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Numerical investigation on induced liquefaction during monopile installation by vibratory driving in a 1G scale test

Etude numérique de la liquéfaction induite lors de l'installation d'un monopile par battage vibratoire dans un essai à l'échelle 1G

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ABSTRACT: The successful deployment of Offshore Wind Turbines (OWTs) requires fast, low- cost, reliable and environmentally friendly foundation installation methods. Vibratory driving, which is an attractive alternative to impact driving, has recently showed great potential in real-world applications. However, the knowledge about its effects on soil properties, and thus on the response of OWTs during the installation of monopiles is still limited. This study focuses on investigating the soil liquefaction which occurs in the vicinity of the foundation during vibratory monopile driving, in a 1G scale test. The combined approach of a vibratory driven pile in the laboratory, by introducing pertinent scaling laws, and the use of a numerical model to simulate the scale model in the laboratory is adopted. The findings from the numerical model provide insight into liquefaction initiation and progression and highlight the potential and limitations of linear models.

RÉSUMÉ: Le déploiement réussi d'éoliennes offshore (OWT) nécessite des méthodes d'installation de fondations rapides, peu coûteuses, fiables et respectueuses de l'environnement. La conduite vibratoire, qui constitue une alternative intéressante à la conduite par impact, a récemment démontré un grand potentiel dans les applications réelles. Cependant, les connaissances sur ses effets sur les propriétés des sols, et donc sur la réponse des OWT lors de la pose des monopieux, restent limitées. Cette étude se concentre sur l'étude de la liquéfaction du sol qui se produit à proximité de la fondation lors du battage vibratoire d'un monopieu, dans le cadre d'un essai à l'échelle 1G. L'approche combinée d'un pieu battu vibratoire en laboratoire, en introduisant des lois d'échelle pertinentes, et l'utilisation d'un modèle numérique pour simuler le modèle réduit en laboratoire est adoptée. Les résultats du modèle numérique donnent un aperçu de l'initiation et de la progression de la liquéfaction et mettent en évidence le potentiel et les limites des modèles linéaires.

Keywords: Monopile foundation; soil liquefaction; vibratory driving.

1 INTRODUCTION

Offshore wind power is a key component in the transition towards a more sustainable energy future. Despite the effectiveness of the predominantly used impact hammering for monopile installation, it poses challenges like noise pollution and concerns over pile durability, which makes vibratory driving an interesting alternative. Vibratory driving uses a high-frequency vibrator that transmits vertical vibrations to the monopile. These vibrations can increase the pore pressures in the vicinity of the driven foundation, resulting in reduction in the inter-particle soil friction, and thus, a decrease in effective stresses, which can lead to liquefaction. While vibratory driving offers a fast, environmentally friendly alternative, there is insufficient knowledge regarding its effects on the evolution of the mechanical properties of the soil, which control the (long-term) response of the OWT systems. In this regard, there has been an increasing interest in studying the development of liquefaction during the installation process (Chrisopoulos et al. 2019; Esfeh and Kaynia 2019). Most efforts use non-linear models, while the application of simpler linear model is limited (Zhang et al. 2012).

This study is structured to present first a scaled 1g test in the laboratory followed by the linear numerical model used to calculate the force imposed on the pile and hence the soil-pile response to the applied force. Then, the model's ability to simulate pore water pressure development corresponding to liquefaction is assessed. Finally, conclusions from the study are presented.

2 PHYSICAL MODELING

The laboratory setup employed is based on the system initially developed by Holeyman et al. (Holeyman 2017; Jafari 2020) and is modified to meet our research needs. The current set up consists of a drop weight (ram) which is attached to a rope and a pulley system, and an anvil. The pile is kept in position using a centring rod and lateral supports. The pile is a hollow steel cylinder of external diameter D = 6 cm, length L = 50 cm and wall thickness t = 6 mm. The pile is driven in a saturated homogeneous sand of unit weight γsat =1920 kg/m^3, and relative density Dr = 68% that is representative of the densities of the soils met in the North Sea. The sand is placed in a steel container of inner diameter D_{box} = 110 cm, inner height H_{box} = 125 cm and thickness t_{box} = 2 mm. The relative density of sand is controlled using a sand pluviation system which allowed relatively homogeneous sand samples to be generated. The acceleration and hence the force imposed on the pile is measured using a 10000g accelerometer. Scaling laws required for down-scaling the applied force by a vibrohammer are adopted as explained byMazutti et al (Hein Mazutti et al. 2022) which designed a mini-vibro hammer for centrifuge testing. However, since we are considering a 1g test,the forces are scaled by a factor of $1/N^2$.

