Engineering Geology 205 (2016) 73–80

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Relationship between soil structure and water retention properties in a residual compacted soil

Ivan Fernando Otalvaro [a], Manoel Porfírio Cordão Neto [b,*], Pierre Delage [c], Bernardo Caicedo [d]

[a] Universidad Javeriana, Cali, Colombia
[b] Universidade de Brasília, Faculdade de Tecnologia, Departamento de Engenharia Civil e Ambiental, Campus Darcy Ribeiro — Asa Norte SG-12, 70910900 Brasília, DF, Brazil
[c] Ecole des ponts ParisTech (Navier/CERMES), Paris, 6–8 Av. B. Pascal, F 77455 Marne la Vallee cdx 2, France
[d] Universidad de Los Andes, Bogotá D. C., Colombia: Cra. 1 Este No. 19 A-40, Bogotá, Colombia

ARTICLE INFO

Article history:
Received 6 April 2015
Received in revised form 12 January 2016
Accepted 29 February 2016
Available online 2 March 2016

Keywords:
Mercury intrusion porosimetry
Water retention curve
Pore size density

ABSTRACT

Soil structure, especially the soil pore size distribution, is a fundamental property that describes the hydro-mechanical behavior of soils. The volume change behavior, shear strength, water retention capacity and hydraulic conductivity of soil are controlled by the pore size distribution. However, research on soil structure has been limited due to the associated expenses and specialized instruments, such as environmental scanning electron microscopes and mercury intrusion porosimeters (MIPs). In this study, the relationship between the soil water retention curve (WRC) along a drying path and the pore size distribution obtained through an MIP method was reviewed. The WRC for a compacted tropical soil was converted into a soil air injection curve and then used to estimate the pore size density (PSD) function. Relative to the data collected from MIP methods, the results showed an acceptable prediction of the PSD function based on a soil air injection curve. Finally, a series of adjustments to the air injection curve were performed to improve the accuracy of the PSD prediction based on the water retention curve.

1. Introduction

Compacted soils are used as construction materials in numerous geotechnical works around the world. Most studies about soil compaction are based on Proctor's studies. This method tries to reproduce field compaction in the laboratory by applying controlled mechanical energy to remove the air within the soil without analyzing the soil microstructure. In the last 20 years, abundant research devoted to explaining compaction curves have used the unsaturated theory of soil behavior, supported with a growing interest in the study of soil structure at multi-scale levels from the micrometric scale to the nanometric scale. These studies have incorporated structural effects into the macroscopic behavior predictions of compacted soils (Alonso et al., 1999; Airò-Farulla et al., 2010; Pham and Fredlund, 2011; Alonso et al., 2011).

However, most previous studies have examined compacted clays derived from sedimentary processes, and little research exists on the behavior of the compacted residual soils that are currently used in geotechnical works in many parts of the world, especially in the subtropical and tropical climates of South America and Africa. In addition to their natural complexity, compacted residual soils exhibit local-specific features. For instance, soils in Ouro Preto, Brazil, are characterized by clay aggregations with two dominant pore sizes (Futai and Almeida, 2005), natural soils in Campinas, Brazil, exhibit two dominant pore size volumes separated by three orders of magnitude (Miguel and Bonder, 2012), and soils from Brasilia exhibit high collapsibility in either natural or compacted states (Otálvaro et al., 2015).

To better understand the properties of compacted residual soils, it is necessary to characterize their composition and structural arrangement by studying their structure (i.e., the combination of structural arrangement, or fabric, and bonding; Mitchell and Soga, 2005). Different techniques have been employed for this purpose: scanning electronic microscopy (SEM) and mercury intrusion porosimetry (MIP; Diamond, 1970; Collins and McGrown, 1974; Delage and Lefebvre, 1984; Mitchell and Soga, 2005; Romero and Simms, 2008).

