The Response of a Driven Pile in Overconsolidated Clay at "Ciudad Universitaria", Bogotá-Colombia: Work in Progress.

Kevin A. Morales[1], Juan D. Hurtado[2], Jhon S. Gómez[3], Leydy T. Bernal[4]
Jorge A. Pineda, PhD[5] and Julio E. Colmenares, PhD[6]
[1] Universidad Nacional de Colombia, Bogotá, kmoraless@unal.edu.co,
[2] Universidad Nacional de Colombia, Sede Bogotá, jdhurtadogo@unal.edu.co,
[3] Universidad Nacional de Colombia, Sede Bogotá, jsgomezca@unal.edu.co
[4] Universidad Nacional de Colombia, Sede Bogotá, ltbernalra@unal.edu.co
[5] Universidad Nacional de Colombia, Sede Bogotá, jpinedaj@unal.edu.co,
[6] Universidad Nacional de Colombia, Sede Bogotá, jecolmenaresm@unal.edu.co

Abstract– The use of deep foundations in the construction of buildings and infrastructure is a key issue in Bogota, Colombia; where there is a deep deposit of soft lacustrine soil lightly overconsolidated near the ground surface. However, the increase in pore pressure in the clayey soil that occurs during pile driving and the uncertainties in shaft strength related to the installation process, are not fully understood. The objective of this paper is to better understand these processes to reduce uncertainty when working with deep foundations. Research on this problem is still ongoing at the campus of the National University of Colombia in Bogota. Therefore, this paper only presents partial results and a route for future research. To evaluate what happens when driving piles in this type of soil, it is necessary to experimentally measure important parameters with field tests (CPTU, SPT) and a laboratory testing program. Then, from these data, a numerical model must be developed to estimate the load-settlement curve of the soil and its ultimate bearing capacity. Finally, to contrast the model predictions with actual conditions, a dynamic field load test and monitoring of soil circumstances during pile driving must be performed, using piezometers and inclinometers as part of the geotechnical instrumentation.

Key Words – Clays, Driven Pile, Pile Driving, Pore water pressure, Numerical Simulation, Pile Settlement, Ultimate Bearing Capacity

I. Introduction

This paper aims to be an investigation tool based on the driving of an instrumented pile in the soft soil zone of the Sabana de Bogotá [1]. For this purpose, the soils within the campus of the Universidad Nacional Colombia are being studied. (See figure 1)

The soils of the city of Bogotá are characterized by the presence of a vast body of soft deposits of lacustrine origin and are geologically constituted by soils with special physical and mechanical characteristics [2]; as a result of the deformations and faulting processes of the Eastern Cordillera during the different orogenic pulses [4]. The use of deep foundations in the soils of the capital city of Colombia is evidenced, given the depth and extension of the sedimentary deposit that composes it. A crucial parameter that must be considered for our purposes is the increase in soil pore pressure that occurs when piles are driven into the soil. This increase in pore pressure usually leads to unexpected behavior of the soil around the piles.

High displacement piles are used in soils similar to those of Bogotá. These piles get their name from the fact that no material must be extracted before they are driven into the ground: the force with which the piles are introduced displaces and compacts the soil laterally. This, in turn, changes the bearing capacity of the soil, which is also determined by its stress history and state of consolidation. High displacement piles are also able to transfer a relatively high load into the ground (in relation to their length). The load transferred from the piles by friction with the ground is particularly important.

