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Geotechnical characterization of a test site in Zeebrugge for large scale tests of monopiles in the framework of the SAGE-SAND project

Caractérisation géotechnique d'un site d'essai à Zeebruges pour des tests à grande échelle de monopieux dans le cadre du projet SAGE-SAND

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ABSTRACT: This paper reports on large scale tests of monopile foundations for Offshore Wind Turbines (OWT) to be conducted in test site in Zeebruges, Belgium, in the framework of the SAGE-SAND project (*Soil ageing around OWT foundations – from operational response to decommissioning*). The project aims to investigate the evolution of the soil mechanical properties with time, and the alternative use of vibratory driving, to hammering, for installation and decommissioning of monopiles. Four hollow steel monopiles will be installed, by impact hammering and by vibratory driving, at a location where the soil conditions are representative of the Belgian sector of the North Sea. At selected time intervals during the project, the piles will be subjected to lateral loading at a fraction of their lateral capacity. Both the soil ageing effects and the influence of the installation method will be investigated. Herein an overview of the SAGE-SAND field testing program is presented, along with geotechnical information obtained from standard in-situ tests. Cone Penetration Tests (CPTs), as well as geological information and existing boreholes in the vicinity of the project are shown. Available correlations and empirical relationships from the Belgian practice are used to infer the soil stratigraphy and relate CPT data to soil properties necessary to perform predictive numerical simulations. Continuous in-situ tests such as cross hole tests and CPTs to the proximity of the piles throughout the duration of the project will allow the examination and the analysis of the soil ageing process.

RÉSUMÉ: Ce document rend compte de tests à grande échelle de fondations monopieux pour les éoliennes offshore (OWT) à réaliser sur un site d'essai à Zeebruges, en Belgique, dans le cadre du projet SAGE-SAND (vieillissement du sol autour des fondations OWT - de la réponse opérationnelle à la mise hors service). Le projet vise à étudier l'évolution des propriétés mécaniques du sol avec le temps, ainsi que l'utilisation alternative du battage vibratoire, par rapport au martelage, pour l'installation et la mise hors service des monopieux. Quatre monopieux en acier creux seront installés, par martelage et par battage vibratoire, dans un endroit où les conditions du sol sont représentatives du secteur belge de la mer du Nord. À des intervalles de temps sélectionnés pendant le projet, les pieux seront soumis à une charge latérale correspondant à une fraction de leur capacité latérale. Les effets du vieillissement du sol et de la méthode d'installation seront tous deux étudiés. Une vue d'ensemble du programme d'essais sur le terrain SAGE-SAND est présentée ici, ainsi que des informations géotechniques obtenues à partir de tests in situ standard. Des essais de pénétration au cône (CPT), ainsi que des informations géologiques et des sondages existants à proximité du projet, sont également présentés. Des corrélations disponibles et des relations empiriques issues de la pratique belge sont utilisées pour déduire la stratigraphie du sol et relier les données CPT aux propriétés du sol nécessaires à la réalisation de simulations numériques prédictives. Des tests in-situ continus tels que des essais de trou traversant et des CPT à proximité des pieux tout au long de la durée du projet permettront l'examen et l'analyse du processus de vieillissement du sol.

Keywords: Offshore geotechnics; mono-pile foundations; site investigation; large-scale tests.

1 INTRODUCTION

Offshore wind energy, decisive in the global shift towards green energy, is marked by ambitious plans worldwide to expand wind farms for a sustainable, long-term renewable energy supply. The wind farms, consisting of large turbines, hold significant potential to generate multi-gigawatts of electricity. The focus on minimizing costs for offshore turbines is crucial for achieving this long-term vision and requires advanced engineering approaches for design and site-specific optimization, especially for the foundations, that constitute approximately 30% of the total cost (Gavin et al., 2016).

