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Geotechnical behavior of Bogotá lacustrine soil through its geological history

Comportement géotechnique du sol lacustre de Bogotá à travers son histoire géologique

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ABSTRACT: The lacustrine deposit in Bogotá (Colombia) is located on a high plateau of the Andes Mountains at 2550 meters above sea level. This deposit covers more than 60% of the urban area. Its soil is characterized as being very soft with a high diatoms content. Such soils have been identified in Mexico City, in the Japan Sea, over the north-east coast of Australia, and the equatorial Pacific amongst other locations. However, there have been very few studies performed on these types of soils that study their mechanical properties. Shallow deposits of 5 to 10 meters in depth are generally overconsolidated, but in deeper layers, the soil can reach extreme values for some geotechnical properties. For example, high Atterberg limits (nearly 400 % for the Liquid Limit), water contents around 200 %, void ratios nearly 5, and compressibility coefficient close to 5, have been observed. Such properties depend on the geological history of the layer. In order to better understand the geotechnical properties of lacustrine deposits in Bogotá, physical characterization has been undertaken, including grain size distribution, Atterberg limits, density of solid particles, organic matter content; and mechanical tests such as oedometric compression tests, unconfined compression, and triaxial tests. Scanning electron microscope (SEM) observation was also completed to evaluate the microstructure of the soil. The results show that with an increase of the diatomaceous content there is an increase in the liquid limit of the soil, as well as an increase in the friction angle. Some of the above features are contrary to classical soil mechanics. In addition, several practical correlations were compared in relation to this soil type.. Such soil characteristics may be explained through the geological history of the soil formation.

RÉSUMÉ: Le gisement lacustre de la ville de Bogotá (Colombie) est situé sur un haut plateau des Andes, à 2550 mètres d'altitude. Ce gisement couvre plus de 60% de la ville de 9 millions d'habitants. Certaines de ses caractéristiques correspondent à un sol très mou lequel, dans certaines de ses couches, a une teneur élevée en diatomées. Bien que peu étudiés, ces sols ont été identifiés à Mexico, en mer du Japon, sur la côte nord-est de l'Australie, dans le Pacifique équatorial et dans le gisement lacustre de Bogotá (Colombie), entre autres. À Bogotá les dépôts peu profonds de sol de cinq à dix mètres de profondeur sont surconsolidés, mais dans les couches plus profondes, le sol peut atteindre des valeurs extrêmes dans certaines propriétés géotechniques. Par exemple, ce sol a des limites d'Atterberg élevées (près de 400% pour la limite de liquidité), une teneur en eau d'environ 200%, des indices de vides proches de 5, un coefficient de compressibilité proche de 5, tout cela dépendant de l'historique géologique de la couche où les échantillons sont obtenus. Pour comprendre les

propriétés géotechniques du gisement lacustre du sol, des tests physiques ont été effectués, tels que la distribution granulométrique, les limites d'Atterberg, la densité des particules solides et la teneur en matière organique. Aussi, des essais mécaniques tels que des essais de compression oedométrique, compression inconfinée et triaxiaux. Les essais de laboratoire ont été complétés par des observations au microscope électronique à balayage (MEB) pour évaluer la microstructure du sol. Les résultats montrent que l'augmentation de la teneur en diatomées entraîne une augmentation de la limite de liquidité, de l'angle de frottement, et de l'influence de la vitesse de déformation sur la résistance au cisaillement. Certaines des caractéristiques ci-dessus sont contradictoires par rapport à la mécanique des sols classique. Aussi, plusieurs corrélations pratiques ont été comparées pour ce type de sol concernant la mobilisation de la résistance au cisaillement et la ligne de compression intrinsèque. Tout ce qui précède a été mis en relation avec l'histoire géologique de la formation des sols.

