Numerical Simulation and Parametric Analysis of Laterally Loaded Piles: Foundation of Tracker Systems

Naloan C. Sampa[1], Gabryel G. Soares[1], Gracieli Dienstmann[1]

[1]*Dept. of Civil Engineering, Federal University of Santa Catarina*
João Pio Duarte da Silva - 205, 88040-900, Santa Catarina, Brazil
naloan.sampa@ufsc.br, gabryel.soares@grad.ufsc.br, g.dienstmann@ufsc.br

Abstract. The need to generate more and more renewable energy has motivated the increasing installation of equipment in onshore and offshore environments in order to take advantage of sunlight, wind and sea waves. The foundation elements that support this equipment are designed to absorb not only axial loads but also lateral loads. This paper investigates, through a 3D numerical model in Abaqus, the effects of the loading and unloading cycle and the Young modulus of soil on load-displacement curves of laterally loaded piles. Two experimental lateral loading tests were used to validate the numerical model, and the results are satisfactory. The load-displacement curves were not affected by the loading and unloading cycle, but the elastic modulus of the system (k) decreases with the eccentricity. Furthermore, eccentricity influences the values of y_{res} and y_{Plas}, while Young's modulus of soil affects the load-displacement curves. The importance of these analyses in planning the lateral load tests and in interpreting the experimental results are presented and discussed

Keywords: numerical analysis, foundation, steel piles, lateral load tests, tracker systems.

1 Introduction

Among various renewable energy sources, solar energy has been growing in Brazil and currently occupies approximately 1.4% of the total renewable energy. In photovoltaic power stations, short steel piles of different profiles are widely used to support trackers and photovoltaic modules used to generate solar energy. The behaviors of these piles are usually investigated through lateral and axial compression and tension static load tests in order to ensure the safety and proper functioning of the photovoltaic modules afterward. In addition, it is also carried out loading and unloading cycles to characterize the elastic behavior of the system.

Concerning the desing of laterally loaded piles, previous experimental and theoretical studies have shown that the interaction mechanism and the load transfer of piles subjected to lateral loads depend on the pile cross-section dimensions, the pile material, the soil parameters, and the eccentricity. The most widespread methods were proposed by Matlock and Reese [1]; Hansen [2]; Broms [3 e 4] and others. Broms [3 e 4] have proposed equations and charts to estimate directly the lateral deflection at the ground surface and lateral capacity for long, short, unrestrained and restrained piles embedded in cohesive and cohesionless soils.

Although field tests are the most suitable and recommended means to obtain the p-y curves and analyze the behavior of laterally loaded piles, numerical modeling using FE is a versatile tool capable of modeling difficult geotechnical problems and has intensively been applied to simulate the behavior of piles under different loading conditions. When well-calibrated and represented, these models allow the performance of parametric analyzes to investigate the influence of several factors on the soil-pile interaction mechanism. Previous numerical studies developed by Desai and Appel [5], Desai and Kuppusamy [6] and Khodair and Abdel-Mohti [7], and others have discussed the interaction mechanisms, bending moments, load transfer and other relevant issues related to laterally loaded piles.

Previous works have contributed to the understanding of the laterally loaded pile-soil interaction, but more studies are required due to the increasing installation of equipment for onshore and offshore power generation - where wind loads act intensely. In particular, many issues related to the planning of lateral load tests and the design of short steel piles of tracker systems are still neither standardized nor fully understood, thus depending on suppliers and designers. In this study, an FE program was used to numerically simulate laterally loaded piles with and without load and unloading cycle, different eccentricities, and different Young's modulus of soil, to investigate their influences on the behavior of load-displacement curves in order to assist in planning the lateral load tests and in interpreting the experimental results.

