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Lateral bearing behaviour of vibratory-driven monopiles: a modified p-y approach based on experimental observations of scaled model tests

Portante latéral des monopieux installés par vibrofonçage: une méthode p-y modifiée basée sur des observations expérimentales d'essais sur modèle réduit

J. Labenski
Former: Institute for Geotechnical Engineering, University of Stuttgart, Germany
Current: Arcadis Germany GmbH, Karlsruhe, Germany

Ch. Moormann
Institute for Geotechnical Engineering, University of Stuttgart, Germany

ABSTRACT: The paper describes the experimental setup used at the Institute for Geotechnical Engineering (IGS) at the University of Stuttgart to investigate the lateral load bearing behaviour of vibratory-driven monopiles in dense saturated sand. The test material, the measurement devices and the experimental procedure are explained in a comprehensive manner. Afterwards the result of the pile installation and the lateral load test of two representative model test are shown and explained. The results are given in dimensionless values, i.e. a comparison with other model tests documented in literature is possible. To demonstrate the installation behaviour, the pile penetration velocities and the vertical pile movements are shown. The lateral load bearing behaviour is investigated using a lateral load-displacement curve of the pile head. The comparison with a analytical determined load-displacement curve shows poor agreement with the two experimental curves, i.e. a modified p-y approach based on investigations by Labenski (2019) is proposed. Good agreement can be achieved using the modified p-y approach to back-calculate the experimental load-displacement curves.

RÉSUMÉ: L'article décrit l'equipment d'essai utilisé à l'Institut de Géotechnique (IGS) de l'Université de Stuttgart pour enquêter le comportement sous charge latérale de monopieux vibrofonçé dans le sable dense saturé. Le matériel de test, les appareils de mesure et la procédure expérimentale sont expliqués de manière complète. Ensuite, le résultat de l'installation du pieu et le test de charge latérale de deux modèles de test représentatifs sont présentés et expliqués. Les résultats sont donnés en valeurs sans dimension. Pour démontrer le comportement de l'installation, les vitesses de pénétration et les mouvements verticaux du pieux sont indiqués. Le comportement en charge latérale est étudié à l'aide d'une courbe de déplacement de charge latérale de la tête du pieu. La comparaison avec une courbe de déplacement de charge déterminée analytique montre un faible accord avec les deux courbes expérimentales, c'est-à-dire qu'une approche p-y modifiée basée sur les recherches de Labenski (2019) est proposée. Un bon accord peut être obtenu en utilisant l'approche p-y modifiée pour recalculer les courbes expérimentales charge-déplacement.

Keywords: Monopiles; Vibratory-driving; Lateral bearing behaviour; p-y method; Scaled model tests

1 INTRODUCTION

Only limited information is available on the lateral bearing behaviour of vibratory-driven monopiles. Only few authors report about the succesfull application of the vibratory installation method for monopiles (cf. Neef et al. 2013, Tara et al. 2014). In literature only one large scale field test is documented investigating the lateral load bearing behaviour of vibratory-driven monopiles (cf. Moormann et al. 2016).

Investigations on the vibro-driveability of piles in sand have shown a significant influence of cyclic and dynamic effects influencing the pile penetration behaviour as well as the pile adjacent soil. Based on scaled model tests and numerical simulations Rodger & Littlejohn (1980) defined two possible vibration modes: cavitational (slow) and non-cavitational (fast) vibratory-driving. These modes mainly influence the behaviour around the pile tip. A cavitational vibration mode leads to slow penetration process due to a mainly elasto-plastic soil behaviour around the pile tip. During non-cavitational vibratory-driving the soil around the pile tip behaves mainly plastic and a fast penetration process is possible. Largely independent of the vibration mode is the soil behaviour around the pile shaft, i.e. a reduction of soil resistance occurs as a result of the cyclic pile movement due to the sinusoidal excitation of the pile during vibratory-driving. Cudmani (2001) as well as Vogelsang (2016) confirmend this theory.