Keywords: Lacustrine deposit; natural soil; soft soil; high friction angle; high void ratio

1 INTRODUCTION

The study of the characteristics of soft clays is a key point in geotechnical engineering because there are difficult soils whose behavior affect the performance of the engineering works constructed on these deposits. The behavior of remolded mixtures of fine soil and diatoms have received huge attention in the last 20 years, Shiwakoti et al. (2002), Díaz-Rodríguez (2011), Wiemer and Kopf (2017) and Wiemer et al.(2017), among others. However, studies about natural clays and diatoms have received less attention: Tanaka and Locat (1999), Díaz-Rodríguez (2003), Kwon et al. (2011), Suganya and Sivapullaiah (2017), and Caicedo et al. (2018), among others. Regarding natural lacustrine deposits, research by Díaz-Rodríguez (2003), Díaz-Rodríguez (2011) and Caicedo et al. (2019) show that the presence of microfossils in the clay of Mexico City modify its shear strength and can explain its high plasticity index. Although the clay in Bogotá has the same lacustrine origin as that in Mexico, Moya and Rodríguez (1987), knowledge on this clay is still limited.

Bogotá is the fifth-most-populous city in South America, with a population near to 9 million inhabitants in 2017. The Sabana de Bogotá is located in a high plateau of the Andes Mountains, at 2550 m above sea level. More than 60% of the city is over the soft clay deposit. In some sites of the plateau, the lacustrine deposit can reach a depth of 586 m (Torres et al. 2005), the shallow deposit of clay (first 5 to 10 meters) is in an overconsolidated state, although, for deeper layers the soil can reach extreme values for some geotechnical properties: consistency index (CI) lower than 0.5, water contents higher than 200%, liquid limit up to 400%, and the void ratio can be as high as 5.

This paper presents a comprehensive study of the geomechanical characteristics of the Bogotá soft clay. The field work consists of some boreholes taking high quality samples using a stationary piston technique, these boreholes reach a depth of 150 m. The laboratory component of this study includes: (i) physical tests such as grain size distribution, Atterberg limits, and organic matter content; (ii) mechanical tests such as oedometric compression tests; (iii) triaxial test with an undrained condition; (iv) triaxial tests with controlled loading paths. Laboratory tests were complemented with SEM observations to evaluate the microstructure of the soil.

Results show that the Bogotá clay has significant diatomaceous components that can explain the very high friction angle of samples having a high liquidity index, in fact a clear

relationship between friction angle and liquidity index is presented in this paper.

2 GEOLOGICAL FRAMEWORK AND CHARACTERIZATION

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 dating method. They estimated the soil's age at 3.2 million years at a depth of 586 m. In addition, chronostratigraphical data was obtained by Torres et al. (2005) based on pollen analysis.

Torres et al. (2005) proposed the following stratigraphy (based in Chronostratigraphical and geological studies) of the deepest deposits: (i) the bottom of the deposit was found at a depth of 586 m. From 568 m to 586 m there is a mixture of clay and sand deposited in a fluvio-lacustrine environment. Then, the water table rose, and from 530 m to 568m lacustrine deposits become dominant; (ii) from 460 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 to 460 m; (iii) from 325 to 445 m, overlying the fluvial deposit, once again there are deep lacustrine and swamp deposits; (iv) from 250 to 325 m the subsidence of the bottom of the deposit and sedimentation continue. This creates a deep basin with a true lacustrine deposit.

However, the present study is only concentrated on the upper 150 m of the deposit corresponding chronologically to the last 1 Ma. Figure 1 shows the average values of the drillings at 150 m, regarding liquid limit, water content, plastic limit, organic matter (Loss on Ignition, *LOI*) and mineralogical composition of grains lower than 2 mm. These results complement the stratigraphy with geotechnical data as follows:

From 0 m to 5 m, the lacustrine deposit has less than 10% of organic matter, 33% in the plastic limit, 80% water content and a liquid limit of around 110%; with the water level around 1.5 m. Regarding mineralogy, the clay has high contents of the Kaolinite and Ilite. Additionally, this layer has the tendency to overconsolidated behaviour, as is shown later.