In this paper, the structural behavior of compacted residual soils was analyzed based on the combined use of MIP and the determination of the water retention curve (WRC) along a drying path. In addition, the relationship between WRC and MIP was investigated to obtain the pore size density based on the WRC. The main advantage of this methodology is the relative simplicity of obtaining water retention curves. The results of the proposed methodology are encouraging and were validated based on a comparison to the results obtained from mercury intrusion porosimetry.

* Corresponding author at: Universidade de Brasília, Faculdade de Tecnologia, Departamento de Engenharia Civil e Ambiental, Campus Darcy Ribeiro — Asa Norte SG-12, Asa Norte, 70910900 Brasília, DF, Brazil.
E-mail addresses: otalvaro.calle@gmail.com (I.F. Otalvaro), mporfirio76@gmail.com (M.P.C. Neto), delage@cermes.enpc.fr (P. Delage), bcaicedo@uniandes.edu.co (B. Caicedo).

http://dx.doi.org/10.1016/j.enggeo.2016.02.016
0013-7952/© 2016 Published by Elsevier B.V.

The methodology and the results obtained can be useful in determining parameters for other hydraulic, thermal and mechanical models. For instance, the distribution of void ratios (small pores and large pores) can be used as input data for constitutive models and conservation equations that are based on the double structure concept of soils.

2. Materials and methods

The effect of compaction in lateritic residual soil was investigated in samples obtained from a roadway excavation in Brasilia, Brazil. Brasilia is located in the central highlands of Brazil on an erosion surface from the Tertiary period composed of metasedimentary rocks from the Canastra, Paranoá, Araxá and Bambuí groups (Freitas-Silva and Campos, 1998). Quartz, kaolinite, gibbsite, goethite and hematite minerals were identified by X-ray diffraction. The presence of kaolinite was also inferred from the Atterberg limits and the low value of the cation exchange capacity (CEC); Table 1 summarizes the index properties. The soil is classified as ML according to the Unified Soil Classification System (USCS).

Fig. 1 shows the grain-size distribution curves obtained through sieving and laser diffraction; the laser method was preferred because it has a larger range of detectable particle sizes and better accuracy in the micron and submicron ranges (Di Stefano et al., 2010). Conversely, tests were performed with and without dispersant to highlight the effect of aggregations. In fact, silt and clay aggregations were observed on the non-dispersed curve with sand grain-sized aggregations, a typical feature of Brazilian lateritic soils (Futai, 2002; Miguel and Vilar, 2009; Miguel and Bonder, 2012). These silt and clay aggregations are present in the soil even after the compaction and help to explain the hydro-mechanical behavior of these materials. These soils are characterized by a double porous structure corresponding to inter-aggregate pores and intra-aggregate pores (Delage et al., 1996; Fiès and Bruand, 1998; Zhang and Chen, 2005; Koliji et al., 2010; Casini et al., 2012).

2.1. Compacted samples

For compaction tests, residual lateritic specimens were made from air-dried material based on the ASTM D698–00a and ASTM D1557–00 procedures. The samples were prepared by manual disaggregation to 17% moisture content (i.e., 3% lower than the natural moisture content of 20%) to push the material through the No. 4 sieve with no difficulty.

The identification of the WRC was carried out under seven compaction conditions at various moisture contents and compaction energies, as shown in Fig. 2. In the figure, PM and PN refer to the modified Proctor and the standard Proctor energies, respectively. PIn indicates the intermediate energy between the modified Proctor and the standard Proctor (approximately 1655 kN m/m^3). The points were obtained using a modified ASTM D698–00a procedure with a 44.5 kN weight hammer. Point NP24 (i.e., a moisture content of 24%) represents a lower energy of 240 kN-m/m^3 that was obtained by reducing the number of blows from 25 to 10 on each layer.

The points at which the investigation was conducted are indicated in Fig. 2 and include both the dry and wet sides of the compaction curves

Table 1
Index properties.