Cudmani (2001) (Figure 1) observed a loss of contact (2-3) between the pile tip and adjacent soil during the upward movement (1-2) of the pile in the case of a cavicational vibration mode. Therefore the downward movement of the pile starts without contact between pile tip and soil (3-4), i.e. the pile tip resistance remains zero. As soon as the pile tip hits the soil, the pile tip resistance is increasing, but without reaching the ultimate state of the soil (4-1'). During the non-cavitational vibration mode the pile tip always remains in contact with the adjacent soil, i.e. no relaxation effects occur in the soil and the soil reaches an ultimate state during the downward movement of the pile.

Investigations by Vogelsang (2016) indicate that the influence on the soil during vibratory-driving by the pile tip is dependent on the vibration mode, whereas the influence by the pile shaft ist mostly independent of the mode. Vogelsang (2016) could identify the displacement amplitude of the pile tip as the important factor influencing the vibration mode. A large displacement amplitude most likely leads to a cavitational vibration mode and thus cyclic effects occur in the soil. If the vibration mode is non-cavicatational due to a small displacement amplitude, mainly monotonic effects similar to pile jacking occur in the soil during vibratory driving.

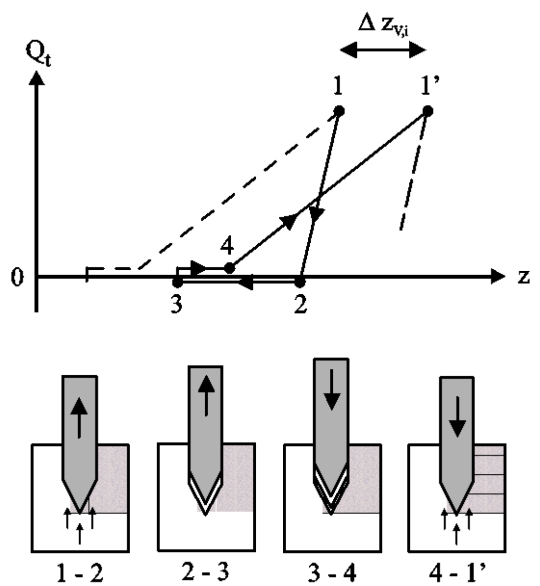

Figure 1. Characteristic curve of the pile tip resistance Q_t during vibratory driving in a cavitational mode (Cudmani 2001)

Current research by e.g. Kallehave et al. (2012) or Klinkvort et al. (2013) on the lateral load bearing behaviour of monopiles focused on the modification of current design approaches, e.g. the p-y approach (DNVGL-ST-0126). In this research pile installation effects are neglected, while the influence of different lateral load situations is investigated. This lack of research was motivation to conduct own experimental tests with the focus on the investigation of the influence of installation effects due to vibratory pile driving on the lateral load bearing behaviour.

2 EXPERIMENTAL SETUP

2.1 Test material – Sand

The scaled model tests have been conducted with saturated Berlin Sand. The sand has a maximum density $\rho_{d,max}$ of 1.856 g/cm^3 corresponding to a minimum void ratio of 0.433, as well as a minimum density $\rho_{d,min}$ of 1.563 g/cm^3 corresponding to a maximum void ratio of 0.702. Further laboratory tests on the sand used for the tests are provided by Le (2015).

2.2 Test material – Pile

The properties of the model pile are depicted in Table 1. In reality steel tube piles are used as monopiles. In the scaled model tests, a glass-fibre reinforced pile has been used instead to accurately scale down the flexural rigidity of the pile (cf. Wood 2004, Labenski 2019). The dimensions of the pile lead to an L/D ratio of 4.2, which is typical for monopiles.