From 5 m to 80 m, there is a lacustrine deposit with a large proportion of organic matter and very soft consistency (0.5> CI), liquid limit of 140%, water content between 70% and 140% and plastic limit between 40% and 50 %. In addition, there are some sporadic episodes of swamp deposits with high proportions of organic matter near to 100%. These episodes are shown in the high liquid limit near to 300% and presence of peat. Finally, this layer may be associated with shallow lacustrine deposits in which diatoms are present. In fact, as the following shows, high plasticity indexes are associated with low clay contents and with the presence of a large number of diatoms.

From 80 m to 150 m, the lacustrine deposit properly continues with soils having less than 10% of organic matter and liquid limit of around 90%, soft consistency (0.5 <CI<0.75). The LOI results do not show peat deposits in this layer. Regarding mineralogy, the clay has high contents of the Kaolinite, Ilite and Smectite, Chlorite appears in less quantities.

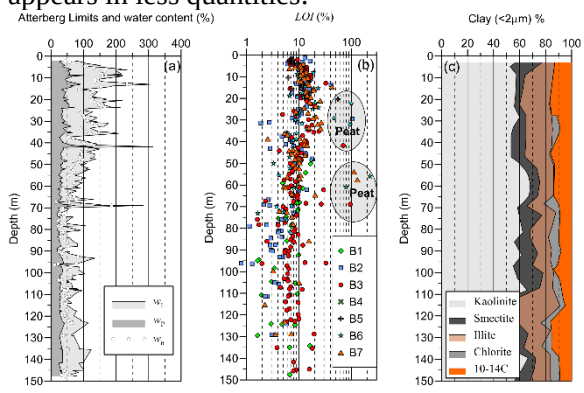


Figure 1. a. Comparison between Attereberg limits and water content; b. Loss on ignition; c. Mineralogy of particles proportion with sizes less than 2 µm (Ingeominas, 2004).

Images in Figure 2 were obtained by using a SEM (scanning electron microscopy) in an undisturbed sample of the layer in the lacustrine zone (From 5 m to 80 m). The figure shows the presence of a high number of diatoms. Also, Figure 2 shows an isotropic structure (non-oriented structure), that it is formed by an aggregate of flocculated particles and a large inter-aggregate porosity. This structure is typically a structure that characterizes a slow deposition, as was the case in the lacustrine deposit of Bogotá.

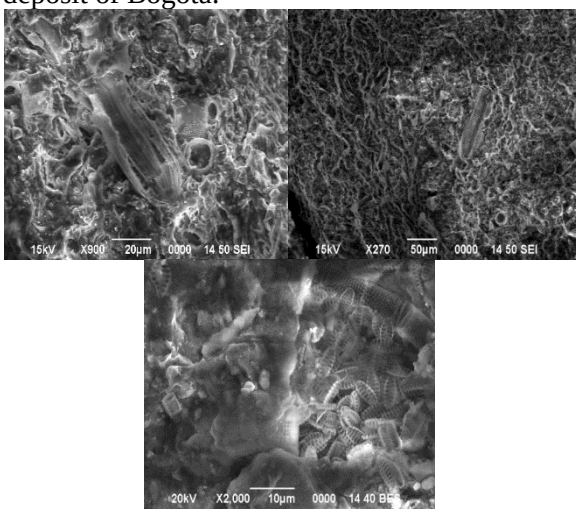


Figure 2. Microscope images of scanning electron in the lacustrine deposit.

In this lacustrine deposit, the average percentage of particles with sizes smaller than 2 µm fluctuates between 0% and 25%. Figure 3 shows particle size distribution by tests of laser granulometry from lacustrine zone (From 2.5 m to 25 m). However, data of the plasticity index and liquid limit (see Figure 2) shows that the soil is classified as clay by the Casagrande chart (ASTM D2487). This is a problem, because according to the classification of soil by sizes the soil is a silt, but according to the classification by the Casagrande chart, the soil is a clay. The reason can be expalined by the high content of the diatoms (particles larger than 10 µm) increasing the plasticity of soil without increasing clay-sized particles. A special characteristic of diatoms is a high porosity and in these pores water molecules can be housed.