2 Field Tests and Problem Definition

For the installation of a solar park with the capability to generate 741.9 MW of power and 1,500 GWh of energy per year, it is planned to install approximately 170,240 piles in an area of 754 hectares. To ensure the good performance of these piles and photovoltaic modules, a set of geotechnical tests, including Pull-Out Tests (POTs), were carried out. POTs comprise compression, tension, and lateral load tests on piles of I, C or Omega profiles. The soil profile consists of silty sand to clayey sand, with Nspt ranging from 9 to 50 blows in the first 4m and the length of the pile in earth (L) is equal to 3.3 m. The eccentricity (e) of the lateral load tests is associated with the configuration of tracker systems, varying between 0.4m and 2.0m. The horizontal displacement due to the applied lateral load is usually measured at point m located 10 cm above the ground surface through a dial height gauge comparator (Fig. 1). In addition, the design load applied on piles is specified by the product suppliers based on the structural analysis of these products, while ASTM D3966.07 and ASTM D3689.07 standards are used to define the load application time and the number of loading and unloading cycles.

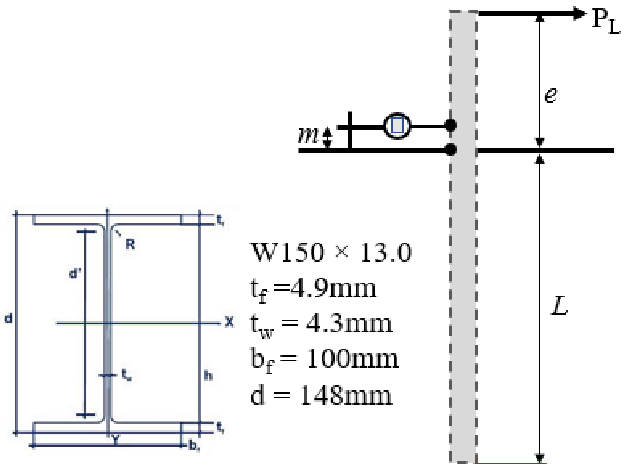


Figure 1. A schematic representation of a pile subjected to a lateral loading test

As acceptance criteria for lateral load tests results, the horizontal displacement at the design load must be less than or equal to 10mm, while the horizontal displacement at the Ultimate Limit State (ULS) must not exceed 25-30mm. Depending on the adopted factor of safety, the ULS load can vary between 1.5 to 2.5 times the design load. When the loading and unloading cycles tests were performed, the residual plastic displacement (y_{Plas}) at zero lateral loads should not be greater than 5 mm after unloading from the design load, and it should not be greater than 10mm after unloading from the ULS load.

This paper presents a numerical investigation performed in Abaqus to study the effects of loading and unloading cycles and Young's modulus of soil on the load-displacement curves. For the analysis, one loading and unloading cycle, five eccentricities and four Young's modulus of soil are considered. Firstly, the numerical model is validated based on the experimental results to allow future parametric analyses. The effects of the Young modulus and loading and unloading cycle on load-displacement curves are presented and discussed.

3 3D Finite Element Model

A 3D FE model to simulate lateral load tests, using the commercially finite element software Abaqus, is presented here. Due to the symmetry condition of the laterally loaded piles, a half soil domain of length 6 m, width 2.1 m and depth 7.5 m is modeled. This domain is large enough to avoid any significant boundary effects on calculated displacement, deformation and load. Refined meshes were used in the vicinity of the pile, regions of concentrated stress and strain. Fig. 2 shows the typical FE mesh of the numerical model. Concerning the boundary conditions, vertical displacement is allowed on all sides of the soil domain except at the bottom, where all displacements are restrained. The vertical plane of symmetry is restrained from any displacement perpendicular to it. The other sides of the soil domain are restrained from any lateral displacement through the roller supports, while the top boundary is free to displace. The pile is modeled with the same cross-section as those of commercial I profiles (W 150 × 13.0) shown in Fig. 1.

The pile was modeled as a rigid body and also as elastic-perfectly plastic material with Young's modulus of 210 GPa and Poisson's ratio of 0.2. The soil is defined as elastoplastic material obeying the Mohr-Coulomb failure criterion. The soil properties were calculated from the laboratory test results and SPT. The internal frictional angle is 37º, the dilatancy angle is 6º, the cohesion of 12.5 kPa, the bulk unit weight is 19 kN/m³, Young's modulus is 40 MPa and Poisson's ratio is 0.3. For the parametric analysis, the Young's Modulus of the soil are 20, 40, 60 and 80 MPa, while eccentricities are 0, 0.3, 0.6, 0.9, 1.2 and 1.5 m. Both materials, soil and pile, are modeled using the C3D8R solid homogeneous elements, which is an 8-noded linear brick element with reduced integration and hourglass control to overcome shear locking.