Monopiles are the most commonly used foundation system for Offshore Wind Turbines (OWTs): large-diameter steel tubes which are either impact- or vibratory driven into the seabed. Recent studies conducted to advance design methodologies for monopiles for OWTs result from the findings of the PISA project. As such, a new design method has been developed by combining numerical modelling approaches and findings from large-scale monopile tests conducted at two sites, namely Dunkirk (dense sand) (Byrne et al., 2020) and Cowden (stiff clay) (Burd et al., 2020). The tests mainly focused on monotonic lateral loading and explored the rate effects and cyclic loading. However, previous research efforts have suggested the need for investigating the effect of soil ageing and installation method on the monopiles' response, as described in the following.

The soil ageing phenomenon, often referred to as "set-up," has been studied in the context of driven piles in clay, where the dissipation of excess pore pressures induced by driving leads to a positive gain in capacity with time (Gavin et al., 2016). However, the understanding of the mechanisms of ageing for piles in sand, as well as the quantification of its effect on the monopile's stiffness and lateral capacity, remains still much less explored. Field studies were conducted by researchers at Imperial College London (IC), the Norwegian Geotechnical Institute (NGI), and University College Dublin (UCD), to shed light on the behaviour of monopiles subjected to ageing processes.

All these studies revealed that ageing effects on steel pipe piles may be responsible for an increase in axial capacity with time (Jardine et al., 2005), although with variable growth rates. Karlsrud et al. (2014) attributed this variability to local soil conditions, emphasizing the need for site-specific considerations in understanding ageing effects.

On top of such considerations, environmental concerns regarding noise emissions during pile driving have led to the development of alternative installation methods to mitigate the impact on marine ecosystems.

The Vibro project conducted a major field trial at Cuxhaven involving six instrumented monopiles. The project's findings, as presented by Achmus et al. (2020), indicate that when monopiles in sand are installed by vibro-driving without specific requirements, reduction factors for stiffness during primary loading and unloading should be considered in the design. The study concludes the need for further research to identify optimum installation parameters.

Figure 1. Experimental site for large scale pile testing established for the SAGE-SAND project in Zeebruges, Belgium.

The SAGE-SAND project *"Soil ageing around offshore wind turbine foundations - from operational response to decommissioning"* aims to study the interaction between soil and pile for OWTs, in order to understand the effects of the soil ageing and of the installation process on the lateral behaviour of the foundation system during its lifetime, up to the decommissioning of the pile. For this purpose, an experimental site has been selected at the Port of Antwerp-Bruges in Zeebruges, Belgium (Figure 1).

The main aim of this paper is to show preliminary findings from the research project's initial stage, focusing on the CPT measurements to enhance understanding of the reference site.

2 OVERVIEW OF THE PROJECT

The experimental campaign provides for: an extensive geotechnical site investigation, the pile installation, lateral pile load tests, and at the end, the pile extraction. The geotechnical site characterization includes borings to identify the soil stratigraphy and retrieve samples for laboratory tests (e.g., soil classification, triaxial test), cross-hole tests, inclinometer measurements, Cone Penetration Tests (CPTs), seismic CPTs, and the geophysical method Multichannel Analysis of Surface Waves (MASW).

The piles have a diameter of 2.0 m and an embedded length of 18 m. According to the initial plan two piles will be vibratory installed, and two piles will be hammered. The dynamic pile response during driving will be measured using accelerometers. The strains along the pile will be continuously measured using optical Fiber Bragg Gratings (FBG's). Piezometric pore water pressures in the vicinity of the piles will detect overpressures, that arise during the driving and can induce liquefaction of the surrounding soil. As the heat from the driving process may influence the chemical and ageing processes in the foundation soil, the temperature distribution will be measured using thermocouples, and the soil plug inside the piles will be monitored.

The long-term monitoring plan includes regular CPTs at the proximity of the piles, repeated cross-hole tests, and pile impedance measurements. The continuous monitoring will be carried out at selected time intervals, following lateral load tests. This way it aims to capture the evolution of soil properties with time, to provide insights crucial to achieve the project's objectives. The present paper focuses on the analysis and interpretation of the CPT campaign.

