







Design of Vibro-Driven Large Diameter Monopiles

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Abstract. A new trend in Offshore Wind, mainly for environmental reasons (reduced noise emissions), is the installation of piles in predominantly sandy soils with the vibratory method rather than with the traditional impact method. An innovative design methodology for vibro-driven open-ended steel large diameter monopiles is derived and already applied in a North Sea project. This methodology is based on the results of a large test site at Altenwalde (Germany), where the different behavior of fully vibrated monopiles compared to impact driven piles under lateral loading was investigated, and on model scale tests undertaken by TU Berlin, where dependencies incorporating the influence of installation parameters during vibratory driving and their influence on the pile behaviour due to horizontal loading of the pile after installation were determined.

Keywords: Vibratory driving · Vibro-driven monopile · Design monopile · Installation effect

1 Introduction

Large diameter monopiles is a widely used foundation solution for offshore wind turbines and platforms. The main loading situation of these usually open ended steel pipe piles is a cyclic lateral loading. Especially in sandy soils vibratory pile driving is a fast and economic method for the pile installation which has the additional benefit of being considerably more silent than the classical installation of the steel pile by impact driving. As current design methods generally consider impact driven piles, it is important to incorporate the vibratory installation effects into the design method.

During the last years, a number of research activities has been undertaken in order to better understand the effect of the vibratory installation on the lateral bearing behavior of a large diameter monopile, e.g. [1]. Based on the results of in situ tests and scaled model tests, as well as numerical simulations, an analytical procedure is conceptually described in order to take into account the installation effect in the pile design.

2 Experimental Investigation

2.1 Small Scale Model Tests

In this study, small scale model tests are conducted to investigate the cyclic and monotonic behavior of the monopile independent on the installation methods. The tests were performed in a steel container with a base dimensions of 1.70 m by 0.90 m and a height of 1.15 m. On the bottom of the container, a drainage layer of 0.25 m was placed (Fig. 1). The sand was prepared using dry pluviation technique. After the filling, the sand placed in the container was saturated from the bottom through the drainage layer. The model pile had an outer diameter of 20 cm and a wall thickness of 4 mm. Penetration of the pile up to 87 cm was tested. A system of guide rollers above the container ensured vertical penetration of the pile along the glass panel and restricted any tilt. In these experimental model tests, images of the soil movement were continuously recorded and these were then analysed using the method of Digital Image Correlation (DIC) [2]. This was possible by using only a half model, meaning that the test container only represented a halved version of a full container. The pile itself was semi-circular and installed along the glass panel which represented the cut edge of the container. Both pile walls were therefore visible through the glass (Fig. 1). This allowed a direct and continuous visualisation of soil movements during installation and loading without disturbing the soil itself through sensors or soil sampling. More details of the test set up are presented by Labenski et al. [3].

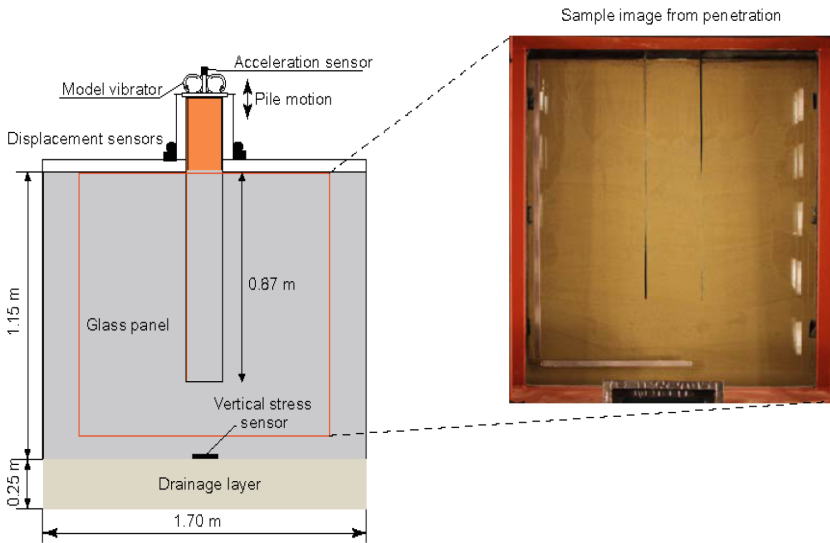


Fig. 1. Schematic view of the test set up with sample image of the glass panel [3]