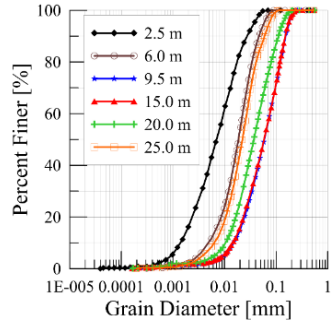


Figure 3. Distribution of particle size in the stratigraphy of 2.5 to 25 m.

3 MECHANICAL BEHAVIOR OF LACUSTRINE SOIL OF BOGOTÁ

In the present reasearch, the mechanical behavior of Bogotá soil was divided into two parts. The first part is the behavior in relation to compressibility and the second part is the behavior in relation to shear stress.

3.1 Compressibility of the lacustrine deposit.

Thirty-eight oedometric tests were performed on samples of the drillings shown above (Figure 1). These tests were divided into liquid limit ranges. Figure 4 shows that a high value of the liquid limit results in a high value of voids ratio. In addition, it is observed that the higher liquid limit also has an effect on the soil compressibility coefficient, as presented in Equation 1. From the previous cases, it is observed that the values of a high compressibility coefficient and void ratio are found in soils with high diatomaceous content.

Figure 4 shows the compression bands in function of the liquid limit. These bands are based on the work of Biarez & Hicher, 1994 to K_0 conditions. The results of tests realized in this

research show that the proposed bands by Biarez & Hicher, 1994 are good for a low liquid limit. However, with high values of liquid limit, the results have high dispertion and the bands increase in size. One reason for this can be a high diatomaceous content that increases the liquid limit. Another reason, this soil has also been mixed with volcanic ash due to the volcanic eruptions that occurred during the soil formation process, which increases the liquid limit and the low soil density. In conclusion, the diatoms and volcanic ash can change the soil behavior.

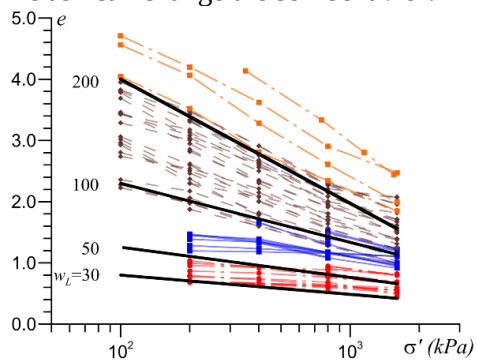


Figure 4. Results of oedometric tests carried out on the Bogotá soil (only the normally consolidated part).

$$C_c = 0.01(w_L - 0.58) \quad (1)$$

The relationship between the compressibility coefficient and the liquid limit are shown in Figure 5. This Figure shows a good correlation between variables (R^2=0.92). In addition, it shows the results of the oedometric compression tests and the results used by Burland, 1990 and Horpibulsuk et al., 2011 with a small diference.

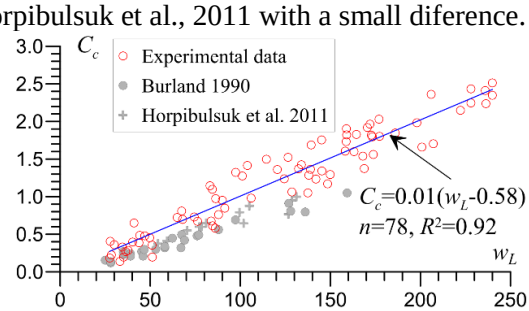


Figure 5. Relationship between the compressibility coefficient and the liquid limit.

Figure 6 shows the relationship between the compressibility coefficient and the initial void ratio, as shows in Equation 2. This relationship is only valid to values of a void ratio less than 3, because for values greater than 3 the coefficient of determination R^2 goes too low. The soils with a high value of liquid limit have a high content of diatoms and volcanic ash. As already shown, the combination of contents changes the behavior of soil.

