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A 1g model experimental study on the effects of installation parameters on vibratory driving performance of monopiles

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ABSTRACT: Monopiles are a common foundation type for offshore wind turbines. Compared with the traditional impact driving installation methods for monopiles, vibratory driving is a promising alternative with advantages of rapid installation, low acoustic noise emission and limitation of stresses during driving. However, uncertainties over vibration parameter effects on driving performance may prove a barrier to widespread adoption of purely vibration based installation. This paper presents preliminary 1g results of an experimental model investigation into these uncertainties. A series of preliminary 1g reduced scale tests were conducted to drive an instrumented model pile in dry medium-dense and dense sand. A mini vibration unit with exchangeable eccentric masses was used to install the pile. The frequency and the force generated by the vibratory driver can be controlled by changing the eccentric masses and electrical power supplied, in which the driving performance under different vibration controls was recorded. The preliminary results indicate that the ultimate installation depth and the driving velocity are influenced by the combined factors of frequency and driving force, and it appears that frequency plays a more significant role in determining installation performance.

1 INTRODUCTION

The global offshore renewable energy provision is expected to grow from 8.8GW in 2022 to 35.5GW in 2027 (GWEC, 2023). To date most of the foundations for offshore wind turbines have been monopiles in shallow water (Bienen et al., 2023). In Europe in 2020, over 280 monopiles were installed, constituting more than 80% of the newly installed offshore wind turbines (Wind Europe, 2021). The conventional installation method for monopiles is impact-driving where hammer blows are applied to the pile top periodically. This dynamic process may cause significant noise emissions and steel fatigue damage.

Vibratory driving provides a promising alternative for monopile installation with much lower underwater noise emission (Molenkamp et al., 2024) and potentially more rapid installation than the impact-driving method. Furthermore, the pile can be arrested, or the rate of penetration controlled during the whole vibratory driving process, minimizing the risk of pile run (Bienen et al., 2023). However, uncertainties over drivability assessment and the vibration parameter effects on driving performance may lead to pile refusal before reaching target depth and low penetration velocities. This knowledge gap may prove a barrier to widespread adoption of purely vibration based installation. To date, experience relating to vibratory pile driving is mainly restricted to onshore sheet pile installation (Massarsch et al., 2022), with experience for monopile installation being limited. Due to the lack of a reliable database of performance and drivability assessment, a vibratory driving prediction method fully recognised by the profession does not currently exist (Holeyman & Whenham, 2017).

Further investigations are required to gain insights into the effect of driving parameters on the vibratory monopile installation. It is a general opinion that the driving frequency has a significant effect on vibratory installation. Moriyasu et al. (2018) installed 6 full-scale tube piles with varying frequencies from 21 Hz to 100 Hz in field tests, obvious reduction of shaft and base resistance were recorded with increasing frequency, leading to a rapid installation to the target depth. The rapid penetration speed was also observed with higher frequency when driven H-section piles were installed in the field (Schönit, 2009). Hartung (1994) performed 1g model tests to investigate the driving frequency (ranging from 20 Hz to 50 Hz) influence on the resistance of pipe piles vibrated into sand. Both the toe and shaft resistance dropped at high frequency (> 30 Hz), and it was found that vibration at resonance frequency (22 Hz) increased the resistance to driving. Previous studies provide an insight into the frequency effects on pile installation processes, but the monopile installation performance including ultimate penetration depth and driving velocity require further investigation due to their large size and L/D ratios.

Driving force is another influential factor on vibratory pile installation performance (Viking, 2002). Nevertheless, the significance of the frequency and driving force of vibratory installation performance has not been fully discussed.

Field tests, physical modelling and numerical modelling offer three methods to investigate this topic. Numerical simulations have been attempted for vibratory installation (Daryaei et al., 2020; Machaček et al., 2021; Zhan et al., 2023), but the results may differ with the constitutive model selection and complex parameter tuning, which may lead to competing outcomes. Field tests can be extremely expensive and time-consuming, site investigations and element testing are required with limited data being generally reported in full scale tests (Achmus et al., 2020; Neef et al., 2013; Tsetas et al., 2023). Physical modelling offers a cost-effective and time-saving option with controlled and repeatable conditions. Several centrifuge tests (Bienen et al., 2023; Mazutti et al., 2022) and 1g model tests (Da Silva et al., 2023) have reported investigation of the bearing capacity of vibratory installed pile. Compared with centrifuge modelling, designing and constructing 1g model tests and apparatus is less complex and the scaling requirements for the dynamic factors are simple. They also prove useful for gaining an understanding of the problem and equipment needed before progressing to centrifuge development or larger scale testing.

