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A new robotic CPT p-y module for offshore seabed characterisation and offshore pile design

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ABSTRACT: There is a growing need to develop in-situ ground characterization tools that collect sufficient data earlier in the project cycle to compress the typical timelines of offshore infrastructure projects. A robotic tool extending the standard cone penetrometer test (CPT) with a separate module capable of horizontal translation - referred to as the p-y module - has been recently developed, as part of the collaborative ROBOCONE project This paper presents a data interpretation framework for ROBOCONE tests undertaken in undrained clay and drained sand respectively. The framework is built upon a suite of finite element analyses of the ROBOCONE p-y module, with a process to convert the ROBOCONE data for use in pile design. The framework accounts for end effects, i.e. the influence of the finite length of the ROBOCONE module, when compared to plane strain conditions or a laterally loaded pile shaft. For undrained clay, the interpretation provides the undrained shear strength and elastic shear modulus from ROBOCONE data. For drained sands, the interpretation framework determines p-y curves for direct use in pile design. As an example of the potential of the ROBOCONE, the corrected and converted ROBOCONE p-y curves were used to directly predict the force-displacement response of a laterally loaded pile, which was simulated in a separate finite element analysis. Overall, the interpretation methods in this paper can underpin the adoption of this new site investigation tool, to accelerate offshore site characterisation and infrastructure design.

Keywords: Cone penetration testing; Offshore seabed characterisation; Pile design; ROBOCONE p-y module; p-y curve

1 INTRODUCTION

A substantial growth in the volume of offshore site surveys and onshore laboratory tests is required to support the expansion of the offshore wind market in order to tackle global climate change and meet the aims of the Paris agreement (Cerfontaine et al. 2023, White 2023, Gourvenec 2024). There is a strong incentive to improve the data that can be collected from offshore in-situ tests so that the number of time-consuming onshore lab testing can be reduced, and thus the timeline of offshore wind farm construction can be compressed.

Cone penetration testing (CPT) is the most prevalent in-situ test in offshore sector. Its primary measurements are tip resistance and sleeve friction which can be empirically interpreted to approximate the stiffness and strength parameters of the Winkler-type soils springs (p-y method) (e.g. Truong & Lehane 2014). However, the soil failure mechanism induced by the vertical CPT penetration is different to that induced by the lateral loading of offshore piles, as illustrated in Figure 1.

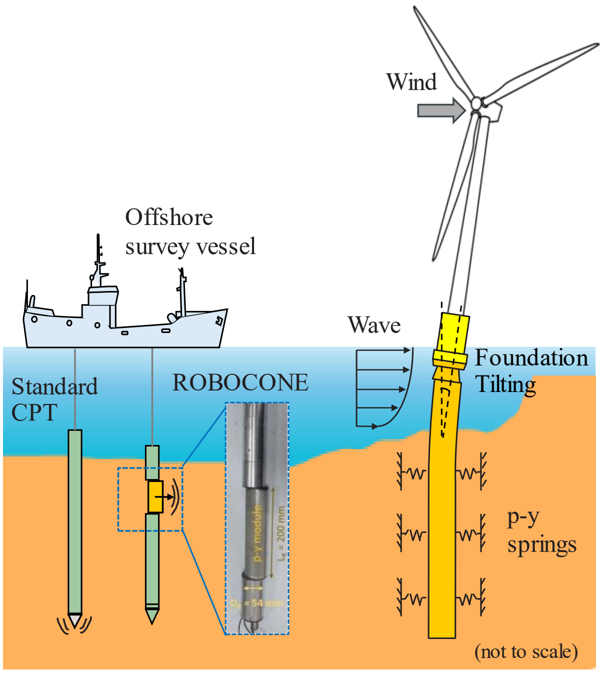

Figure 1. Schematic illustration of ROBOCONE p-y module and the nonlinear p-y design approach for offshore piles

The ROBOCONE p-y module extends the kinematic range of the CPT, thanks to recent advancements in robotics, control systems and sensor miniaturisation. This module is designed to be integrated into the string of a standard 15cm^2 CPT and is capable of horizontal translation (Figure 1). The resulting stress path imposed on the ground better mimics the stress paths imposed by laterally loaded piles than a CPT penetration test. More specific details of the prototype p-y module are described in Diambra et al. (2022) and Creasey et al. (2024).

