Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-430

Discrete element modelling of centrifuge experiments on pile jacking

Modélisation par éléments discrets des expériences de centrifugation sur le fonçage de pieux

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ABSTRACT: The cyclic behavior of pile foundations is studied using the Discrete Element Method (DEM) through simulated centrifuge experiments. The centrifugal acceleration enables reproducing real-scale problems on reduced models, while DEM provides access to microscopic information on the particles-structure interactions. First, a discrete model based on spherical particles involving elasticity, friction and rolling resistance is calibrated against monotonic, drained triaxial tests to reproduce the behavior of Fontainebleau NE34 sand. Then, the cyclic response of the material is evaluated by means of cyclic triaxial tests. Finally, the model is applied to a quasi 2D simplification (semi-infinite plate with periodic boundary conditions) of the behavior of a pile foundation. After an investigation of the effect of sample size and boundary conditions, the study tests different pile jacking techniques, monotonic and cyclic strokes, exploring their impact on the total of the shaft and tip resistance of the pile. The importance of installation velocity is investigated for each technique. The geometry of future experiments in the geotechnical centrifuge is presented in this work and used as a basis for the numerical simulations. In conclusion, this research provides important information about the impact of different modes of installation on pile foundation behavior.

RÉSUMÉ: Le comportement cyclique des fondations sur pieux est étudié à l'aide de la méthode des éléments discrets (DEM) au moyen d'expériences simulées en centrifugeuse. L'accélération centrifuge permet de reproduire des problèmes à échelle réelle sur des modèles réduits, tandis que le DEM donne accès à des informations microscopiques sur les interactions particules-structure. Dans un premier temps, un modèle discret basé sur des particules sphériques impliquant élasticité, frottement et résistance au roulement est calibré sur des essais triaxiaux drainés monotones pour reproduire le comportement du sable de Fontainebleau NE34. Ensuite, la réponse cyclique du matériau est évaluée au moyen d'essais triaxiaux cycliques. Enfin, le modèle est appliqué à une simplification quasi 2D (plaque semi-infinie avec conditions aux limites périodiques) du comportement d'une fondation sur pieux. Après une étude de l'effet de la taille de l'échantillon et des conditions aux limites, l'étude teste différents types de techniques de fonçage de pieux, à coups monotones et cycliques, en explorant leur impact sur la résistance totale du fût et de la pointe du pieu. L'importance de la vitesse d'installation est étudiée pour chaque technique La géométrie des futures essais dans la centrifugeuse géotechnique est présentée dans ce travail et sert de base aux simulations numériques. En conclusion, cette recherche fournit des informations importantes sur l'impact des différents modes d'installation sur le comportement des pieux.

Keywords: DEM simulations; pile jacking; fontainebleau sand NE34; centrifuge modelling.

1 INTRODUCTION

Wind turbines play a significant role in the generation of renewable energy and have several important advantages. However, it is essential to recognize the challenges that arise throughout the implementation process. One technique that is often used for the installation of such structures is pile jacking. Applying quasi-static stress cycles to jack the pile in the ground is one method of installation. Studies on different techniques for pile jacking using centrifuge model testing are previously done by El Haffar et al. (2017); Blanc et al. (2019). Interesting results revealed a significant difference between piles installed at 1g and at 100g. Three times higher resistance in compression was recorded for piles jacked at 100g. Differences were also seen between piles jacked monotonically and those jacked cyclically (by a series of strokes). The tip capacity in compression decreased, while the pull-out capacity showed a clear tendency to increase with the increasing number of installation strokes.

Numerous studies have explored the effects of cyclic loading using discrete element method (DEM) (Cundall and Strack, 1979) simulations such as the work by Jiang et al. (2019); Zorzi et al. (2017), that studied the behavior of model sands during a cyclic triaxial loading path. Other studies have demonstrated the ability of DEM to model soil-structure interactions (Ciantia et al., 2019; Arroyo et al., 2011). Moreover, Zhang and Wang (2015) used DEM to simulate monotonic pile jacking at increased acceleration to simulate and compare with experiments in the geotechnical centrifuge.

