A case study of using VCPTu for drivability analysis of vibratory pile driving

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ABSTRACT

Impact pile driving is the conventional method for the installation of monopiles in the offshore wind industry; however, this installation method is environmentally unfriendly and can induce high fatigue in piles. To overcome these issues, the vibratory pile driving method was introduced. However, one major obstacle to utilizing the vibratory pile driving method, is the lack of a well-established drivability analysis method. So far, the most reliable approach for drivability analysis of vibratory pile driving is based on the back-analysis of instrumented test piles in the same soil condition, which is highly costly and time-consuming. The inability to develop a robust drivability analysis method is due to uncertainties related to the cyclic soil resistance during vibratory penetration. The one possible approach explored here is to investigate the cyclic soil resistance during vibratory penetration is the use of Vibratory CPTu (VCPTu). VCPTu is an in-situ soil investigation device that penetrates the ground while inducing cyclic strains with different vibration modes. The collected data can be post-processed to determine a reduction in cyclic soil resistance due to the vibratory mode of penetration. In this study, we adopted wave equation analysis and back analyzed the installation data of a monopile, obtained from the VIBRO project at Cuxhaven-Germany, where three monopiles have been installed using the vibratory pile driving method, and several VCPTus have already been performed there. The reduction in the cyclic soil resistance to vibratory driving, known as degradation factor i.e., Beta Factor, was then calculated and compared with the Beta Factor values obtained from the VCPTu tool. Results showed that the VCPTu data are promising, to some extent and that the results can be considered as roughly representative for the installation of piles. VCPTu is a potential investigation method for challenging sites in the future.

Keywords: 1D-model, VCPTu, Drivability analysis, Vibratory pile driving

1 INTRODUCTION

The present and future of the world's energy, especially European energy, are tied to offshore wind energy. Globally, the installed capacity of offshore wind in 2020 was 5519 MW and the total increased from 200 operational projects to 32906 MW by the end of 2020 (National Renewable Energy Laboratory, 2020). Large wind turbines require large foundations, i.e., XXL piles. These large foundations, however, lead to challenges in the installation process. Large diameter monopiles are the most economically foundation for water depths of less than 35 m (Doherty *et al.*, 2015). Both impact and vibratory pile driving are used to install the piles to the desired depth. The vibratory pile driving method has advantages compared to impact pile driving, because it produces less noise, less damage to the pile, and is therefore potentially more cost-efficient (Viking, 2002; Holeyman and Whenham, 2017). Experience has shown that using vibratory pile driving is a efficient installation method in granular soil (Holeyman, 2002; Viking, 2002), and that the installation effect on lateral pile response is not significant for the final design (Achmus *et al.*, 2020). However, the drivability analysis for the vibratory pile driving method is still challenging. The challenge lies in the uncertainty of the vibrator-pile-soil interaction behavior during vibratory pile driving (Viking, 2002; Holeyman and Whenham, 2017).

Different models were suggested to describe the vibrator-pile-soil interaction behavior. "Force equilibrium" models were developed to investigate whether or not a vibratory hammer can overcome the soil resistance during penetration (Holeyman, 2002; Viking, 2002). The Beta Factor was introduced as a ratio between the vibratory and static resistance, and some constant values obtained empirically were suggested for different types of soils form project experience (Jonker, 1987). This method is unable to provide vibratory penetration speed. "Energy-based" models represent a relationship between applied and consumed energy along with empirical factors for considering energy loss in the system (Warrington, 1989). "Momentum conservation" models include a balance between soil resistance impulse and the total weight of the vibratory system for one cycle (Schmid, 1969). "Integration of laws of motion" models which integrate the equilibrium conditions of the system at all times to predict driveability. There are also different radial (Berghe and Holeyman, 2002) and longitudinal one-dimensional wave equation models such as (Smith, 1960; Jonker *et al.*, 1988, and Moulai-Khatir *et al.*, 1994), which can be categorized as a subsection for integration of laws of motion.

The soil in 1-D models is represented as a spring-slider-dashpot such as the Smith model. Therefore, the selection of soil parameters to predict the soil behavior significantly affects the driveability prediction of the pile (Viking, 2002). Relative displacement between pile and soil to reach the plastic regime (quake), soil damping constant, and Beta Factor are important parameters for 1-D model. Beta Factor which is used to determine the dynamic soil resistance of vibratory driven pile is considered just related to the soil type. However, this is not be true for all the cases (Al-Sammarraie, 2020).