The ROBOCONE can be used to accelerate the design of offshore laterally loaded piles in two ways: (i) by deriving soil constitutive model parameters in-situ (such as undrained strength, elastic shear modulus) and thus reducing the need of onshore lab testing; (ii) by measuring p-y curves in-situ to support the design of laterally loaded piles. However, in both cases, the ROBOCONE data must be corrected to transformed parameters obtained by a finite length probing device, to plane strain parameters; this is referred to as the "end effect" correction. Similar end effects have been identified and corrected for other in-situ tools such as the pressuremeter (Yu 2006).

The objective of this paper is to introduce two interpretation frameworks to process ROBOCONE data obtained in clay or sand. In both cases, simulated ROBOCONE tests are corrected to account for end effects, to derive either soil strength and stiffness parameters (clay) or plane strain p-y curves (sand). Implementation and performance of the ROBOCONE framework is demonstrated by comparing the lateral response of a pile obtained by the ROBOCONE p-y curves with a separate 3D FE simulation of pile.

2 FINITE ELEMENT MODELLING

Both interpretation frameworks were derived based on a large database of finite element models. The geometry of the p-y module has two planes of symmetry, so only a quarter of the problem is simulated to reduce computational demand. All analyses were carried out in PLAXIS3D v23 (PLAXIS 2023). Figure 2 shows the ROBOCONE (shaft, p-y module and movable connection rings) and the soil domain. The modelled p-y module has an external diameter (D_{RC}) of 54 mm, a height (H_{RC}) of 100 mm and a wall thickness of 2 mm (Creasey et al. 2024). The contact between the ROBOCONE and the soil was simulated by zero-thickness elements characterised by an elastic-perfectly-plastic model.

A cylindrical soil domain is 0.5 m thick (= 5H_{RC}) and 1.68 m diameter (=31D_{RC}). These dimensions were chosen to ensure minimal boundary impact on the p-y module's response. The soil constitutive models for clay and sand will be described in the subsequent sections. Any displacements in the X and Y directions at the vertical cylindrical boundary were restrained, while orthogonal displacements were prevented at the two planes of symmetry.

The first simulation phase involved creating an isotropic stress state within the soil, by imposing a uniform surcharge pressure (σ_v') at the soil domain top surface and a K_0 of unity. In this study, the magnitude of surcharge pressure represents the operation depth of the p-y module. Subsequently, any soil deformation induced by the surcharge pressure was re-zeroed before activating the p-y module. The lateral monotonic loading was simulated by applying a prescribed displacement at the p-y module. The reaction force on the p-y module was then tracked at the rigid body reference point.

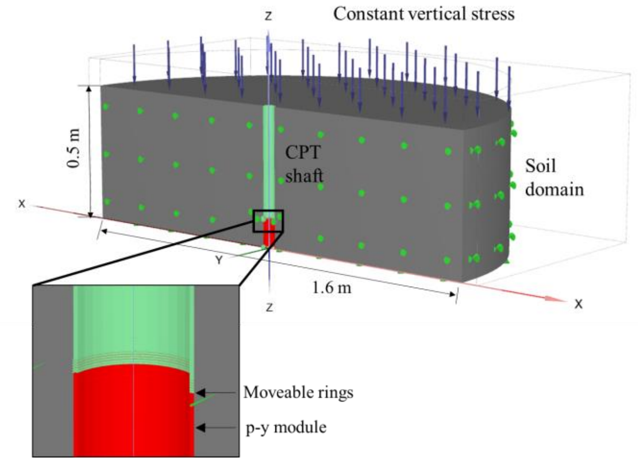

Figure 2.Geometry and boundary conditions of FE modelling for ROBOCONE p-y module. Representative of D_{RC} *= 54 mm and* H_{RC} *= 100 mm*

3 INTERPRETATION FRAMEWORK IN UNDRAINED CLAY

The aim of the interpretation framework in clay is to derive the in-situ undrained shear strength (s_u) and elastic shear module (G) from ROBOCONE data.