Figure 2 left shows the deformation behavior of a vibratory pile under static horizontal loading. The lateral load was continuously increased. Unloading–reloading cycles were carried out at lateral loads of 0.9 kN and 1.8 kN. To consider the capacity of the

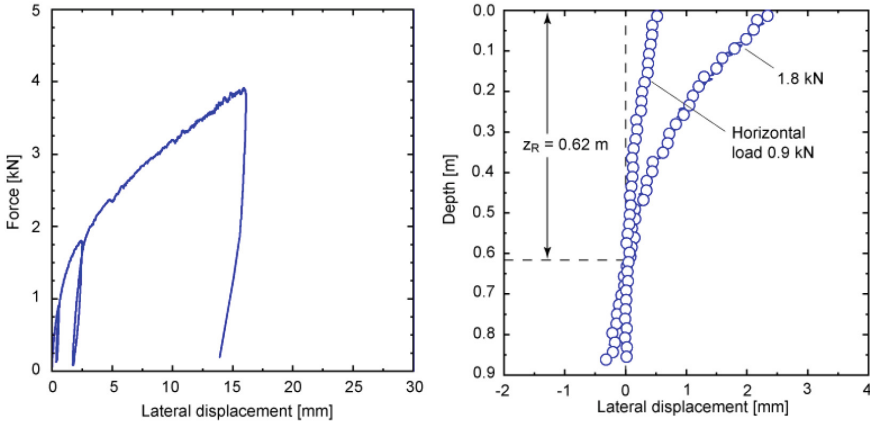


Fig. 2. Lateral load-displacement curves and deflection curves of the vibratory driving pile by dense sand ($I_D = 75\%$)

full-pile, the lateral load of the half-pile test was multiplied by a factor of 2 in the figure. This is valid due to the symmetry conditions of the half-pile model. It was observed that only relatively small lateral deformations occurred. At a lateral load of 1 kN, the lateral displacement equals a value of approximately 1 mm, corresponding to $0.005 D$. A lateral displacement of $0.1 D$ was reached at the maximum lateral load of 4.5 kN.

In Fig. 2 right, the lateral pile-bending curves of two different lateral load levels are shown. These curves from the model test are the results of the analysis of the digital image correlation. Images of the visible cut edges, were taken and the deformation of the pile itself quantified. The depth of pile rotation point, z_R , is equal to 0.62 m. This corresponds to 71% of the penetration depth, which is in accordance with the statement of Klinkvort and Hededal [4], stating that z_R approaches 70% with increasing lateral load, and the investigations of Li et al. [5], who obtained a range of $z_R = 73$ to 85%.

2.2 Large Scale Model Tests

In order to investigate the differences between impact-driven and vibro-driven piles with respect to their lateral capacity, large scale tests were conducted in predominantly dense, non-cohesive, saturated soil in the test site Altenwalde, located on the North Sea coast of Germany near Cuxhaven [6, 7].

Six open-ended steel piles of 4.3 m outer diameter and 21 m length were tested. The penetration depth of the piles reached approximately 18.5 m. The piles were tested in pairs; one pile was impact-driven and the other one vibro-driven.

A number of CPT tests were carried out at various distances from the piles before and after pile installation in order to measure the changes in the relative density of the soil due to installation. Moreover, load-displacement curves of the pile head during testing were recorded and evaluated.

The comparison of the various test results showed that under lateral loading the vibro-driven piles behaved weaker than the impact-driven ones with deflections between 24% and 58% greater, depending on the load magnitude.

A general conclusion of these large scale tests is that the design of vibro-driven monopiles in sand would require the application of reduction factors regarding stiffness. If, however, the installation process could be scheduled in a way that would lead to much less loosening of the surrounding soil, then a similar behavior to impact-driven piles could be expected.

3 Numerical Investigation

3.1 Installation Process

The design approach for vibro-driven monopile required extensive knowledge about the influence of pile penetration on the soil conditions. Additional to the various experimental investigations, numerical simulations were performed. On one side, with the numerical models, different parameters of the soil condition which are not able to be measured in the experimental model can be quantified (such as stress condition). On the other side, the experimental model tests are expensive and time consuming. In the study, only a limit number of tests could be realized. With the numerical models, effects of different parameters could be investigated in details.

