Journal of Rock Mechanics and Geotechnical Engineering 10 (2018) 367–379

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Behavior of diatomaceous soil in lacustrine deposits of Bogotá, Colombia

Bernardo Caicedo [a,*], Cristhian Mendoza [b], Fernando López [c], Arcesio Lizcano [d]

[a] Department of Civil and Environmental Engineering, Universidad de Los Andes, Bogotá, Colombia
[b] Department of Civil Engineering, Universidad Nacional de Colombia Sede Manizales, Manizales, Colombia
[c] Ecole Centrale Paris, Laboratoire MSSMat-UMR CNRS 8579, Paris, France
[d] SRK Consulting, Vancouver, Canada

ARTICLE INFO

Article history:
Received 5 July 2017
Received in revised form
3 October 2017
Accepted 8 October 2017
Available online 20 February 2018

Keywords:
Diatomaceous soil
Soft soils
Compressibility
Friction angle
Natural soil

ABSTRACT

This work presents a study on the behaviors of diatomaceous soils. Although studies are rarely reported on these soils, they have been identified in Mexico City, the Sea of Japan, the northeast coast of Australia, the equatorial Pacific, and the lacustrine deposit of Bogotá (Colombia), among other locations. Features of this kind of soil include high friction angle, high initial void ratio, high compressibility index, high liquid limit, and low density. Some of these features are counterintuitive from a classical soil mechanics viewpoint. To understand the geotechnical properties of the diatomaceous soil, a comprehensive experimental plan consisting of more than 2400 tests was performed, including physical tests such as grain size distribution, Atterberg limits, density of solid particles, and organic matter content; and mechanical tests such as oedometric compression tests, unconfined compression tests, and triaxial tests. Laboratory tests were complemented with scanning electron microscope (SEM) observations to evaluate the microstructure of the soil. The test results show that there is an increase in liquid limit with increasing diatomaceous content, and the friction angle also increases with increasing diatomaceous content. In addition, several practical correlations were proposed for this soil type for shear strength mobilization and intrinsic compression line. Finally, useful correlations were presented, such as the relationship between the state consistency and the undrained shear strength, the friction angle and the liquid limit, the void ratio at 100 kPa and the liquid limit, the plasticity index and the diatomaceous content, among others.

1. Introduction

The characteristics of soft soils are of critical importance in geotechnical engineering because the behavior of the soils affects the performance of engineering works constructed on these deposits. The soils basically have low bearing capacity, which can cause the geotechnical structures to be subjected to excessive settlements. The behavior of remolded soils has received a great deal of attention over the last 6 decades, for example, from Roscoe et al. (1958), Tavenas et al. (1979), Burland (1990), Biarez and Hicher (1994), and Horpibulsuk et al. (2011). Meanwhile, studies of natural clays by Leroueil and Vaugham (1990), Beaumelle (1991), and Tatsuoka et al. (2000) have received less attention. Even few studies are reported on the diatomaceous soils (very soft soils), which have been identified elsewhere in the world by Diaz-Rodriguez (2011) in Mexico City, Holler (1992) in the Sea of Japan, Chen et al. (1993) and Ladd et al. (1993) on the northeast coast of Australia, and McKillop et al. (1995) in the equatorial Pacific. As described by Diaz-Rodriguez (2011), the diatomaceous soils have extreme Atterberg limits (approximately 400%), water contents (approximately 300%), void ratios (approximately 8), coefficient of compressibility (approximately 5) and microfossils in the structure. The present study discusses the aforementioned issues that are undoubtedly of interest for practical design engineers or researchers in this area.

This paper presents a study on the geomechanical characteristics of a diatomaceous soil deposit, aiming at a better understanding of the behaviors of these soils when compared to the majority of soils found in the world. In most soils, the index properties are related to mechanical behavior. However, in a diatomaceous soil deposit, these correlations cannot work, or should be modified. Additionally, some explanations are given for the special behaviors of these types of soils. The soil used in the present

* Corresponding author.
E-mail address: bcaicedo@uniandes.edu.co (B. Caicedo).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.10.005

work is from the lacustrine deposit of Bogotá (Colombia). The field work consisted of taking high-quality samples from 2400 m of boreholes using the stationary piston technique. Some of these boreholes reached 250 m deep. The laboratory component of this study includes: (i) physical tests such as grain size distribution, Atterberg limits, density of solid particles, and organic matter content; and (ii) mechanical tests such as oedometric compression tests, unconfined compression tests, and triaxial tests. Laboratory tests were complemented with scanning electron microscope (SEM) observations to evaluate the microstructure of the soil. This is a contribution to the knowledge of the diatomaceous soils, because the previous studies on diatomaceous soils have been performed over reconstructed or shallow samples.

The lacustrine deposit of the city of Bogotá (Colombia) is located on a high plateau of the Andes Mountains at 2550 m above sea level. More than 60% of the area of this city with 9 million of inhabitants is located on soft soil deposits. At some sites of the plateau, the depth of the lacustrine deposit can reach 586 m (Torres et al., 2005). Shallow deposits of soil from 5 m to 10 m deep are overconsolidated, but in deeper layers, the soil can reach extreme values for some geotechnical properties: consistency indices lower than 0.5, water contents higher than 200%, liquid limits up to 400%, void ratios as high as 5, and high diatomaceous percentage.

