Dynamic FE-based approach to determine the axial bearing capacity of piles

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ABSTRACT

Piles are commonly used foundation structures. The installation process of piles is governed by dynamic processes which induce stress waves into the pile and the surrounding soil. Hence, the bearing capacity of the installed piles is influenced by the dynamic behavior and the resulting pile-soil interaction. To predict realistic bearing capacities, it is important to establish a thorough understanding of the underlying processes. Based on an understanding of both pile design and installation of offshore piles it is possible to identify the main influencing factors of dynamic load tests and to derive as well as to validate a new evaluation method for dynamic load tests. Another application that focuses on the dynamic pile behavior is the pile driving analysis. The impact of (unexpected) obstacles such as boulders in the ground represents a critical design consideration for pile driving. An approach to evaluate the pile behavior when impacting boulders during driving by applying one-dimensional wave theory is described. The example also emphasizes the limitations of using one-dimensional wave theory to evaluate the pile-soil interaction and provides an alternative outlook based on the proposed evaluation method for dynamic load tests.

Keywords: pile design, obstacles, pile bearing capacity, dynamic load test

1 INTRODUCTION

Piles are commonly used foundation structures in onshore as well as offshore applications. The installation process of piles, especially for tubular offshore piles, is governed by dynamic processes which induce stress waves into the pile and the surrounding soil. Hence, the bearing capacity of the installed piles is influenced by the dynamic behavior and the resulting pile-soil interaction.

In accordance with design guidelines, load tests under field conditions after pile installation are necessary to identify the pile bearing capacity under compression load on construction sites and to assure the validity of the design. Static load tests are the most reliable method because the static pile bearing capacity is measured directly. Due to onerous conditions as well as the economic impact, static load tests are usually not suitable for this purpose in an offshore environment. Hence, dynamic load tests (DLTs) represent a suitable alternative. Within such an application the pile bearing capacity is estimated by analyzing stress wave measurements at the pile head.

To derive realistic bearing capacity values, it is important to establish a thorough understanding of the underlying processes during such tests. In this case, a Finite Element (FE) model and centrifuge test results of DLTs are introduced to identify the main influencing factors of dynamic load tests.

Applying a model based on the Finite-Element-Method (FEM), the parameters defining these key factors within the model are derived to develop a new technique for the evaluation of DLTs on piles. The derived method is validated based on dynamic and static load test data obtained from centrifuge tests on large diameter monopiles.

Another application that focuses on the dynamic pile behavior is the pile driving analysis, an integral part of the foundation design process. Particularly, the impact of (unexpected) obstacles such as boulders in the ground represents a critical design consideration. An approach to evaluate the pile behavior when impacting boulders during driving by applying one-dimensional wave theory is described. As a result, the consequences of a potential boulder impact may be integrated and considered in the design process.

The abovementioned example provides insights into the vast limitations of existing techniques for the evaluation of dynamic pile behavior and of the pile bearing capacity representing major design drivers.

2 DYNAMIC LOAD TESTS

To address the problem of identifying the pile bearing capacity realistically, the static axial pile bearing capacity and possible in-situ testing methods are analyzed. This has the objective of developing a new evaluation technique for the pile bearing capacity.

The static pile bearing capacity depends on different parameters such as pile characteristics, pile installation method, and soil conditions. All these parameters influence the pile-soil interaction. This emphasizes that a thorough understanding of the pile-soil interaction is key to predicting the bearing capacity of a pile.

Static load tests are the most reliable technique to determine the pile bearing capacity after installation because the bearing capacity is measured directly. However, due to economic and practical reasons a static load test is usually not feasible in an offshore environment. DLTs represent an effective alternative.

Therefore, dynamic load tests will be assessed with the objective of developing a new evaluation technique which addresses known shortcomings and allows for the consideration of obstacles.

3.1 State of the art

DLTs are a pile load test method which facilitate the determination of the pile bearing capacity by applying a dynamic load on the pile head. This dynamic load, for example a hammer blow, induces a propagating wave in the pile. Due to large differences in density between pile and soil, the wave is reflected at the pile tip, which causes a return wave to propagate back to the pile head.