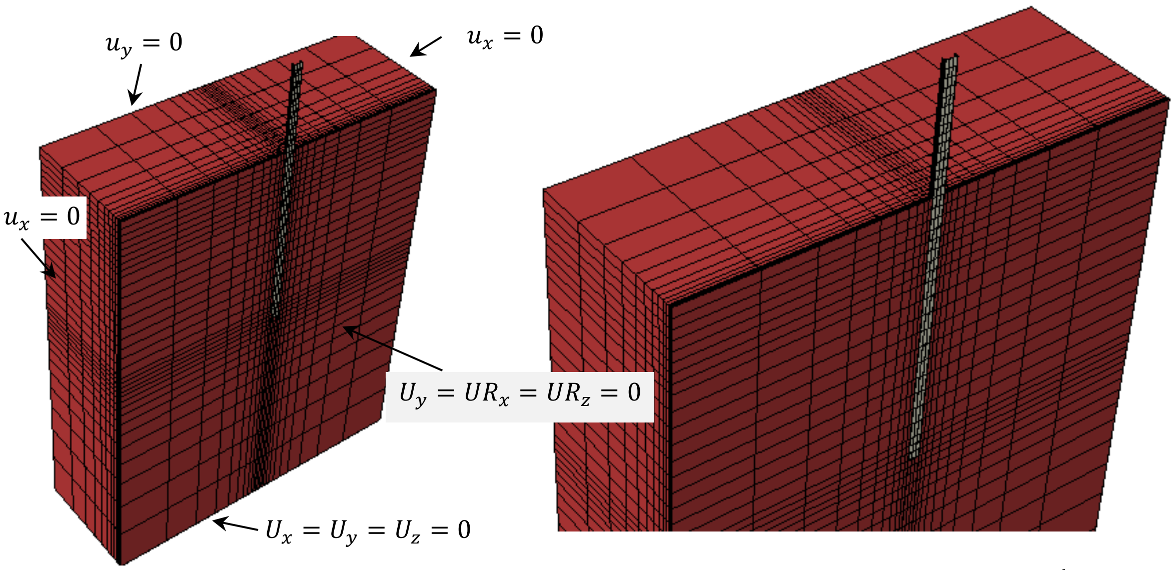


Figure 2. Representation of discretized finite element domain and boundary conditions (2nd case).

The contact surfaces between the pile and the soil are discretized using the surface-to-surface contact technique with the master-slave contact algorithm. Hard contact is assumed as the normal contact of all interfaces, and the shear contact between soil and pile is modeled as the Coulomb friction model. Among several expressions available to calculate the friction coefficient of the pile-soil interface, the expression $\left(\mu = \tan\left(\frac{2}{3}\phi'\right)\right)$ is adopted, where μ is the friction coefficient and ϕ' is the internal friction angle of the soil.

Numerical analyses are performed in three steps: a) body force option was used to establish the initial self-weight stress field on the soil domain, considering K_0 equal to 0.40 ($= 1 - \sin\phi'$), b) installation of the pile and c) application of the lateral load by a displacement boundary condition at the eccentricity. The maximum displacement applied was 0.1 m, based on the steel pile width ($b_f = 10$ cm). Horizontal displacements are collected at two points – 1) point *m* and 2) point located on the ground surface.

4 Results and Discussion

A series of full-scale field load tests were carried out to investigate the behavior of steel piles used as the foundation of the tracker systems. Results from two of these experimental tests with one loading and unloading cycle were used to calibrate the numerical model. Figure 3 shows a satisfactory agreement between the experimental and numerical curves for eccentricity of 1.2 m and Young's modulus of 40 MPa, thus validating the response of the numerical model and enhancing the reliability of this model for the application in the parametric studies. The following figures present only the main parametric analysis from the numerical results due to the limited number of pages.

