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Prediction of monopile driveability under vibratory driving using wave equation analysis

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ABSTRACT: One of the most well-known tools used in the industry, particularly for impact hammers, is the GRLWEAP software, which uses one-dimensional wave equation analysis to simulate the penetration process of a single pile into the ground. This paper presents the results of a case study on the prediction of vibratory monopile driving using GRLWEAP. The simulation of the driving process and the validation using measured data of a real offshore monopile during installation are described in detail. The simulation with GRLWEAP with CPT data from the site investigation show good agreement with the measured data from the installation. In the further part of the paper, the influence of the hook load on the driveability of the pile is investigated. Advantages and limitations of the method are discussed in detail.

Keywords: Installation process, Pile penetration, GRLWEAP, Driveability, Vibratory driving

1 INTRODUCTION

The process of penetration of piles has been one of the most complex and challenging aspects of geotechnical engineering. This process may encompass a multitude of complex soil mechanical phenomena, including liquefaction, fluidisation, cavitation, excess pore water pressure, friction degradation and plugging. For different conditions and types of soils, various installation methods can be applied (e. g. impact or vibratory driving, monotonic jacking and drilling). In offshore conditions, the most popular method is impact driving, where the pile is driven by impulse loads. In recent years, vibratory installation has emerged as an alternative approach for piling offshore foundations and to mitigate the risk of pile run. This method offers several advantages over impact driving, including reduced installation time and cost, as well as reduced stressing of steel during driving. Furthermore, underwater noise emissions can be decreased with the use of vibratory driving instead of impact driving. The fundamental differences between the mechanisms of impact and vibratory driving were discussed by Massarsch et al. (2022).

It is of great importance in the planning process and design stage to predict the driveability of the pile. For this purpose, several approaches have been developed. In general, driveability assessment methods can be categorised into four groups: (a) using empirical approaches or in situ measurement with back analysis (Massarsch et al., 2022; Westerberg et al., 1995); (b) using dynamics analysis (El Haffar et al., 2023; Holeyman et al., 2020; Holeyman & Whenham, 2017; Konstadinou et al., 2023; Rausche, 2002); (c) using large deformation numerical analyses such as CEL, ALE, MPM (Berki et al., 2024; Daryaei et al., 2020; Rackwitz, 2020), and (d) using machine learning (Alexander et al., 2024).

One of the most well-known tools which is mainly being used for the impact hammers in the industry is the software GRLWEAP, which employs the one-dimensional wave equation analysis to simulate the penetration process of the single pile in soil. However, the use of this tool for vibratory driving is still unusual. This paper presents the results of a case study using GRLWEAP to predict the drivability of vibratory piles. The simulation of the installation process of a large offshore monopile in sand is described in detail. Furthermore, the advances and limitations of this method are discussed.

2 GRLWEAP

The prediction of the pile penetration in the following sections are calculated with version GRLWEAP 14 Offshore. The programme is based on the one dimensional equation of waves propagating in the pile by an impact load. The whole system includes three separate components: the driving hammer, the pile and the soil (Figure 1). The pile is devided in several elements with usually 1 m length. These elements are coupled into a multiple mass-spring-damper systems.

Depending on the system and type, the hammer included assembly, drop weight or eccentric mass, helmet and cushions can be integrated in the model. The interactions and the effects of the soils are modelled with the system of linear elastic-plastic springs and dampers. Based on the site investigations data (CPT, SPT) or laboratory testing, the characteristics of the resistance of the ground during the driving process can be quantified (Byrne et al., 2018; Davidson et al., 2019; Qin et al., 2023, Yenigul et al., 2023).

This software can be used for the simulation of different types and geometries of piles such as timber, steel or concrete piles.