The clay was modelled by a linear elastic model with Tresca failure criterion described by the undrained shear strength (s_u). Figure 3 shows a typical force-displacement response, where p is the reaction force ($F_{t,\,RC}$) normalised by the projected surface area of the ROBOCONE module ($H_{RC}D_{RC}$) and the lateral displacement (y) is normalised by D_{RC}. An elastic linear response is experienced at small displacements, followed by stiffness degradation until reaching a plateau of ultimate resistance ($p_{u,RC}$).

The bearing factor (N_{RC}) and elastic stiffness factor (K_{RC}) are defined to link the measured ROBOCONE response, such as $p_{u,RC}$ and $k_{i,RC}$, to soil properties from the following developed framework across a wide range of soil properties.

$$N_{\mathrm{RC}} = p_{u,RC}/s_u \tag{1}$$

$$K_{\mathrm{RC}} = k_{i,RC}/G \tag{2}$$

where $k_{\mathrm{i,RC}}$ is the initial gradient of the normalised force-displacement response, $k_{i,RC} = (p/\bar{y})_i$.

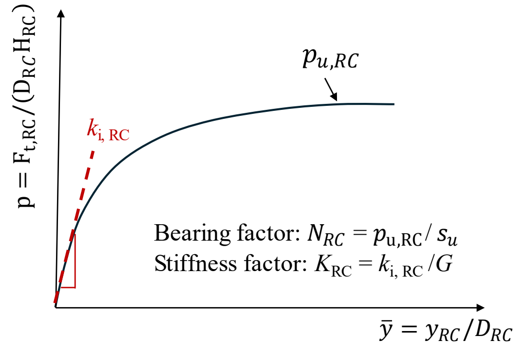

Figure 3. Typical normalised force-displacement response in undrained clay

Extensive FE analyses of the ROBOCONE p-y module have been carried out in clay (Wen et al. 2024a), with the dual objective of developing an interpretative framework and identifying the optimal ROBOCONE geometry. Figure 4 shows the bearing factors N_{RC} as a function of the aspect ratio ($H_{\mathrm{RC}}/D_{\mathrm{RC}}$) of the p-y module geometry. Each family of dots represents a different interface roughness, α. The variation of N_{RC} with interface roughness at $D_R/H_R \approx 0$ (denoted as $N_{\mathrm{s,RC}}$) is consistent with the plasticity lower and upper bound solutions for an infinitely long rigid pile set out by Martin and Randolph (2006).

The bearing factor grows linearly with the increase in D_R/H_R, independently of the interface roughness. This is due to the end effect created by the finite length of the ROBOCONE module, whereby the soil shear strength is mobilised above and below the upper and lower plates respectively. This increases the measured bearing factors when compared to the targeted plane strain value.

The following empirical model was developed by Wen et al. (2024a) to capture the variation of the bearing factor as a function of the aspect ratio:

$$N_{\mathrm{RC}} = \left[1 + 0.23 \cdot \left(\frac{D_{RC}}{H_{RC}}\right)\right] N_{\mathrm{s,RC}} \tag{3}$$

where $N_{\mathrm{s,RC}}$ is the bearing factor for an infinite shaft length ($D_{RC}/H_{RC} \approx 0$). Equation (3) is similar to an upper bound semi-analytical solution (Wen et al. 2024a) that explicitly accounts for the failure zone above and below the upper and lower plates of the ROBOCONE p-y module via an upper bound solution.