This paper presents the preliminary results of vibratory installation in 1g model tests. A model tubular steel pile was driven into medium-dense and dense sand beds separately. The effects of installation variables on the ultimate driving depth and penetration velocity were investigated. The results provide further insight into the influence of different installation parameters in preparation for development of centrifuge vibro-driving equipment.

2 EXPERIMENTAL SETUP

2.1 Installation and testing facilities

A model scale vibration source (Figure 1) was developed for decommissioning offshore tubular piles with vibration by Davidson et al. (2017). A pair of counter-rotating eccentric masses (ERM) was driven by two identical Como Drills 719RE380 DC motors, which were controlled by a single speed regulator. The rotational speed of the two ERMs was proven to be consistent at various current levels. Modifications were made to the original design to allow use for pile installation. The lifting eye was substituted with a 3D-printed plastic platform to interface with the LVDT for displacement measurement. The threaded bar at the bottom was trimmed to accommodate connection with the load cell, which is shown in Figure 2. ERMs with various offset and weight were prepared to generate various centrifugal force and frequency during the tests, details of three sets of ERMs are shown in Table 1.

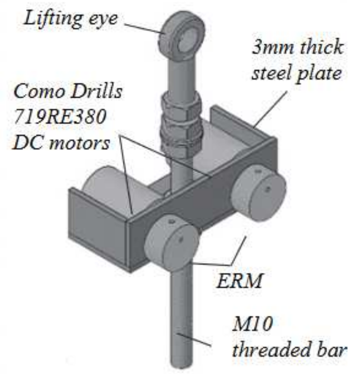

Figure 1. Schematic of the initial vibrator prior to modification. ERM = eccentric rotating mass (Davidson et al., 2017).

Table 1. ERMs property details.

Property	A	B	C
Radius (mm)	12.5	12.5	15.0
Thickness (mm)	12.0	6.0	6.0
Offsets (mm)	5.0	5.0	5.0
Weight (g)	51.6	25.7	33.6
Moment (mN·m)	5.06	2.52	3.29

** Radius and thickness are the dimensions of the ERM cylinder. Offset is distance between the centre of ERM to the centre of motor mounting hole.*

The vertical pile displacement was measured by LVDT position sensor, which interfaced with the platform in the top of the vibrator system (Figure 2). The pile and the vibratory driver were connected by an RDP RLT0100 load cell with a capacity of 981 N and the force generated by the vibrator was recorded as applied to the pile. An ADXL 377 triaxial accelerometer with ± 200 g testing range was attached on the pile to measure acceleration data. The sampling frequency of all the devices were set as 500 Hz in LabVIEW, much higher than the pile driving frequency. A 3D-printed guide frame was employed to ensure the pile remained vertical during installation. Polytetrafluoroethylene (PTFE) layers were inserted into the cylinders that the pile passed through in the guide to reduce friction. The tests were undertaken in a testing box with internal dimension of 500 × 468mm and 668mm deep. The distance between the pile and the box walls was $7.30D$, where D is the pile diameter. The separation between the pile tip to the box base was $10.07D$. Given these proportions, the influence of boundary effects can be considered negligible (Jeffrey et al., 2016; Robinsky & Morrison, 1964).

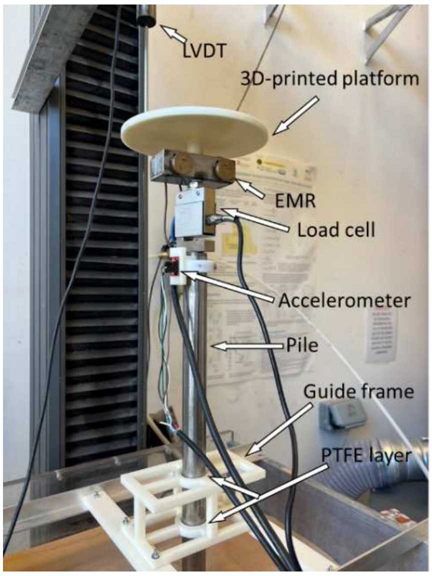

Figure 2. Experimental setup used for pile installation.

2.2 Soil and pile characteristics

Two scenarios of sand bed at relative densities of D_r=53% and D_r=80% were slot pluviated for the dense and medium-dense respectively. The sand used in all the tests was HST95, the properties of this material have been fully investigated in previuous studies at the University of Dundee (Al-Defae et al., 2013; Lauder et al., 2013), which is summarized in Table 2. Pluviation was undertaken using a slot pluviator with slot widths calibrated to give the required densities.