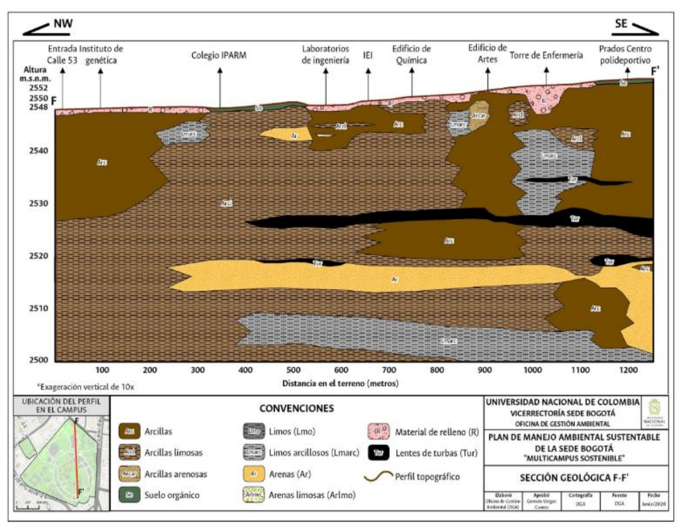


Fig. 1 Geological profile FF', Universidad Nacional de Colombia [1]

Despite the increase in soil pore pressure during pile driving, this phenomenon has not yet received adequate attention in the study of deep foundations in Colombia. The purpose of this study is to be a tool to improve design processes and to understand the short- and long-term behavior of deep foundations.

II. Research Proposal

The research schedule for the present project includes 4 clearly differentiated stages. Figure 2 shows the process map and a description of each of the planned research stages.

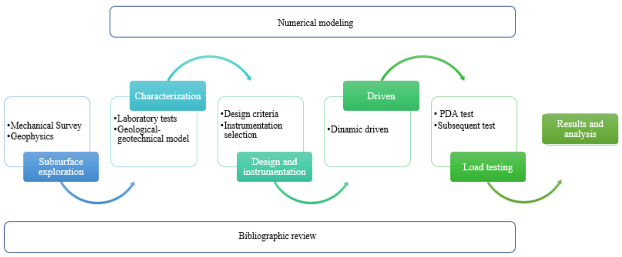


Fig. 2 Proposed process map

Stage I - Characterization of the subsoil

The city of Bogota is geologically located on an extensive sedimentary fill that forms the Sabana de Bogota. This corresponds to the central part of its area [2]. The deposit over the area of the National University of Colombia has an approximate thickness of 180m and corresponds to deposits made up of predominantly plastic clays to silty clays, with liquid limits ranging from 30% to more than 200%, and plasticity indexes higher than 100% [3]. It should also be noted that these sediments are mostly composed of overconsolidated material whose overconsolidation index (OCR) decreases with depth [3].

This project contemplates two explorations of the subsoil in the campus of the Universidad Nacional de Colombia, of which one is already finished. The first drilling (S1) was carried out with the aid of a 28-horse-power reformed Petty machine of the longyear type. Preliminary information led us to choose this machine as the most fitting one to retrieve inaltered of samples that we needed, since its thin-wall pipe prevents them from being altered too much when they are extracted. The second drilling (S2) will be done with the same machine. However, in this case, standard penetration tests (SPT) and vane shear tests on the drilled shaft will be done sequentially throughout the process of retrieving new samples.

Thus, we measured the thicknesses of the different soil layers and evaluated their composition. We were then able to create a geological-geotechnical model based on what was collected through the development of physical and mechanical characterization tests and on previously available data from other models.

Stage II - Design and Instrumentation

Digital Object Identifier: (only for full papers, inserted by LACCEI).
ISSN, ISBN: (to be inserted by LACCEI).
DO NOT REMOVE

Given the features of the soils of the Sabana de Bogotá, the pile that will be driven on the campus of the Universidad Nacional de Colombia in the future stages of this research will have to work by shaft resistance and by point resistance, developed at the soil-pile interface, since there is no bedrock at a reasonable depth that could offer support at the base of the pile [7].

The design criteria for this pile include diameter and length, concrete compressive strength, and construction methodology [8]. In addition, it follows the suggestions for determining ultimate load capacity, admissible load capacity and negative friction.