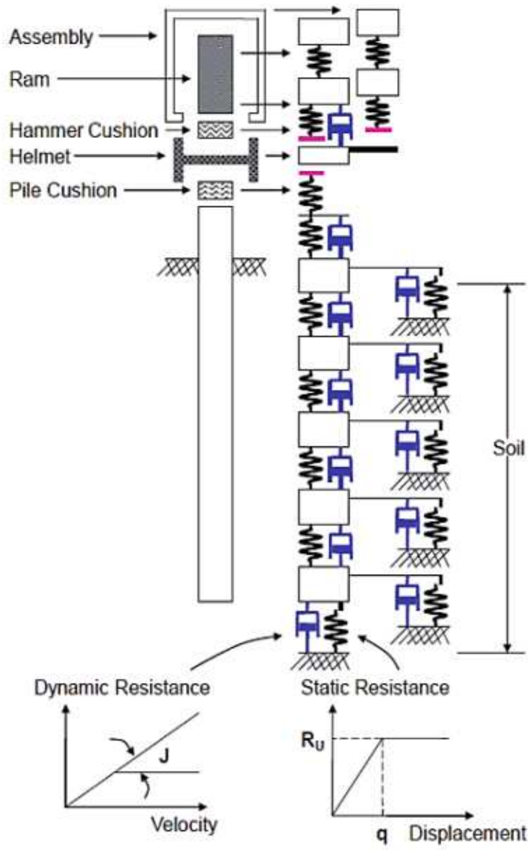

Figure 1. Schematic view of the model used in programme GRLWEAP (Pile Dynamics, 2021)

3 CASE STUDY OF A VIBRATORY INSTALLATION

3.1 Research Project VISSKA

The data used in this study were derived from the joint research project entitled: "*VISSKA - Measurement, modelling and assessment of vibratory pile driving in relation to installation, noise emissions and effects on harbour porpoises at an offshore wind farm*" (Berki et al., 2024). This project investigates the problem of underwater wave propagation during monopile installation. The aim of the project is to develop and validate a prediction model for the installation of monopile foundations using vibratory technology. Furthermore, the prediction model for the resulting underwater noise emissions is also a focus of the project.

The offshore project in the North Sea of Germany is one of the first offshore wind farms in the world using the novel installation method with vibratory driving. The wind farm consists of 38 turbines of 9 MW each, founded on monopiles. In the VISSKA project, seven of these monopiles are instrumented with several sensors for monitoring of different parameters using for the research. In this study, the installation of the pile at test location is investigated in detail.

3.2 Dimension of the monopile

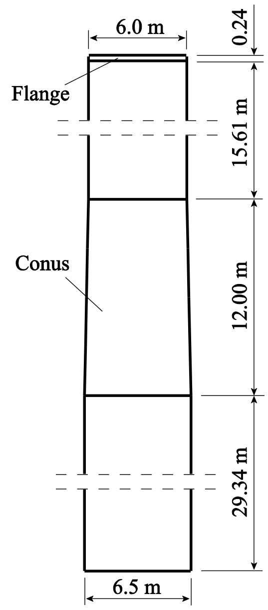

Figure 2. Geometry of the monopile

The monopile at the test location was instrumented and monitored during the installation. It has a conventional geometry (Figure 2). The pile is manufactured with 18 segments and has a total weight of 612.9 to and a total length of 57.19 m. The embedded part of the pile has a constant outer diameter D = 6.5 m. This diameter is reduced to 6 m with a conus section above the seabed. The wall thickness t of the pile varies from segment to segment with the smallest value at the tip. In the simulation of this study, the pile is modelled with four parts (Table 1). The thickness of each part is constant and it is calculated that the weight of the pile remains the same. The steel pile has a density of 7,850 kg/m³. The Young's modulus is 210 kN/mm².

Table 1. Geometry and weight of the pile.

Nr.	Segment	*L* (m)	*t* (cm)	*D* (m)	Weight (to)

1	1	0.24	32.8	6.0	11.0
2	2-5	15.61	7.1	6.0	162.5
3	6-9	12.00	6.6	6.0-6.5	121.5
4	10-18	29.34	6.8	6.5	317.9

3.3 Vibratory hammer

A vibrator hammer of the manufacturer CAPE Holland from type TRIBLE CV-640-VLT-U for flanged piles was used in the project. The hammer weighs 444 to including lifting frame and clamping system. The maximum working frequency is 23.3 Hz with a maximum eccentric moment of 18,836 kNm. The clamp system is suitable for piles with a diameter between 6 m and 7 m.

3.4 Ground conditions

An extensive site investigation programme has been carried out for the design and planning of the construction works. Five boreholes and several CPTs are distributed over the 17 km² area of the wind farm. In general, the soil profiles show mostly dense to very dense sandy ground. The first topsoil layer is normally identified as a mobile North Sea sand which consists in a range from silt to sand. The behaviour shall be like sand.