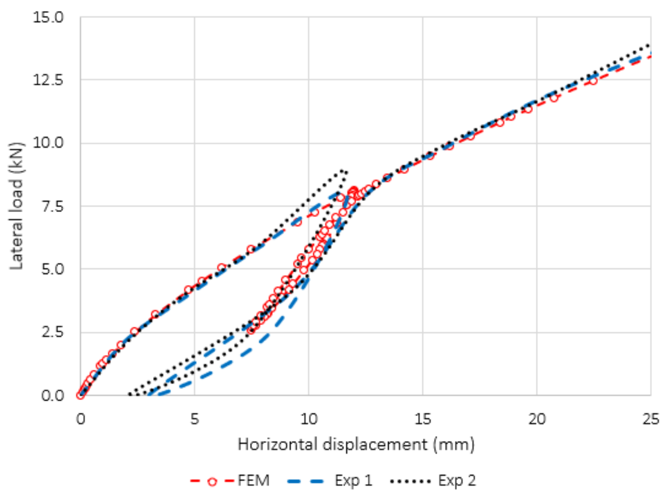


Figure 3. Comparison of FEM with experimental results

Figure 4 compares the load-displacement curves of monotonic tests with the curves of tests with one loading and unloading cycle, for different eccentricities. The horizontal displacements of the monotonic tests were measured at two different points: ground surface and point m = 10 cm. By the superposition of the curves, it is possible to conclude that one loading and unloading cycle does not affect the behavior of the load-displacement curves, and consequently does not change the interaction mechanism between pile and soil.