Table 1. Properties of the model pile

Property	Value	Unit
Diameter *D*	0.208	(m)
Length	2.00	(m)
Embedment length *L*	0.87	(m)
Wall thickness	0.0032	(m)
Mass	10.0	(kg)
Mass incl. vibrator and vibrator mount	75.0	(kg)
Flexural rigidity *EI*	550	(kNm^2)

2.3 Test container and measurement devices

The set-up of the 1-g scaled model tests is illustrated in Figure 2. The scaled model tests were conducted in a cylinder shaped concrete container with a diameter of 2.0 m and a height of 2.5 m. The container was filled with a 0.3 m drainage layer followed by 2.2 m of Berlin Sand. The two layers were separated by a fleece. The whole concrete container can be flooded with water rising from the bottom, which has the advantage that the structure of the installed sand is not disturbed and remained homogeneous while being saturated. The dimensions of the concrete container ensure a horizontal distance of 4.5D from the external pile shaft surface to the boundaries and a vertical distance of 7.5D from the bottom of the pile to the bottom of the concrete container.

During the pile installation, the acceleration at the pile head was measured with a triaxial accelerometer. Furthermore, a position transducer was continuously monitoring the penetration of the pile. In further tests, acceleration sensors have been placed within the soil to precisely investigate the dynamic behaviour of the sand during pile installation. During the lateral pile load test, the bending moment of the pile was measured with strain gauges, which were placed along the part of the pile shaft that is embedded into the sand. Only one pair of strain gauges was placed at the pile head where no bending occurs, i.e. temperature effects can be compensated. In total, nine strain gauge measurement layers were placed on the pile. Furthermore, the pile head displacement was measured with three displacement sensors. With these quantities, the lateral pile-soil interaction could be investigated in detail. In Table 2 the abbreviations used in Figure 2 are documented.