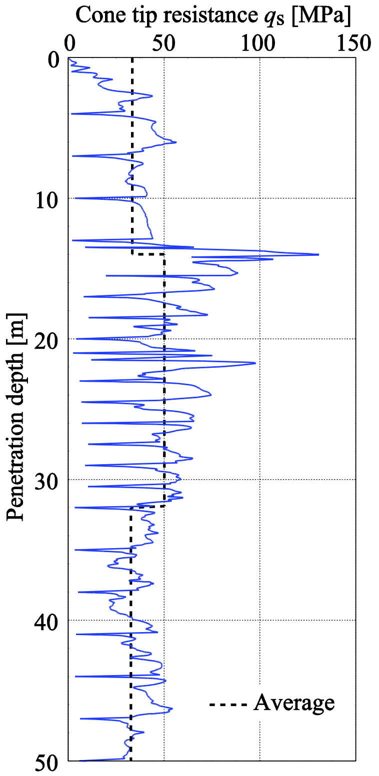

Figure 3. Results of the CPT at the test location and the estimated average values

Figure 3 presents the cone tip resistance of the CPT at test location. The investigation was carried out to a depth of 50 m. The evolution of the cone tip resistance shows that at a depth of 14 m there is a soil layer with a significantly higher stiffness. At a depth of 32 m, the resistance decreases and remains at a relatively similar level. For the simulation in this study, the average values of q_s were used. Up to a depth of 14 m, a value of q_s = 33.5 MPa is estimated. This value increases between the depths of 14 m and 32 m to q_s = 50.2 MPa. From 32 m, the average values is q_s = 32.7 MPa (Figure 3).

3.5 Installation process

The development of the pile penetration curve is shown in Figure 4. At the beginning, the initial penetration of the pile is 3,0 m (penetration under its self-weight and the weight of the hammer and clamps). The pile was kept vertical by the crane. During the installation, the load on the hook changes according to the penetration of the pile. At the observed location, the pile refused after approximately 30 minutes. The final penetration depth by vibratory driving was 17.25 m. The pile was then driven to the final depth of 26.8 m using an impact hammer. In this study, only the vibratory process is considered.

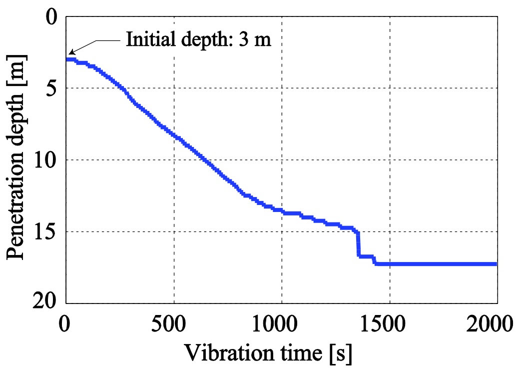

Figure 4. Installation process of pile: Penetration depth versus vibration time

4 SIMULATION OF THE PENETRATION

4.1 Ground model

In the programme GRLWEAP, different approaches can be used to calculate the shaft resistance and the bearing capacity of the pile-soil interaction. In this study, the standard A&H approach according to Alm and Hamre (2001) was applied for the calculation of the unit shaft and toe resistance. This approach required the CPT data from the site investigation. For the analysis of the monopile at observed location, the average cone tip resistances shown in Figure 3 were used. The sleeve frictional resistance is not required for the calculation of unit shaft and toe resistance by sandy soil in the A&H approach. The soil was assumed to be homogeneous sand layer with a submerged unit weight of soil of 10.5 kN/m³. The water table was 21.0 m above seabed.

In the analysis of the penetration process, the static resistance to driving (SRD) is evaluated according to the long term static resistance (LTSR). In the calculations presented in this paper, the standard setup analysis of GRLWEAP for estimation of SRD with constant setup factor of 5.0 was used. The shaft resistance during vibration was not considered (Gain/Loss factor for shaft resistance = 0). The calculations have the best fit with the factor for the toe resistance by 65 % (Gain/Loss factor = 0.65). A similar calculation procedure for the SRD was applied successfully by Konstadinou et al. (2023). In this study, the angle of friction between the pile and the soil is set by default to 28.6° (equivalent to 2/3 φ').

