Experimental results obtained from undisturbed, reconstituted and compacted specimens subjected to different hydraulic and mechanical paths are described. As with mechanical investigations, the reconstituted state is proposed to be used routinely as a reference state for comparison of undisturbed and compacted soil. The microstructural evolution of the compacted clay, prepared on the wet side of standard Proctor optimum water content, with an initially high void ratio, is examined along the main drying path. Importantly, a monotonic suction increase from the as-compacted state is shown to have negligible effect on the distribution of macro-pores. However, a new insight is provided based on the evolution of the dominant micro-pore entrance diameter which is shown to reduce with increased suction. This micro-pore entrance diameter is shown to correspond with the theoretical suction back-calculated from a simple capillary tube model, up to a limit. It is observed that, under oedometric conditions, the as-compacted microstructure is erased during saturation (soaking) and resembles the reconstituted microstructure. For this particular material and preparation conditions, it is demonstrated that a bimodal microstructure is not recovered on drying from a saturated state.

1. Introduction

The microstructure of soil has previously been recognized to influence the mechanical behaviour of natural and compacted geomaterials. The pore size density (PSD) functions, for both saturated and unsaturated soils, obtained from mercury intrusion porosimetry (MIP) have been shown to evolve as a result of hydraulic, mechanical and chemical changes (Delage and Lefebvre, 1984; Delage et al., 1996; Romero et al., 1999; Simms and Yanful, 2001; Koliji et al., 2006; Casini et al., 2012; Musso et al., 2013; Wang et al., 2013). Despite this, there is still limited understanding of how the soil microstructure evolves during combined hydraulic and mechanical paths. This paper focuses on the distribution of pore sizes and their separation into micro and macro components. Many additional factors contribute to soil microstructure (e.g. geometrical arrangement of pores, cementation/binding, pore-water chemistry), however these are not specifically investigated here.

The complexity of microstructural behaviour has led to compacted and reconstituted soils being considered as fundamentally different materials. However, the boundary between compacted and reconstituted soils is not always well defined in terms of microstructure (Tarantino, 2011). Soils compacted dry of the standard Proctor optimum water content, are commonly reported to exhibit a bimodal PSD function. This characteristic is sometimes reported as an intrinsic characteristic of soils compacted dry of optimum. However, previous MIP studies have shown that on saturation the bimodal microstructure can either evolve towards a unimodal structure (Monroy et al., 2010) or remain unchanged (Thom et al., 2007). This conflicting experimental evidence makes difficult the development of unified frameworks and highlights the necessity for further experimental research.

The behaviour of materials compacted on the wet side of standard Proctor optimum water content is also relevant to engineering practice.

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For example, in the design of landfill barriers and clay cores for embankment dams (Fell et al., 2005; Mitchell and Soga, 2005). However, despite the practical relevance, microstructural investigations of soils prepared on the wet side of standard Proctor optimum water content are rather limited. It is widely believed that a compacted soil prepared on the wet side of optimum is homogeneous and has a unimodal pore size distribution (Tarantino, 2011). However, Simms and Yanful (2001) showed that samples prepared on the wet side can also be bimodal, albeit for a material with a coarse shielding skeleton (Romero, 2013).

Microstructural experimental evidence has been used for the development of constitutive models which attempt to describe the behaviour of unsaturated soils (e.g. Gens and Alonso, 1992; Alonso et al., 1999, 2010, 2013; Koliji et al., 2010; Della Vecchia et al., 2013; Mašín, 2013). In the model of Alonso et al. (1990), and models built upon this, a fundamental ingredient is the concept of a LC yield curve which relates the plastic compression of unsaturated soils to compression and suction variations. Alonso et al. (1987) and Sheng (2011) pointed out that the notion of a LC curve is inextricably linked to that of a bimodal PSD. For example, let us consider a compacted soil at point A, shown in Fig. 1, which is assumed to have a bimodal structure. On saturation to point B, i.e. full saturation but not just zero suction, the size of macro-pores decreases with the possible combined effects of expansion of the clayey aggregates and collapse. This induces a predominant unimodal PSD. If the sample is then dried to a suction above the air-entry value and compressed to point C, the movement of the LC curve suggests that collapse can occur again which implies that at point C the sample should recover a bimodal PSD. On the other hand, for soils that contain a "shielding skeleton" of coarse particles it is possible to envisage that the shielding skeleton limits the shrinkage on drying of the bulk sample while the clayey fraction may continue to shrink and create macro-pores (Romero, 2013). It is well known that collapse can occur in silty soils, similar to the loess described by Muñoz-Castelblanco et al. (2011) and the volcanic ash described by Ferrari et al. (2013). This paper on the other hand is concerned with a high plasticity clay. Due to the soil-dependent evolution of the PSD additional microstructural experimental evidence is needed in order to understand the role played by the soil microstructure in the LC concept as well as its evolution with combined stress paths.