In this study, the driveability analysis for two vibratory driven piles in a sandpit near Altenwalde/ Cuxhaven, Germany, were performed using wave equation analysis from AllWave-VDP (Allnamics, 2020). The suggested values by AllWave-VDP after entering CPT data for key parameters that affect the soil response during installation, Beta Factor, quake, and damping constant, were used at first. The net driving time obtained from the pile driving data in the field and analysis were compared to each other to investigate whether the suggested parameters need to be revised. Extra analyses were performed to fit the prediction of the wave equation analysis with the pile driving data from the field, and the new input parameters of soil response were compared with the ones obtained from Vibratory CPT performed in the same site.

2 EXPERIMENTAL PROGRAM

Three open-ended steel monopile (P1, P4, and P5) with an outer diameter of 4.3 were installed using a vibratory hammer (Achmus *et al.*, 2020). The total length of piles was 21 m. Piles were assembled with two parts. The first part had a wall thickness of 45 mm up to 6.2 m from the pile head, and the second part had a thickness of 40 mm for the remaining length.

PVE 500M vibrator was used to install the piles. Four clamps were used to connect the pile to the vibrator. The frequency of 12 Hz was used until a penetration depth of 9 meters from the head pile, and 22.5 Hz was used for the remaining depth (Table 1). Considering that the installation procedure was unintentionally interrupted for P1, the two remaining piles were analyzed in this paper.

Strain and acceleration were also recorded for pile P5 during installation. Sensors were located at 4 m below the pile head. End of driving stress and displacement amplitudes were estimated from the sensor data.

Subsoil conditions of the site were examined using CPTs. The characteristic CPT profile for each pile was obtained by averaging values for four CPTs around the future pile location. The averaged cone resistance and sleeve friction for piles P4 and P5 are depicted in Fig. 1. Most soil layers consist of fine to medium glaciofluvial silica sands with the presence of a thin till layer of clayey silty gravely sand around the depth of 5 meter, all of Saalian age. The groundwater table was located around 4 meters below the surface.

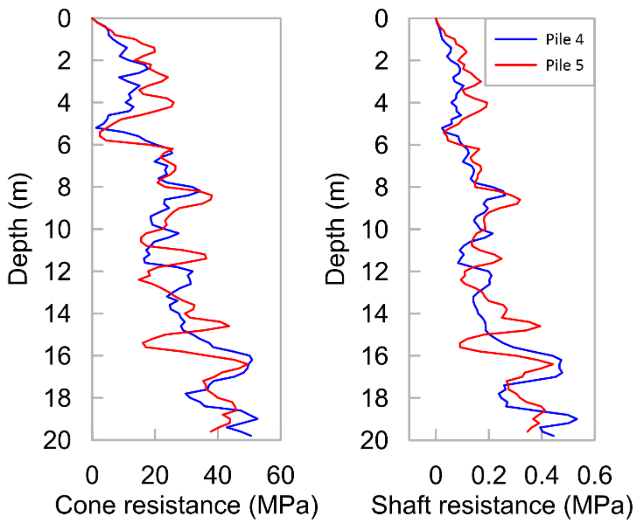

Fig. 1. CPT results for piles P4 and P5.

Table 1. Driving specifications of piles P4 and P5 (Achmus *et al.*, 2020).

	Unit	Pile 4	Pile 5
Installation method	[-]	vibrated	vibrated
Driven depth	[m]	18.70	18.80
Frequency	[Hz]	12 (0-8.5 m)	12 (0-9.5 m)
	[Hz]	22.5 (8.5-18.70 m)	22.5 (9.5-18.80 m)
Net driving time	[min]	4	3

3 METHODS

A complete drivability prediction model includes three main sections: hammer, pile, and soil. Modeling of hammer and pile is straightforward based on the hammer specifications, pile dimension, and material of pile in the framework of wave equation analysis. Nevertheless, the soil-pile interaction is much more complex and harder to be modeled. The Smith and TNO models are implemented in AllWave-VDP. These models simulate the soil as a combination of springs and dampers attached to the pile. These two models are explained briefly below.