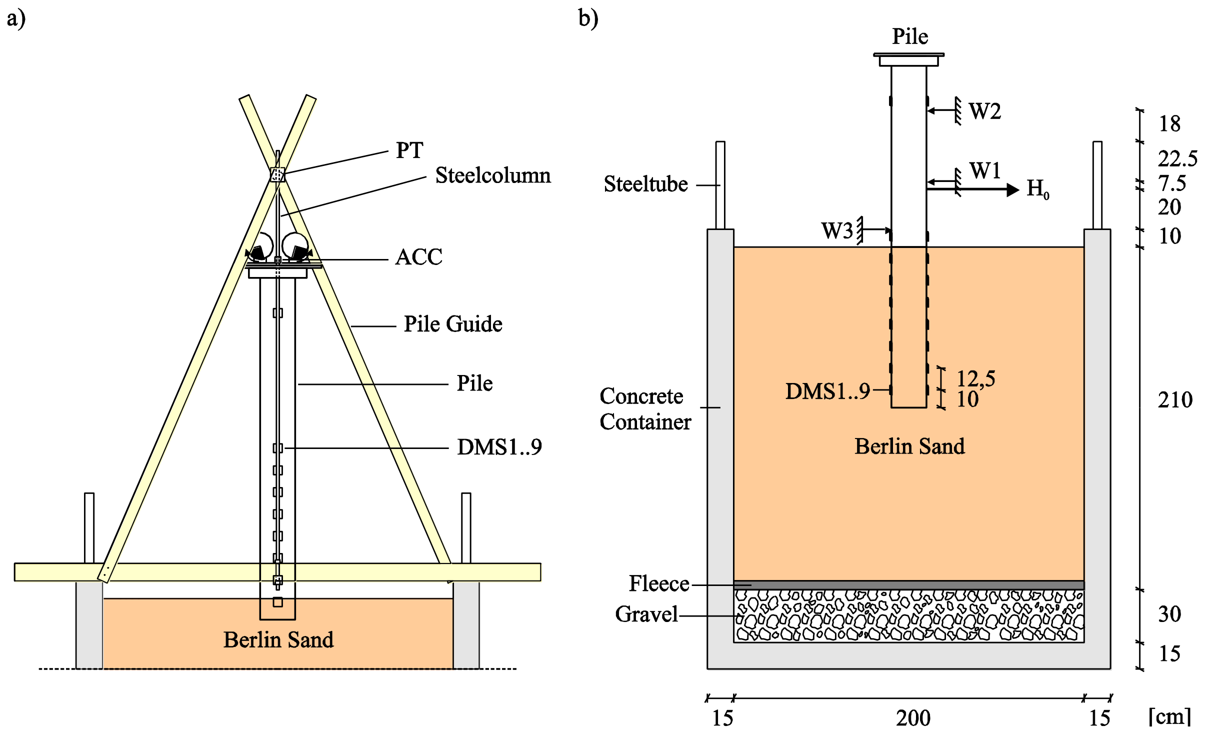

Figure 2. Model setup a) for pile installation and b) for lateral pile load test

Table 2. Sensors used in the scaled model test

Shortcut	**Sensor**
ACC	Acceleration Sensor
PT	Position Transducer
DMS 1..9	Strain Gauges
H_0	Load Cell
W1, W2, W3	Displacement Transducer

2.4 Experimental procedure

The main target of the scaled model tests was to investigate the influence of different installation parameters on the static lateral load bearing behaviour of vibratory-driven monopiles. Installation parameters are the frequency *f* and the static moment M_{stat} of the vibrators. Besides the installation parameters, also the density of the sand was varied.

The scaled model tests consist of different steps. In the first step, the sand was filled homogeneously in the model container. In the second step, the pile was vibratory-driven to the desired embedment depth. In the third step, the lateral pile load test was carried out to investigate the lateral load bearing behaviour.

The tests were conducted in medium-dense, dense and very-dense sand. The sand was installed layer by layer. Trickling of the sand was not possible, because the sand could not be dried after each test, thereby remaining moist. Every layer was compacted by an electrical vibratory plate.

The pile was installed in the sand with a vibrator unit consisting of two WUERGES HV 6/4-18, which generates a maximum centrifugal force of 4.4 kN at a frequency of 25 Hz. The frequency and harmony of the vibrators was controlled by a frequency converter.

The lateral pile load test was carried out with a pneumatic cylinder, which generates the tension force H_0. The pneumatic cylinder was controlled by an electric function generator. This setup has the advantage that only with slight modifications a cyclic lateral force can be applied as well.

In total 33 tests with vibratory-driven piles and two tests with jacked piles have been carried out.

3 EXPERIMENTAL RESULTS

In the following sections two representative results of the scaled model tests are presented. Both tests have been carried out in medium-dense sand and with the same vibration frequency. One test was carried out with a ratio of dynamical force F_{dyn} (kN) to static weight F_{stat} (kN) of 4.6 and a cavitational vibration mode occurred. The other test was carried out with F_{dyn}/F_{stat} of 3.3 and a non-cavitational mode occurred.

3.1 Pile installation

In Figure 3 the pile penetration curves of the two tests are shown. Prior to the vibration both piles were embedded ~1D in the soil by selfweight. It can be observed that the pile, which was vibrating in a cavitational mode, had a longer installation time than the pile with a non-cavitative vibration mode.

The vertical displacement of the pile s_z during pile installation, presented in Figure 4, indicates significant differences between the two tests and vibration modes respectively. The down- (negative) and upward (positive) directed displacements of the non-cavitational vibrated pile are smaller than of the cavitational vibrated pile. Especially the difference in the downward directed movement is distinct. But, according to Vogelsang (2016) and Labenski (2019), the upward directed movement is the substantial factor influencing the vibration mode, i.e. this evidently small difference in upward directed displacement between the two tests leads to either a mainly cavitational or non-cavitational vibration mode.

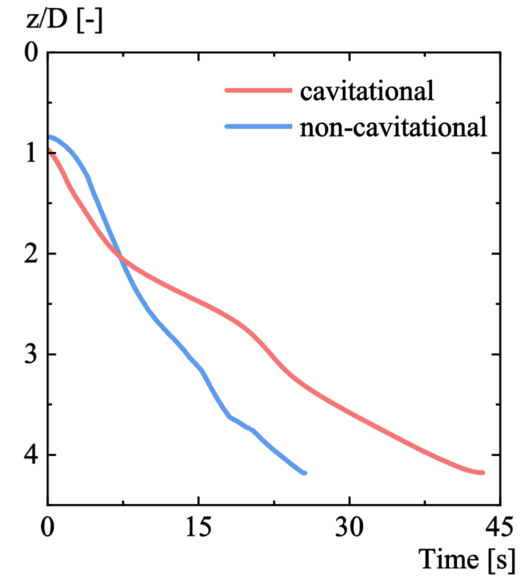

Figure 3. Penetration depth z normalized with the pile diameter D over installation time for the two tests presented in this paper (cf. Labenski 2018)