3 GEOLOGICAL INFORMATION

Preliminary information about the local geology has been obtained from the Databank Ondergrond Vlaanderen (DOV). This is a database that provides geological and geotechnical information from the Flemish subsurface, available via the online DOV Portal (DOV, 2023). The subsoil at the test site consists of Quaternary deposits up to a depth of 22.50 m, Tertiary (Eocene) and Quaternary layers up to a depth of 27.5 m, on top of Tertiary layers. The groundwater is saline. A complete set of data is retrieved from an existing borehole, near the test site (borehole: 1439-BB69-1818, DOV portal).

The samples extracted during the execution of this borehole are available in the Geotheek, the Flemish repository for samples from the subsurface (DOV, 2023). This helped gain an initial understanding of the stratigraphy at the nearby test location. In this regard, eight layers have been identified (starting from the ground surface): silt, fine sand interspersed by silt, silty clay, peat, silty sand, medium sand interspersed by thin lenses of fine sand.

4 CONE PENETRATION TESTS

4.1 Description of the equipment and test locations

Four electrical cone penetration tests (e-CPTs) were conducted at the locations of the piles, as shown in Figure 2. The probes were performed using a 10 cm^2 electric cone. The cone resistance, q_c, and the friction resistance, f_s, are measured at depth intervals of 1 cm. Their ratio, expressed as a percentage, yields the parameter R_f, friction ratio.

Figure 2. CPTs performed at the locations of the piles.

4.2 CPT data and soil layering

The CPTs data are used to determine the stratigraphy of the subsoil and estimate its properties. In particular, the acquired data are interpreted using available empirical methods to estimate the soil engineering parameters, such as strength and stiffness, that are required to conduct installation and lateral load analyses of the test piles. In particular, the subsoil at the test location has been idealized as a layered deposit, where each layer is considered homogeneous, and it is characterised by average constant q_c and R_f values. These values are calculated by omitting the extreme peaks, identified using the statistical method called "interquartile range" to find the outliers of a dataset. Figure 3 shows the CPT data in terms of q_c and R_f, at the four investigated locations S1, S2, S3 and S4, as well as the idealized soil layers. The complete set of the CPT data will be made available on the database titled Databank Ondergrond Vlaanderen (URL:https://www.dov.vlaanderen.be/portaal/?module=verkenner).