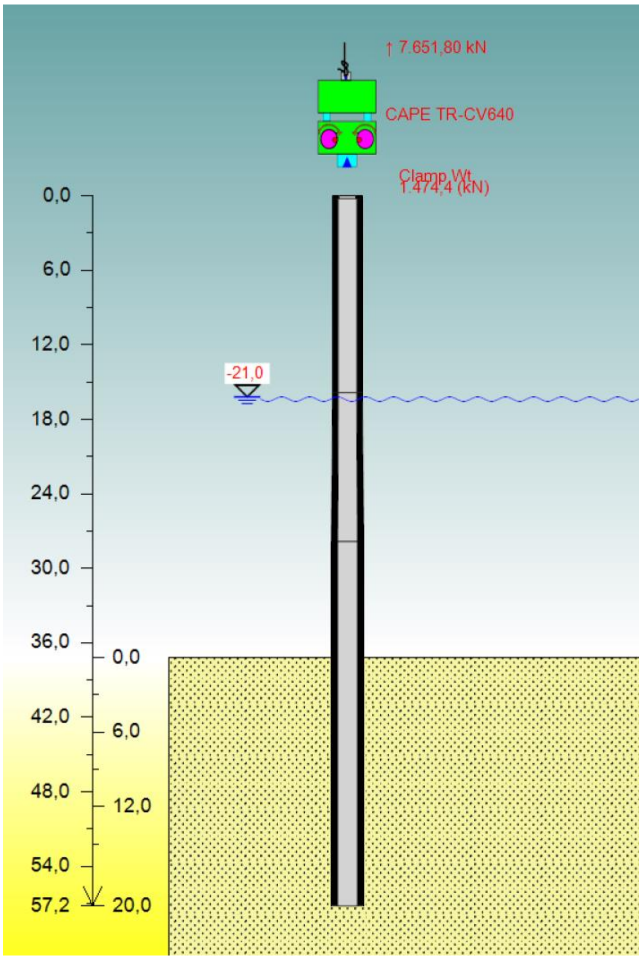

Figure 5. Schematic view of the model in GRLWEAP

4.2 Hook load and penetration curve

The development of the hook load is an important factor in the simulation of pile penetration. During installation, the hook load was continuously recorded with an additional load sensor on the vibrator. As an example, Figure 6 shows the hook load of the monopile at observed location. At the start of vibratory driving, the hook load is approximately 810 to. It changes continuously during the driving and reaches zero at the end of the installation. In the GRLWEAP analysis procedure, the hook load can be taken into account for each calculation step and can be inserted into the programme as a parameter. In the calculation in this study (Figure 5), the hook load was approximated with a constant value of 780 to (7651.8 kN), which is appr. 74 % of the total weight by pile and vibrator system.

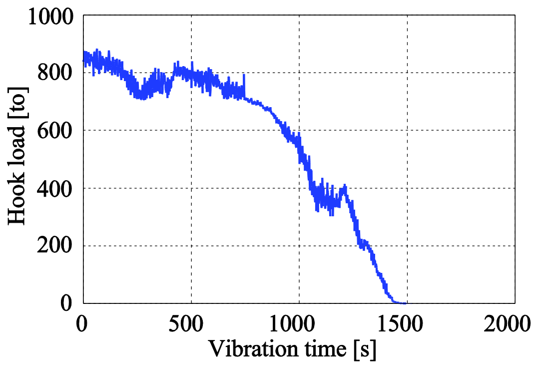

Figure 6. Hook load versus vibration time during the installation process

4.3 Vibratory driving

The vibration frequency in the simulation was set to 20 Hz as in the measurement via an acceleration sensor at the pile head. The efficiency of an impact hammer depends on several factors such as the type of hammer, cushions, pile material, pile inclination etc. This value varies from 0.5 to 0.95 for impact hammers. For vibratory driving, the hammer efficiency can be assumed to be 1.0 (Pile Dynamics, 2021).

The viscous rate effects, characterised by skin and toe damping values, contribute to increased soil resistance during pile driving and influence pile capacity and driveability (Maron & Delimi, 2022). However, accurate determination of these values remains challenging. The use of default values is therefore recommended. In this study, all simulations use the standard GRLWEAP damping values of 0.164 s/m for skin friction and 0.49 s/m for toe resistance.

The term "quake" refers to the maximum displacement of the pile, marking the limit at which the soil behaviour can still be considered elastic. A typical value is around 2.5 mm. This default value is recommended for both impact and vibratory driving and for all soil types, but it should be noted that it is not a fixed value. In this study, the default value resulted in an earlier refusal of the pile. For this reason, the skin and toe quake was adjusted to match the penetration. The input value for skin and toe quake is set at 0.25 mm.