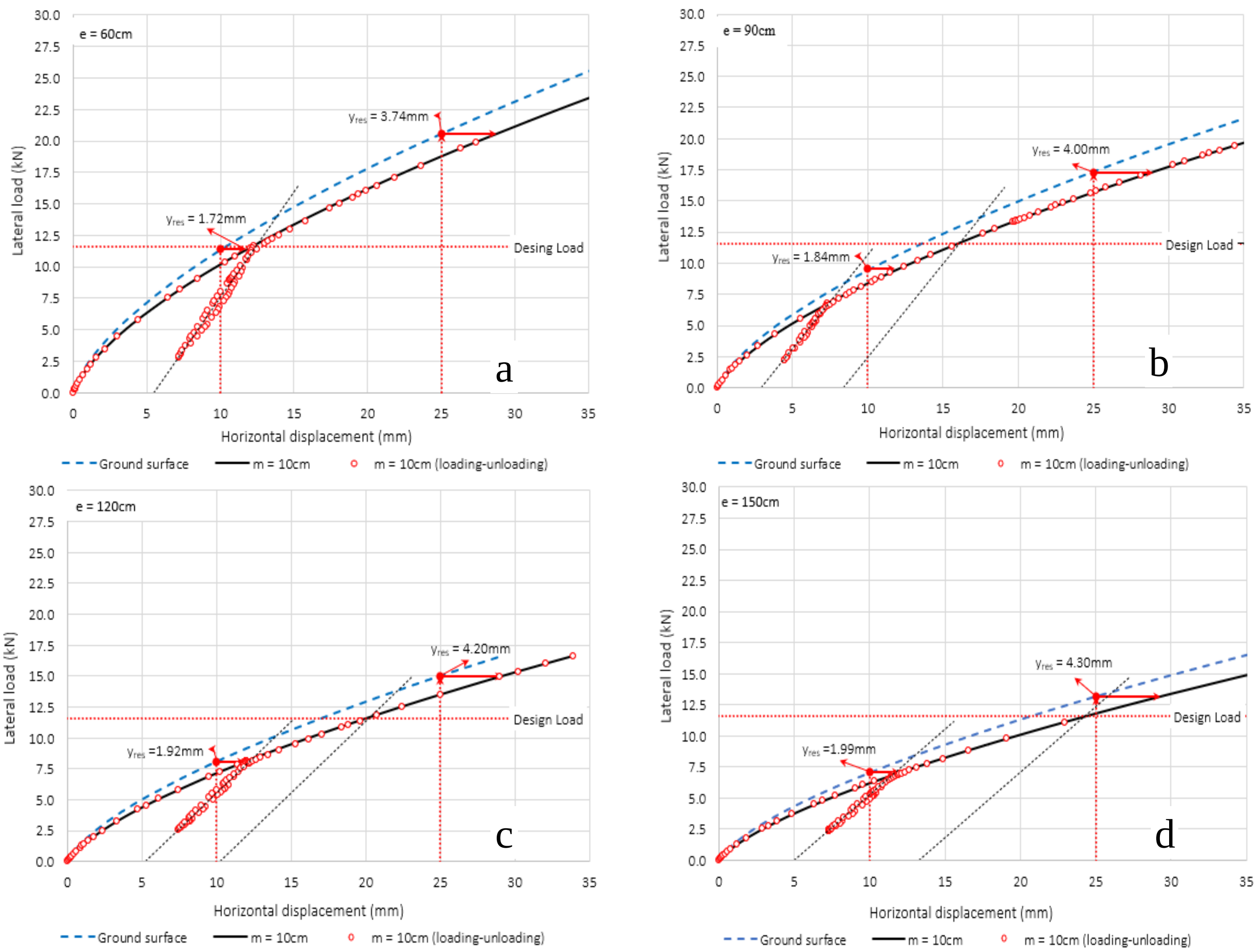


Figure 4. Load-displacement curves for monotonic and load-unloading cyclic tests

On the other hand, these curves show a significant change of the slope of the elastic section of loading and unloading - elastic modulus of the system (k) - with the eccentricity, i.e., the system rigidity is affected by the eccentricity. Extrapolating the linear section to the position of zero lateral loads provides the maximum expected residual plastic displacement (y_{Plas}), which increases with eccentricity. Comparison of the monotonic test curves for the same lateral load shows an increase in the difference of the horizontal displacements measured at the ground surface and at point m. This difference (y_{res}) increases with eccentricity, and can significantly influence the acceptance criteria of the lateral load test results. This topic has been extensively discussed in another paper.

In another perspective, Figs. 5a and 5b show a reduction in elastic modulus of the system (k) and an increase in residual plastic displacement (y_{Plas}) with eccentricity, respectively. Equations presented in figures described well the behavior of these curves, presenting a high R^2 value. The values of y_{Plas} for eccentricities lower than 1.2 m are smaller than 10 mm and satisfy the acceptance criteria of the tests for Serviceability Limit State condition.

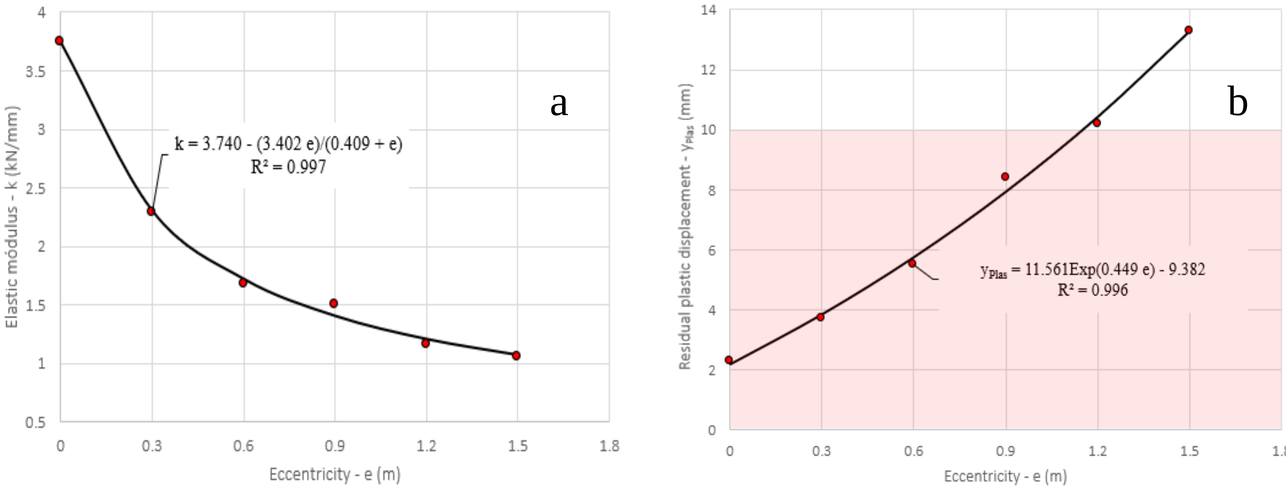
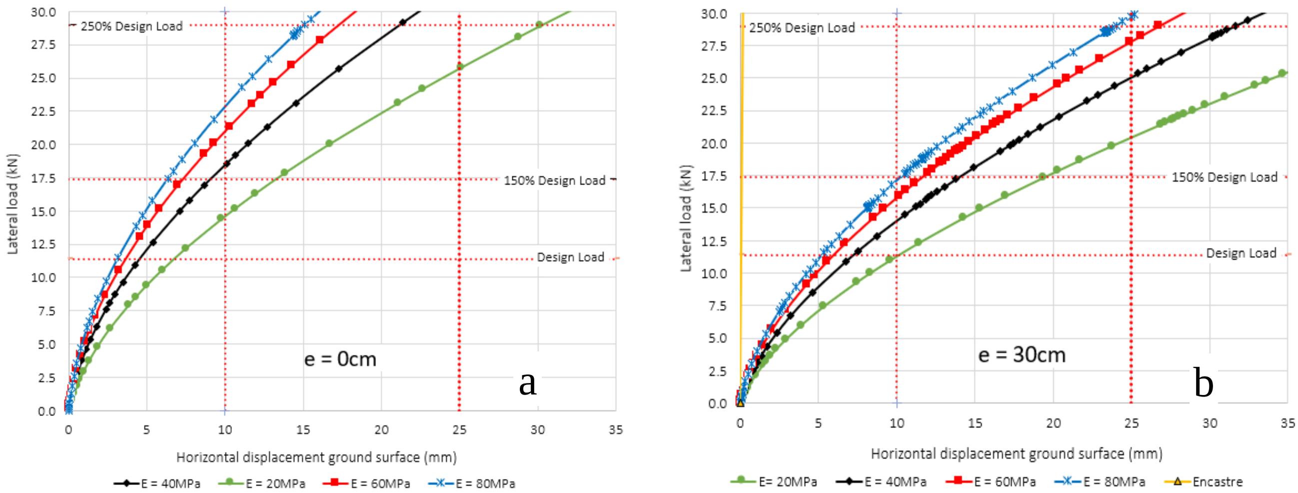