The reasons for developing an efficient geotechnical instrumentation, at the Universidad Nacional de Colombia, according to Das [7] are based on the verification of the design and long-term behavior of the pile, as well as the control of the construction and safety of the structure. Therefore, the instrumentation program is proposed according to the following factors:

- Site Conditions and Purpose of Instrumentation
- Identification of variables to monitor
- Prediction of behavior
- Instrument selection
- Instrument Layout Planning
- Instrument Acquisition and Installation
- Monitoring

The instrumentation stage includes the installation of different equipment prior to pile driving, to measure parameters associated with its behavior and load capacity over time, as shown in the Table I. The main instrumentation consists of vibrating string piezometers to measure pores pressure dissipation and inclinometers to measure lateral ground deformation. The secondary instrumentation consists of the installation of devices on the internal structure to measure strain with strain gauges, stress with vibrating wire extensometers and temperature with thermocouples.

TABLE I
Summary of Measurement Parameters, Instruments, and Instrument Types for the Instrumented Test Piles (after Paikowsky and Hajduk, 1999 [8])

Parameter	Measuring Instrument	Gage Type	Instrument Abbrebation
Excess Pore Pressure Dissipation	Piezometers	Vibrating Wire	VWPG
Deformation	Inclinometer	Vertical in-place System	VIPS
Interior Stress Wave Measurements	Abstract, Index Terms	Vibrating Wire	VWSG

Stage III - Numerical modeling

Our approach for a mathematical model is implemented by means of an analysis of the soil mechanics from continuum mechanics and the description of a classical linear porous medium model, as proposed by Maurice Biot [9]; making a reduction of the temporal terms to obtain a quasi-static model of two systems of equations: one of momentum (1) and one of mass conservation where Darcy's law is applied (3).

$$\nabla \cdot \sigma(u_s) = f \quad (1)$$

$$\sigma(u_s) = \sigma(u_s)_e - \alpha p I \quad (2)$$

$$\alpha \frac{\partial \nabla \cdot u_s}{\partial t} - \nabla \cdot \left(\frac{\kappa}{\mu} \nabla p \right) = g \quad (3)$$

To solve this system of partial differential equations, a finite element implementation is developed as explored by Haagenson in the solution of the Terzaghi problem [10], using Open Source libraries. Likewise, a library such as FEniCS, in which all the computational simulation will be developed to execute methodologies for terrain stabilization, applying the mathematical developments made in recent years such as those made by Egger with higher order elements [11].

Stage VI - Stressing and Load Testing

Once the necessary instrumentation has been installed in the pile, the pile will be driven into the ground by dynamic driving. This method is the preferred method since it is a good alternative for the foundation of structures in soft soils and at the same time improves the intrinsic characteristics of the soil. Another method proposed is the pressure driving system, which is a relatively new methodology, so there are few antecedents and technical documents that can be consulted in the literature [12].

During the dynamic driving procedure, a test will also be performed with the Pile Driving Analyzer (PDA) system, incorporating sensors in it just after the completion of the driving process and recording the blows required for the test [12]. Two weeks later, another load test will be performed on the pile; the period between tests has been chosen following recommendations for working with high displacement piles [15]. Finally, the results of these tests will allow us to calculate the bearing capacity of the pile and create an approximate load distribution profile for the system.

III. Some Advances

Characterization

After reviewing the scientific literature in search of a general characterization of the soils of the Sabana de Bogotá, we proceeded to characterize the soil of the area where we would work. A 25 m deep borehole was drilled with a Shelby type sampler at a radius of 1 m from the point where the pile will be installed in the future. Thus, we were able to recover with continuous sampling along the drilled hole. In addition, there are drilling logs with gross results of 4 boreholes in the study area with different types of sampling, these at distances no greater than 100m from the study area; three boreholes were carried out at 50m depth and one at 41m depth. The results of this last exploration indicate that the Universidad Nacional de Colombia has soils with high water content, which varies between 27% and 130%. Due to the presence of organic matter lenses at 18 m depth, it has specific gravity values that are between 2.44 and 2.64. Likewise, total unit weights are between 12.0 kN/m3 and 19.3 kN/m3.

According to the process carried out in the field and the characteristics of the samples obtained, a test plan was designed in order to adequately organize the schedule of activities and give continuity to the previously proposed methodology; this plan includes mainly the performance of 8 consolidations, 4 direct cuts and 4 triaxial CU cuts. Knowing that permeability plays a fundamental role in the study of pore pressure increase and field displacements [14], it was proposed the development of horizontal permeability tests by obtaining unaltered horizontal samples at certain depths. Another test of special characteristics proposed is the direct shear test, where the tested sample corresponds to soil and mortar in equal proportion, especially analyzing its shear plane at the mortar-soil interface.