The discretisation of the model is 1.0 m according to the segment length of the pile elements.

5 RESULTS

5.1 Validation

In this study, the calculation procedure and the model of the simulation in GRLWEAP were validated by the measured data in situ. Figure 7 shows the comparison of the simulation and in situ penetration curves. It can be seen that the simulation result is in very good agreement with the measured curves. The characteristic trend of the penetration curves in situ can be well modelled in GRLWEAP. In both the simulation and in situ, the pile refused after 17 m of penetration. At 14 m there is a characteristic change in the curve of the simulation. The curve shows a decrease in the rate of penetration. This is consistent with the change in stiffness of the soil layer observed from the CPT results (Figure 3). After 15 m depth, the pile in situ has a steep rise. This cannot be fully explained by the behaviour of the soil.

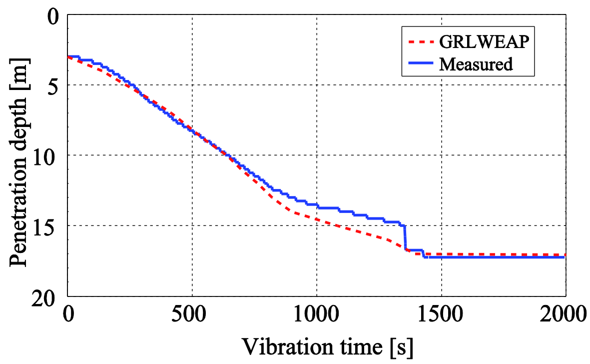

Figure 7. Comparison of the penetration curves

5.2 Influence of the hook load

During installation, the crane is used to stabilise the pile. The hook load plays in this process an important role in the driveability of the pile. In reality, the hook load is not constant. It varies with the movement of the pile and the depth of penetration as well as on manual handling (Figure 6). In the case of prediction at the design stage, the evolution of the hook load is usually unknown. In the simulation it has to be assumed as a constant value. The effects of the hook load have been investigated in detail in a parameter study. Figure 8 shows the results of simulations where the hook load is varied from 0 to 850 to. The graphs show that the higher the hook load, the slower the penetration of the pile. At a hook load of 850 to the pile does not move downwards. It hangs quasi on the crane.

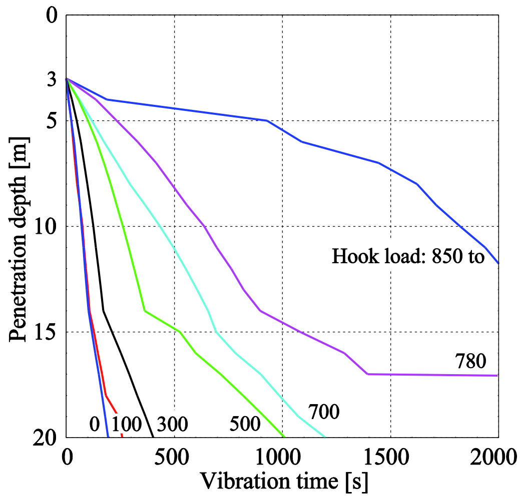

Figure 8. Effect of the hook load on the penetration process

6 CONCLUSIONS AND OUTLOOK

The study shows an example of modelling the penetration of a monopile under vibratory driving using GRLWEAP. The simulation was successfully validated using measured data from a real offshore project. The estimation of soil resistance based on CPT profile results using the A&H approach for estimation of the unit shaft and toe resistance in combination with the standard setup analysis for SRD gives a good result. The hook load plays an important role in the simulation. The higher the hook load, the slower the penetration of the pile. For the simulation, it can be assumed as a constant value for the whole installation process.

The method is commonly used for impact driving. Accordingly, there is a lot of experience with impact driving. For vibratory driving, it is lacking in several aspects, such as low and high frequency vibratory driving, behaviour of shaft resistance and end bearing capacity during vibrating, behaviour on different soil types. Further research is required in this field. There are several different approaches to estimating the static resistance by driving. A thorough investigation is required to understand their advances and limitations.

AUTHOR CONTRIBUTION STATEMENT

First Author: Methodology, Conceptual, Calculation with GRLWEAP, Writing the paper; second Author.: Methodology, Supervision, Reviewing and Editing, Ideator, Funding acquisition.

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