Use of Random Fields in the Prediction of Displacements in Laterally Loaded Piles

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Abstract. Soil is a composite material that has evolved over time, reflecting the natural processes involved in the formation and development of the planet, in fact, soil exhibits characteristics of randomness. In this context, the present study employs random field theory in conjunction with the finite element method to estimate the behavior of laterally loaded piles. Two literature cases were analyzed. For both cases, the basic geotechnical profiles were initially characterized, and variability was defined based on data from boreholes, piezocone tests, dilatometric tests, and seismic measurements. Based on this spatial characterization, different three-dimensional random fields of the parameter of interest were generated using the Local Average Subdivision (LAS) algorithm developed by Fenton and Vanmarcke. The parameter of interest in the soil variability analysis was the modulus of elasticity. The study modeled the behavior of two piles using stochastic methods and compared the results with real load tests. The comparison showed good agreement between the predicted behavior and the actual test results, with an average deviation of about 15% between the estimated values from the models and the actual load tests in both cases analyzed.

Keywords: Piles; Foundations; Random Fields; Probabilistic Analysis.

1 Introduction

The case of laterally loaded piles is a topic of significant complexity. From a geotechnical perspective, this issue is fundamental when lateral displacements or soil failure around the pile are predominant characteristics during the structure's service life. This scenario includes foundation systems for structures in port areas subjected to transverse loads, foundations for wind turbines, photovoltaic panels, among others (Santos [2]).

The most widely accepted theories for dealing with uncertainties in geotechnics are those based on the observational method. This is largely due to the fact that pioneers in geotechnics, such as Carl Von Terzaghi, migrated from classical schools of structural engineering and mechanics. Terzaghi authored several theories used in modern geotechnical engineering. In the search for a more formal basis to address the uncertainties inherent in materials used in geotechnical engineering, the use of reliability theory has been growing within the geotechnical community to manage these uncertainties (Baecher and Christian [3]).

Given this, the objective of this work was to apply random field theory to the prediction of horizontal displacements in laterally loaded piles.

2 Randon Fields in Geotechnics

2.1 Randon Fields

The application of random field theory to geotechnical issues is based on the assumption that the spatial variable of interest is derived from a random process. However, mean and standard deviation values are not sufficient for characterizing spatial variability (Baecher and Christian [3]). Under the simplifying assumptions that the random field is Gaussian and exhibits stationary homogeneity, we need to know three things to characterize the random field according Fenton and Griffiths [4] approach:

- The mean of the field, μ_X;
- The variance of the field, $\sigma^2{}_X$;
- How the field varies in space.

The way the field varies in space is termed the Fluctuation Scale, also known as the correlation length or autocorrelation distance. The fluctuation scale can be calculated by different methods, from classic methods such as the Vanmarcke Expedient Method (VXP) to methods considering autocorrelation functions (ACF). Preference has been given to the latter due to their ease of numerical implementation. The following sections briefly describes the Vanmarcke Expedient Method.

2.2 Expedited Method of Vanmarcke (VXP)

In the Expedited Method of Vanmarcke, it is assumed that the fluctuation scale can be correlated with the trend line related to the variation of the parameter along the soil profile (Figure 1). The estimation of the fluctuation scale is done by evaluating the crossing distance (d_1, d_2, d_3, d_n) between the trend line and the results obtained from the test.

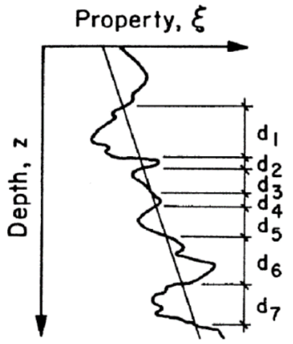

Figure 1. Principle of Vanmarcke's Method (Kenarsari, Chenari e Eslami [5]).

To determine the fluctuation scale value using the VXP, based on cone test resistance, Kenarsari, Chenari, and Eslami [5] proposed the following equations:

$$d = \frac{1}{n}\sum_{i-1}^{n} d_i \quad (1)$$

$$\theta = \sqrt{\frac{2}{\pi}}\, d \quad (2)$$

Where d is the average crossing distance and θ is the fluctuation scale value.

2.3 Random Finite Element Method (RFEM)

Starting in the early 1990s, a new method called the Random Finite Element Method (RFEM), proposed by Fenton and Vanmarcke [1], was developed. This method combines random field theory with the finite element method and has been used in probabilistic geotechnical engineering, being applied to various areas of geotechnical engineering (Allahverdizadeh et al. [6]).

In RFEM statistical properties are incorporated directly into the finite element equations, by a spatial variability of soil properties. Different algorithms can be considered for spatial variability characterization, the Local Average Subdivision Method (LAS) was considered in the present analysis.