The results of the lacustrine deposits of Bogotá showed a high friction angle (close to 45°) and a high plastic index (close to 200). These results are not common in the classic mechanics of soil because the increase of the plastic index causes a decrease of the friction angle (Mitchell, 1993). A possible explanation is that the soil had a high content of diatoms in its structure, and these diatoms changed its behavior (Santamarina and Diaz-Rodriguez, 2003; Diaz-Rodriguez, 2011). Another interesting result was that an increase in diatoms (particles larger than 10 μm) increases the plasticity of soil without increasing clay-sized particles. This characteristic creates a disagreement between the classification system based on Atterberg limits and the classification system based on grain size. Moreover, some correlations are presented in this work, including those between the Atterberg limits and the undrained shear strength, the friction angle and the liquid limit, the void ratio at 100 kPa and the liquid limit, and the plasticity index and the diatomaceous content. In addition, several practical correlations were tested and applied to this type of soil as found by Vardanega and Bolton (2011) for shear strength mobilization, and the intrinsic compression line proposed by Burland (1990), among others. The results showed several different features of the diatomaceous soils, which are not typical in the majority of soils in the world.

2. Geological framework

The high plain of Bogotá is located at 4°N and 74°W (geographical coordinates) at an altitude of 2550 m. Its origin lies in a Plio-Pleistocene lake that was filled with water over time. The deep deposit of soils is explained by the subsidence of the bottom of the basin and the gradual accumulation of main lacustrine sediments during the last 3 million years (Hooghiemstra and Sarmiento, 1991). The chronostratigraphy of the deposit was studied by Andriessen et al. (1993) using the fission track-dated method. They estimated the soil's age at 3.2 million years at a depth of 586 m. In addition, chronostratigraphical data were obtained by Torres et al. (2005) based on pollen analysis. Fig. 1 depicts some of the deposition processes that have taken place in the basin of Bogotá. As shown in Fig. 1a–d, the main deposition mechanism was controlled by the level of the water table, which was in turn dependent on the differential rate between the subsidence of the bottom of the deposit and sedimentation. Possible deposition mechanisms were: (i) sedimentation of predominant fine-grained materials in a low energy regime taking place under deep water (Fig. 1a); (ii) sedimentation of predominant silt and sand in a high energy regime occurring in low water tables near river mouths (Fig. 1b); and (iii) swamp and fluvio-lacustrine deposits with high proportions of organic matter in shallow water tables (Fig. 1c).

Chronostratigraphical and geological studies by Torres et al. (2005) at the deepest site of the deposit, located in the city of Funza near Bogotá, proposed the following stratigraphy of the deepest deposits:

(1) The bottom of the deposit was found at 586 m deep. From 568 m to 586 m, there is a mix of clay and sand deposited in a fluvio-lacustrine environment. Then, the water table rises throughout history and lacustrine deposits become dominant in the interval from 530 m to 568 m.
(2) From 460 m to 530 m, there are deposits with high contents of organic matter, which suggests lacustrine and swamp deposits. Sandy deposits resulting from a high energy fluvial environment appear at the Funza site from 445 m to 460 m.
(3) From 325 m to 445 m, once again there are deep lacustrine and swamp deposits overlying the fluvial deposit.
(4) From 250 m to 325 m, subsidence predominates. This creates a deep basin with a true lacustrine deposit.

The geotechnical study of the basin presented in this research concerns the upper 250 m of the deposit, corresponding chronologically to the last 1 million years (Fig. 1h). Fig. 1e–g presents the mean values of organic matter loss on ignition (LOI), liquid limit, and percentage of grains with sizes less than 2 μm calculated from the whole geotechnical investigation described in Section 3. These results complement the stratigraphy proposed in Torres et al. (2005) with the following geotechnical data:

(1) From 180 m to 250 m, the lacustrine deposit properly continues with soils having less than 10% of organic matter and liquid limit of around 50%.
(2) From 155 m to 170 m, there is a swamp deposit with a large proportion of organic matter and a mean liquid limit approaching 100%.
(3) From 155 m to 80 m, the lacustrine deposit dominates again.
(4) From 5 m to 80 m, which corresponds to the last 250,000 years, there are some sporadic episodes of swamp deposits with high proportions of organic matter. This corresponds to alternating rises and falls of the water table. At the same time, the mean value of the liquid limit increases from 50% to 200%. In this deposit, the mean percentage of particles with sizes less than 2 μm fluctuates from 0% to 20%. From 50 m deep to the surface, the chronological measures carried out by Torres et al. (2005) (Fig. 1h) show a deposition rate of 3440 yr/m.
(5) In the first 5 m of the deposit, the amount of organic matter and the liquid limit decrease, while the content of particles with size smaller than 2 μm increases.

SEM images were taken from a sample at 16 m depth in the lacustrine zone. Fig. 2a shows an open structure similar to that observed by Sides and Barden (1971). This open structure could be the result of a lacustrine deposit from calm (low energy) lake water as described above. Moreover, in the case of Bogotá soil, there are fossils in these deposits, as shown in Fig. 2b and c. A detailed examination of the previous images reveals the high content of frustules from diatoms (Fig. 2d–f). As described by Diaz-Rodriguez (2011), sedimentary diatomaceous soils have silica contents of 90%