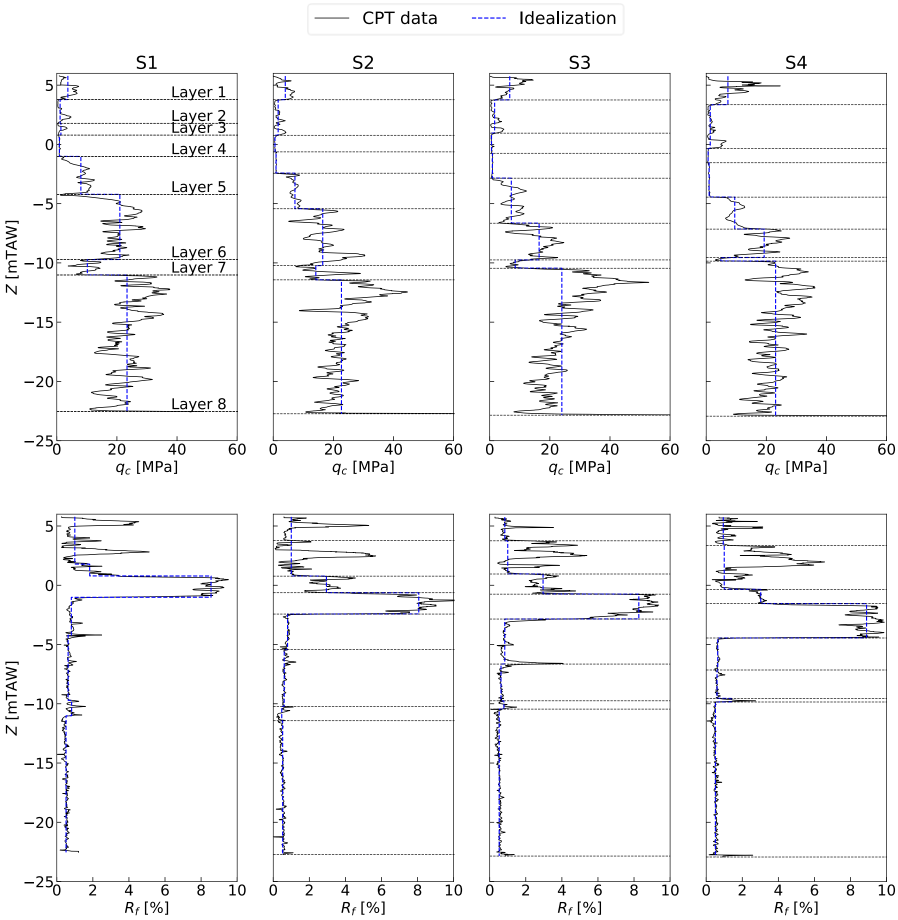

Figure 3. CPT data and layer idealization at the 4 investigated locations.

Table 1. Average values of q_c and f_s per soil layer at the 4 investigated locations.

	S1		S2		S3		S4	
Layer	q_{cm} (MPa)	f_{sm} (MPa)	q_{cm} (MPa)	f_{sm} (MPa)	q_{cm} (MPa)	f_{sm} (MPa)	q_{cm} (MPa)	f_{sm} (MPa)
1	3.69	0.040	4.01	0.040	6.66	0.061	7.22	0.057
2	1.10	0.019	1.63	0.020	1.64	0.027	1.36	0.032
3	1.38	0.020	0.57	0.016	0.59	0.02	0.64	0.019
4	0.87	0.076	0.93	0.074	0.90	0.073	0.98	0.088
5	8.01	0.066	7.22	0.056	7.19	0.060	9.49	0.061
6	20.98	0.133	16.46	0.103	16.43	0.112	19.29	0.117
7	10.17	0.079	14.16	0.064	8.48	0.068	4.85	0.069
8	23.37	0.118	22.69	0.118	23.98	0.120	23.09	0.117

5 BELGIAN GUIDELINES FOR CPT DATA INTERPRETATION

The recommendations by the Belgian standard 'NBN EN 1997-1 ANB' were adopted to identify the mechanical properties of the soil layers. The average q_c and f_s values are used to provide such estimates. Table 2 presents the soil effective unit weight γ', the friction angle φ', the undrained shear strength c_u, and effective cohesion c'.

Table 2. Soil mechanical properties per layer according to the Belgian practice (NBN EN 1997-1 ANB).

Layer	γ' (kN/m^3)	φ' (°)	c_u (kPa)	c' (kPa)
1	9	28	-	-
2	8	25	25	2
3	7	23	14	2
4	2	15	20	5
5	9	30	-	-
6	10	35	-	-
7	10	30	-	-
8	10	35	-	-

6 GEOTECHNICAL CORRELATIONS USING CPT DATA

Suitable correlations from the literature have been selected to provide additional CPT-based predictions of the soil parameters.

The total unit weight, γ, was estimated from CPT data using the relationship proposed by Robertson and Cabal (2015):

$$\frac{\gamma}{\gamma_w} = 0.27\ logR_f + 0.36\ log\left(\frac{q_t}{p_a}\right) + 1.236 \quad (1)$$

where γ_w is the unit weight of water, p_a is atmospheric pressure, q_t is the CPT corrected total cone resistance.

To estimate the peak friction angle, φ', the expression by Uzielli et al. (2013), valid for clean quartz sands, was adopted:

$$\varphi' = 25\left[\frac{(q_t/p_a)}{\sqrt{\sigma'_{v0}/p_a}}\right]^{0.1} \quad (2)$$

where σ'_{v0} is the in-situ vertical effective stress.