2.4 Local Average Subdivision Method (LAS)

To create the multidimensional random field, it is necessary to use a method for subdividing the soil mass. In this work, the Local Average Subdivision (LAS) method was used.

The LAS method is a fast and generally accurate technique for generating discrete random fields with a "local average" process (Fenton and Griffiths [4]). A LAS model can have 1 to 3 dimensions. Each element created using the LAS method has a discrete local mean, which allows the mesh to be refined infinitely without losing statistical precision. For a detailed definition of the method, one may see Fenton and Griffths [1]

3 Implementation

To represent the soil-pile behavior, a numerical model was developed using Abaqus software, which is fully three-dimensional and without symmetry axes. For modeling the pile, a purely elastic constitutive model was used, and for the soil, an elastoplastic model with a Mohr-Coulomb failure criterion was employed.

The elements used in the model were 8-node solid elements, with CAX8R for the pile and CAX8P for the soil. The main difference is that the CAX8P element accounts for pore pressure if water is present. The interaction between the pile and the soil was modeled using the penalty method, with a friction value of 0.3 on the sides and "hard contact" at the base. Integration and hourglass control techniques were used in the model to prevent excessive distortions.

The element sizes varied across the mesh, ranging from 25 centimeter near the pile to 80 centimeters at the edges of the model, which was taken as 30 times the pile diameter laterally and 15 meters below the pile base for the vertical limit. Details can be observed in Figure 3.

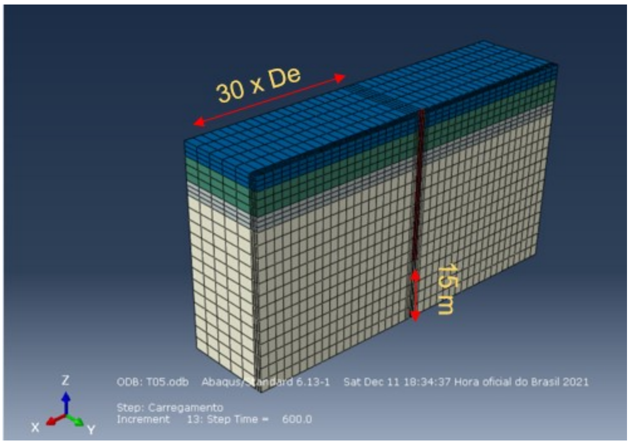

Figure 3. ABAQUS® Model – Mesh and Limits.

Considering that the study aims to evaluate the displacement observed in piles under lateral loading, the modulus of elasticity was chosen for the implementation of the random field, given its significant importance in the mechanical behavior of the pile.

After a thorough analysis of the sections presented in the cases described in the literature, Huang et al. [8] and Born [9], the numerical implementation of the random fields was carried out. For this, the information on the mean and standard deviation of the characterized parameters, theoretical function, and fluctuation scales were input into the software RSetl3D by Fenton and Griffiths [4]. The software generates a three-dimensional field that was exported to the finite element software ABAQUS®. A general image of the pile model and response, based on the work of Huang et al. [8], modeled in the software can be seen in Figure 4. N different random fields were generated for each evaluated case, using a Monte Carlo (MC) approach, where the aim was to analyze the dispersion of lateral loads considering the local soil as a random field.

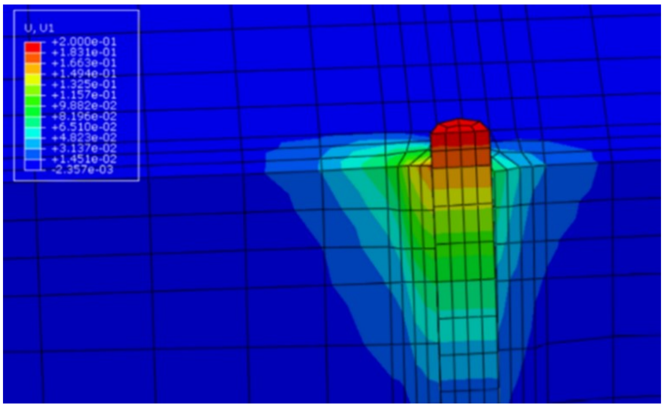

Figure 4. ABAQUS® Numeric model – Case 1.

The import of random fields generated in RSetl3D into ABAQUS® and the processing of the simulation results were performed using a routine programmed in Python, following a procedure similar to that carried out by Ziesmann [7]. Finally, a statistical analysis of the results was conducted to identify the mean force observed for a given displacement applied to the pile.