TABLE II
Soil Properties

Material	Initial Depth	Final Depth	γ_t	w	Gs	Cu	E	ν - Poisson
	m	m	kN/m3	%	-	kN/m2	kN/m2	-
M1	0	4.70	19.30	27	2.64	91.25	1729	0.35
M2	4.70	7.40	17.50	40	2.62	40.00	2717	0.35
M3	7.40	18.50	19.00	10	2.66	25.00	334	0.35
M4	18.50	19.30	12.05	136	2.44			0.35
M3	19.30	27.00	16.50	40	2.53	5.00	1252	0.35

Design and geotechnical instrumentation

With the pile design and installation parameters established in Stage II, the implementation of a precast concrete pile with a square section of 0.3mx0.3m and a length of 22m, divided into 11m sections, is established. Having joints to join on site the standard length and thus achieve the perfect grip and fastening between them [15]. These characteristics will be used because the usual lengths of this type of piles vary from 10m-45m, and their maximum load ranges from 7500kN-8500kN. In addition, this type of piles can be subjected to difficult excavations, are corrosion resistant and can be easily combined with the concrete superstructure [5].

Currently the project has a Casagrande piezometer (CPG) manufactured with a 0.381m diameter pipe PVC and installed at 12m depth, whose objective is to measure the water table in the study area. Since in soils of high hydraulic conductivity the water level will stabilize approximately 24 hours after the end of the exploration, it was decided to monitor the days of the geotechnical exploration and the days after it. The results are presented in figure

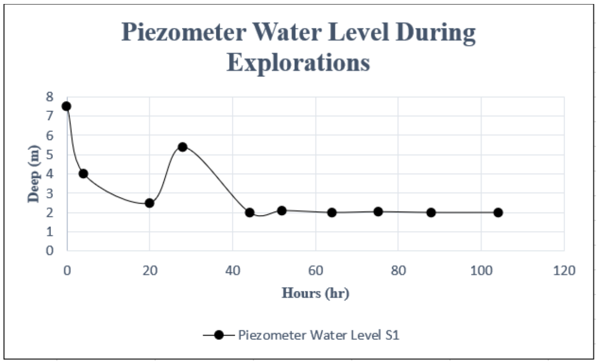


Fig. 3 Water level monitoring

Numerical modeling

In the first approach, the problem is approached using a linear elastic constitutive model given the ease of implementation in linear terms, such that the effective stress $\sigma(u_s)_e$ is defined as in eq. (4) where λ and μ are the Lame coefficients.

$$\sigma(u_s)_e = \lambda tr(\varepsilon)I + 2\mu\varepsilon \quad (4)$$

$$\varepsilon = \frac{1}{2}(\nabla u_s + (\nabla u_s)^T) \quad (5)$$

Data obtained in previous explorations in the vicinity of the study area were used, considering 5 main strata up to 50 meters depth. The physical properties of these soils are shown in the Table. It is necessary to emphasize that the Biot Coefficient was assumed as 1, since laboratory test results are required to establish it for each stratum; this is an objective to be carried out with the samples obtained in borehole 1.

The results of the simulation are presented in Figures (4), (5), (6) and (7). These represent a scalar field of safety factor to the Mohr Coulomb failure envelope. Values above 1 are below the failure envelope and values below 1 touch the envelope (shear failure). Isolines referring to the increase in pore pressure for 4 different driving depths are evidenced over this field.

Ultimate Compressive Load Prediction

Based on the compilation of background information on dynamic pile driving in the city of Bogota and dynamic load tests performed in Colombia and other countries, a load capacity prediction was made based on an established geological-geotechnical model. Finally, the aim is to correlate the predictions with the results obtained from the tests performed with the Pile Driving Analyzer (PDA) system.