3.1 The Smith model

The total resistance for driving in this model is a combination of static, and dynamic. (Smith, 1960):

$$R_{t,Smith} = R_s + R_d \quad (1)$$

$$R_s = ku\,;\; R_d = J_s R_s v \quad (2)$$

$$R_{t,Smith} = ku(1 + J_s v) \quad (3)$$

where R_t is total soil resistance, R_s is static resistance to driving, R_d is dynamic soil resistance, k is the spring stiffness, J_s is Smith damping factor, u is displacement, and v is velocity. The Smith model is a linear elastic perfectly plastic model which considers an equal stiffness for loading and unloading (Fig. 2). Soil stiffness is in this model usually defined as the ratio of soil resistance to quake.

There are different suggested values for the Smith damping factor for shaft and toe. Smith, (1960) suggested 0.16 s/m for the shaft and 0.49 s/m for the toe for all types of soil. Different ranges for Smith damping factor for shaft and toe were also suggested by Mukherjee and Nagarajub, (2013).

Litkouthi and Poskitt, (1980) conducted some experiments and suggested that the damping exponent (n) is around 0.2 for the side. AllWave-VDP software used 0.2 for the toe and 1.0 for the shaft when layers are sandy soil.

$$R_d = J_s R_s v^n \quad (4)$$

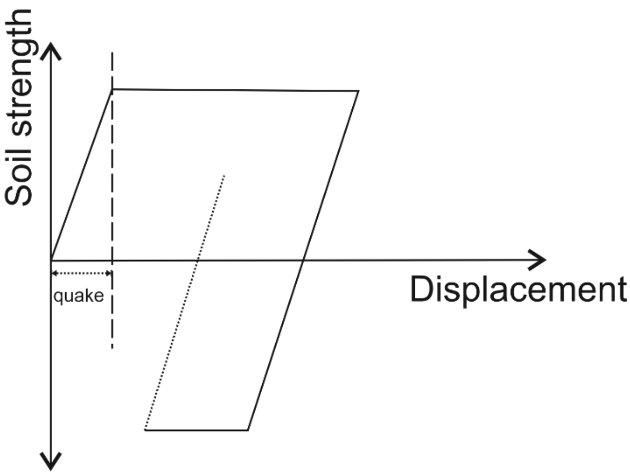

Fig. 2 Static shaft resistance for the Smith model (Rausche, 2002)

3.2 TNO model

The TNO model is similar to the Smith model; however, it differs in using two quake values, leading to different stiffnesses for loading and unloading. The damping absorbs energy during downward and upward movement. The damping force given by:

$$W_v = Cv^{alpha}, v > 0$$
$$W_v = -Cv^{alpha}, v < 0 \quad (5)$$

where W_v is the damping force, C is the damping constant, and alpha is an exponent for the velocity (Allnamics, 2020, Fig. 3). Damping constant in TNO soil model for the shaft is expressed as (Allnamics, 2020):

$$C = \sqrt{G\rho} \quad (6)$$

and for toe:

$$C = 1.08\sqrt{G\rho}/(1 - v) \quad (7)$$

where G is the soil shear modulus, ρ is soil density and, v is Poisson's ratio.

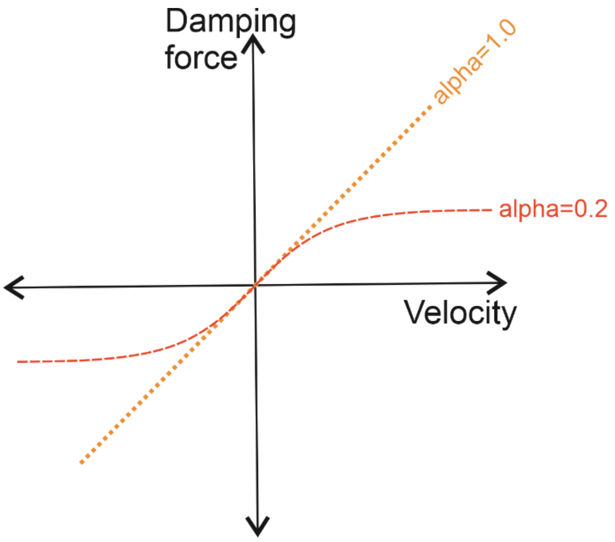

Fig. 3. Damping model for the TNO model (Allnamics, 2020)

3.3 Soil degradation

During vibratory pile driving, the soil resistance will degrade. To estimate the degradation in the cyclic soil resistance, Jonker, (1987) introduced a simple parameter named Beta Factor which is the ratio of the residual (degraded) soil resistance and the initial value for a particular soil type.

$$\beta = \frac{F_{residual}}{F_{initial}} \quad (8)$$

The soil around the shaft can experience a very high number of cycles during penetration. However, this is not the case for the pile toe. Generally, the Beta Factor for the shaft should be lower than that of the pile toe. Middendorp and Verbeek, (2012) suggested Beta Factor be equal to 0.1 for round coarse sand and 0.4 for clay.