3.1 Case Study 1: Huang et al. [8]

The monitored load test described by Huang et al. [8] in their article was conducted to evaluate the load capacity of piles subjected to lateral actions, for studies related to high-speed trains in Taiwan. Piles of various diameters, both with and without a cap block, were installed at the study site. Although the base article does not clearly specify the procedure for the pile test, it appears to be a cyclic test. This work evaluated the "B7" type piles from the base article, which were installed using bentonite slurry and have a diameter of 1.5 meters, with a depth of 31 meters.

The subsoil consists of a layer of residual soil composed of silts and silty sands, according to the tests presented in the article. A field testing campaign was conducted at the experimental site, which included CPT (Cone Penetration Test), SCPT (Seismic Cone Penetration Test), and DMT (Dilatometer Test).

Based on the results of the tests, the classification of the soil mass behavior was performed using the SCPT tests, specifically the borehole designated SCPT-1, as shown in Figure 5. This classification aimed to assess possible segmentation of the profile in terms of soil behavior, at the end, the analysis concluded that the soil can be considered a single layer.

The adopted vertical and horizontal fluctuation scale values were 0.9 meters and 10.0 meters, respectively. The vertical fluctuation scale was obtained using the VXP (Expedited Method of Vanmarcke) based on the Dilatometer Test, while the horizontal fluctuation scale was defined with values in accordance with the literature.

The adopted value for the modulus of elasticity was obtained from the seismic test, which showed a mean of 198,219.0 kPa and a standard deviation of 75,539.0 kPa. The probability density function used was the lognormal distribution.

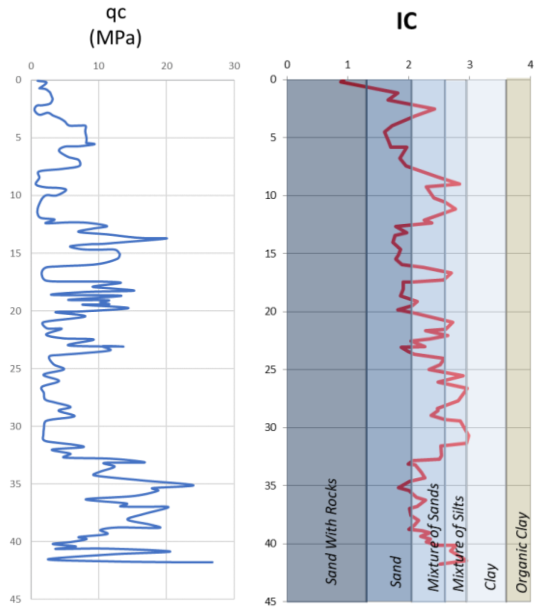

Figure 5. Soil Classification for Case of Study 1 by CPT Test and Robertson's [10] Classification Index.

A total of 956 iterations were performed based on the estimated soil data and fluctuation scale, with 505 iterations reaching stabilization. For each iteration, the force required to displace the top of the pile by 25 millimeters was recorded. The graph presented in Figure 6 shows the evolution of the mean horizontal forces observed at the top of the pile and the value of e, which represents the estimated error considering a normal distribution and a 95% confidence level, as more iterations were included in the determination.

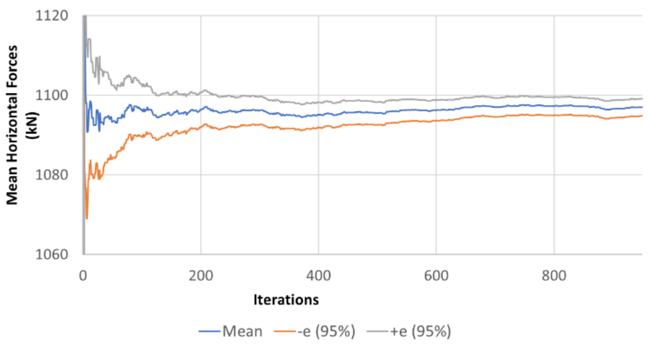

Figure 6. Case 1: Mean Observed Forces for a 25 millimeters Displacement.

Compared to the real scale load test, the mean observed for the model resulted in conservative values regarding the applied load for a 25 millimeters displacement, with a variation of about 10% less than the value observed in the real load tests. The observed standard deviation was around 2% of the mean value.

3.2 Case Study 2: Born [9]

The load test presented by Born [9] in his doctoral thesis aimed to evaluate the behavior of piles under static lateral loads. A set of 7 monitored piles embedded in residual soil was tested at the experimental field of the University of Passo Fundo, located in Passo Fundo, RS. The pile used in the modeling of this work was the one named C5, which has a diameter of 152.4 millimeters and an embedment depth of 3.79 meters.

