# Effect of soil-pile contact parameters on pile bearing capacity value

*Darym* Campos[1], *Thiago* Morandini[2], *Stéphanie* Ferreira[1], *José* Camapum[1], *André* Cavalcante[1], *and Luan* Ozelim[1]

*[1,] University of Brasilia – UnB, Brasília, Brazil*
*[1] Federal Center for Technological Education of Minas Gerais - CEFET, Belo Horizonte, Brazil*

## ABSTRACT

The soil and foundation elements are fundamental to the behavior of a structure. When the foundation soil has a low capacity, it is necessary to transmit the loads to a deeper and more resistant layer, using deep foundations. A pile load test is a field measurement of the bearing capacity (vertical or horizontal) of a foundation element. In addition to a physical model of a load test, the use of computational tools can bring additional understanding. In order to analyze the responses obtained by numerical models compared to field test results, tools that use Finite Element Methods (FEM) and that have a series of constitutive models become a great alternative. This paper aims to study the behavior of Continuous Flight Auger (CFA) piles, aiming to understand the soil-pile interaction regarding the effect of soil-pile contact parameters on pile bearing capacity value. In this way, experimental data from three load tests were compared with numerical simulations using the Mohr-Coulomb constitutive model. Also, a parametric study was completed based on the collected soil data from the literature of the region that most affected the settlement behavior of the load pile. It was concluded that there is a direct and significant influence of the friction coefficient on the pile bearing capacity. In addition, by incorporating more real soil data and parameters representing its actual formation, the results of the pile load test simulation can be taken as an alternative to estimate the ultimate capacity of a vertically loaded pile in the absence of the static load test, which has been widely observed in engineering practice.

**Keywords:** Pile Bearing capacity; foundation; load.

## 1. Introduction

The quality and reliability of a foundation design depend on the designer's understanding of the soil, its morphology, and its properties, as well as modeling and analysis techniques. The soil and the foundation elements are critical when analyzing the behavior of the structure. Depending on the stratigraphic profile, piles can be used to transmit loads to deeper and more resistant levels. In this load transfer process, the contact between soil and pile is an important factor. During this process, there is a soil reaction against the load from the pile, either by lateral friction due to shear stresses or by normal stresses at the tip of the pile. The lateral friction mobilized depends on the intrinsic properties of the soil, the constituent material of the pile, and the level of interaction and contact mobilization of the elements involved. It is worth noting that the total mobilization of resistance by lateral friction along the shaft occurs with small displacements. A simple but effective way to perform the modeling of this effect is to use a lateral friction model.

In order to evaluate the adequacy of the responses obtained numerically to those of reality, some authors have used Finite Element Method (FEM) to reproduce different types of load tests on compression-loaded piles. Hung & Kim (2010) showed good agreement of the load versus settlement curve between the numerical simulation and the physical data of the load test performed on a steel pile. The significant difference between the curves was observed in the yield zone of the pile. Duarte (2012), for example, compared load-rebound curves obtained numerically and experimentally, verifying the influence of the number of piles on the foundation behavior, conferring the group effect to the analyses. Other authors, such as Zeleke (2015) and Campos et al. (2020), created axisymmetric finite element models in their simulations for comparison with the results of load tests, using excavated piles and CFAs.

According to Alonso et al. (1987), to properly predict the mechanical behavior of the material subjected to the stress field, it is necessary to create constitutive models capable of reproducing with significant accuracy the behavior observed in the desired material under study.

This paper aims to study the behavior of three continuous flight auger piles, comparing the results of the load tests with the numerical simulations. For this, a 3D model that portrays the stratigraphic profile of the analyzed work will be used. To understand the soil-pile interaction, the influence of the lateral friction coefficient on the pile bearing capacity value will be observed, as well as the soil properties surrounding the pile shaft. Finally, to model the soil behavior, the established Mohr-Coulomb (MC) constitutive model was considered.

## 2. Computational Tools

Problems involving bearing capacity in deep foundations can be studied analytically, numerically, or experimentally. Unfortunately, the use of analytical solutions is not always possible, because several issues, in practice, are too complex to be mathematically modeled through the use of exact differential equations, generating the need to use approximations. This argument already justifies the use of numerical methods, since with the growing technological advances it is already possible to describe complex problems with the use of computers at a low cost and speed. Finally, experimental methods are used to verify in practice the results obtained by numerical approximations but are almost always associated with high costs.