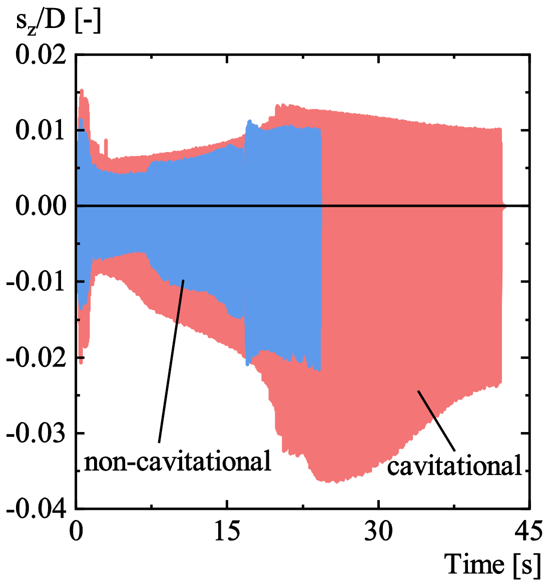

Figure 4. Vertical displacement of the pile s_z normalized with the pile diameter D over installation time for the two tests presented in this paper

3.2 Lateral pile load test

The lateral load-displacement curves of the two tests are shown in Figure 5. Dimensionless parameters are used (cf. Klinkvort et al. 2013, Le 2015) to ensure a better comparability between the tests:

$$P^* = \frac{H}{\gamma' \cdot K_p \cdot D^3} \quad (1)$$

$$K_p = \tan(45° + 0.5\,\varphi')^2 \quad (2)$$

$$\varphi' = 31.5°\, e^{0.42 \cdot {I_D}^{2.9}} \quad (3)$$

Where P^* (-) is the dimensionless lateral force, H (kN) the lateral force, γ' (kN/m^3) the buoyancy weight of the soil, K_p (-) the Rankine passive earth pressure coefficient, φ' (°) the friction angle of the soil and I_D (-) the relative density of the soil.

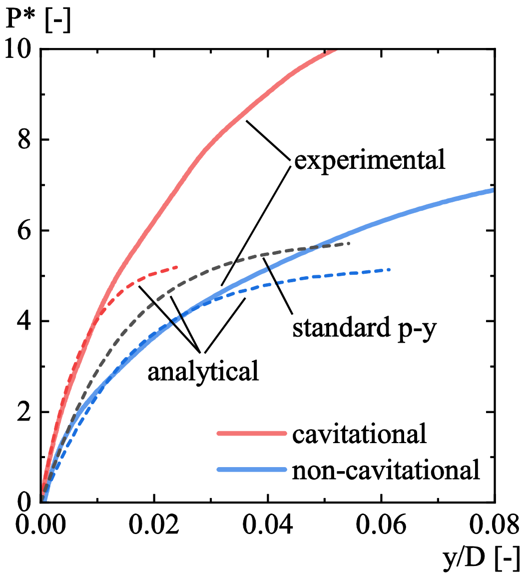

Figure 5. Experimental (solid lines) and analytical (dashed lines) dimensionless lateral load-displacement curves

It can be observed that the pile with a cavitational vibration mode mobilizes a significantly larger lateral resistance in comparison to the pile with a non-cavitational mode. It should be noted that the load-displacement curves of these two tests represent the best and the worst observed lateral bearing behaviours of all at the Institue for Geotechnical Engineering with vibratory-driven piles conducted tests (cf. Labenski 2018, 2019). Beside the two experimental determined load-displacement curves also analytical determined curves are presented in Figure 5. The load-displacement curve titled *standard p-y* was calculated using the standard p-y approach published in the DNVGL-ST-0126 (2016) standard, which is equivalent to the method proposed by Murchison & O'Neill (1984). It is evident that this analytical determined curve does not fit to the two experimental determined curves, though it might be in the same range (cf. Labenski & Moormann 2018). The other two analytical determined curves were calculated using a modified p-y approach, which will be explained in the following section.