At the pile head the wave propagation through the pile is measured as strain $\varepsilon(t)$ and acceleration $a(t)$ over time. These quantities are transferred to velocity $v(t)$ and force $F(t)$:

$$F(t) = v(t)Z = Z\int a(t)dt \qquad (1)$$

$$F(t) = \varepsilon(t)EA \qquad (2)$$

The conversion of measured velocities to forces is achieved by multiplication of the velocity with the impedance of the pile Z, which describes the ratio of the cross-sectional stiffness of the pile EA and the wave speed within the pile c. These so-called pile head signals are evaluated to obtain the ultimate axial static pile bearing capacity.

Within the state of the art – comparable to the drivability analysis – one dimensional wave theory is applied for this evaluation. This approach was derived for full-section piles and is based on an embedded rod (Paikowsky and Chernauskaus, 2008). In accordance with EA-Pfähle (2012) the evaluation can be performed using so-called “direct” or “advanced” methods.

Direct methods determine the mobilized soil resistance directly from simplified equations. The existing approaches – for example the TNO- or the CASE-approach (EA-Pfähle, 2012) or the approach according to Kolymbas (Kolymbas, 1991) - differ mainly in their description of the skin friction.

The advanced methods such as ALLWAVE or CAPWAP are explained for example in Randolph and Deeks (1992), Randolph (2003), Stahlmann et al. (2004), Rausche et al. (2010), and EA-Pfähle (2012). These methods are based on simple rheological models of the pile-soil system including springs, point masses, dampers, and sliders. The description of the pile is based on one-dimensional linear elastic elements and a constitutive model for the description of the stress-strain behavior of the soil. The pile-soil interaction is defined by skin friction (spring-damper elements along the shaft of the pile) and tip pressure (characteristic curves for the spring-damper elements at pile tip). The unknown variables within this model such as the spring stiffness and the damper coefficient are the input parameters for the evaluation. The described numerical model is used to perform an inverse calculation to achieve a signal matching between measured and calculated pile head signal. To achieve this, the unknown parameters are varied within reasonable boundaries to obtain a match or best fit. The derived parameters of the best fit are used to model a static load test, from which the ultimate static bearing capacity is obtained. This problem does not have a mathematically unique solution and is dependent on the user. Consequently, knowledge and sufficient experience are necessary to apply the advanced methods.

The application of the advanced methods to full-section piles is based on sufficient experience and has been performed as a state of the art for a long time. Due to a lack of alternatives this approach is applied to open-ended piles as well.

However, the specifications of open-ended piles do not allow for the application of one-dimensional wave theory. Dynamic loading causes a multi-dimensional and complex wave propagation within pile and soil (Paikowsky and Chernauskaus, 2008). Furthermore, the applied methods do not describe the pile-soil interaction sufficiently (Randolph, 2003).

Therefore, the applicability of the advanced methods to open-ended piles needs to be verified. Due to the limited understanding of the main influencing factors and underlying processes within pile and soil, further investigations are necessary.

3.2 Main influencing factors

To obtain a better understanding of the behavior of pile and soil during dynamic loading, numerical simulations and centrifuge tests are performed at 100g.

Details about these investigations can be found in Heins and Grabe (2016), Heins and Grabe (2017), Heins et al. (2018), Heins (2018), Heins (2019) and Heins et al. (2020).

These analyses investigated the influence of pile-soil interaction, drainage conditions, degree of saturation of the soil, the relative density of the soil, pile geometry as well as the pile installation method on pile head signals and the static bearing capacity.

The key aspects for the system response at pile head caused by a dynamic load are the drainage conditions within the soil and the pile-soil interaction. Aspects such as pile characteristics, the soil state and the pile installation method have an impact on the pile head signals only by influencing the pile tip resistance, which is part of the pile-soil interaction.

3.3 FE-based evaluation technique

The defined evaluation technique is based on a combination of mathematical optimization and Finite-Element-Analysis (FEA) to identify the pile-soil interaction which defines the static axial pile bearing capacity. Details about this method are given in Heins (2018). The procedure is illustrated in Fig. 1.