3.3 Modeling of the pile

A pile could be considered as a rigid body if the driving frequency is equal to or less than 10% of the natural frequency of a pile as a freely vibrating rod (Viking, 2002). However, in this study, the pile was considered flexible because of the long piles used in this study, the amplitude changes along the pile length; therefore, the rigid body assumption is not valid. AllWave-VDP uses the Method of Characteristics which models the amplitude of displacements and forces along the shaft and at the pile toe (Allnamics, 2020).

3.4 Initial simulations

Initially, the simulations were performed using the software's default values (Table 2). Drivability prediction of the piles P4 and P5 were assessed. This study analyzes a large diameter pile, an unplugged scenario is assumed. Therefore, a lower inside resistance factor is considered than the outside resistance factor for the monopile as most layers are sandy soil (API, 2021).

The CPT profile was used as an input, and the changes of the operation frequency at 9 m are also applied in the software. The TNO and Smith models were both used in two separate drivability analyses. The driving time is used as a measure to assess the accuracy of the initial drivability predictions. Then, the Beta Factor parameter is revised to improve the driving time prediction to match the actually observed driving time on the site. VCPTu results obtained from the Altenwalde site are used to justify the changes of the Beta Factor (Al-Sammarraie, 2020).

3.5 Effect of Beta Factor

If the initial suggested values for quake and damping are assumed to be acceptable, the Beta Factor which reduces the resistance during driving is the key parameter to be revised in order to investigate its effect on the penetration. Al-Sammarraie, (2020) conducted VCPTu in this test site with a frequency of 20 Hz and displacement amplitudes ranging from 3 to 7 mm. Based on the results, degradation of soil resistance increased significantly with increasing amplitude, leading to a low value for the Beta Factor (Al-Sammarraie, 2020; Al-Sammarraie et al., 2022). The pile driving amplitude in the field was around 5 mm based on the recorded data, which reduces the initial considered value of Beta Factor for shaft from 0.1 to 0.05 and toe from 0.5 to 0.15. These values were chosen based on the obtained Beta Factor by conducting VCPTu with 5 mm as a displacement amplitude. This reduction was used for both piles (P4 and P5) and soil models (Smith and TNO), and in this study, they were considered constant with depth for simplicity.

Table 2. Initial input parameters for piles P4 and P5.

	Smith		TNO	
Parameter	Unit	value	Unit	value
Quake	[mm]	2	[mm]	2
Damping	[s/m]	0.26(Shaft) 0.50 (Toe)	[kNs/m^3]	Based on Eqs. (6 & 7)
Power Alpha	[-]	1.0(Shaft) 0.2 (Toe)	[-]	1.0(Shaft) 0.2 (Toe)
Beta Factor (sandy soil)	[-]	0.10(Shaft) 0.50 (Toe)	[-]	0.10(Shaft) 0.50 (Toe)
Inside Factor	[-]	0.8	[-]	0.8
Outside Factor	[-]	1.0	[-]	1.0

4 RESULTS

The penetration rate results for both piles based on the initial input parameters for Smith and TNO soil models are illustrated in Fig 4. These results are obtained by analysis per each meter of penetration. As can be seen, after the depth of around 9 meters, the penetration rate increases first because of the increased frequency; however, it starts to decrease because of the increase in the soil resistance (Fig. 1). Both piles were predicted to have refusal at depths around 9 and 14 m for TNO, and 16 m for the Smith model. Therefore, values of the Beta