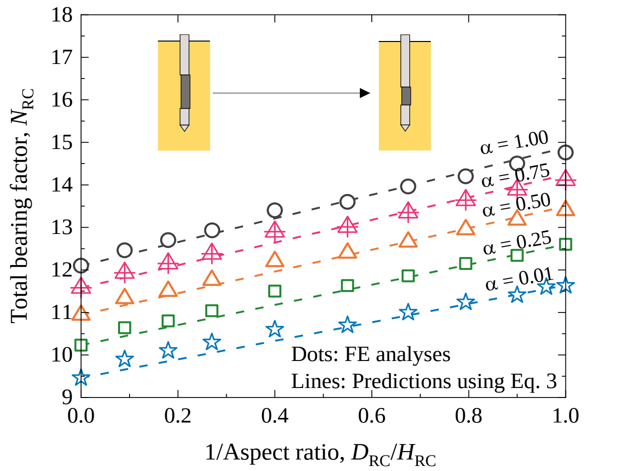

Figure 4. Effects of ROBOCONE geometry and roughness on N_{RC}

The stiffness factor (K_{RC}) for the p-y module also varies with the ROBOCONE geometry, as shown in Figure 5. It ranges between 4.0 and 6.0 for an infinite length, which is considerably greater than the equivalent stiffness factor of a pressuremeter ($K_{RC} = 2$). An approximately threefold enhancement in K_{RC} is obseved as H_R/D_R decreases from infinity to unity, in comparison to the modest 21%~23% increase in the bearing factor, N_{RC} (see Figure 4). The interface roughness has a negligible influence on the stiffness despite affecting the resistance at the failure load. The following empirical model was developed to estimate the stiffness factor for a particular ROBOCONE geometry and is superimposed on Figure 5:

$$K_{RC} \approx 4.13 + 12.5\left(\frac{D_R}{H_R}\right)^{0.8} \geq 5.0 \tag{4}$$

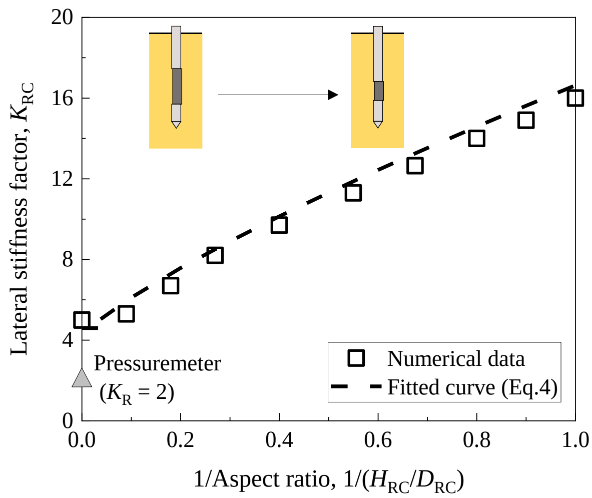

Figure 5. Effect of ROBOCONE aspect ratio on K_{RC}

4 INTERPRETATION IN DRAINED SAND

The aim of the interpretation framework in sand is to derive the in-situ p-y reaction curves directly from ROBOCONE data. This approach is preferred because the stress dependency of sand properties makes their direct determination cumbersome.

To explore this behaviour, FE analyses have been performed in which the sand properties are simulated by a bounding surface plasticity model (SANISAND-MS, see Liu & Pisanò 2019). This model can capture the effect of void ratio and mean effective stress on strength and stiffness with a single set of parameters.

Two types of FE analyses were undertaken (see Figure 6), from which the reaction force acting on the ROBOCONE module was measured.

- Case A: a lateral monotonic displacement is prescribed to the rigid p-y module, while the rest of the shaft is fixed. This corresponds to the normal operation of the ROBOCONE. The measured net reaction pressure p is denoted p_{RC}.
- Case B: the rigid p-y module and the rest of the shaft move together, ensuring zero relative displacement between two parts. This corresponds to plane strain conditions and to the p-y curve used for pile design. In this case the measured net reaction pressure p is denoted p_{PS}.