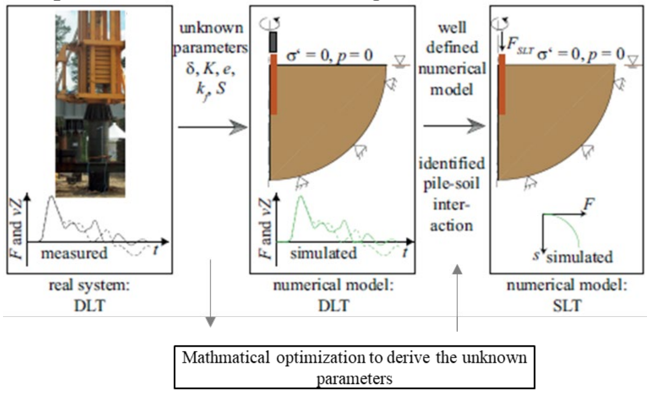

Fig. 1. Simplified procedure of the FE-based evaluation technique in accordance with Heins (2018)

A DLT is performed in-situ on an open-ended pile while the pile head signals are measured. Based on this in-situ test a numerical model is created using the FEM, which describes the real load test as realistically as possible. Hence, the pile specifications from the pile design and the soil layering as well as the soil parameters determined from in-situ investigations and laboratory tests are input values to the model. The parameters which describe the soil state, the drainage conditions within the soil as well as the contact between pile and soil are unknown. Consequently, the unknown parameters are the permeability of the soil k_f, the void ratio of the soil e, the degree of saturation S, the earth pressure coefficient K, and the wall friction angle δ between pile and soil. These parameters were identified as the main aspects for the numerical model of a DLT since they influence the pile-soil interaction.

For the numerical simulation of the load test, assumptions must be made for these unknown parameters, due to which a deviation between measured and simulated pile head signal is observed. However, considering the case for which these unknown parameters are defined precisely, the deviation will be negligible. Hence, the unknown parameters need to be determined. This is done, as Fig. 1 emphasizes, using mathematical optimization based on a multi-objective evolutionary algorithm (MOEA). This approach was developed by Kinzler (2011). Basically, the unknown parameters are identified through an iterative process, which considers a variety of solutions that are adapted by processes based on biological adaption. An initial solution is obtained by chance. For each new solution an FEA of the load test is performed and the deviation between measurement and simulation is determined (cf. Fig. 2).

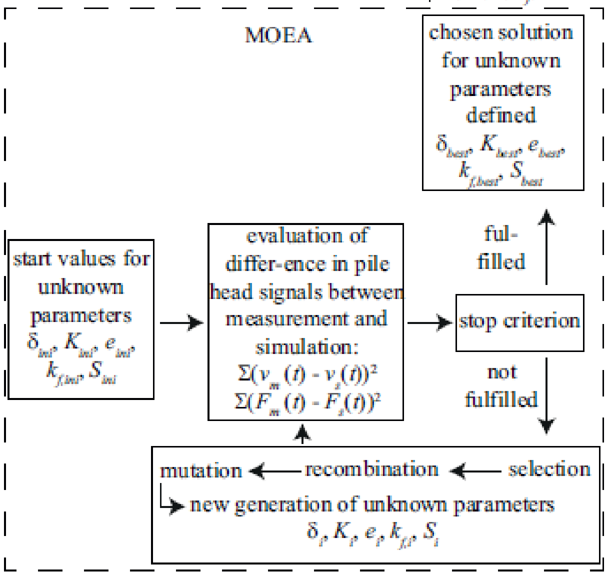

Fig. 2. Simplified procedure of mathematical optimization using MOEA in accordance with Heins (2018)

The error is calculated by two objective functions, which are defined by a normalized sum of the squared difference between measured (index m) and simulated pile head signal (index s) from the start ($t = 0$) until the end of the pile head signal ($t = t_{end}$). The first function considers the velocity and the second one the force:

$$f_{t1} = \frac{\sum_{t=0}^{t=t_{end}}[v_m(t)-v_s(t)]^2}{\sum_{t=0}^{t=t_{end}}[v_m(t)]^2} \quad (3)$$

$$f_{t2} = \frac{\sum_{t=0}^{t=t_{end}}[F_m(t)-F_s(t)]^2}{\sum_{t=0}^{t=t_{end}}[F_m(t)]^2} \quad (4)$$

The normalization is necessary to obtain the same magnitude for both functions and hence to not influence the optimization procedure.