Among the most widely used numerical methods for analyzing mechanical problems, the Finite Element Method (FEM) stands out. This method is one of several numerical methods that can be used to obtain the solution to boundary value problems. In the present study, Abaqus is considered a computational tool.

The software also allows for the stipulation of the desired interface zone for soil-pile interaction through the "Tangential Behavior" option, where an equivalent friction coefficient is assigned to the contact. In simplified form, this option models the sliding resistance of the contact between the parties as a linear function of the load normal to the contacting surfaces. A coefficient of friction is used as the linear coefficient of this relationship.

This paper, in order to try to reproduce the results of stress and strain fields found in proof loading experiments, varied the values of friction coefficients and soil properties to understand their behavior and the best option to portray the experimental result. To obtain the simulation domain, from a stratigraphic point of view, the geometry of the soil layers was obtained from the spatialization of boreholes made at the load testing site. This was done using the RockWorks software, interpolating the probing results over the entire terrain area. For the interpolation, the Inverse-Distance Anisotropic weighted distance method was used, with the aid of the Smooth Grid data filter, eliminating the data with "flaws", and generating a better smoothing trend.

## 3. Characteristic of the construction

The studied construction was carried out in Brasilia, the capital of Brazil. First, a retaining wall curtain system was implemented for the stability of the wall, and later, when the excavation reached the projected elevation or level, a specific drilling campaign was initiated to enable design and construction of the foundation. Thus, four SPT boreholes were performed. Three compression load tests were performed, named PC01, PC02, and PC03, with slow loading, taking each pile to a load corresponding to at least 1.6 times its respective working loads, always attending to the NBR 12131 criteria (ABNT, 2006). All CFA piles are 50cm in diameter and 14m deep.

Fig. 1 shows the ground spatialization from the interpolation of the borehole results. It also shows the location of each test performed, as well as the load tests. In Fig. 2, a strategic cut in the direction of the load tests was chosen, facilitating the visualization and understanding of the soil layers near each test.

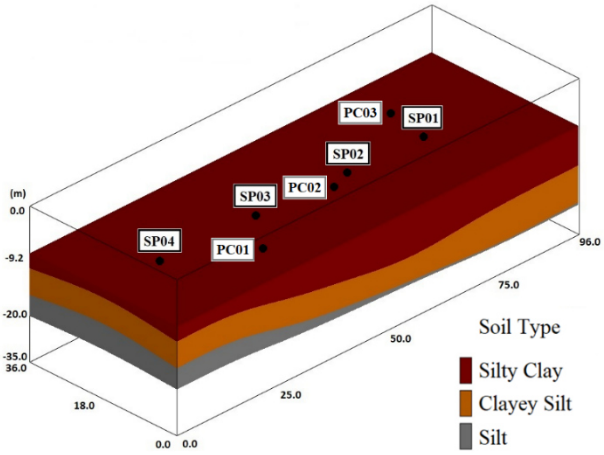


**Figure 1.** 3D model of the foundation stratigraphy built from the percussive tests

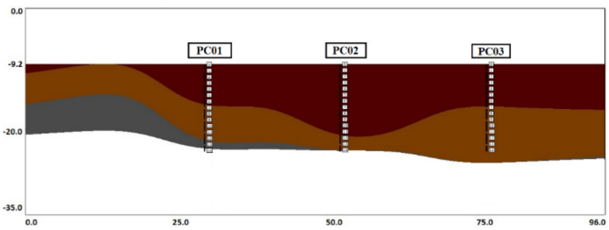


**Figure 2.** Section of the stratigraphic profile in the direction of the load tests performed

## 4. Numerical Simulations

### 4.1. Constitutive Models

To model the soil behavior, the Mohr-Coulomb constitutive model was considered, since it depends on parameters that are more easily found in the literature and local research. The method considers the material to be isotropic with linear-elastic behavior until the yield surface, where unrecoverable plastic deformations begin.