The experimental field has a subsoil characterized by residual soil predominantly composed of Sandy Clay. For geotechnical characterization of the mass, SPT, CPTu, and SDMT tests were conducted. As it is a site for ongoing academic study, additional tests are available in the literature, such as triaxial tests and physical index tests.

Soil classification was carried out using the 5 available CPT tests, as shown in Figure 7, with the aim of verifying the behavior classification with depth and identifying the presence of more evident transition layers that may require distinct data treatment. The analysis concluded that the soil can be considered a single layer.

The adopted vertical and horizontal fluctuation scale values were 1.0 meters and 10.0 meters, respectively. The vertical fluctuation scale was obtained using the VXP (Expedited Method of Vanmarcke) based on the Dilatometer Test, while the horizontal fluctuation scale was defined with values in accordance with the literature.

The adopted value for the modulus of elasticity was obtained from the seismic test, which showed a mean of 212,929.72 kPa and a standard deviation of 90,580.52 kPa. The probability density function used was the lognormal distribution.

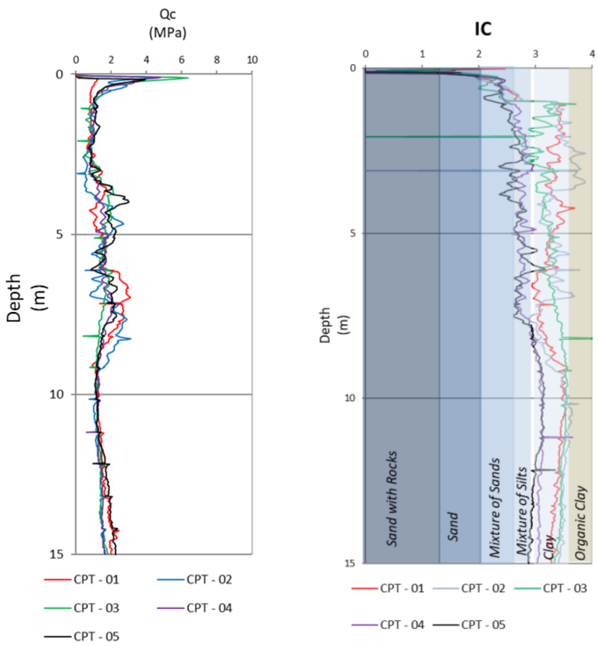

Figure 7. Soil Classification for Case of Study 2 by CPT Test and Robertson's [10] Classification Index.

A total of 1,197 iterations were performed based on the estimated soil data, with 512 iterations reaching stabilization. For each iteration, the force required to displace the top of the pile by 25 millimeters was recorded. The graph presented in Figure 8 shows the evolution of the mean observed forces at the top of the pile and the value of e, which represents the estimated error considering a normal distribution and a 95% confidence level, as more iterations were included in the determination.

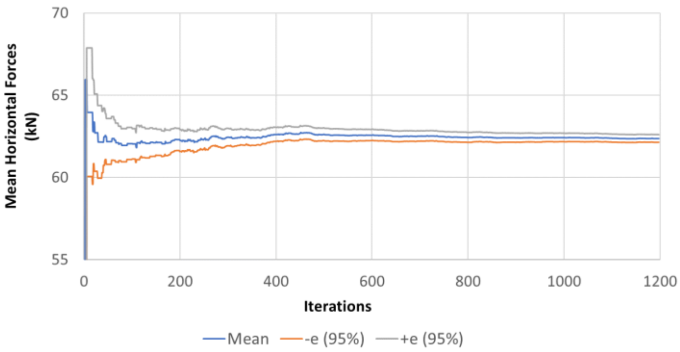

Figure 8. Case 2: Mean Observed Forces for a 25 millimeters Displacement.

The mean observed for the model resulted in values higher than those observed in the load test, concerning the applied load for a 25 millimeters displacement. A variation of approximately 17% higher in the mean was observed compared to the value seen in the real scale load tests. The observed standard deviation was around 4% of the mean value.

4 Conclusions

In this paper, the forces required to displace the top of the pile by 25 millimeters were estimated using Monte Carlo simulation, incorporating variable fields with the finite element method, in 2 case studies.

Regarding the estimates using stochastic methods, in Case 1, a round pile with 1.5 diameter and a depth of 31 meters, in silty soil, the estimates showed good adherence, diverged by approximately 10% from the real scale load tests, with a low standard deviation. In Case 2, a steel pile diameter of 152.4 millimeters and an embedment depth of 3.79 meters in clay soil, the estimates diverged by approximately 17% from the real scale load test, also showing a low standard deviation.

At the end of this article, we conclude that stochastic methods proved to be valid and can be used for this type of problem and in the location studied, provided that a small safety factor is considered.

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