The soil relative density, D_R, was estimated by the formula proposed by Jamiolkowski et al. (2003), which is valid for clean silica sands:

$$D_R = 100\left[-0.675 + 0.268\,ln\left(\frac{q_c/p_a}{\sqrt{\sigma'_{v0}/p_a}}\right)\right] \quad (3)$$

The overconsolidation ratio, OCR, was evaluated as the ratio between the soil effective yield stress, σ'_p, and σ'_{v0}. To estimate σ'_p, the correlation provided by Mayne (2013) valid for all soils was adopted:

$$\sigma'_p = 0.33(q_t - \sigma_{v0})^m (p_a/100)^{1-m} \quad (4)$$

where σ_{v0} is the total vertical stress, m can be calculated by Eq. (5) as suggested by the author:

$$m = 1 - \frac{0.28}{1 + (I_c/2.65)^{25}} \quad (5)$$

where I_c is the soil behaviour type index as reported in Robertson and Wride (1998) and Robertson (2009).

The following relationship between c_u and OCR, valid for fine-grained soils, was adopted, considering that the compression indices and φ' are not known with confidence (Ladd and DeGroot, 2003):

$$c_u = \sigma'_{v0}0.22OCR^{0.8} \quad (6)$$

To estimate the small strain shear modulus, G_0, the well-known relationship between G_0 and the shear wave velocity, V_s, provided by the elasticity theory, has been considered. A number of empirical correlations to estimate the V_s profile using CPT data are available in literature. Herein, the in-situ V_s profiles were estimated using the equation derived by Mayne (2006) which was obtained from a well-documented experimental dataset of saturated clay, silt, and sand sites:

$$V_s = 118.8\log f_s + 18.5 \quad (7)$$

where V_s is in (m/s) and f_s in (kPa).

A more accurate estimation of G_0 will result from the interpretation of the MASW data and cross-hole tests data.

Table 3 presents the estimated values of the layers' physical and mechanical properties, namely the soil effective unit weight, γ', peak friction angle, φ', relative density, D_R, overconsolidation ratio, OCR, undrained shear strenght, c_u, and small strain shear modulus, G_0.

Table 3. Soil mechanical properties per layer according to correlations for the CPT interpretation at the test site.

Layer	γ' (kN/m^3)	φ' (°)	D_R (%)	OCR (-)	c_u (kPa)	G_0 (MPa)
1	9	-	-	18	20	89
2	7	-	-	3	13	66
3	7	-	-	3	23	59
4	8	-	-	5	42	104
5	9	39	53	3	-	98
6	10	42	70	3	-	130
7	9	38	49	2	-	104
8	10	42	69	2	-	132

Note that values for the soil mechanical properties are not reported for the layer types that fall outside the applicability range of the adopted correlations. Detailed analyses are included in the geotechnical report titled "Interpretation of CPT results for the SAGE-SAND test site in Zeebrugge" (Letizia et al., 2023). By comparing the estimated parameters presented in Tables 2 and 3, large differences in values can be observed. This discrepancy can be attributed to the fact that the Belgian guidelines provide a rather conservative estimation of the soil parameters to be used in design based on the experience of the local soils.

7 CONCLUSIONS

This study presents an analysis of geotechnical data obtained from the SAGE-SAND project's site CPT campaign. Specifically, the geotechnical interpretation of four CPTs conducted at the site in Zeebruges, Belgium, is presented. The research project aims to quantify the impact of the soil ageing and installation process, namely impact hammering and vibratory driving, on the lateral capacity and stiffness of monopiles for offshore wind turbines, as well as on extractability of such foundations during the decommissioning phase. This work focuses on the geotechnical characterization of the test site, and provides its soil stratigraphy by interpreting CPTs using the Belgian design guidelines and correlations from the existing literature. Additional tests which include geophysical methods (MASW), cross-hole tests, seismic CPTs and extensive laboratory tests are currently ongoing to best identify the soil properties to be used consequently to simulate the pile installation and make predictions of the lateral monopile response.

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