It is important to note that in this case study, by observing the load versus settlement curves, it was noted that there was no occurrence of total rupture in the pile-soil system. In general, the total mobilization of resistance by lateral friction along the shaft occurs with small displacements. However, to achieve the mobilization of the tip reaction, much larger displacements are required, especially in excavated piles.

### 4.2. Soil Properties

No specific tests were performed to obtain the parameters used in the model, all were adopted from average values in the literature of typical materials of the region near the work studied, such as Araki (1997), Guimarães (2002), Perez (2017) and Rebolledo (2019), respecting the types of soil characterized in the reports of the surveys. The concrete parameters, on the other hand, were used according to the properties of the concrete of the tested piles. The data are shown in Table 1.

**Table 1.** Soil Properties

| Soil | Density (kg/m³) | E (MPa) | ν | ϕ (°) | c (kPa) |
|---|---|---|---|---|---|
| Silty Clay | 1500 | 13 | 0.35 | 27 | 24 |
| Clayey Silt | 1700 | 20 | 0.2 | 27 | 40 |
| Silt | 1900 | 37 | 0.2 | 26 | 45 |
| Concrete | 2500 | 25000 | 0.2 | - | - |

It is important to point out that, for simplicity, as the water table was only about 2 meters below the top of the pile, the model was considered saturated. It should also be noted that the parameters indicated in Table 1 were used only as a first approximation. Later on, during calibration, these parameters were changed until an agreement with the actual load tests was observed.

### 4.3. Element type and mesh

For the development of three-dimensional finite element models, a mesh with C3D8R type elements was used, linear hexahedral brick type, with eight nodes having three degrees of freedom each (translations in the x, y, and z directions) and with an integration point in the middle of the element where stresses and strains are calculated quite accurately. Subsequently, different mesh sizes were chosen, reducing the size of the finite elements in areas of greater interest, thus implying better numerical interpolation and error minimization. On the other hand, the distance between the nodes is also reduced, an aspect that increases the computational cost due to the even larger number of equations to solve. The larger elements, on the other hand, were placed in less requested areas.

## 5. Results and Discussions

From the average vertical displacements measured by the strain gauges at the top of the tested piles, the load versus settlement curves were plotted. The results are illustrated in Fig. 3.

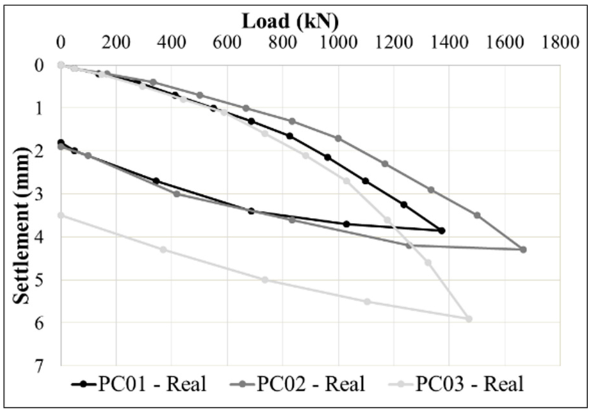


**Figure 3.** Load versus settlement curve of the load tests PC01, PC02, and PC03.

The failure criterion of NBR 6122 (ABNT, 2019) was used by extrapolating the curves using the Van der Veen method (1953), according to Fig. 4.