This paper examines the existence and evolution of a bimodal PSD in compacted clay prepared on the wet side of the standard Proctor optimum water content. Maryland clay, a high plasticity residual soil from New South Wales (Australia) has been used for this purpose. The PSD of the compacted soil is evaluated in relation to those of undisturbed and reconstituted specimens which are used as a reference framework for interpreting the experimental results. The PSD obtained after the application of hydraulic (wetting and/or drying) as well as combined hydro-mechanical (wetting at constant stress) paths is used to evaluate the evolution of microstructure. Starting from the as-compacted state the PSD evolution along a monotonic drying path is investigated, and the evolution of the dominant micro-pore diameter (i.e. the peak of the PSD in the micro range) monitored. Soil microstructure is also evaluated after monotonic wetting paths (by soaking) applied to compacted specimens under different vertical stress levels. The possibility for developing a bimodal PSD in compacted–saturated specimens when subjected to air drying is also investigated.

2. Material, equipment and methods

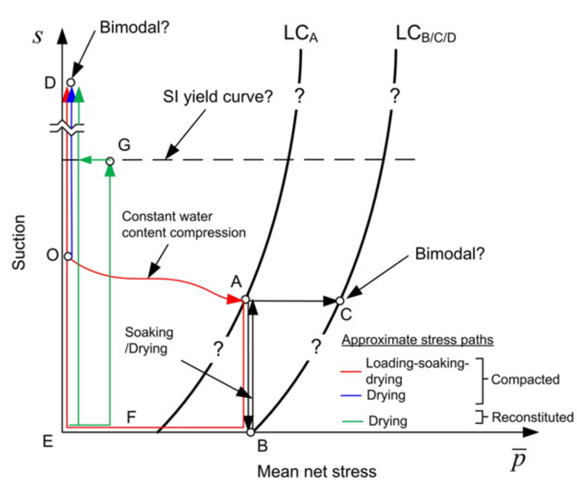
2.1. Soil tested

Maryland clay is a residual soil, from west of Newcastle (Australia), derived from the weathering of the parent mudrock material (Fityus and Smith, 2004). The material has a liquid limit of $w_L = 69\%$, plasticity index $I_P = 43\%$ and specific gravity of $G_s = 2.65$. The standard Proctor maximum dry density is 1.5 Mg/m^3 (void ratio 0.76) and the standard Proctor optimum water content is 24.8%.

Three different soil conditions were tested in this study: 1) natural or undisturbed, 2) reconstituted, and 3) compacted. Two undisturbed samples were collected from slightly different locations in a test-pit excavated at the Maryland test site to assess the in situ variability. The in situ water contents were 22.7% and 23.6%, respectively. Block samples were sealed with successive layers of plastic wrap, aluminium foil and wax. These block samples were then stored in a fog room for later testing. The structural arrangement of the undisturbed soil was qualitatively evaluated by means of scanning electron microscope (SEM) images as shown in Fig. 2. Two structural levels can be clearly defined. Large macro-pores are evident in Fig. 2a, which defines the macro porosity. At larger magnification (Fig. 2b) a rather homogeneous structural arrangement, albeit displaying a complex geometrical arrangement, seems to define the micro porosity.

Reconstituted specimens were prepared by mixing dry powdered Maryland clay with deionized water at water content roughly 1.5 times the liquid limit. The slurry was then one dimensionally consolidated in a mould to a vertical stress of around 50 kPa. At the end of consolidation the samples had water contents between 50.6% and 54.6%.

To prepare the compacted samples, the powdered clay was mixed with water to a gravimetric water content of around 28% (≈3% higher than optimum). The blended material was then sealed in air tight vacuum storage bags and allowed to equilibrate. The samples were statically compacted to the target void ratio (1.27) in a single layer 10 mm high



Sample	Stress path
R1	E
R2	E-D
R3	E-O(400)
R4	E-D
R5	E-D(800)

Suction

Sample	Stress path
C1	O
C2	O-D(2160)
C3	O-D(2190)
C4	O-D(4150)
C5	O-D(8170)
C6	O-D(11910)
C7	O-D(18050)
C8	O-D(27470)
C9	O-D(44370)

Suction

Sample	Stress path
C10	O-A(2)-B
C11	O-A(20)-B
C12	O-A(100)-B
C13	O-A(200)-B
C13/1	O-A(200)-B-E-D
C14	O-A(600)-B
C15	O-A(2)-B-E-D

Vertical stress at soaking

Fig. 1. Evolution of loading-collapse type yield curves and associated assumptions related to microstructure. Approximate stress path of some tests in the paper is shown.