The capability and constraints of DEM for simulating soil structure problems need to be fully explored through further research. For this purpose, this work studies the effect of sample and particle size as well as the installation speed on the response of a quasi-two-dimensionally simplified pile foundation installed under centrifugal acceleration, with monotonic and cyclic strokes. The geometry of experiments from the geotechnical centrifuge are shown as a basis for the numerical simulations that will later be used for similar experiments aiming to confirm the validity of the DEM model.

2 EXPERIMENTAL SETUP

The experimental setup of the centrifuge model, which is used as a reference for the simulations, is detailed in Figure 1. The setup comprises a container of dimensions 800x450x200mm with one transparent side made of plexiglass enabling the visual observation of the soil during installation followed by PIV analysis. To allow this observation around the pile as well as the comparison with the numerical model, a wall is taken as a quasi 2D pile of width 16mm, depth of 224mm and thickness of 200mm. Dry Fontainebleau NE34 sand is deposited in the container by air pluviation, aiming to achieve a relative density (D_r) of 68% up to a depth of 400mm. The material properties of NE34 are documented in Andria-Ntoanina et al. (2010).

During the tests, a centrifugal acceleration of 25 times gravity is applied. The model wall is installed at a velocity of 0.1 mm/s. Both the wall and the soil are instrumented with sensors to measure the total stress exerted within the system during the tests.

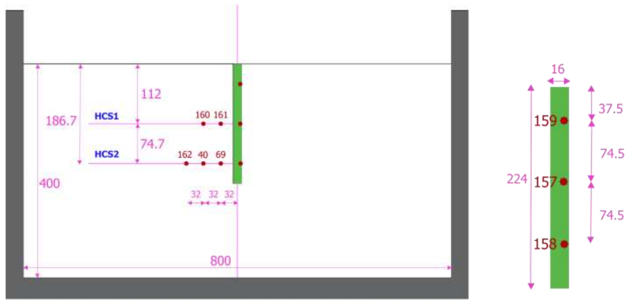

Figure 1. Experimental setup showing the model wall and the positions of total stress sensors in the sand and on the wall shaft.

3 DEM MODEL

A quasi 2D model pile is installed in a material that is calibrated to reproduce the behavior of NE34 using YADE, an open-source software developed by Kozicki and Donze (2009). The numerical model used is a classical linear contact law with Mohr-Coulomb plasticity surface and a moment that resists rolling to account for real particle shape when using spheres. The model description and calibration process are found in Ezzeddine et al. (2023), while the parameters used are presented in Table 1.

Table 1. Calibrated parameters of the contact model.

E (MPa)	α	φ (°)	α_r	η_r	Density (kg/m^3)
500	0.3	24	0.1	0.4	2650

The sample is generated with periodic boundary conditions on the horizontal directions and a rigid wall serving as a boundary at the bottom of the sample depth while keeping a free surface at the top. To enhance computational efficiency, the particle size distribution of NE34 is multiplied by a scaling factor denoted as "*F*". Particles are initially generated within a confined box and left to settle under the influence of gravity. Once they settle and the forces stabilize, a sample of dimensions *L*, *w*, and *h* is prepared as shown in Figure 2. In order to be able to obtain samples with different values of initial porosity, the inter-particle friction angle φ set in YADE is decreased during the preparation process to obtain denser samples.

4 PILE JACKING SIMULATIONS

In order to establish sample boundaries that effectively mitigate any finite size effects, a systematic investigation is done, examining the influence of sample dimensions and particle size.