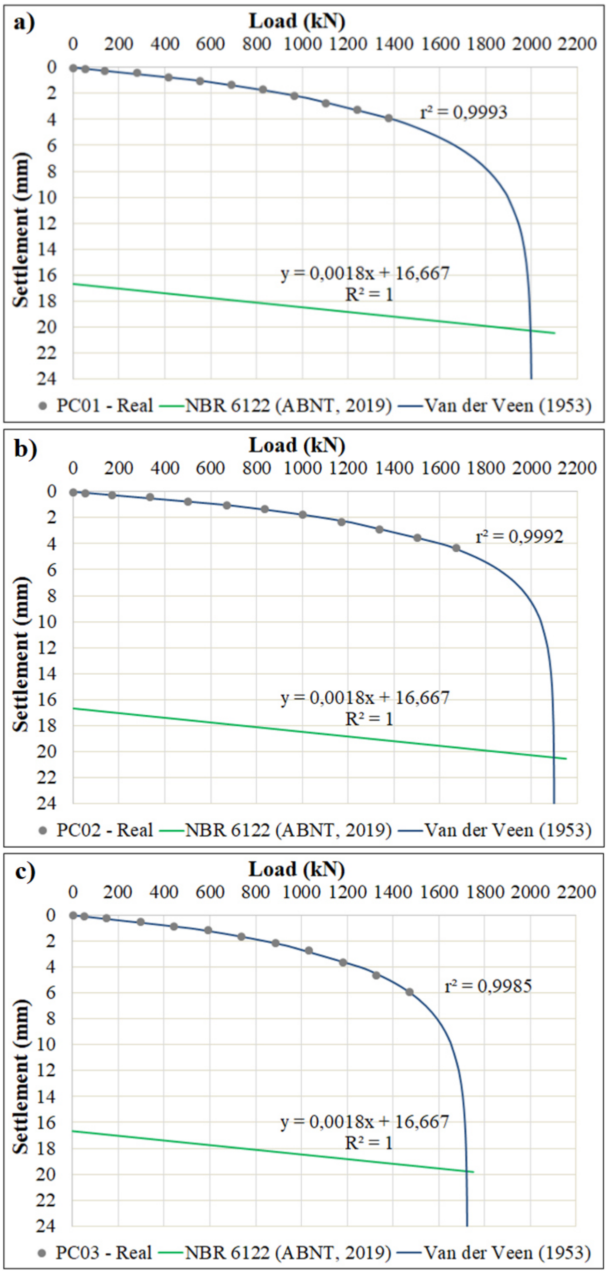


**Figure 4.** Load versus settlement failure criterion: a) PC01; b) PC02; c) PC03.

For the PC01 pile, the failure load was estimated at 204tf, presenting an FS of 2.34. For the PC02 pile, it was estimated at a breaking load of 214tf resulting in an FS of 2.10, and finally, the PC03 pile resulted in a breaking load of 175.8tf and FS of 1.91.

In the Abaqus software analysis, a vertical displacement value sufficient to reach the maximum load achieved in the experimental load test was strategically imposed at the top of each modeled pile. Figs. 5 and 6 shows the simulated model.

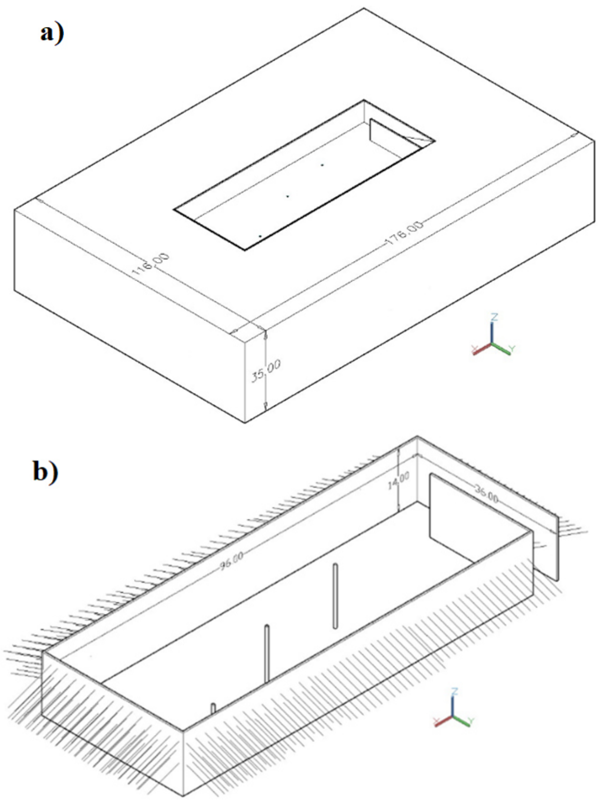


**Figure 5.** Model simulated by Abaqus: a) Organization of the construction site; b) Organization of the piles and auxiliary structures