The prediction consists of determining the ultimate bearing capacity of the pile by calculating the tip resistance using the Meyerhof and Vesic methods, and the frictional bearing capacity using the Alpha (α) and Lambda (λ) methods. However, the pile's own weight must be considered.

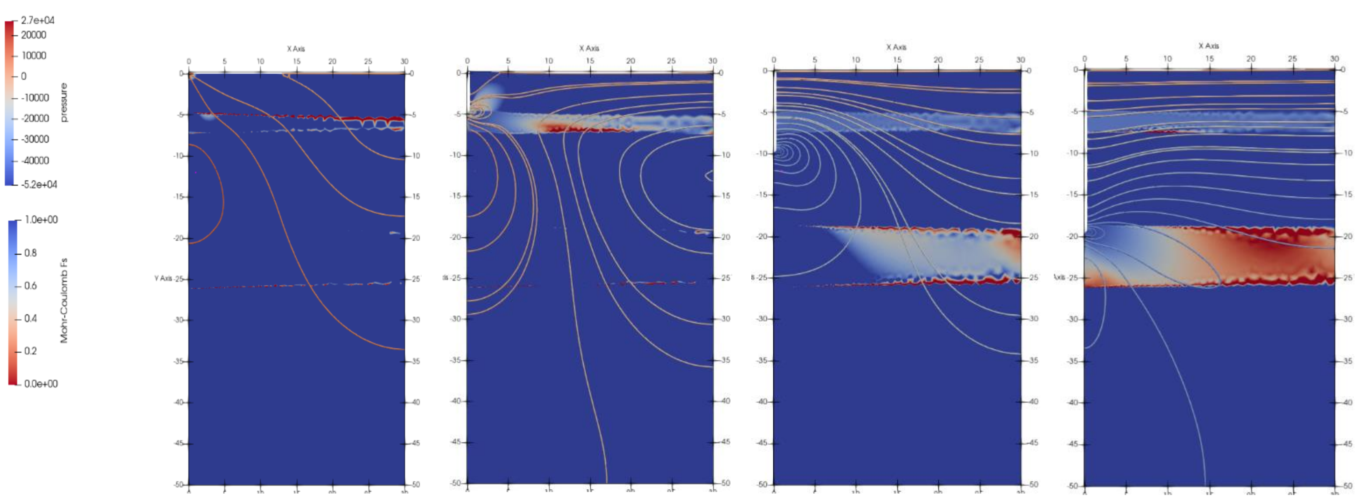
Based on the geomechanical parameters established as typical for the Universidad Nacional de Colombia clay, some initial results of the ultimate load prediction, bare presented in the table below.

TABLE III
Ultimate Strength per Shaft and tip

Method	Q_p	Q_p PDA	Method	Q_f	Q_f PDA
	kN	kN		kN	kN
Meyerhof	20.25	50.14	α	199.92	653.37
Vesic	17.79	18.71	λ	18.35	52.36

Where:

- Q_P : Ultimate point resistance
- Q_S : Ultimate shaft resistance



(A) (B) (C) (D)

Fig. 4 Sequence pile driving at 5 m (A), 10 m (B), 15 m (C) & 20 m (D)

IV. Partial Conclusions

- The material at the pile installation site corresponds to soft soils, according to what was observed and described in the drilling performed, thus determining a correlation with what was consulted in the bibliography.

- According to the data compilation and the different methods to determine the ultimate resistance of the pile, it is determined that there is a significant variation between the values obtained for the tip and shaft resistance in relation to the values of the dynamic load tests (PDA).

- In the simulation we can observe how the strata that have a lower resistance dissipate the stress, this is observed by increasing the safety factor in these strata once they are crossed by the pile and we can also observe the typical pore pressure increase bulb at the tip of the pile as the pile is driven.