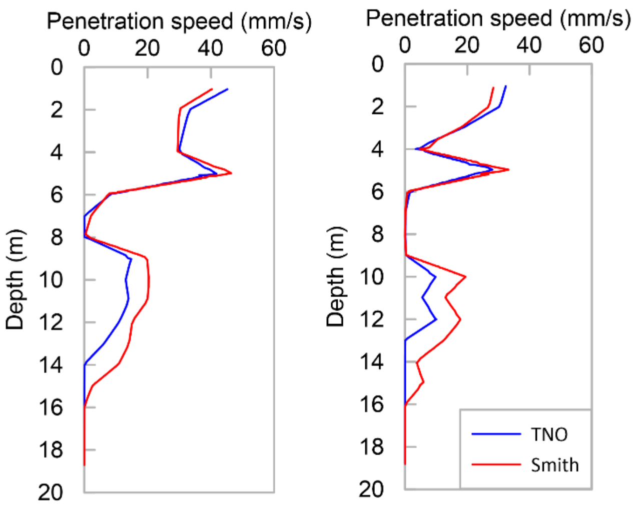

Fig. 4 Predicted penetration rate for pile P4 (left) and pile P5 (right)

Factor were changed in order to investigate, if a comparable driving time between the analysis results and the data obtained from the full-scale pile installation in the field could be obtained; and to eliminate the early refusal which was not observed in the field.

After changing the Beta Factor, from 0.1 to 0.05 for the shaft and 0.5 to 0.15 for the toe, the penetration speed and driving time were plotted in Fig. 5. The obtained values for the driving time were close to the reported value in the field (Table 1). No early refusal of penetration was observed for both piles in both smith and TNO models. The results obtained via the TNO soil model seem conservative even after using the lower Beta Factor for both shaft and toe (Fig. 4 and 5). Due to variability of cone resistance values with depth, the results may change slightly with choosing different depths for multiple penetration runs.

To validate the accuracy of the drivability analysis, the recorded acceleration and strain data of pile P5 during installation were processed to obtain the displacement and stress data, respectively. The obtained

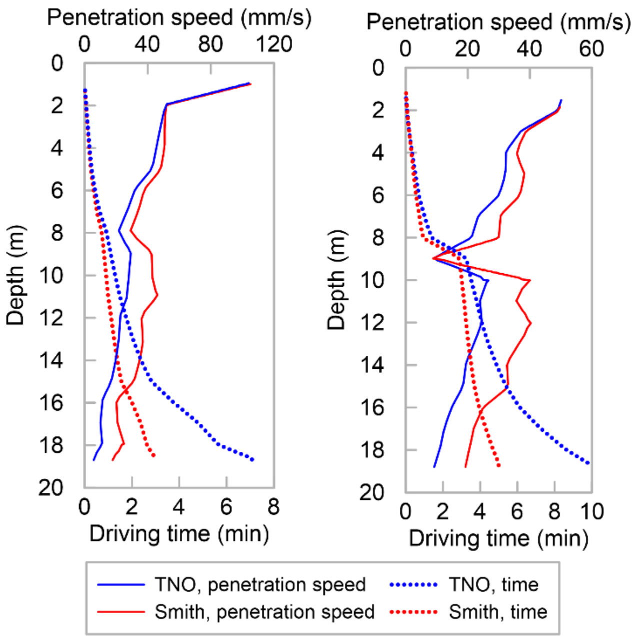

Fig. 5. Predicted penetration rate with modified Beta Factors for pile P4 (left) and pile P5 (right)

results were then compared with the results of displacement and stress obtained from the analysis for pile P5 for both smith and TNO model at the end of driving (Fig.6). As it can be seen, the results for both soil models are comparable to the field data, which proves a reasonable level of accuracy in the modeling.

5 DISCUSSION

The early refusal and the different driving time of the drivability analysis and actual driving in the field, prove that using the suggested initial input soil parameters sometimes lead to inaccurate drivability prediction results (Fig. 4). The improved prediction of the driving time, displacement, and stress, when changing the Beta Factor to VCPTu derived values gives evidence that the main uncertainties in the analysis are related to insufficient knowledge of how the amplitude and frequency of vibration affect the degradation of cyclic soil resistance (Fig. 5 and 6). The Beta Factor which describes the degradation of cyclic soil resistance, is usually estimated from the experience of full-scale vibratory driven piles in certain soil types with no regard to the effect of vibratory driving parameters (Jonker *et al.*, 1988). The revised Beta Factor values that were chosen for the second part of the analysis were based on the similarity of the amplitudes of VCPTu and vibratory driven piles at the site, although the penetration velocities were different. This might be justified, because the degradation of cyclic cone resistance during vibratory driving was found to be independent of the frequency in a study comparing the cone resistance of CPT and VCPT in the MARUM Calibration Chamber (Bhaskar *et al.*, 2022). A complex quasistatic behaviour was recognized, which caused the cyclic cone resistance