Table 2. HST95 sand material properties (Al-Defae et al., 2013; Lauder et al., 2013).

Property	Value
Effective particle size, $\boldsymbol{D_{10}}$ [mm]	0.09
Average particle size, $\boldsymbol{D_{50}}$ [mm]	0.14
Peak friction angle, $\boldsymbol{\phi'_{pk}}$, medium-dense [°]	40
Peak friction angle, $\boldsymbol{\phi'_{pk}}$, dense [°]	45
Critical state friction angle, $\boldsymbol{\phi'_{crit}}$ [°]	32
Sand–steel interface friction angle, $\boldsymbol{\delta'_{crit}}$ [°]	24
Angle of dilation, $\boldsymbol{\psi}$ [°]	16
Maximum dry density, $\boldsymbol{\rho_{max}}$ $[\boldsymbol{kN/m^3}]$	17.58
Minimum dry density, $\boldsymbol{\rho_{min}}$ $[\boldsymbol{kN/m^3}]$	14.59

** From peak strength relationship from direct shear tests for data at effective stresses between 50 and 200 kPa, at 80% relative density* (Al-Defae et al., 2013).

The model pile utilized in all tests was a stainless-steel open-ended tube pile with a length (L) of 560mm and an outer diameter (D) of 30mm, and a slenderness ratio (L/D) of 18.37. The wall thickness of the pile was 1.47 mm, a threaded bar was welded across the top of the pile to connect the pile and the vibro-driver rigidly. It was assumed that the average roughness of both the internal and external surfaces of the pile was uniform. The grain scaling effects need to be considered in model test. It is noted that this effect can be neglected when $D/D_{50} > 50$ for a model pile (Fioravante, 2002; Garnier et al., 2007). It is therefore assumed that no issues are caused by grain size effects because D/D_{50} was 214.

2.3 Testing programme

The pile was freely driven under vibration into medium-dense sand and dense sand. For test Group-MD in medium-dense sand, various current values were supplied to the motors without altering the ERMs, in which the ERM set B was adopted. The changes in current can change the rotation rate of motors, which results in the changing in installation parameters (frequency, force, acceleration, etc.). Group-D was tested in dense sand with consistent current input and different ERM sets A, B and C. When employing a single ERM set, the generated driving force grows with the increase of frequency. However, by utilizing various ERM sets, it is possible to achieve different combinations of installation parameters. In this way, the effect of single variable can be obtained. Frequency and driving force at different current levels for this vibrator have previously been investigated by Davidson et al. (2017), and these values were used in this study. The testing programme for the two groups is shown in Table 3.

Table 3. Summary of test programme.

Test ID	Power (w)	Sand bed	$\boldsymbol{f}$ (Hz)	$\boldsymbol{F_d}$ (N)
MD-1-B	7.7	MD	47	34.3
MD-2-B	12.9		69	63.2
MD-3-B	19.2		76	66.0
D-1-A	15.8	D	40	135.4
D-2-B	19.2		63	65.2
D-3-C	19.5		52	68.5

** f is the driving frequency. F_d is the driving force.*

Two installation parameters, frequency f and driving force F_d, were obtained by the load cell in the tests. Frequency f was deduced from Fourier transform of the force-time data. In terms of the driving force F_d , it can be defined as:

$$F_d = F_{ERM} + F_0 \qquad (1)$$

where F_{ERM} is the max centrifugal force generated by ERM rotation and F_0 is the static weight of vibrator and platform. As shown in Figure 3, the minimum downward force values were extracted from recorded force dataset, and the average was taken as the driving force F_d. Here, the force dataset from test MD-2-B between 80 ~ 80.3s was selected as an example.

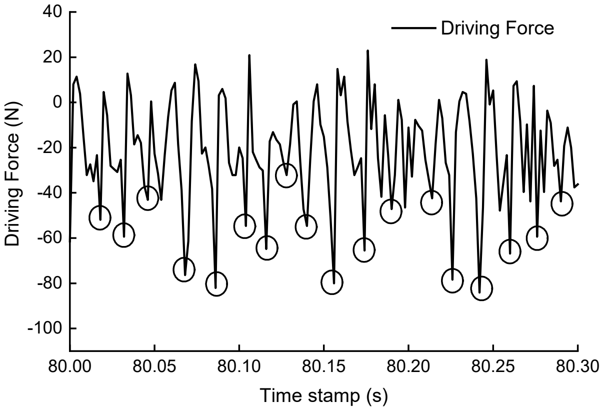

Figure 3. Selected dataset of driving force and frequency determination in MD-2-B (circular markers used for force determination).