3 VIBRATORY DRIVING MODEL

Herein a sub-structure approach is adopted: (i) the pile-soil system (pile and sandbox) is modeled using an axisymmetric finite element (FE) model to provide the pile head stiffness; and (ii) the calculated pile head stiffness is implemented in the Hybervib analytical model (Holeyman and Whenham 2017) to obtain the dynamic force imposed by the vibratory hammer. The force is then applied on the pile head using the FE model to conduct the drivability analysis. Within the framework of the analytical model, the harmonic force exerted by a vibro-hammer F_r working at frequency ω is defined as the mass of the eccentric masses me, multiplied by their corresponding acceleration.

$$F_r = me\omega^2 \sin(\omega t) \tag{1}$$

However, this model is extended to account for the displacement of the vibratory block m$_b$ that constantly moves during the driving process. This is achieved by defining the total displacement of the system u_m as the relative displacement of the rotating masses u_r and the displacement of the block u_b:

$$u = u_r + u_b = e \sin \omega t + u_b \tag{2}$$

The different elements of the model are shown in Figure 1 in which the rigid pile is represented by its dynamic stiffness k^*.

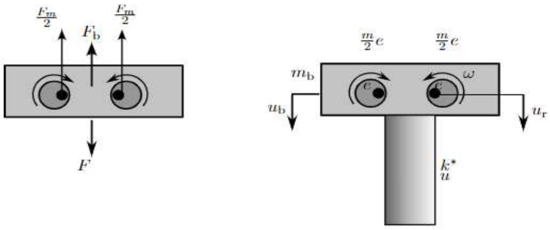

Figure 1. Schematic representation of the different elements of the vibratory driving model.

Hence, the total force exerted by a vibrohammer F is the summation of the force F$_r$ and the force by the block F$_b$, which is defined as the product of the mass m$_b$ and its acceleration $\ddot{u}_b$.

$$F = F_r + F_b \tag{3}$$

And in the frequency domain is,

$$k^*\hat{u} = me\omega^2 + m_b\omega^2 \tag{4}$$

where $\hat{u}$ is the pile head displacement at in the frequency domain, which is function of the dynamic stiffness of the rigid pile. Hence, this is computed initially and then followed by solving the system of equations of motion of the rigid system to compute the displacement.

The numerical implementation is done in MATLAB using the toolbox Stabil (François et al. 2021). The pile and the soil, which reflect on the setup, have been discretized using 2-noded line elements and 4-noded quadrilateral elements, respectively. The mesh size has been determined based on a 10-elements-per-wavelength rule.

Figure 2 shows the wave propagation in the sand box for a selected amplitude of the applied force at a frequency equal to 1000 Hz which is representative of real scale driving at 25 Hz, using the proposed FE model. As shown in the figure, Rayleigh waves at the surface lose energy and attenuate with distance. Surface waves (C_s = 140 m/s) along the depth of the pile continue to propagate horizontally with a wavelength big enough to be fully captured in the system. P-waves, which travel at a faster speed (C_p = 280 m/s), are seen as a standing wave in the pile and propagate in radial direction below the pile. In order to mitigate reflections at the edge of the box, a 2 cm thick damping layer from rubber material is proposed whose effect is shown in figure 2.

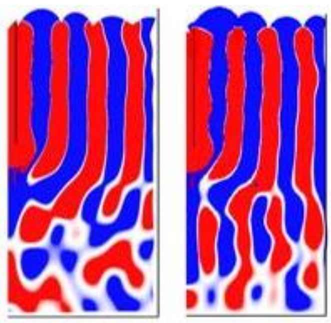

Figure 2. Animated representation of the wave propagation in the axisymmetric sand box model with a damping layer (left) and without a damping layer (right) at 1000 Hz.