The contribution of the end effect (p_{EE}) to the measured p-y curve can be estimated as the difference between those two cases:

$$p_{\mathrm{EE}} = p_{\mathrm{RC}} - p_{\mathrm{PS}} \qquad (5)$$

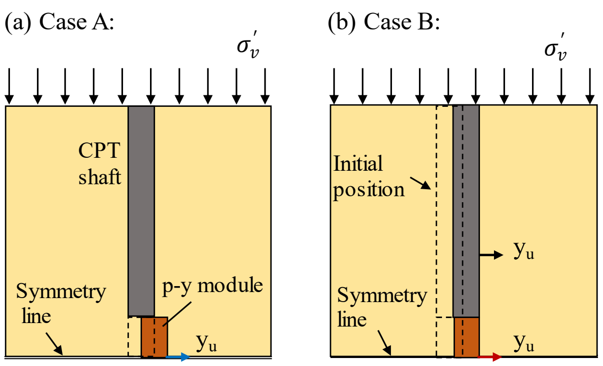

Figure 6. Determination of end effects through simulations of two loading conditions

An extensive finite element study has been undertaken to calibrate a correction model for the end effect, across a range of sand densities, surcharge pressure and ROBOCONE module geometries (Wen et al. 2024b). For a representative case with H_{RC}/D_{RC} = 3.7, Figure 7 illustrates the ROBOCONE resistance (p_{RC}, Case A), the measured plane strain p-y curves (p_{PS}, Case B) and the calculated end effect (p_{EE}) using Eq. 5. In this case, the relative density corresponds to 83% and surcharge pressure is 200 kPa. At small displacement, the total behaviour seems to be dominated by the plane strain component, while the end effects can account for 34% of measured total resistance at a displacement of 10%D_{RC}.

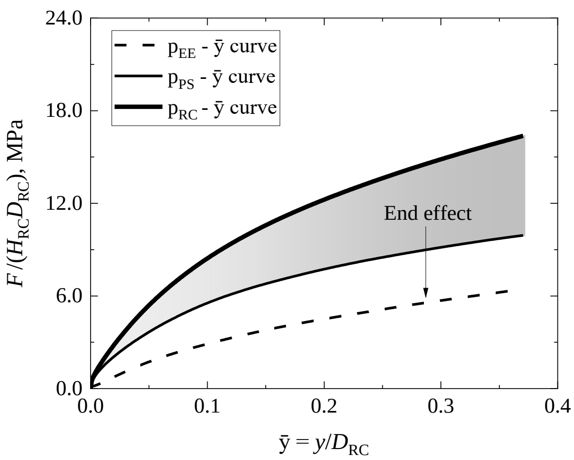

Figure 7. ROBOCONE response in sands: representative case: H_{RC}/D_{RC} = 3.7, D_R = 83% and σ_v' = 200 kPa

Figure 8 shows that the evolution of the ratio $p_{\mathrm{EE}}/p_{\mathrm{RC}}$ throughout the loading, with different p-y module aspect ratios. All of the curves demonstrate a increase in the relative contributions of end effect to the measured total force, with the increase in lateral displacement. For H_{RC}/D_{RC} = 16, the ratio of $p_{\mathrm{EE}}/p_{\mathrm{RC}}$ reduces by half relative to that for H_{RC}/D_{RC} = 3.7. This trend can also be identified through the field of accumulated soil vertical displacement near the ROBOCONE end, as seen in Figure 9, which shows ROBOCONE at 20% D_{RC} displacement. The longer the p-y module, the smaller the end effect contribution, which is beneficial. However, a longer p-y module requires larger force to displace it laterally, which is limited by the capacity of the actuation system.