3 RESULTS AND DISCUSS

The pile was installed by vibration into medium-dense sand in test Group-MD. The initial penetration or stab due to the self-weight of pile and vibrator system was approximately $z/D \approx 1.20$, hence the vibratory driving started from this point (Figure 4(a)). The ultimate penetration depth of MD-2-B ($z/D \approx 7.50$) and MD-3-B ($z/D \approx 7.90$) significantly exceeds that of MD-1-B ($z/D \approx 5.57$). Figure 4(b) shows the pile penetration velocity in medium-dense sand. For the three tests, rapid penetration happened down to $z/D \approx 3.2$ and slowed down gradually with increasing depth. The velocity of MD-2-B and MD-3-B are higher than that of MD-1-B, but there are only marginal differences between MD-2-B and MD-3-B, especially below $z/D = 5$.

Different ultimate driving depth and penetration velocity were exhibited in three tests in Group-MD. Compared with MD-1-B, a significant increase in both values is shown in MD-2-B and MD-3-B with 22Hz and 29Hz increase in frequency, respectively. In terms of MD-2-B and MD-3-B, slight differences can be seen with only a 7 Hz increase in frequency.

Figure 5(a) shows the penetration of pile installed in dense sand. The penetration depth due to self-weight was around $z/D \approx 0.6$. Test Group-D in dense sand was used with the identical current input and different ERM sets. Various driving frequency was used to complete the installation, resulting in distinct differences between the three tests in Group-D. Shallowest ultimate depth was recorded in D-3-C at $z/D = 2.54$, utilizing a frequency of 52Hz which was followed by D-1-A at $z/D = 3.87$ (frequency was 40Hz). D-2-B achieved the deepest driving depth at $z/D = 6.56$ with the highest driving frequency (63Hz).

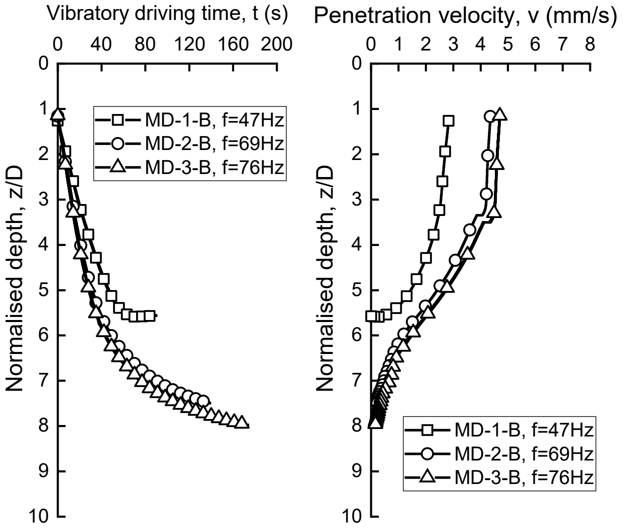

Figure 4. Vibratory driving in medium-dense sand: (a) Penetration; (b) Velocity.

The penetration velocity in dense sand is shown in Figure 5(b). The pile with D-3-C exhibited the highest penetration speed initially, but it rapidly diminished to zero at $z/D = 2.54$. The velocity of D-1-A was around $1.0\ mm/s$, but a fluctuation was observed before $z/D = 3$. The velocity of D-2-B maintained at $1.85\ mm/s$ until $z/D = 4.4$, after which it gradually declined to 0 mm/s. Apart from the initial phase, the velocity of D-2-B remained consistently high and stable for an extended duration with highest frequency at 63 Hz.

A clear trend is apparent that the increased frequency leads to deeper penetration and higher driving velocity in all the tests except D-3-C. This observation of penetration and velocity increase is in line with the experience of vibratory tubular pile installation onshore where the penetration performance had a strong dependency on the driving frequency where driving depth and velocity increase were recorded with the higher frequency (Hartung, 1994). Moriyasu et al. (2018) conducted a series of tubular pile installation field tests, where apparent reduction of shaft and base resistance was observed for higher frequency penetration (100 Hz) compared to that at low frequency (21 and 50 Hz), which lead to more rapid installation to the target depth. These results are also in line with H-beam vibratory penetration tests (Schönit, 2009). In terms of D-3-C, one reasonable explanation is that the pile oscillated at the natural frequency of the system and resonance happened, which led to amplified ground vibration and reduced pile penetration velocity (Massarsch et al., 2022). Similar situation happens in MD-1-B (47Hz) in medium-dense sand. More investigation is needed to analyse the natural frequency and resonant effects.