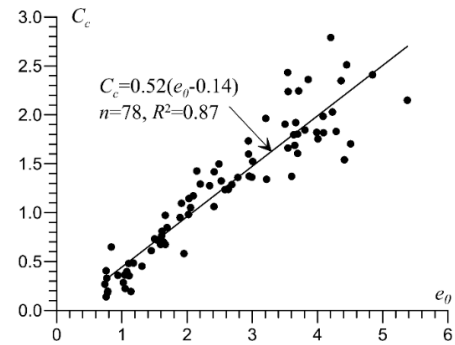


Figure 6. Relationship between the compressibility coefficient and the initial void ratio.

$$C_c = 0.52(e_0 - 0.14) \quad (2)$$

Another correlation commonly used is to relate the recompression coefficient C_s to the compressibility coefficient C_c. The results of the present research show a relation of 7.6 between the compressibility coefficient C_c and the recompression coefficient C_s.

3.2 Shear strength of lacustrine deposit.

The shear strength of soft soils in Bogotá was studied by undrained triaxial tests.

Figure 7 shows a typical triaxial test for the soft soil of Bogotá. This test has a friction angle close to 40 degrees. This behaviour is atypical for most clays that have friction angles less than 20 degrees (Whitlow, 1990). Another important aspect shown in this figure is the high liquid limit and content of organic matter in the sample tested.

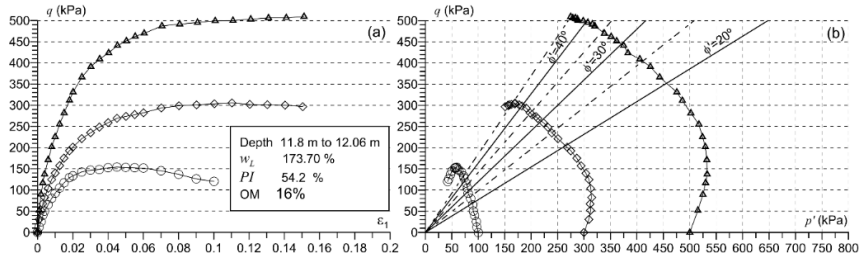
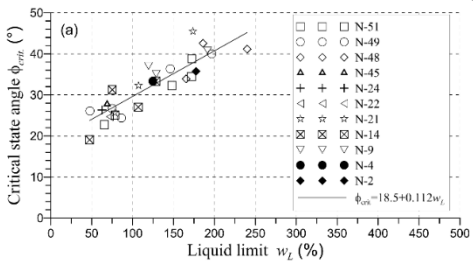


Figure 7. Results of a triaxial test (in undrained condition) performed with high organic matter content.

Based on the previous figure, it was decided to graph the friction angles and liquid limit. This was obtained from 80 triaxial tests in which liquid limit tests were done, as shown in Figure 8. From this figure, an existing correlation between the friction angle and liquid limit is observed, as shown the Equation 3. As an important aspect, an increase of the friction angle is shown with the increase of the liquid limit, this was already shown indirectly by the experimental works in soils with microfossils presented by Díaz-Rodríguez 2003 and Shiwakoti et al. 2002. Although it is a contradictory result to the majority of results found in classical literature (Kenny, 1959, Ladd et al., 1977, among others). Another aspect shown in Figure 8 is the increase of the friction angle to an increase of the organic matter that this type of soil presents. From this aspect Equation 4 was obtained.

$$\phi_{crit} = 18.5 + 0.1112 w_L \qquad (3)$$

$$w_L = 13.52 OM \qquad (4)$$



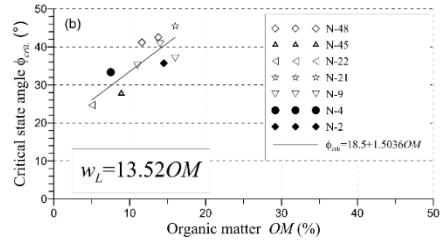
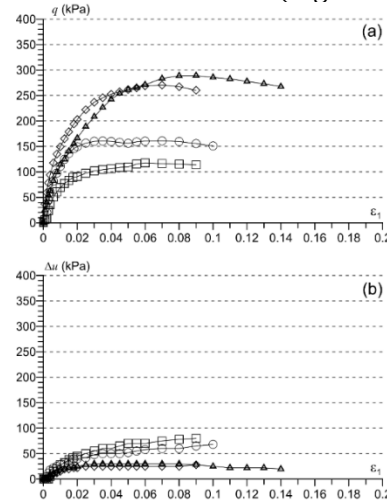


Figure 8. a. Relationship between friction angle at the critical state and liquid limit. b. Relationship between friction angle at the critical state and organic matter.