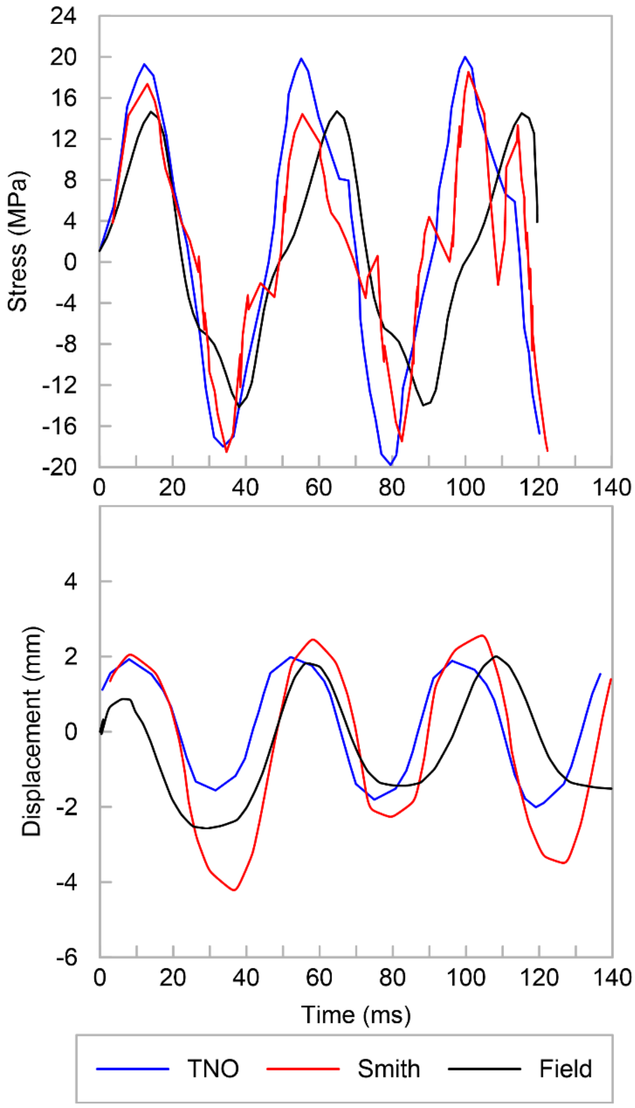

Fig. 6 Comparison of predicted displacement and stress amplitude using modified Beta Factor for shaft and toe (Pile P5, at sensor levels in the field)

degradation. This quasistatic behavior was tentatively accounted to a cavity that forms between the cone and soil during the upward movement of the cone, and the length of this upward displacement of cavitation was found to be dependent on the amplitude and independent of vibratory driving parameters (Al-Sammarraie *et al.*, 2022; Bhaskar *et al.*, 2022). However, the authors suggested that more experiments with higher frequencies and different driving amplitudes are needed to make a definite conclusion (Bhaskar *et al.*, 2022).

The conservative results obtained from the TNO soil model after using a lower Beta Factor for both shaft and toe (Fig. 5) could be related to the damping force formula used in the TNO soil model. This formula has a shear modulus parameter inside itself, and this value is obtained using an empirical formula dependent on cone resistance. On the other hand, using the lower Beta Factor with the Smith model gives a driving time closer to field data.

This study showed that - as expected - the Beta Factor significantly affecs the drivability predictions and that VCPTu results can be used to choose an appropriate value at least for this one example. VCPTu moreover helps to understand how the Beta Factor changes in different soil layers and how it is affected by different driving amplitudes. However, more simulations and experiments need to be conducted to evolve this scheme to a reliable pile drivability analysis.

6 CONCLUSIONS

This study analyzed two vibratory-driven piles at the Cuxhaven sandpit site. The initial results showed that the suggested values used in the software for Beta Factor led to refusal during pile installation, which was not observed in the field. Therefore, based on the VCPTu data and the amplitude of pile driving, the Beta Factor was changed to improve the drivability predictions for both piles. The results with a lower VCPTu chosen Beta Factor gave better match between the drivability analyses and the actual driving in the field.

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