4 LIQUEFACTION POTENTIAL

To evaluate the potential for liquefaction, the scheme described in (Seed 1971 and Towhata et al. 2008) is adopted. The strains within the soil are determined from the nodal displacements, leveraging the use of finely discretised transfinite mesh elements. The stress-strain relationship of the soil adheres to Hooke's law allowing us to employ a material stiffness matrix **D** that relates stresses **σ** to strains **ε** in the axisymmetric finite element model using the soil's modulus of elasticity E, and Poisson's ratio, ν:

$$\begin{Bmatrix} \hat{\sigma}_{rr} \\ \hat{\sigma}_{\theta\theta} \\ \hat{\sigma}_{zz} \\ \hat{\tau}_{rz} \end{Bmatrix} = \begin{bmatrix} 1-\nu & \nu & 0 & 0 \\ \nu & 1-\nu & 0 & 0 \\ 0 & 0 & 1-\nu & 0 \\ 0 & 0 & 0 & 0.5-\nu \end{bmatrix} \frac{E}{(1+\nu)(1-2\nu)} \begin{Bmatrix} \epsilon_{rr} \\ \hat{\epsilon}_{\theta\theta} \\ \hat{\epsilon}_{zz} \\ \hat{\epsilon}_{rz} \end{Bmatrix} \tag{5}$$

The stresses (all in kPa) obtained in the radial $\hat{\sigma}_{rr}$, circumferential $\hat{\sigma}_{\theta\theta}$ and the longitudinal directions $\hat{\sigma}_{zz}$ are used to calculate the maximum cyclic deviatoric stress exerted on the soil element, $\hat{q}$ where:

$$\hat{q} = \tau_{cyc} = \sqrt{3\hat{J}}_2 \tag{6}$$

and

$$\hat{J}_2 = \frac{1}{6}[(\sigma_{rr} - \sigma_{\theta\theta})^2 + (\sigma_{\theta\theta} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{rr})^2 + \sigma_{rz}^2] \tag{7}$$

This shear stress is then utilized to compute the Cyclic Stress Ratio (CSR), which is defined as the ratio between the shear stress and the effective vertical stress σ'$_v$:

$$CSR = \frac{\tau_{cyc}}{\sigma_v'} \tag{8}$$

Subsequently, the relative excess pore pressure r_u, which is equal to the ratio between excess pore pressure Δu and initial effective vertical stress σ_v' is employed as described by (Seed and Rahman 1978, Meijers 2007).

$$r_u = \frac{\Delta u}{\sigma_v'} = \frac{2}{\pi} \arcsin\left(\frac{N}{N_{liq}}\right)^{\frac{1}{2\theta}} \tag{9}$$

In which N is the applied number of cycles, equivalent to the frequency, N_{liq} is the required number of cycles to cause liquefaction and the empiral parameter θ = 0.7 is chosen (Seed and Rahman 1978, Meijers 2007). N_{liq} is calculated from the relationship proposed by (Rahman and Jaber 1986).

$$CSR = 0.44aN_{liq}^{-b} \tag{10}$$

in which b = 0.2 and a=0.44.

Figure 3 illustrates the results obtained employing an in terms of deviatoric stress q, critical stress ratio (CSR), and relative excess pore pressure, the latter being essential for computing the excess pore water pressure induced during the pile driving process. An eccentric moment of 1.2x10^{-3} kg.m is employed which demonstrates both the impact and the necessity for a minimal mass. These findings show stress concentration beneath the pile while driving in addition to stress generation due to surface waves. The results also underscore the potential for soil around the pile, rather than within it, to experience liquefaction.

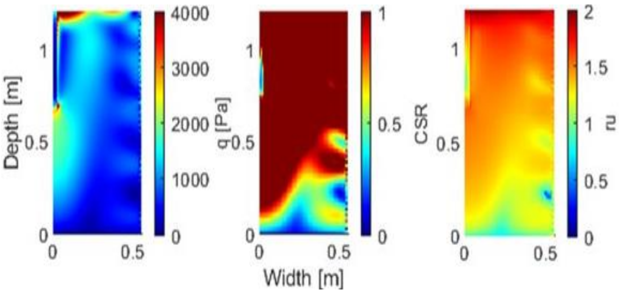

Figure 3. Variation of cyclic deviatoric stress q (left), the critical stress ratio CSR (middle) and the relative excess pore pressure r_u *(right) along the sand box depth.*

5 CONCLUSIONS

This paper presents an attempt to study induced liquefaction during vibratory pile driving with a focus on offshore applications. For this purpose, a a linear numerical model reflecting on an existing laboratory-scale experimental setup is employed. This is achieved by adopting scaling laws to obtain a vibratory hammer force. The results provide an overview of the wave propagation in the sand box, highlighting the need for adding a damping layer. Results in terms of cyclic shear stress development accounting for liquefaction phenomenon during driving, indicate the need to further investigate such mechanism using an equivalent linear approach.

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