Figure 5. a) variation of the elastic modulus k with eccentricity, and b) variation of y_{Plas} with eccentricity.

The influence of Young's modulus of soil (E) on the behavior of the load-displacement curves is shown in Fig. 6, for different eccentricities. As expected, for a given lateral load, increasing the E decreases the horizontal displacement of the pile. Again, it can be observed that the criterion of 10 mm displacements for Serviceability Limite State (SLS) and 25 mm for Ultimate Limit State (ULS) tend to be satisfied at lower eccentricities. The eccentricity of 1.2 m (typical case) does not meet the criteria of displacements in both SLS and ULS, even for a higher E. The smaller the factor of safety adopted (1.5 or 2.5), the greater the possibility of satisfying the acceptance criteria established for the ULS at eccentricities smaller than 0.9 m.



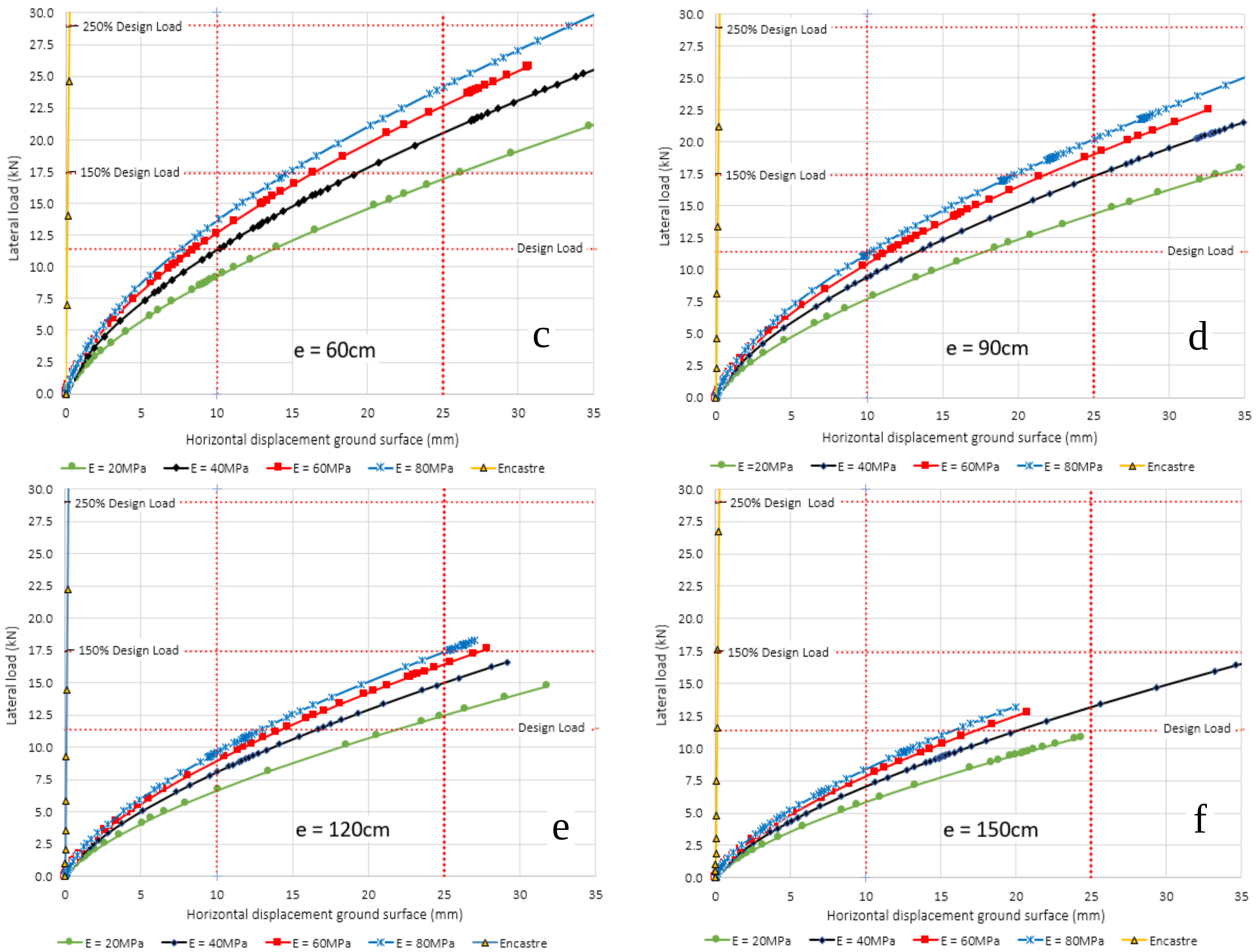


Figure 6. a) variation of the horizontal displacement with eccentricity, and b) variation of the lateral load with eccentricity.

Considering that the eccentricity depends on the configuration of the photovoltaic modules, increasing the stiffness of the soil around the piles seems to be an adequate solution to meet the displacement conditions imposed by the photovoltaic module suppliers. This can be seen in the crimping (encastre) curve shown in Fig. 6, which corresponds to the curve of the smallest possible displacements, involving only the pile deflection. The larger E is, the farther to the left the load-displacement curve goes.