Figure 9 shows triaxial tests for different overconsolidation ratios (OCR), with a soil of a high content of organic material and a high liquid limit. The results show a decrease in the excess pore pressure with the increase in OCR (Figure 9 b). In addition, with the increase in OCR, the soil tends to be dilatant (Roscoe et al., 1958). Another aspect is that regardless of the OCR all the tests have the same critical state line (Figure 9c).



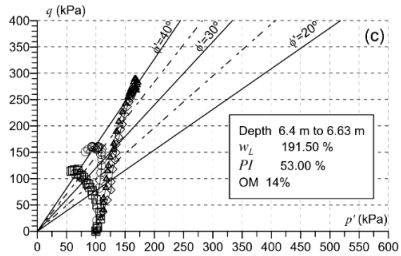


Figure 9. Triaxial tests to different OCR relations.

From a shallow sample, 3 undrained triaxial tests were performed under anisotropic stress conditions, in the normally consolidated state. The tests were consolidated with anisotropic trajectories of η= q/p '= 0.375, 0.5 and 0.625, after which shear stress was generated in undrained conditions, as shown in Figure 10. Figures 10b and 10c show that all the tests tend to the same line of the critical state. In addition, the soil retains the effect of barotropy (increased shear strength with the increased confinement). The excess pore pressure in the tests was stabilized after 6% of axial strain (Figure 10b).

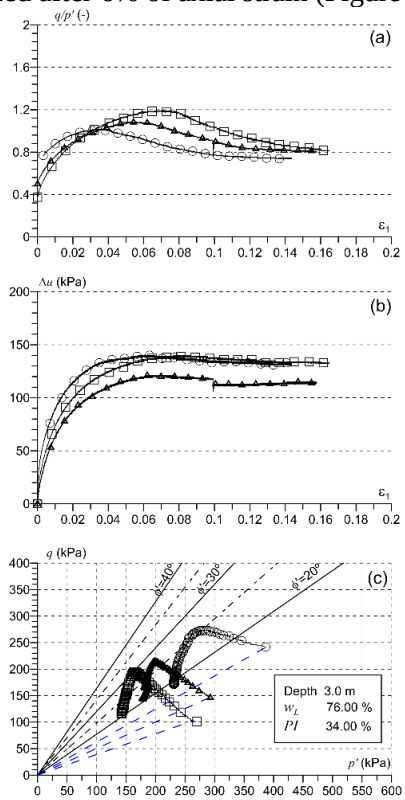


Figure 10. Triaxial tests to different anisotropic paths of stresses

4 CONCLUSIONS

Lacustrine soils of Bogotá present high percentages of diatoms and could be associated with very high values of clay activity. In addition, the high values of activity are related to high percentages of organic matter, high values of void ratio, high values of compressibility coefficients and high values of angle of friction.

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6 REFERENCES

Andriessen P.M.A., Helmens K., Hooghiemstra H., Riezebos P.A., Van der Hammen T. (1993). Absolute chronology of the Pliocene–Quaternary sediment sequence of the Bogotá area, Colombia Quaternary Science Reviews, **12**(7), 483-501.

ASTM Standard D2487, 2006. ‘‘Standard Practice for Classification of Soils for Engineering Purposes (unified Soil Classification System)’’ ASTM International, West Conshohocken, PA. www.astm.org.

Caicedo B., Mendoza C. C., López-Caballero F., Lizcano A. (2018). Behavior of diatomaceous soil in lacustrine deposits of Bogotá, Colombia. Journal of Rock Mechanics and Geotechnical Engineering, **10**(2), 367-379.