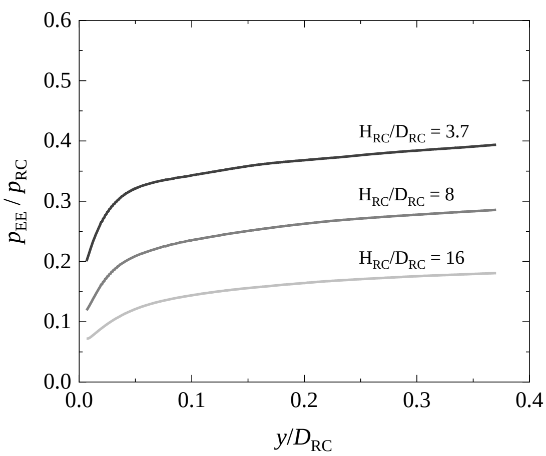

Figure 8. Effect of ROBOCONE geometry on the relative contribution of end effects to the measured total force

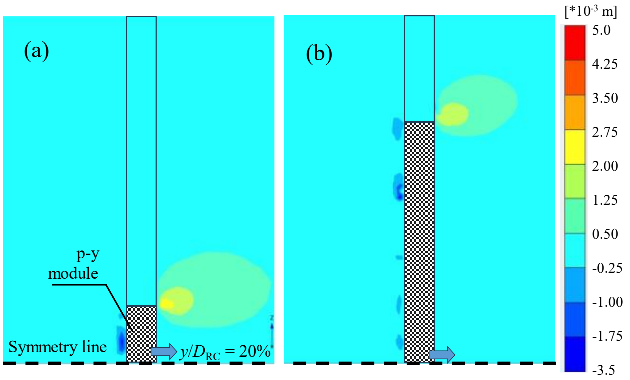

Figure 9. Accumulate soil vertical displacement near at at y/D_{RC} = 20%: (a) H_{RC}/D_{RC} = 3.7; (b) H_{RC}/D_{RC} = 16.0

An end effect model has been developed to enable correction of the ROBOCONE data across a range of lateral displacements to calculate the plane-strain $p_{\mathrm{PS}} - y$ curves directly in-situ (Wen et al. 2024b). To this end, the calculated end effect curves, $\tilde{p}_{\mathrm{EE}} - y$, obtained from the finite element parametric study can be fitted by the following explicit four-parameter conic function, which has been used previously to represent pile p-y reaction curves (Burd et al. 2020):

$$\tilde{p}_{\mathrm{EE}} = \tilde{p}_{u,EE} \frac{2c}{-b+\sqrt{b^2-4ac}} \tag{6}$$

$$\tilde{p}_{\mathrm{EE}} = \tilde{p}_{u,EE} \tag{7}$$

where

$$\tilde{p}_{\mathrm{EE}} = p_{\mathrm{EE}} * (H_{RC}/D_{RC}) \tag{8}$$

$$a = 1 - 2n_R \tag{9}$$

$$b = 2n_R \frac{\bar{y}}{\bar{y}_u} - (1 - n_R)\left(1 + \frac{\bar{y}k_R}{\tilde{p}_{u,EE}}\right) \tag{10}$$

$$c = \frac{\bar{y}k_R}{\tilde{p}_{u,EE}}(1 - n_R) - n_p \frac{\bar{y}^2}{\bar{y}_u{}^2} \tag{11}$$

Figure 10 represents the conic curves and the interpretation of each of the four parameters (k_{R}, $\tilde{p}_{u,EE}$, n_{R}, $\bar{y}_u$). The parameter k_{R} controls the initial slope, while the $\bar{y}_{\mathrm{u}}$ is the normalised displacement at which the normalised ultimate soil reaction $\tilde{p}_{u,EE}$ is attained. Beyond $\bar{y}_{\mathrm{u}}$, $\tilde{p}_{u,EE}$ remains constant. The parameter n_{R} ($0 \leq n_{\mathrm{R}} \leq 1$) influences the shape of the curve; for n_{R} = 0 or 1.0, the function reduces to the bilinear forms.