Samples with varying *L* and *F* are generated at a constant $\varphi = 10°$ during preparation. φ is then changed

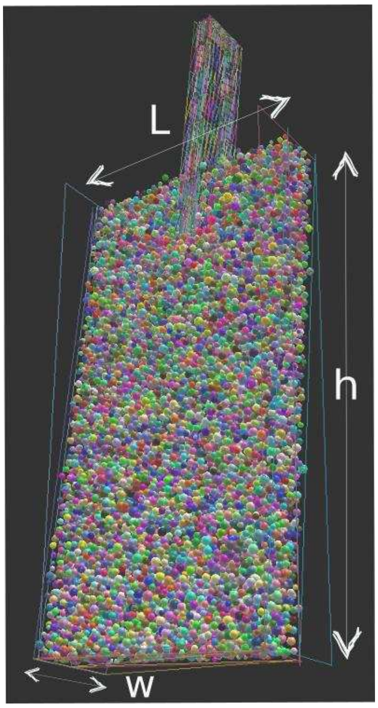

Figure 2. Numerical sample dimensions and boundaries.

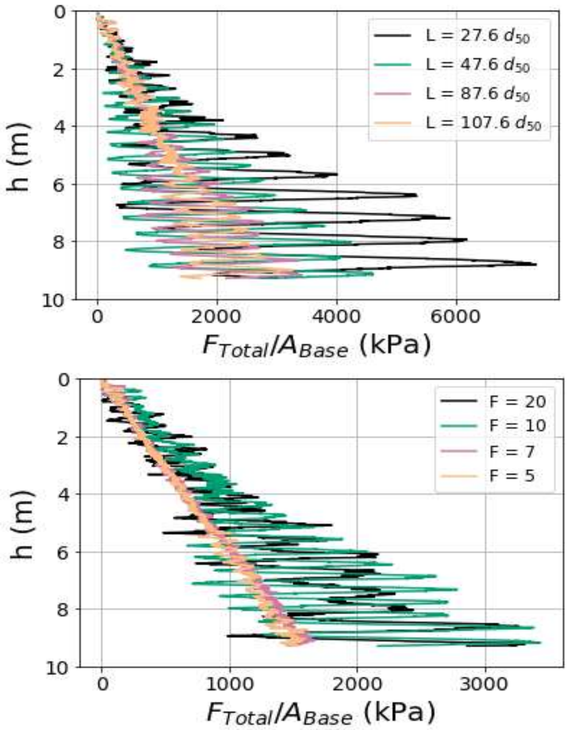

Figure 3. Total normalized force on the wall with depth for varying a) normalized length L/d_{50} b) factor F.

to its calibrated value in Table 1. The resultant average porosity of the sample is maintained at 0.44. The model wall has a width of 16mm, depth 100mm and is infinite on the periodic direction *w* whose value is taken as the width of the sample $10d_{50}$. To select an appropriate value for *w* two values, $10d_{50}$ and $20d_{50}$, are initially examined and found to give close results. It is then installed at a velocity v_p such that the ratio of inertial forces to confining forces is $I < 10^{-2}$ for quasi-static conditions (Janda and Ooi, 2016), under an acceleration of 100g, effectively simulating conditions similar to those in a centrifuge experiment. Results are compared in terms of total (tip and shaft) unit resistance to assess the influence of each variable. The results are presented in prototype scale. The total force is normalized by the area of the tip to obtain the unit resistance.

4.1 Effect of dimension *L*

Four values of *L* are compared: L/d_{50} = 27.6, 47.6, 87.6, 107.6, where *F* = 10 and d_{50} = 2.1mm. The results are shown in Figure 3, where it is evident that in the sample with the smallest dimension *L*, the distance between the walls within the periodic sample is insufficient to avoid their interaction, leading to noticeable fluctuations in the results. As *L* increases, these fluctuations diminish. Furthermore, it can be observed that the effect of *L* on pile resistance is more pronounced at greater depths, owing to the fact that the zone of influence of the pile extends with increasing depth. The test with L/d_{50} = 87.6 seems to avoid any significant boundary effects while maintaining a reasonable computational time Let's denote this value of *L* as «L_1» in further analysis.

