Hydro-mechanical behaviour of compacted soils with a pronounced natural multi-modal pore structure

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1 Introduction

Natural structured soils such as loess deposits, lateritic and residual soils, vegetated soils, and fissured clayey formations often exhibit a pronounced multi-modal pore system associated with aggregation, cementation, desiccation features, or biological activity. These materials typically contain large and highly connected pores between aggregates, fissures, or root channels, together with smaller pores within the soil matrix or inside aggregates. Such hierarchical pore organisation governs their hydro-mechanical response and strongly influences their collapse susceptibility upon wetting.

In their natural state, these soils commonly exhibit low density, high porosity, partial saturation, and metastable structures sustained by suction and weak bonding such as clay bridges, carbonates, gypsum, or iron and aluminium oxides. Upon wetting, suction reduction and bond degradation may induce significant volume changes, loss of stiffness, and collapse settlements under relatively low engineering stresses [1].

For this reason, natural deposits with pronounced open structures are generally unsuitable for direct use in earthworks and foundation applications without improvement. Compaction is commonly adopted to increase density, reduce macroporosity, and improve mechanical stability. However, several studies suggest that compacted structured soils may still preserve part of their inherent pore hierarchy and aggregation fabric, particularly when compaction is performed on the dry side of optimum conditions [2]. As a consequence, even after compaction, these materials may retain a distinct bimodal water-retention response and remain sensitive to hydraulic loading paths, especially drying–wetting cycles. The persistence of connected macrostructural pores may still promote collapse upon saturation and induce significant hydro-mechanical strains, resembling the behaviour traditionally associated with soft soils.

This paper investigates the hydro-mechanical behaviour of compacted soils with pronounced natural multi-modal pore structures. Two natural soils are considered: a collapsible lateritic residual soil from southern Brazil and a low-density carbonated clayey silt from the Ebro basin in north-eastern Spain. Both materials exhibit metastable aggregated fabrics and pronounced macrostructural porosity in their natural state. The study focuses on the persistence of the inherited pore hierarchy after compaction and its implications for water retention, collapse susceptibility, and volume change behaviour under engineering stress levels.

2 Soil characteristics

Two natural structured soils with pronounced multimodal pore systems were investigated: a lateritic residual soil from Cruz Alta (southern Brazil) and a low-density carbonated clayey silt from the Segarra–Garrigues area in the Ebro basin (north-eastern Spain).

The Brazilian soil (BS) is derived from weathered basalts of the Serra Geral Formation (Paraná Basin) and classified as low-plasticity silt with sand (ML) according to the Unified Soil Classification System (USCS) and as a clayey lateritic soil (LG') according to the Miniature Compacted Tropical (MCT) classification for tropical soils [3]. The BS exhibits a strongly aggregated fabric dominated by kaolinite, with high sesquioxide contents promoting interparticle bonding and aggregation. The Spanish soil (SS) was deposited in flat-bottom valleys under semi-arid conditions and is characterized by open metastable structures stabilized by carbonate and gypsum cementation. The soil is classified as CL–ML to ML according to USCS [4]. Both materials, in their natural state, present low-density, high void ratio and partial saturation (Table 1), resulting in a metastable structure highly sensitive to suction changes and wetting-induced collapse.

To investigate the effect of compaction on the hydro-mechanical improvement of these soils, reconstituted specimens were prepared under controlled compaction conditions using Standard Proctor (SP) energy. For both materials, specimens were compacted at optimum water content. In addition, the Brazilian soil was also compacted on the dry side of optimum conditions, while an additional condition was considered for the Spanish soil by drying the specimen after Standard Proctor compaction (Table 1). Compaction produced a clear increase in dry density and a reduction in void ratio. However, further hydro-mechanical investigation is required to assess whether these improvements are sufficient to suppress the inherited multimodal structure and its associated collapse susceptibility.

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Table 1. Initial conditions of the studied soils.

Soil	Condition	Water content (%)	Dry density (Mg/m^3)	Void ratio	Degree of saturation	Initial suction (MPa)
Brazilian Soil (BS)	Natural (BS_N)	31.8	1.16	1.41	0.63	0.02
	Compacted at the optimum(1) (BS_O)	22.4	1.61	0.73	0.85	0.19
	Compacted on the dry side(2) (BS_D)	20.4	1.53	0.83	0.69	0.25
Spanish Soil (SS)	Natural (SS_N)	13.2	1.32	1.06	0.33	1.00
	Compacted at the optimum(1) (SS_O)	15.1	1.87	0.44	0.91	0.38
	Compacted at the optimum and dried(3) (SS_OD)	5.5	1.91	0.41	0.37	26.00

Notes: (1) Standard Proctor test; (2) Water content of 2.00% below the optimum water content and relative compaction of 95%; (3) From the optimum conditions of the SP, the soil was dried to a relative humidity of around 82%.