IV. Future Activities

Based on the research proposal and the progress made in the project, activities will be carried out to determine the behavior of the soil-pile system, produce research papers and thus generate an advance in the state of the art of deep foundations for the city of Bogota. The proposed activities are listed below:

- Execution of laboratory tests.
- Static penetration test with seismic piezocone (down-hole) SCPTU.
- Subsurface exploration with standard penetration tests (SPT) and shear tests with field vane.
- 3D modeling of topographic survey performed with drone.
- Extraction of material at 3.5m to determine special mineralogical composition encountered.
- Exploration to determine horizontal permeability and correlate with depth.
- Shear tests of clay-concrete interface.
- Comparative analysis of bearing capacity Conventional Methods-Dynamic load tests.
- Implement plastic constitutive model for effective soil stresses.

Acknowledgment

The authors appreciate the support of Universidad Nacional de Colombia, Sede Bogotá, for financing the research project originated this work. They also appreciate the technical support provided by the Geotechnical Laboratory at Engineering Faculty for the support in the development of the lab testing program. The authors also appreciate the stimulating exchange of opinions with some members of Geotechnical Engineering Research Group- GENKI, especially Mr. César Ramírez and Mr. Carlos Reina. We also thank the engineer Camilo Bayona Roa, Scientific Director of CIAID, who has supported the development of the numerical model.

References

[1] Oficina de gestión Ambiental, “Plan de manejo ambiental sustentable de la sede Bogotá”, Universidad Nacional de Colombia, Sede Bogotá, Sección geológica F-F, 2020

[2] Ingeominas, “Microzonificación sísmica de Santa Fe de Bogotá”,1997

[3] A Rodríguez. “Obtención de parámetros geomecánicas con piezocono sísmico en el campus de la Universidad Nacional Sede Bogotá”, M.S. thesis, Departamento de Ingeniería Civil y Agrícola, UNAL,Bogotá,2013

[4] J. Moya, J Rodriguez, “The subsoil of Bogotá and the problems in Foundations”, VIII Pan American Conference on Soil, Mechanics and Geotechnical Engineering Cartagena, 1987

[5] B. Das and N. Sivakugan, *Fundamentals of geotechnical engineering*. Australia: Cengage Learning, 2016.

[6] M. Tomlinson and R. Boorman, *Foundation design and construction*. Harlow, England: Pearson Education, 2001.

[7] B. Das and N. Sivakugan, *Principles of foundation engineering*, 9th ed. Cengage learning, 2018.

[8] L. David Suits, T. Sheahan, S. Paikowsky and E. Hajduk, "Design and Construction of Three Instrumented Test Piles to Examine Time Dependent Pile Capacity Gain", *Geotechnical Testing Journal*, vol. 27, no. 6, p. 12191, 2004. Available: 10.1520/gtj12191.

[9] M. Biot. “General theory of three-dimensional consolidation”. Journal of Applied Physics, 12:155–164, 1941.

[10] R. Haagenson, H. Rajaram, and J. Allen. “A generalized poroelastic model using fenics with insights into the noordbergum effect”, *Compute& Geosciences*, 2019.

[11] H. Egger and M. Sabouri, “On the structure preserving high-order approximation of quasistatic poroelasticity”, *Mathematics and Computers in Simulation*, 237-252, vol. 189, 2021.

[12] A. Martínez et al, “Guía para hincado a presión de pilotes prefabricados de concreto reforzado en cimentación profunda, con base en reglamento colombiano de construcción sismo resistente (nsr 10)”, Thesis, Universidad La Gran Colombia, 2017.

[13] J. Palacios et al, “Estado del arte del proceso de instalación de pilotes por presión estática, analizando las técnicas y características que permitan establecer su potencial de uso como alternativa de cimentación profunda en Colombia”, Thesis, 2019.

[14] A. Lee P, “Field Investigations intro Pile behaviour in Clay”, P.H.D. thesis, Imperial College of Science Technology and Medicine, 2002.

[15] J. árcos and M. De Juan, "Pilotes prefabricados: una solución óptima para cimentaciones profundas. ´ Cemento Hormigón´ , 2007.

[16] J. Rodríguez and E. Velandia, “Optimización de cimentaciones en suelos blandos de Bogotá”, M.S. thesis, Departamento de Ingeniería Civil, Pontificia Universidad Javeriana. Jeoprobe Ltda, Bogotá, 2009.