The penetration of pile is one of the most complex processes from a soil mechanic point of view. The simulation of this process requires advanced calculation techniques which are able to handle large deformations of the soil due to penetration of the pile. At the same time, sophisticated constitutive model to describe the soil behaviour is necessary. In this study, the pile penetration process using vibratory and impact method was modelled. The theoretical backgrounds and details regarding numerical algorithms and procedures applied by MMALE technique were published in previous works by the research group at TU Berlin [8, 9]. The results used in the study and further details about the boundary conditions of the simulations were presented by Daryaei et al. [10].

3.2 Monopile Under Lateral Loading

For the investigation of the deformation behavior of the monopile under cyclic loading with consideration of the installation effects, different numerical approaches were developed. In the first study, a simple model with a loosening zone directly at the pile shaft and a compaction zone around was applied [11]. Using the results of the experimental model tests, the relative densities in these zones could be estimated. However, in this approach, only the change in density was considered. The influence of the pile penetration on the stress condition was ignored. To overcome this disadvantage, the simulation of the installation process was performed (Sect. 3.1). In a second calculation with a new model, the initial condition of the soil (distribution of the void ratio and stress) was adapted from the previous simulation. This numerical approach is a combination of two separate calculations, where both parameters density and stress condition were taken into account. The calculation concept with these two calculations and their boundary conditions, as well as several results are presented by Le & Rackwitz [12] in detail.

4 Design Approach

The design of a fully vibrated monopile in sandy soil requires the consideration of the installation effects in order to predict the loading behavior. Results of numerical simulations can be utilized to assess the installation effects and to develop and validate the design approach. As described above, numerical simulations are performed to simulate the installation and loading process of a large diameter monopile in order to determine the behavior of the pile under lateral load. Numerical simulations can generally be performed as an independent design approach but, since the computations require considerable effort, they are not suitable for a location specific design at each wind turbine position. Therefore, the here described analytical approach gives the opportunity to provide a relative quick statement of the loading behavior of a fully vibrated large diameter open end steel pipe pile based upon the site conditions, as well as installation and pile parameters.

Since the commonly used lateral soil support in terms of so-called p-y-curves was determined for impact driven piles, these approaches inherently encounter for the installation effect of an impact driving process. One of the most important parameters besides the soil type and the strength of the soil is the stress state, which plays a significant role for the stiffness of the lateral support. The vibratory and the impact driven installation methods are compared on the basis of radial stresses acting on the pile surface and in the vicinity of the pile after the installation. These stresses are determined in numerical simulations and are further utilized to alter the classical p-y-response in order to derive the behavior of a vibrated pile under lateral load.

Numerical simulations allow the determination of radial stresses around a pile installed by vibration or by impact driving. The resulting stresses are obtained at different radial distances to the pile axis. These stresses are put in relation to each other by the calculation of the ratio $\sigma_{\text{vib}}/\sigma_{\text{impact}}$ (radial stresses after installation) for each radial distance. In order to facilitate the interpretation of the results, the pile is subdivided into a specific number of segments (e.g. 2 m). Subsequently, the ratios $\sigma_{\text{vib}}/\sigma_{\text{impact}}$ that belong to one segment are averaged, so each segment has one representative value. At this point, the ratios $\sigma_{\text{vib}}/\sigma_{\text{impact}}$ are available for each segment and at different radial distances to the pile axis. These results represent the influence of the installation by vibration with respect to an impact driven pile for different radial distances and depths. Figure 3 below shows for example the vibration ratios of a 4 m diameter pile with an embedment length of 16 m, for two depths and different distances to the pile axis from a numerical simulation.

Considering that a p-y curve represents the response of the soil at any particular depth, it has to correctly represent the simultaneous response of the soil located at all different radial distances at that same depth. Since the soil closer to the pile is expected to have a greater impact on the lateral response than the soil located further away, a weighting function that decreases with radial distance is required. In order to obtain reasonable weighting functions, a finite element model is used. In this model, a horizontal displacement is applied at the mudline of the pile under consideration and deformation curves are obtained at each segment depths and radial distance. The results of these curves are normalized with the maximum deformation obtained at the outer pile diameter. The