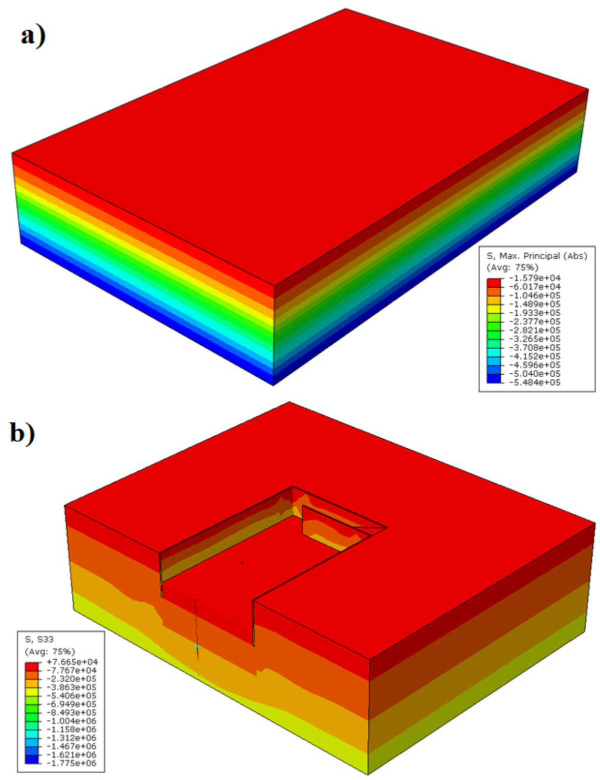


**Figure 6.** Model simulated by Abaqus: a) Geostatic conditions prior to excavation; b) Illustrative result of one of the simulations, with vertical displacement of 2 cm imposed on the top of the pile.

Fig. 7 presents a compilation of the curves obtained in the numerical analyses. For a first analysis, the effect of the friction coefficient of the soil-pile contact on the bearing capacity value was evaluated.

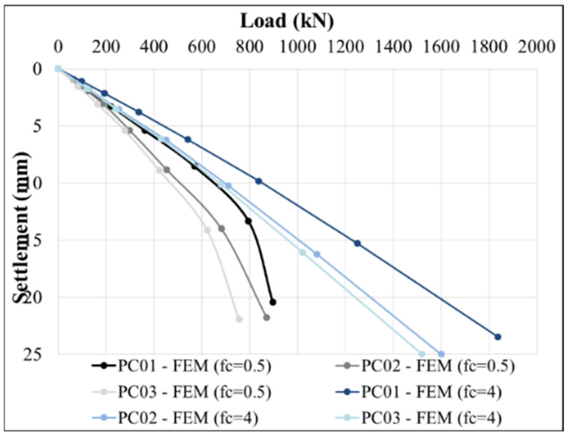


**Figure 7.** Comparison of curves obtained numerically and experimentally by varying the friction coefficient

It was noted first that the highest value of bearing capacity would be given with a large coefficient of friction, i.e., the higher the value of the coefficient, the more clearly a condition of almost zero relative displacements is observed between the surfaces of the pile shaft and the surrounding soil. On the other hand, the closer to 0, the greater the relative displacement between the contact surfaces. Thus, Fig. 7 shows this variation of the coefficient value. It was noticed that by keeping the values of the literature parameters and changing only the friction coefficient, both for a small value and for a high value, the influence of the tip resistance of the pile or the shaft becomes more evident, respectively. With the applied value of 0.5, it was noted that the displacement behavior of the top in each pile is completely different from what was measured in the field. However, with arbitration value equal to 4, the extrapolated rupture loads start to get closer to the real one, but in general, with the variation only in the friction coefficient, the curves are still far from the results when using the properties predicted in the literature.

On the other hand, to have a greater similarity observed between the experiment and the simulation, the soil parameters and the friction coefficient were varied. Theoretically, the properties that most influence the behavior of the pile are the soil layers inside the stress bulb and the layers surrounding the pile shaft. This was verified in the numerical simulation performed. To portray and analyze a behavior close to the one tested, it was realized that by intentionally increasing the modulus of elasticity and decreasing the values of cohesion and friction angle of these layers, the same would occur. This action aimed to increase the slope of the elastic range of the settlement load curve. At first, the aim was to adjust the slope of this section, not its curvature. This is more pronouncedly affected by the adopted constitutive model. The results are seen in Fig. 8 and the modified parameters of the materials used are shown in Table 2.