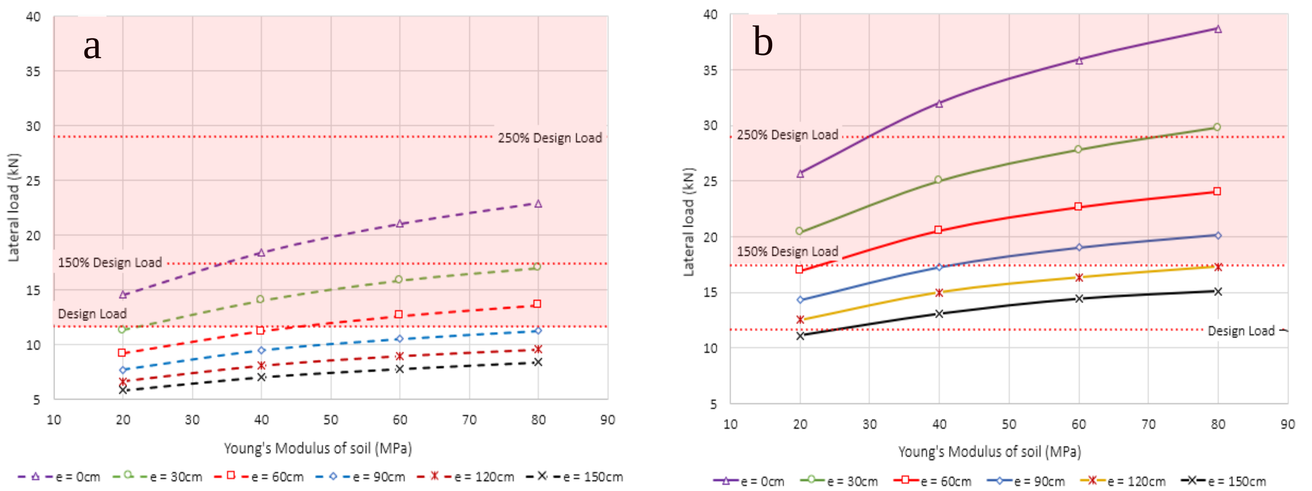


Figure 7. a) lateral load *versus* E for horizontal displacement of 10 mm, b) lateral load *versus* E for horizontal displacement of 25 mm

The influence of Young's modulus (E) on the lateral load can be seen in Figs. 7a and 7b for horizontal displacements of 10 mm and 25 mm, respectively. Both figures show a slight reduction of lateral load with the decrease of E. In Fig. 7a, it can be observed lateral load values higher than the design load only at eccentricities less than 0.6 m, while Fig. 7b shows lateral load values higher than 150% of the design load at eccentricities smaller than 0.9 m.

Topics, such as lateral soil resistance, bending moment, load distribution and the influence of the pile diameter on the load-displacement curve - of great interest for the understanding of the interaction mechanism between soil and piles subjected to wind loads are analyzed in other papers.

5 Conclusions

This paper investigates, through a 3D numerical model in Abaqus, the effects of the loading and unloading cycle and the Young modulus of soil on load-displacement curves of laterally loaded piles. Some conclusions drawn from the numerical analysis are listed below:

- one loading and unloading cycle does not affect the behavior of the load-displacement curves and consequently does not change the interaction mechanism between pile and soil. However, the elastic modulus of the system (k) decreases with the eccentricity.
- y_{res} and y_{Plas} increase with eccentricity, and their magnitude can significantly influence the acceptance criteria of the lateral load test results. For eccentricities lower than 1.2 m, values of y_{Plas} are smaller than 10 mm and satisfy the acceptance criteria of the tests for Serviceability Limit State condition.
- for a given lateral load, increasing the E decreases the horizontal displacement of the pile. For this reason, increasing the stiffness of the soil in the vicinity of the piles can be an adequate solution to meet the displacement acceptance criteria imposed by the photovoltaic modules suppliers.
- There is a slight reduction of lateral load with the decrease of Young's modulus of soil, for a given horizontal displacement.

Acknowledgements. The authors thank the Federal University of Santa Catarina for the infrastructure and financial support and the SETA-Araxá Consortium for the data and technical support during the development of this research project.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] H. Matlock, and L. C. Reese, "Generalised solutions for laterally loaded piles". J. Soil Mech. Found. Div., vol. 86, pp. 91-97, 1960.
[2] L. C. Reese, W. R. Cox and F. D. Koop, "Analysis of Laterally Loaded Piles in Sand". In Offshore Technology Conference, Proceedings…Texas, 1974.
[3] B. B. Broms, "Lateral resistance of piles in cohesive soils. Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, vol .89, pp. 27-63, 1964.
[4] B. B. Broms, "Lateral resistance of piles in cohesionless soils". Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, vol. 89, pp. 123-157, 1964.
[5] C. S. Desai, G. C. Appel, "3-D analysis of laterally loaded structures". Second International Journal Conference on Numerical Methods in Geomechanics, pp. 405–418, 1976.
[6] C. S. Desai, T. Kuppusamy, "Application of a numerical procedure for laterally loaded structures". Numerical Methods in Offshore Piling, pp. 93–99, 1980.
[7] Y. Khodair and A. A. Mohti, "Numerical analysis of pile-soil interaction under axial and lateral loads". International Journal of Concrete Structures and Materials, vol. 8, pp. 239 – 249, 2014.