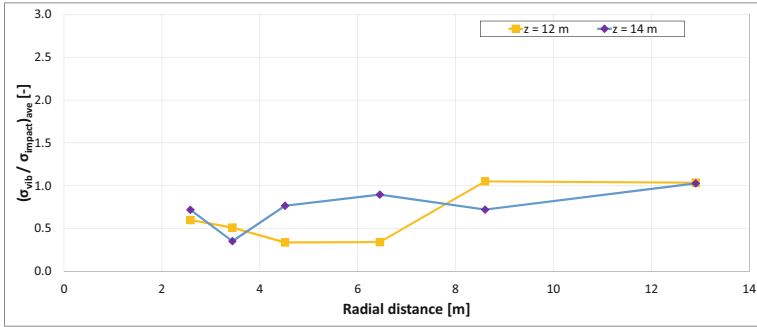


Fig. 3. Vibration ratios of a 4 m diameter pile from numerical simulations

following Fig. 4 shows an example of a weighting function at a specific depth derived from the 3D finite element model of a 4 m diameter monopile in sandy soil.

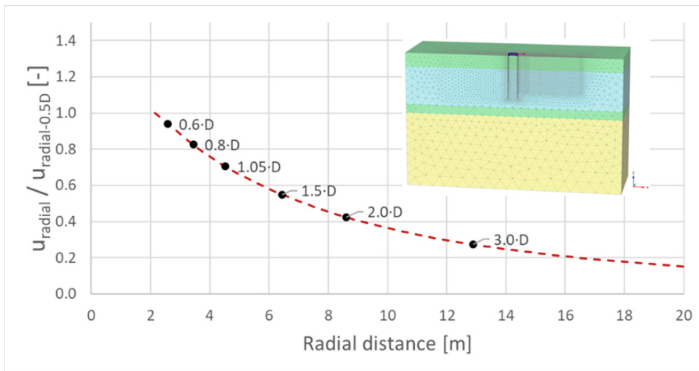


Fig. 4. Example of a weighting function derived from a 3D finite element model

These curves are used as the functions to compute a weighted average of the results of the $\sigma_{vib} / \sigma_{impact}$ ratios at different distances to the pile. By doing so, a vibration factor (VF) is obtained for each depth considered along the pile. The vibration factors represent the influence of the installation by vibration at each depth considered (with respect to a pile installed by impact driving).

For each depth considered in the analyses, $(p-y \text{ curves})_{impact}$ are determined according to general offshore practice, possibly with modifications for small strains and large diameters [13]. The $(p-y \text{ curves})_{vib}$ are determined by the same procedure, only that the general stress state is adjusted by determining an equivalent depth for each curve in a manner that the depth is multiplied by the corresponding vibration factor. The following Fig. 5 shows exemplary the vibration factors obtained by the prescribed procedure for a 4 m diameter monopile with 18 m embedment length.

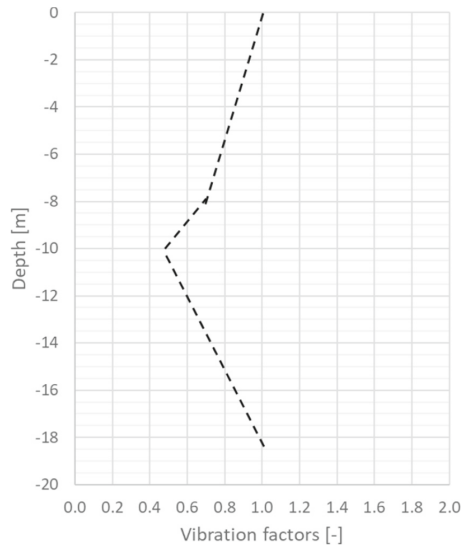


Fig. 5. Vibration factors of a 4m diameter pile from numerical simulations

5 Conclusions

Small scale model tests of vibro-driven piles in sand performed by TU Berlin, showed that only relatively small lateral deformations occur. In addition, the depth of pile rotation point, z_R , was found to correspond to 71% of the pile penetration depth, in accordance with literature references.

Large scale model tests conducted in the test site Altenwalde (Germany) showed that, depending on the load magnitude, vibro-driven piles under lateral loading behave weaker than the impact-driven ones with deflections between 24% and 58% greater.

A design approach for vibro-driven piles in sand under lateral loading is proposed here based on modifications by the so-called vibration factors of the p-y curves determined according to standard offshore practice for impact driven piles. Mathematical functions derived from 3D finite element models with site specific layers are used to compute weighted averages of the results of the $\sigma_{\text{vib}}/\sigma_{\text{impact}}$ ratios at different distances to the pile, in order to derive such appropriate vibration factors for each depth along the pile.

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