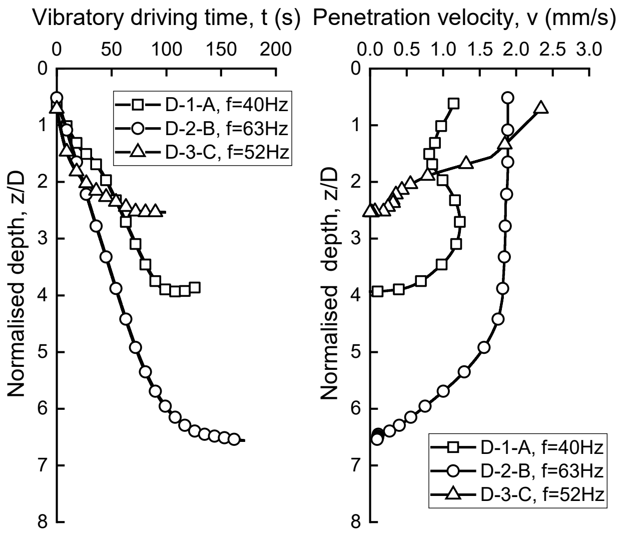

Figure 5. Vibratory driving in dense sand: (a) Penetration; (b) Velocity.

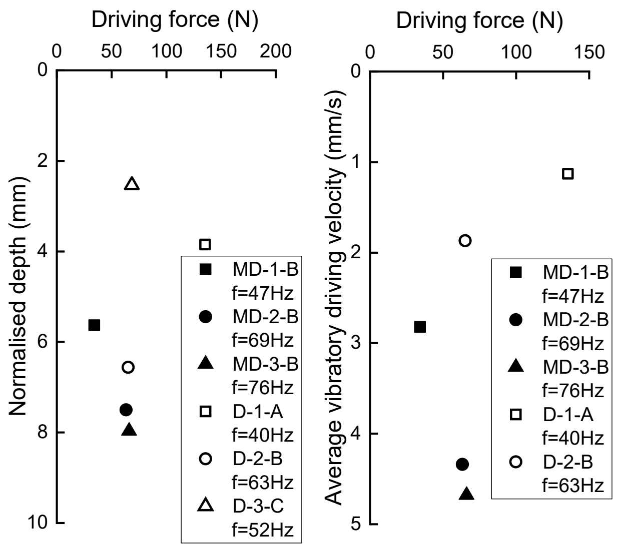

Figure 6. Driving performance at different force level: (a) Penetration; (b) Average velocity.

It is suggested that driving force is also an important factor influencing the vibratory installation performance (Viking, 2002). Figure 6(a) shows the penetration depth at different force levels in the tests, and the average velocity is presented at Figure 6(b). Here, the averages of velocity before $z/D \approx 3.2$ in Group MD and $z/D \approx 3.0$ in Group D are employed, which are the values before velocity declined. It should be noted that D-3-C is not included in velocity analysis due to the rapid reduction in velocity. For the tests in medium-dense sand, the driving forces of MD-2-B and MD-3-B are comparable, but the penetration depth and average driving velocity of MD-2-B is slightly greater due to its higher frequency. In terms of tests Group D in dense sand, there was over twice the penetration depth observed in D-2-B compared to D-3-C with similar exciting force (65.2 N and 68.5 N respectively) and 23 Hz higher frequency. Furthermore, D-1-A with lower frequency but higher driving force presents worse performance in both depth and velocity than D-2-B with higher frequency but much lower force. These results indicate that the frequency in vibratory pile installation appears to play a more significant effect. Further research is necessary to quantitatively investigate the influence of various installation parameters on the driving performance.

4 CONCLUSIONS

In this study, two groups of 1g model tests were conducted to investigate the effects of driving parameters on installation performance of a monopile at 1g and as a preliminary study to aid in designing in-flight centrifuge vibratory driving equipment. It was found that frequency has a significant influence on both ultimate penetration depth and driving velocity in the two group tests. The installation performance was investigated by varying the frequency at the same driving force level, the results appear to suggest that frequency plays a more significant role in determining installation performance compared to driving force. Further study is necessary to obtain the respective impacts of frequency and driving force on the driving performance. The results of this study will be used to assist in the development and design of on-board centrifuge vibro-driving systems.

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