**Table 2.** Modified parameters of the Soil Properties

| Soil | Density ($kg/m^3$) | E (MPa) | ν | ϕ (º) | c (kPa) |
|---|---|---|---|---|---|
| Silty Clay | 1500 | 13 | 0.35 | 27 | 24 |
| Clayey Silt | 1700 | 20 | 0.2 | 27 | 40 |
| Silt | 1900 | 37 | 0.2 | 26 | 45 |
| Concrete | 2500 | 25000 | 0.2 | - | - |

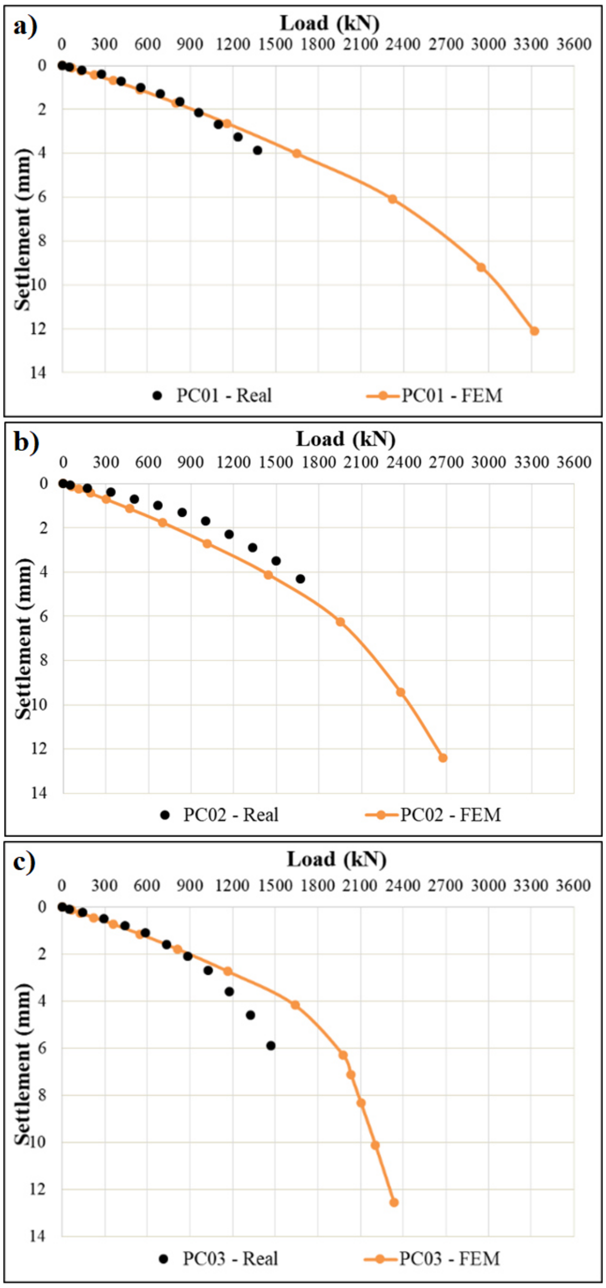


**Figure 8.** Comparison of curves obtained numerically and experimentally by varying the soil parameters: a) PC01, b) PC02; c) PC03

The approximation of the results was due to the increase in the modulus of elasticity of the silty clay layer to 130MPa and clayey silt to 200MPa, as well as the decrease in the friction angle to 17° and the cohesion to 7kPa in both layers. For the friction coefficient, the dimensionless value of 1 was used.

After adjusting the modulus, it was verified that for the same applied displacement (2cm), the inflection point changed for the elastic range and the plastic range of the soil-pile contact. This is expected because the increase in modulus generates a greater structure hardening, demanding more load application for the same displacement level. On the other hand, the reduction of the cohesion and friction angle for the layers surrounding the pile implied a faster plastification of the interface, which pulls the inflection point to the left and changes the curvature of the curve, because there is less resistance in the soil-pile contact.