Caicedo B., Mendoza C. C., López-Caballero F., Lizcano A. (2019). Some contributions to the mechanical behaviors of lacustrine deposit from the city of Bogotá. Journal of Rock

Mechanics and Geotechnical Engineering, **11**(4), 1-12.

Biarez, Jean & Hicher, Pierre-Yves. Elementary mechanics of soil behaviour: saturated remoulded soils. AA Balkema. 1994.

Burland, J. B. (1990). On the compressibility and shear strength of natural clays. Geotechnique, Vol. 40, 329-378.

Díaz-Rodríguez J.A. (2003). Characterisation and engineering properties of Mexico City lacustrine soils. In Tan et. al., editor, Vol. 1: Characterisation and engineering properties of natural soils, 725–56.

Diaz-Rodriguez J.A. (2011). Comportamiento monotónico de suelos diatomáceos, Revista. Internacional de Desastres Naturales, **12**(1), 28-34.

Hooghiemstra H., Sarmiento G. (1991). Long continental pollen record from a tropical intermontane basin: late Pliocene and Pleistocene history from a 540-meter core, Episodes, V. **14**, 107-115

Horpibulsuk, Suksun and Yangsukkaseam, Narongded and Chinkulkijniwat, Avirut and Du, Yan Jun (2011). Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. Applied Clay Science, 52, 2, 150-159.

Ingeominas, 2004, Aspectos Geoambientales de la Sabana de Bogotá, Publicación No. 27.

Kenney, T.C. (1959). Discussion on Geotechnical Properties of Glacial Lake Clays. Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, Volume **85**(3), 67-79.

Kwon T. H, Lee K. R, Cho G. C, Lee J. Y. (2011). Geotechnical properties of deep oceanic sediments recovered from the hydrate occurrence regions in the ulleung basin, east sea, offshore Korea. Marine and Petroleum Geology **28**(10),1870–1883.

Ladd, C., Foot, R., Ishihara, K., Schlosser, F., and Poulos, H. (1977). Stress-deformation and strength characteristics. In Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, 10–15 July 1977. Japanese Society of Soil Mechanics and Foundation Engineering, Tokyo, Japan. Vol. 2, pp. 421–494

Moya J., Rodriguez J. (1987). El subsuelo de Bogotá y los problemas de cimentaciones. Proceedings of the 8th panamerican conference on soil mechanics and foundation engineering, Universidad of Nacional de Colombia, 197-264.

Roscoe, K. H., Schofield, A. N., &Wroth, C. P. (1958). On the yielding of soils. Geotechnique **8**, 1, 22–52.

Shiwakoti D.R., Tanaka H., Tanaka M., Locat J. (2002). Influences of diatom microfossils on engineering properties of soils, Soils and Foundations **42** (3), 1-17.

Suganya K., Sivapullaiah, P.V. (2017). Role of composition and fabric of Kuttanad clay: a geotechnical perspective. Bulletin of Engineering Geology and the Environment; **76**(1), 371-81.

Tanaka H., Locat J., Shibuya S., Soon T.T., Shiwakoti D.R. (2001). Characterization of Singapore, Bangkok, and Ariake clays. Canadian Geotechnical Journal, **38**(2), 378-400.

Torres V., Vandenberghe J., Hooghiemstra H. (2005). An environmental reconstruction of the sediment infill of the Basin of Bogotá (Colombia) during the last 3 million years from abiotic and biotic proxies Palaeogeography, Palaeoclimatology, Palaeoecology, **226**(1–2), 127-148.

Whitlow R. (1990). Basic soil mechanics, John Wiley & Sons, New York.

Wiemer G., Kopf A. (2017). Influence of diatom microfossils on sediment shear strength and slope stability, Geochem. Geophys. Geosyst **18**, 333–45.

Wiemer G., Dziadek R.E., Kopf A. (2017). The enigmatic consolidation of diatomaceous sediment. Marine Geology **385**, 173-84.