The two objective functions are evaluated for each solution. Using these results, a new solution for the unknown parameters is created by selection, recombination, and mutation. This iterative process described by these adaptions is stopped once a predefined stop criterion is reached, which defines the minimum of the objective functions.

This solution for the unknown parameters is the chosen parameter set. For this solution it is assumed that the unknown parameters of the numerical model are defined precisely and that this describes the real system accurately. Since these parameters are input values for the pile-soil interaction within the numerical model, the determined parameters also define the pile-soil interaction of the real system.

In summary, the FE-based evaluation technique derives the pile-soil interaction for an open-ended profile from measurements of a DLT. The unknown parameters of the numerical model of the DLT are derived by mathematical optimization. The ultimate axial static bearing capacity is determined from a numerical simulation of a static load test using the system data of the DLT including the determined pile-soil interaction. Therefore, this procedure is based on fundamental geotechnical properties and includes only a few unknown parameters.

3.4 Validation

A validation of the described FE-based evaluation technique is performed using centrifuge test data. A validation case is established by performing a dynamic and a static load test at 100*g* on the same jacked tubular pile in saturated, loose sand. This case is then modeled numerically as part of the FE-based evaluation.

Details about this and other validation cases, the centrifuge test and the numerical model can be found in Heins (2018), Heins (2019) and Heins and Grabe (2019).

The primary goal of the evaluation technique is the identification of the pile-soil interaction and the static pile bearing capacity. As a first step the unknown parameters of the soil state are identified using mathematical optimization. The results of the optimization performed for validation purposes are shown in Fig. 3 as the deviation between measurement and numerical simulation.

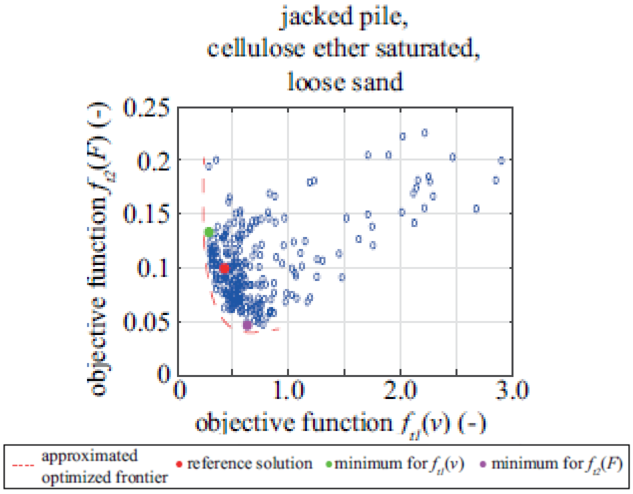

Fig. 3. Deviation between measurement and numerical simulation in terms of the objective functions $f_{t1}(v)$ and $f_{t2}(F)$ taken from Heins and Grabe (2019)

The best solutions for the unknown parameters are visualized by a frontier – the so-called pareto frontier. Along this line not one solution for the optimization problem exists, but rather either the deviation between measured and simulated velocity (function $f_{t1}(v)$) or the deviation between measured and simulated force (function $f_{t2}(F)$) can be minimized. The minimization of one function leads to an enlargement of the other function. Consequently, the solution needs to be a compromise between the two functions. Since the force is an input parameter to the numerical model, the function $f_{t2}(F)$ leads to small deviations during the whole optimization process. Hence, the minimum of the other function $f_{t1}(v)$ is chosen as the solution for this optimization process.

Fig. 4 shows the resulting pile head signals of the simulated and the measured DLT. The deviation between simulation and measurement is small, which indicates that the determined unknown parameters describe the measured situation well and that the parameters are determined sufficiently well. The determined parameters describe the pile-soil interaction during the centrifuge test. Hence, it is plausible to assume that the FE-based evaluation reflects the pile-soil interaction for this validation case realistically.