In practice, Van Impe (1994) alerts to the great influence of the method of execution of the foundation on the ratio between the displacement and the diameter of the base. According to the same author, the modifications of the characteristics and the stress state of the soil around the pile are dependent on the type of its installation and sensitively influence the performance of the foundation and, consequently, its bearing capacity.

## 6. Conclusions

This research aimed to understand the impact of the of soil-pile contact and soil properties in numerical analyses when compared to experimental ones. The importance of this evaluation in the value of the bearing capacity.

Thus, as expected, it was found that there is a direct influence of the friction coefficient on the bearing capacity results. In addition, the soil parameters under the influence of the pile are also fundamental in the behavior of the curve.

This comparison between the values obtained experimentally and numerically shows the importance of associating these concepts with the practice of foundation engineering, because the modeling of soil behavior is complex and usually beyond the capability of most traditional forms of physically based engineering methods. The mathematical choice of the set of parameters resulted in a reduction of the physical meaning in the context of the current understanding, but the intention was to try to bring the greatest adherence to the load and settlement values, which point to the need for re-reading the physical meanings of the parameters that prevail today. Note that the curves were reasonably well fitted, so as to consider the results satisfactory.

Finally, the tool used proved to be adequate for this study due to its ability to simulate the process.

## Acknowledgements

The authors thank the Foundation for Research Support of the Federal District (FAPDF) and the Foundation for Research Support of the State of Minas Gerais (FAPEMIG: process APQ 00835-16) for the financial support of the project.

## References

ABNT NBR 6122. 2019. Foundation design and execution (Brazilian Standard). Rio de Janeiro.

Alonso, E. E., Gens, A., & Hight, D. W. 1987. Special Problem Soils. 9th European Conference of Soil Mechanics and Foundation Engineering. General Report, (pp. 1087-1146). Dublin, IE.

Araki, M.S. 1997. Aspects regarding the properties of collapsible porous soils in the Federal District. Master's Dissertation, Publication: G. DM – 040A/97, Department of Civil Engineering, University of Brasília, Brasília, DF,121p.

Campos, D. J., Carvalho, J. C., Silva, C. M., Cavalcante, A. L., & Ozelim, L. C. 2020. Effect of Soil-Pile Contact Friction Coefficient on Bearing Capacity Value. XX Brazilian

Congress on Soil Mechanics and Geotechnical Engineering, (p. 8). Campinas, SP

Duarte, L. N. 2012. Evaluation of the Soil-Structure Behavior of Foundation Elements of the Pileated Footing Type. Department of Civil Engineering, Federal University of Viçosa. Doctoral Thesis, Viçosa, MG, 150p.

Guimarães, R. 2002. Analysis of the Properties and Behavior of a Laterite Soil Profile Applied to the Study of the Performance of Excavated Piles. Master's Dissertation, Publication: G.DM – 091A/02, Department of Civil Engineering, University of Brasília, Brasília, DF. 183p.

Hung, L. C., & Kim, S. R. 2010. Numerical Analysis of Pile Loading Test, A case Study in Dunkirk, France.

Perez, R.F. 2017. Hard inclusion for settlement control in collapsible soils of the Federal District. Master's Dissertation, Publication: G.DM-284/17, Department of Civil Engineering, University of Brasília, Brasília, DF, 160p.

Rebolledo, J.F.R; León, R.F.; Camapum De Carvalho, J. 2019a. Obtaining the mechanical parameters for the hardening soil model of Tropical soils in the city of Brasília. Soils and Rocks, 42(1):61-74. DOI: http://dx.doi.org/10.28927/SR.421061.

Van Der Veen, C. 1953. The bearing capacity of a pile. 3rd International Conference on Soils Mechanics and Foundations Engineering (pp. 84-90). Zurich: 2.

Van Impe, W.F. 1994. Influence of screw pile installation parameters on the overall behaviour. Workshop "Piled foundations: full scale investigations, analysis and design". Napels.

Zeleke, B. 2015. Simulation of Pile Load Test Using Finite Element Method. Department of Civil and Environmental Engineering. AAU/Addis Ababa institute of technology, geotechnical engineering, Ethiopia, 116p.