3 Hydro-mechanical properties

3.1 Collapse behaviour under one-dimensional loading

The collapse susceptibility of both soils was investigated through oedometer tests performed under controlled wetting conditions.

For the Brazilian lateritic soil, collapse tests on natural specimens (BS_N) were conducted using a single-stage wetting procedure [5] in which inundation was imposed under different vertical stresses. Additional tests were carried out on specimens compacted on the dry side of optimum (BS_D) conditions using a two-stage procedure, comparing the compressibility response before and after saturation.

For the Spanish clayey silt, wetting-induced collapse tests were performed on specimens in the natural condition (SS_N), compacted at Standard Proctor optimum conditions (SS_O), and compacted specimens subsequently subjected to drying (SS_OD). In this latter condition, the compacted soil was dried to a higher suction state before wetting in order to investigate the effect of post-compaction drying on collapse susceptibility.

The axial deformation during collapse, also known as collapse potential, was quantified following Equation (1):

$$\varepsilon_a = -\frac{e_i - e_f}{1 + e_0} \tag{1}$$

where e_0 is the initial void ratio at natural/compaction water content, e_i is the void ratio at the target vertical stress before the wetting and e_f is the void ratio after wetting.

Figure 1 shows the one-dimensional compression response and collapse potential of the Brazilian lateritic soil. The natural material exhibits pronounced collapse strains, with collapse deformation increasing significantly with vertical stress, reaching values slightly above 15% at 800 kPa. Nevertheless, for higher loads it is expected that the natural structure is partially affected and the subsequent collapse deformation is reduced (maximum collapse is expected at engineering stresses). In contrast, dry-side compaction substantially reduces collapse susceptibility, although collapse is not completely suppressed. In this case, collapse will increase with load within the normal engineering stress range. These results indicate that compaction effectively densifies the soil and reduces the magnitude of macrostructural collapse, but part of the inherited aggregated pore structure remains active during wetting.

A similar tendency was observed for the Spanish clayey silt (Figure 2). The natural material exhibits very large collapse strains, reaching values close to 10% under moderate vertical stresses. Compaction at optimum conditions almost suppresses collapse, indicating the strong reduction of macrostructural porosity induced by densification. However, when the compacted material is subsequently dried to high suction states before wetting, collapse susceptibility partially reappears despite the higher dry density. This behaviour suggests that drying after compaction promotes the development or reopening of macrostructural pores associated with aggregate shrinkage and suction hardening.

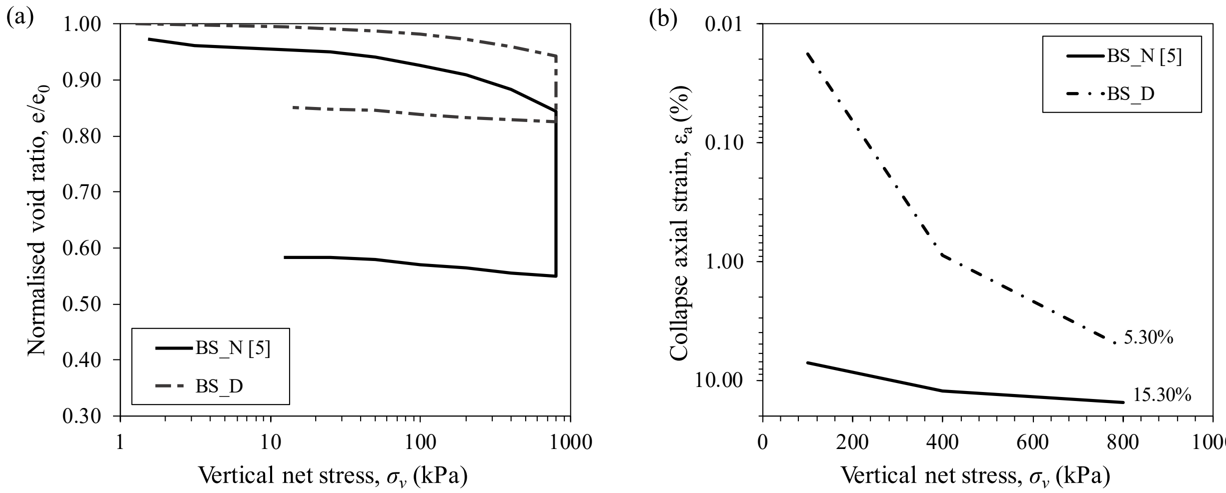

Figure 1. Wetting-induced collapse of the Brazilian soil (BS) under natural and compacted conditions: (a) collapse behaviour at vertical stress of 800 kPa; (b) collapse strains at different stress levels.