4 PROPOSED MODIFICATION OF THE P-Y APPROACH

To calculate the static lateral load bearing behaviour of vibratory driven monopiles, Labenski (2019) proposed a modification of the Murchison & O'Neill (1984) p-y approach which was reformulated by Klinkvort & Hededal (2014). Based on experimentally determined p-y curves, Labenski (2019) modified the initial stiffness of the analytical p-y approach with an installation factor α_{vib} while the ultimate resistance remained unchanged, as 1-g model tests tend to overestimate failure in comparison to prototype dimensions. The factor α_{vib} can be determined via a dependency function considering the vibration mode, the vibration frequency, the dynamic force and the amount of energy transferred to the soil during vibratory pile driving.

In Figure 6 the experimental as well as the analytical determined p-y curves are shown for a depth of $z/D = 2$ in a dimensionless form (cf. Eq. 4).

$$p^* = \frac{p}{\sigma_v'(z) \cdot K_p \cdot D} \quad (4)$$

Where p^* (-) is the dimensionless lateral pile-soil reaction, p (kN/m) the lateral pile-soil reaction and $\sigma_v'(z)$ (kN/m^2) the effective vertical stress in the desired depth.

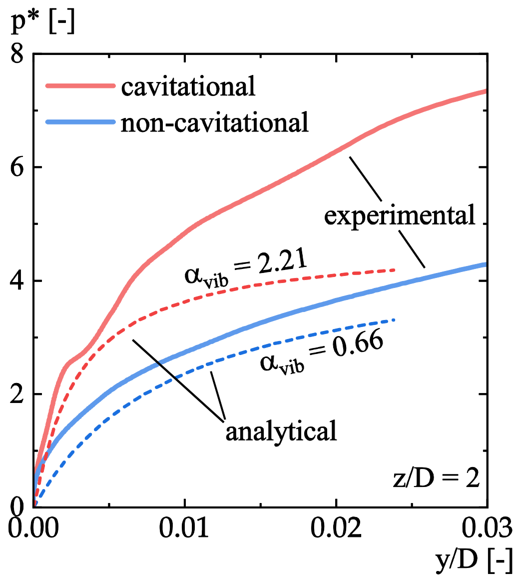

Figure 6. Experimental and analytical dimensionless lateral pile-soil reaction curves in a depth of z/D = 2

Furthermore the corresponding values of α_{vib} used to determine the analytical p-y curves for the two tests are depicted. The comparison of the experimental and analytical curves indicates an underestimation of the lateral soil resistance by the analytical curves. Though, the corresponding curve pairs behave similar up to $p^* = 3$. With increasing p^* the analytical and experimental curves start to deviate as the failure load of the analytical p-y approach was not modified.

To proof the applicability of the modified approach, Figure 5 shows the analytical calculated load-displacement curves of the two in this paper presented model tests. A good match between experimental and analytical determined curve could be achieved up to $P^* = 5$. Afterwards the curves start to deviate due to the non-modified failure load of the original p-y approach.

5 CONCLUSIONS

In this paper the experimental setup as well as two representative results of scaled model tests with vibratory-driven piles carried out under 1-g conditions have been presented. The results regarding the pile installation process have shown a different vibration behaviour observed for the two vibration modes *cavitational* and *non-cavitational*. The results regarding the lateral pile load test showed that the load bearing behaviour is dependent on the vibration mode during installation. It could be further observed that the standard p-y approach is not suitable to determine the lateral bearing behaviour of vibratory-driven monopiles. Thus, a modified approach including pile installation effects was proposed leading to a good agreement between analytical and experimental load displacement curves. The modified p-y approach has the advantage that it can be easily included in current design practise, as the p-y approach itself is a well-know and common design method and no further 3D FEM calculations are needed.

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