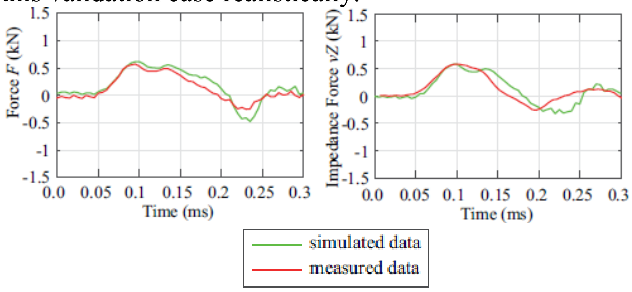

Fig. 4. Pile head signals as force *F* and impedance force *vZ* for the measured and the optimized numerical data taken from Heins and Grabe (2019)

With these obtained parameters a static load test can be performed. The comparison of the load-displacement curves of measurement and simulation is provided in Fig. 5, and shows a good agreement. The determined static bearing capacity does not vary significantly between measurement ($Q = 3{,}75$ kN), and simulation ($Q = 3{,}42$ kN). Hence, the validation proves that the determined pile-soil interaction describes the considered system efficiently and with sufficient accuracy.

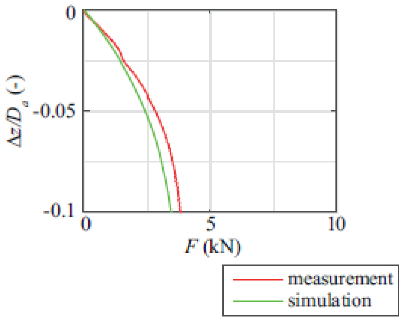

Fig. 5. Load-displacement curves for measured and numerically simulated static load tests taken from Heins and Grabe (2019)

Consequently, the derived FE-based evaluation approach for DLTs considers the key aspects for the system response at pile head during dynamic loading and is based on unknown parameters common in soil mechanics. Furthermore, the described approach leads to promising results for the determination of the pile-soil interaction and the ultimate axial static pile bearing capacity.

Compared to the state of the art the developed approach considers the specific (multi-dimensional) wave propagation within pile and soil. Further, it is based on a few unknown parameters common within soil mechanics. A result check is possible because the results represent the soil state during the field test. Obviously, a relatively high number of numerical simulations is necessary when applying this technique. However, by creating an efficient FE model the calculation time of the whole procedure can be kept within reasonable limits.

3 PILE DRIVING ANALYSIS

In addition to the determination of the bearing behavior of a driven pile in representative or expected soil conditions, the proposed approach may also be employed in context with boulders that are encountered during pile driving. In certain cases, such boulders may prevent a pile from being driven to the designated target depth, a situation that may under certain circumstances mandate a re-evaluation of the foundation as the bearing capacity is influenced by the boulder. Likewise, if boulders pose a potential risk in certain locations, this situation may be analyzed beforehand. For this task, a potential boulder can be considered within the FEA. Hence, the influence of the boulder on the pile head signal and the wave propagation may be considered.

Generally, pile driving predictions are typically an integral part of the pile design process in the design industry. Depending on the expected soil conditions and the intended turbine size, planned pile foundations are assessed several times in an iterative scheme to find the most suitable and cost-effective design solution. Typically, the tools that are applied as part of a drivability assessment should therefore be able to yield reliable results within a reasonable time frame.

One-dimensional wave propagation models to predict the pile drivability have proven suitable for these tasks in the past. Commercial software which is based on this concept is readily available and supports the design engineer in fulfilling these tasks, providing a good outlook for the pile installation as well as the fatigue loads that are acting on the pile during driving.

However, the simplifications that need to be made to reduce this three-dimensional problem to a one-dimensional model may set constraints which yield inaccurate results for more specific and differentiated tasks. One prominent example of this is the assessment of a pile encountering an obstacle, e.g., a boulder of significant size. Such an obstacle will typically act on the pile tip or the pile shaft close to the tip and could hence influence the load-bearing behavior of the pile as well as its structural integrity. The usually eccentric nature of the interaction renders a one-dimensional model ill-suited to solve such problems.