Natural moisture content (%)	23
Liquid limit (%)	40
Plasticity index (%)	12
Specific gravity (Gs)	2.76
pH distilled water	6.0
pH KCl solution	5.6
CEC (mE/100 ml)	8.0
Ss (m^2/g) — BET[a]	39.4
USCS classification	ML

[a] Brauner, Emmett and Teller (BET); specific surface is derived from an isotherm for nitrogen (N_2) adsorption.

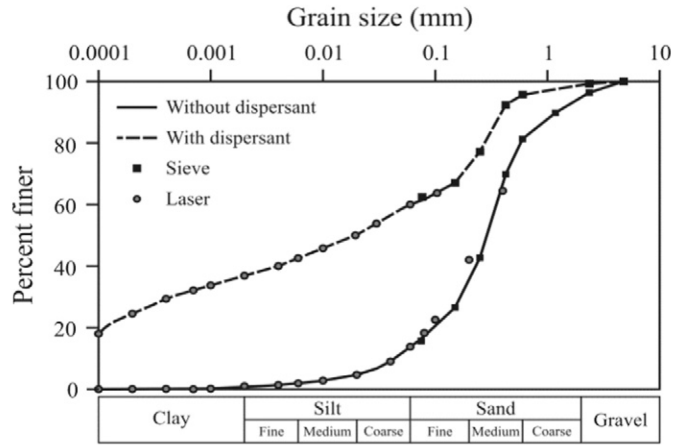

Fig. 1. Grain-size distribution.

and the normal and modified Proctor optima. Fig. 2b indicates the negative pore water pressure (i.e., suction) of the tested points, which were obtained using filter paper.

2.2. Water retention curve

Previous studies indicated that the WRC of the same Brasilia soil studied here has a bimodal nature (Guimarães, 2002; Delgado, 2002; Silva, 2007). To cover a wide range of suction values from 1 kPa up to 30,000 kPa, a combination of two techniques was used. A suction plate, based on that presented by Feuerharmel et al. (2006), was used for suction ranges equal to or smaller than 16 kPa. In this system, a

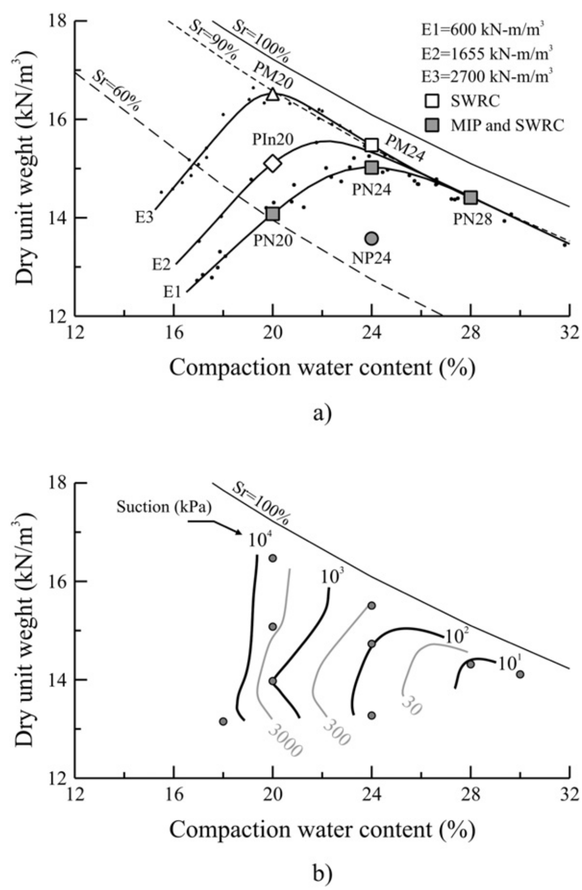

Fig. 2. a) Proctor compaction test and analysis points; b) initial suctions (ASTM Standard D698–00a, 2000).