The developed model consists of a set of calibrated relationships between the conic function parameters and the soil conditions (relative density, surcharge pressure), which can be determined from CPT data. A two step optimisation was adopted to do so (Wen et al. 2024b). This model enables a reasonably accurate prediction of the plane strain p-y curve from measured ROBOCONE data.

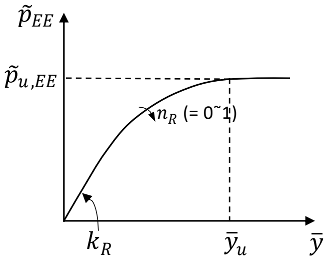

Figure 10. Illustration of conic curve and primary governing parameters

5 FROM ROBOCONE DATA TO PILE DESIGN

The feasibility of using ROBOCONE p-y curves for pile design is illustrated in this section. An additional 3D finite element model of an open-ended pile in sand was created. The pile was modelled as 1.0 m diameter, 20m long, with wall thickness of 0.04 m. The sand constitutive model and parameters are identical to the FE analyses of the ROBOCONE described above.

The $p_{\mathrm{RC}} - y$ curves were determined at every 1.5m depth from FE simulations of the ROBOCONE p-y module. They were used directly in the 1D beam-spring simulation software *LAP* (Doherty 2016) to determine the load-displacement relationship at the pile head, which is compared to the 3D simulation results in Figure 11. Also plotted is the pile head response using the corrcted $p_{PS} - y$ curves of ROBOCONE . Results indicate that once end effects are eliminated, the ROBOCONE data can provide encouraging predictions of the pile head response.

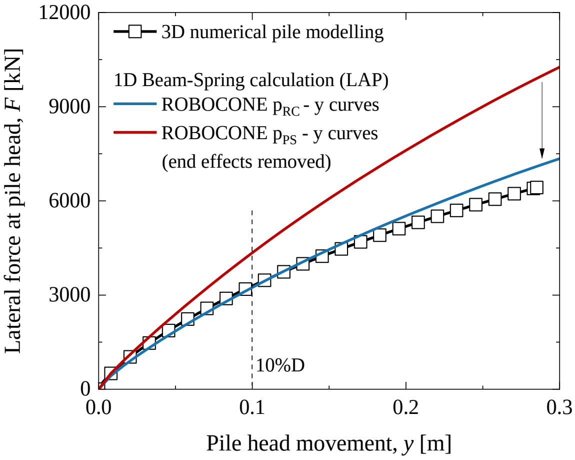

Figure 11. Comparison of lateral load-displacement relationship from 3D FE pile simulations and 1D pile simulations based on ROBOCONE p-y curves

6 CONCLUSIONS

This study presents interpretation frameworks to acquire design parameters for laterally loaded piles using a novel robotic ROBOCONE p-y module. The frameworks are based on extensive 3D finite element analyses of ROBOCONE in sands and clay.

The study has shown that for lateral pile design in undrained clay, soil parameters, including undrained shear strength and elastic shear modulus, can be accurately derived from the in-situ data of ROBOCONE through the developed models of bearing factor and stiffness factors. The bearing factor model is found to be a function of the aspect ratio and roughness of the p-y module, while the stiffness factor is mainly influenced by the aspect ratio.

For lateral pile design in drained sands, plane strain p-y curves can be extracted from ROBOCONE data using the presented end effect model, which account for surcharge pressure and relative density.

The obtained ROBOCONE p-y curves have been successfully used in 1D lateral pile analysis software to predict the force-displacement response of open-ended pile in sands, indicating a encoraging match to the 3D numerical response at the pile head.

AUTHOR CONTRIBUTION STATEMENT

First Author: Data curation, Formal Analysis, Methodology, Visualisation, Writing- Original draft. **Other Authors**.: Software, Conceptualization, Methodology, Supervision, Funding acquisition, Writing- Reviewing and Editing.

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