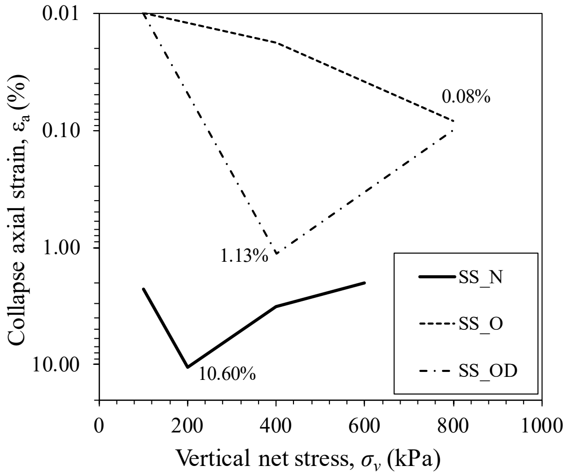

Figure 2. Wetting-induced collapse of the Spanish soil (SS) under natural and compacted conditions: collapse strains at different stress levels.

3.2 Water retention behaviour

The effect of compaction on the pore structure of the Brazilian lateritic soil was further investigated through the water retention curves (WRCs) obtained for the natural condition (BS_N), compaction at optimum conditions (BS_O), and dry-side compaction (BS_D). Figure 3 presents the relationship between suction and degree of saturation along the drying paths.

The experimental data for the BS_N were obtained through the filter paper method. The tests were performed in accordance with ASTM D5298-16, using Whatman No. 42 filter paper [5]. The experimental data for the BS_O and BS_D were obtained through different techniques, including the suction plate, WP4C psychrometer, and tensiometer. For clarity, the experimental data were fitted using the dual van Genuchten model [6].

The natural soil exhibits a pronounced bimodal retention response associated with its aggregated structure. The first air-entry value corresponds to the drainage of large inter-aggregate pores, whereas the second retention domain is associated with smaller intra-aggregate pores and the soil matrix. The enhancement of the dual-porosity water-retention response after shrinkage is attributed to the enlargement of inter-aggregate macropores caused by aggregate contraction, while the surrounding soil skeleton undergoes comparatively lower shrinkage.

Compaction significantly modifies the retention behaviour by reducing the volume and connectivity of the largest pores, leading to higher degrees of saturation and increased air-entry values. Nevertheless, despite the clear reduction in void ratio after compaction, subsequent drying still induced a marked double-porosity response, particularly for the sample compacted at the dry side, in which the initially larger inter-aggregate pore network underwent further enlargement during shrinkage. This behaviour indicates that part of the inherited pore hierarchy remains after densification.

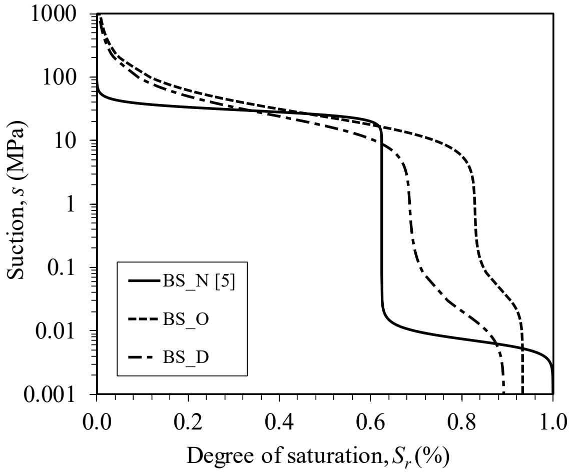

Figure 3. Water retention curves of the Brazilian soil (BS) in natural and compacted conditions.

4 Conclusions

This study investigated the hydro-mechanical behaviour of two natural structured soils with pronounced multimodal pore systems subjected to compaction under Standard Proctor conditions. The results showed that compaction substantially increases dry density and reduces void ratio, leading to a significant improvement in collapse resistance under wetting. However, the experimental results also demonstrated that compaction does not completely suppress the inherited multimodal pore structure of these materials. The Brazilian lateritic soil retained a marked bimodal water-retention response after compaction and subsequent drying, indicating the persistence or even enhancement of distinct inter- and intra-aggregate pore domains. This behaviour is attributed to differential shrinkage within the soil structure, in which aggregate contraction promotes the enlargement of inter-aggregate macropores while the surrounding soil skeleton undergoes comparatively smaller deformations. Similarly, both compacted soils still exhibited measurable collapse strains after drying or when compacted at dry conditions, showing that hydraulic stress paths may reactivate part of the macrostructural pore network despite the higher density achieved during compaction. These findings suggest that the hydro-mechanical behaviour of compacted structured soils cannot be interpreted exclusively in terms of global density or void ratio. The persistence or reactivation of macrostructural pores inherited from the natural fabric continues to govern wetting-induced collapse and water-retention behaviour, even after significant densification. The results highlight the importance of considering microstructural features and hydraulic stress paths when evaluating the long-term performance of compacted collapsible soils in earthworks and geotechnical engineering applications.

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