4.2 Effect of *F*

Additional tests are done keeping L_1 and varying *F* = 5, 7, 10, 20 to investigate the influence of particle size on the pile's response. Strong fluctuations are seen for *F* = 10, 20. With the decrease of *F* from 10 to 7, a variation of the pile to grain size ratio shows a clear influence on the behavior. When further decreasing *F* to 5, no effect is seen.

4.3 Effect of v_p: monotonic and cyclic strokes

The sample with L_1 and *F* = 7 constituting of 249254 spheres is selected as the reference configuration for the subsequent tests. Three values of jacking velocity (v_p = 0.1, 0.5, 1 m/s) are compared for two cases: monotonic installation and by strokes of 10 mm (1 m prototype scale). The effect of the velocity in the monotonic case is only noticeable at the starting point. It is clearly more crucial for the installation by strokes, where the high fluctuations seen for v_p = 1 m/s, particularly at higher depths decrease but stay visible at v_p = 0.5 m/s, and diminish at v_p = 0.1 m/s. This suggests that, in cyclic jacking, conditions that are more restrictive may be imposed on the criterion for choosing the velocity than in monotonic loading, since jacking by subsequent strokes can induce important force fluctuations.

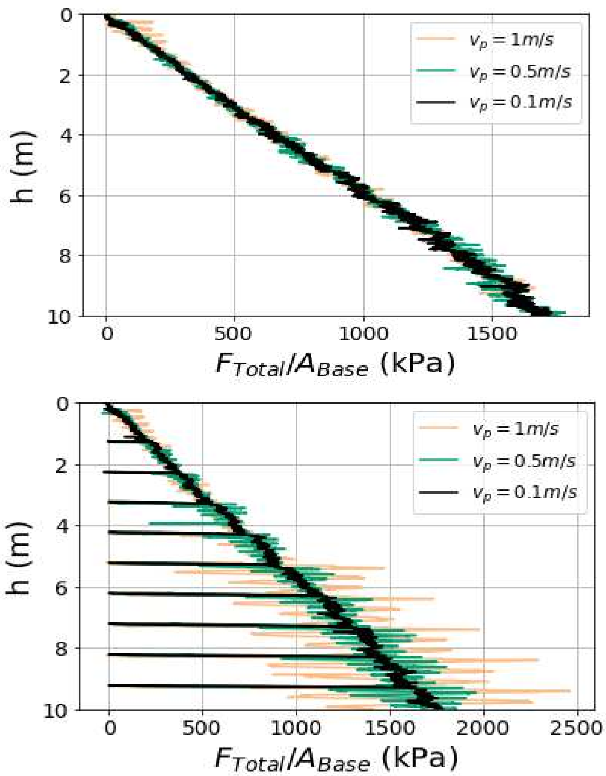

Figure 4. Effect of velocity on the total normalized force on the wall with depth for a) monotonic b) cyclic case.

5 CONCLUSIONS

In this study, the installation of pile foundations is investigated through simulated DEM centrifuge experiments. A simplified 2D representation of a pile is modelled and the effect of model and particle size on the behavior of the quasi 2D model during installation are explored. After deciding on the suitable model dimensions, the effect of jacking velocity on the pile's resistance is checked for the monotonic and cyclic jacking techniques. This work aims to explore the effect of various parameters on DEM's ability to simulate complex geotechnical soil-structure interactions. In the very next future, numerical simulations of the jacking and pullout of the model pile, with the parameters identified in this work, will be performed and compared to the corresponding centrifuge model tests.

ACKNOWLEDGEMENTS

The authors would like to thank the high-performance computing centre of Pays de la Loire (CCIPL) and the European project GEOLAB for their valuable support during the course of this research. The acknowledgments are further extended to Gustave Eiffel University and the Region Pays de la Loire for their financial support through thesis grants.

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