Attempts have been made to predict the pile behavior and damage propagation during such an encounter (Aldridge, 2005), or to amend the existing models to predict which of the potential interaction mechanisms are most likely to occur, i.e. if a pile will be able to withstand the additional localized forces, and/or if it will be able to either push the obstacle into the soil matrix or to simply split it (Holeyman, Peralta and Charue, 2015). Fig. 6 shows an example of such a study, based on this approach.

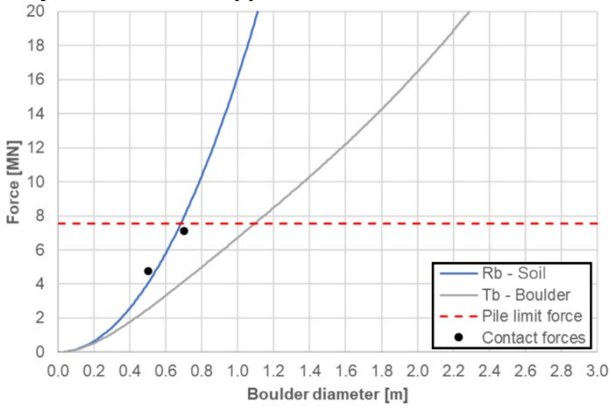

Fig. 6. Example of a study of a pile encountering a boulder

Nonetheless, as these models focus on the mechanisms that occur during the actual driving process, no indication is given about the long-term bearing capacity of such piles in the case of notable interactions or even a refusal. Therefore, this problem needs to be addressed in a more comprehensive way to allow designers to predict the outcome of the pile driving process and to gauge what implications potential refusals may have.

For this reason, the proposed technique to predict the pile bearing capacity based on the results of DLTs is proposed to be extended to such tasks, as it is deemed suitable to consider most of the involved mechanisms. Likewise, the number of simplifications to set up the analyses is reduced significantly.

4 CONCLUSIONS

The paper deals with the dynamic behavior of foundation piles in general and presents a novel evaluation technique for DLTs. The main influencing factors of DLTs are derived based on an understanding of both pile design and installation using an FE model and centrifuge test results. The drainage conditions and the pile-soil interaction (mainly the pile tip support) are identified as the main influencing factors. The parameters defining these key factors within an FE model are derived.

Using this knowledge, a new technique for the evaluation of DLTs on piles based on an FE model is developed. Within this approach the considered pile with the embedding soil is defined within a numerical model, simulating the performed DLT. Using mathematical optimization, the key parameters of influence for this model are varied until the measured and the modeled DLT results agree. As a result, the soil state present during the performed DLT within the field is derived, and the pile-soil interaction can be determined. Based on this soil state, a static load test is modeled to predict the bearing capacity of the pile. With this approach, the previously identified main factors of the pile-soil interaction for DLTs are implemented, and site-specific conditions are considered to numerically derive the static pile bearing capacity.

The derived method is validated based on dynamic and static load test data obtained from centrifuge tests on large diameter monopiles. Proof is given that the pile-soil interaction is identified well and that the pile bearing capacity is determined precisely.

The area of applications can potentially be expanded to cover the modelling of drivability analyses and more specifically, the encounter of a boulder and the consequences thereof. Widespread one-dimensional approaches to the problem are addressed and their intrinsic shortcomings are indicated.

Based on the understanding of these limitations, the presented approach may be used to identify the influence of obstacles on the wave propagation within the pile and may even be used to infer the pile capacity if an obstacle has been encountered and has resulted in failure to reach the target penetration.

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REFERENCES

1) EA-Pfähle (2012): Empfehlungen des Arbeitskreises "Pfähle"– EA-Pfähle der Deutschen Gesellschaft für Geotechnik (DGGT), 2 edn. Ernst & Sohn

2) Heins E. (2018): Numerical based identification of the pile-soil interaction in terms of the axial pile bearing capacity. Dissertation, Technische Universität Hamburg, Veröffentlichungen des Instituts für Geotechnik und Baubetrieb, Heft 44

3) Heins E. (2019): Numerisch basierte Identifikation der Pfahl-Boden-Interaktion unter Berücksichtigung der axialen Pfahltragfähigkeit. In: Tagungsband zum Pfahlsymposium 2019 in Braunschweig, Mitteilungen des Instituts für Grundbau und Bodenmechanik der TU Braunschweig, Heft 107, S. 47-71

4) Heins E., Bienen B., Randolph M.F. und J. Grabe (2020): Effect of installation on static and dynamic load test response for large diameter open-ended piles in sand. In: International Journal of Physical Modelling in Geotechnics 20(1):1-23

5) Heins E., Grabe J., Bienen B. and M.F. Randolph (2018): Dynamic load tests on large diameter open-ended piles in sand performed in the centrifuge. In: Proceedings of 9th International Conference on Physical Modelling in Geotechnics (ICPMG) in London/UK, A. McNamara et al. (eds.), CRC Press, pp. 749

6) Heins E., Grabe J. (2016): Coupled deformation-seepage analysis of dynamic capacity tests on open-ended piles in saturated sand. In: Acta Geotechnica 12:211

7) Heins E. und J. Grabe (2017): Finite-Elemente basierte Auswertungsmethode für die dynamische Pfahlprüfung an offenen Profilen. In: Tagungsband zum Pfahlsymposium 2017 in Braunschweig, Mitteilungen des Instituts für Grundbau und Bodenmechanik der TU Braunschweig, Heft 102, S. 111-124

8) Heins E. und J. Grabe (2019): FE-based identification of pile-soil interactions from dynamic load tests to predict the axial bearing capacity. In: Acta Geotechnica, Ausgabe Mai 2019, S. 1-21, DOI: 10.1007/s11440-019-00804-y

9) Kinzler, S. (2011): Zur Parameteridentifikation, Entwurfs- und Strukturoptimierung in der Geotechnik mittels numerischer Verfahren. Doktorarbeit, Veröffentlichungen des Instituts für Geotechnik und Baubetrieb der Technischen Universität Hamburg-Harburg, Heft 23

10) Kolymbas, D. (1991); Longitudinal impacts on piles. Soil Dynamics and Earthquake Engineering 10(5), S. 264–270.

11) Paikowsky, S., Chernauskaus, L.R. (2008): Dynamic analysis of open-ended pipe piles. In: J.A. Santos (ed.) Proceedings of 8th International Conference on the Application of Stress Wave Theory to Piles in Lisbon, Portugal, pp. 59–76. IOS Press

12) Randolph, M.F. (2003): Science and empiricism in pile foundation design. Geotechnique 53(10), 847–875.

13) Randolph, M.F., Deeks, A.J. (1992): Dynamic and static soil models for axial pile response. In: F.B.J. Barends (ed.) Application of Stress-Wave Theory to Piles, pp. 3–14

14) Rausche, F., Likins, G., Liang, L., Hussein, M. (2010): Static and Dynamic Models for CAPWAP Signal Matching. In: M.H. Hussein, J.B. Anderson, W.M. Camp (eds.) Art of Foundation Engineering Practice, pp. 534–553.

15) Stahlmann, J., Kirsch, F., Schallert, M., Klingmüller, O., Elmer, K.H. (2004): Pfahltests – modern dynamisch und / oder konservativ statisch. In: Tagungsband zum 4. Kolloquium "Bauen in Boden und Fels" der Technischen Akademie Esslingen, pp. 23–40

16) Aldridge, T.R., Carrington, T.M., Kee, N.R. (2005): Propagation of pile tip damage during installation. In: Gourvenec & Cassidy (eds), Frontiers in Offshore Geotechnics, ISFOG 2005 - Proceedings of the 1st International Symposium on Frontiers in Offshore Geotechnics in London, UK, pp. 823–827

17) Holeyman, A., Peralta, P., Charue, N. (2015): Boulder-soil-pile dynamic interaction. In: Meyer (Ed), Frontiers in Offshore Geotechnics, ISFOG 2015 - Proceedings of the 3rd International Symposium on Frontiers in Offshore Geotechnics in London, UK, pp. 563–568