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Evaluation of CPT-based p-y curves for large diameter monopiles in clay

Zhaoyao Wang, Hans Petter Jostad
Norwegian Geotechnical Institute, Oslo, Norway, zhaoyao.wang@ngi.no

Gudmund Reidar Eiksund
Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT: In offshore wind projects, the p-y curve method is widely employed to model the soil reaction forces and stiffnesses along monopile depth. Since Cone Penetration Test (CPT) is extensively used in offshore site investigation to acquire in-situ data, efforts have been made to develop models that derive p-y curves directly based on CPT data. However, these empirical formulas based on specific sites and soil conditions are not necessary representative at other sites. In this study, the pile push-over analysis in hypothetical clay profiles with different Over Consolidation Ratio (OCR) and Plasticity Index (I_P) profiles are modelled by 3D Finite Element Method (FEM) using the commercial finite element program Plaxis 3D, and the results are compared with several existing CPT-based p-y formulas available in literature. The stress-strain relationships of the clays established from published data in the literature are modelled by the NGI-ADP soil model available in Plaxis 3D. The results show notable discrepancies between CPT-based p-y analyses and the 3D-FEM simulations, particularly in Serviceability Limit State (SLS) analyses. Nevertheless, CPT-based formulas generally outperform API recommendations in most cases. The performance of the methods evaluated differs for various OCR conditions. For the three cases representing low, medium, and high OCR profiles in this study, CPT-C, CPT-B, and CPT-A, respectively, show the best agreement with the FEM results. The performance of CPT-based methods remains consistent under varying IP levels, and FEM results indicate that IP has less effect on pile response. Caution is necessary when applying the CPT-based methods to clays of higher OCR, as they may underestimate the displacements, leading to non-conservative design. These findings highlight the potential benefits of improving CPT-based methods and underscore the importance of incorporating soil index parameters when deriving the p-y curves for monopiles in clay.

KEYWORDS: Offshore wind; monopile; CPT; p-y curve; numerical simulation.

1 INTRODUCTION

The global transition toward sustainable energy systems has led to a significant expansion in the offshore wind energy sector. Among various foundation options, monopiles have emerged as the most widely used. In monopile design, various limit states must be evaluated. While the Ultimate Limit State (ULS) ensures ultimate bearing capacity, the Serviceability Limit State (SLS) often governs the design. SLS criteria typically constrain the pile head rotation to within 0.5 degrees or limit the lateral deflection to 1% of the pile diameter to ensure acceptable operational performance (DNV, 2016). In accordance with the code, the effects of cyclic loading must also be considered in the design process. Consequently, an investigation into the lateral load-deformation response of monopile foundations is crucial to optimize design methodologies and enhance the reliability of offshore wind infrastructure.

The p-y curve method is widely employed to model the soil reaction forces and stiffnesses along pile depth. These p-y curves ignore the differential vertical shear action at the front and back of the monopile and the coupling between the spring along the pile, but they can significantly reduce the complexity of pile-soil interaction analyses and give satisfactory results. Following the foundational work by Matlock (1956) and Reese et al. (1974), the p-y method has been widely used, and many p-y models have been proposed for the laterally loaded piles in different soils (Wang et al., 2020).

The monopiles in offshore wind fields usually have a large diameter and small ratio of length over diameter, and the traditional rule-based p-y formulas derived from slender piles in oil and gas industry may not be accurate. The PISA Project (Byrne, 2020) developed an extended spring-based 1D method that adds extra springs to the p–y approach, allowing soil reaction curves to be derived from rules or, more importantly, calibrated using 3D finite element analysis.

The Cone Penetration Test (CPT) is extensively used in offshore site investigation to acquire continuous in-situ data, and efforts have been made to establish p-y curves based on CPT data. CPT-based methods can generally be categorized into two types: those that use CPT data to estimate parameters for traditional methods, and those that derive the p-y curves directly from CPT measurements, often based on net cone resistance (q_{net}).

The API (2014) p–y curve method for lateral pile design in clay relies on undrained shear strength (s_u) and a strain parameter (ε_{50}) representing the deflection at 50% of ultimate resistance. While s_u can be reliably estimated from CPT data using established correlations, ε_{50} remains a major source of uncertainty due to its reliance on limited laboratory data. Some studies tried to correlate ε_{50} with CPT data. Kim et al. (2014) rewrite the API formula with data from cone penetration. Ebrahimian et al. (2015) investigated the correlation between CPT data and ε_{50} based on statistical studies. Some also tries to PISA springs based on CPT data.

Alternatively, some have proposed p-y curves directly on q_{net}. Guo and Lehane (2014) conducted centrifuge tests in normally consolidated to lightly over-consolidated kaolin clay and developed a p-y formula as a function of q_{net}, soil depth, and pile diameter. Truong (2017) derived the CPT-based p-y curves by FEM.

However, these empirical formulas based on specific sites and soil conditions are not necessary representative at other sites. Therefore, this paper aims to investigate the performance of the proposed CPT-based p-y curves in the literature through numerical case studies, assessing their applicability and reliability across different soil conditions. Although the effects of cyclic loading should be considered (DNV, 2016), this study focuses solely on monotonic loading scenarios for clarity and simplicity of illustration.

2 CASE OVERVIEW

Knowledge of index parameters in design provides valuable insights into soil behaviour and supports more accurate foundation analysis (Andersen et al., 2023). For example, in offshore wind projects, over-consolidated (OC) clay is commonly encountered, which has a significant effect on soil strength and stiffness properties. The plasticity index (I_P) often affects the stiffness, and further the pile behaviour. Therefore, it is selected for this study to vary OCR and Ip to evaluate the CPT-based p-y formulas.

Five cases with different soil profiles are selected, each with a constant OCR and I_P along the depth (Table 1). Case 1 serves as the baseline parameters for the parametric study. In this paper, Norwegian marine clay is selected as its properties are well documented in the literature.

Table 1. Soil properties for each case.

Parameters	Unit	Case 1	Case 2	Case 3	Case 4	Case 5
OCR	/	1	4	10	1	1
I_P	%	27	27	27	10	40
Sensitivity	/	3	3	3	3	3

3 FINITE ELEMENT ANALYSES

3.1 *NGI-ADP constitutive model*

NGI-ADP (Grimstad et al., 2012) available in Plaxis is particularly useful for total stress analyses, as it uses soil parameters directly measured for input, including undrained strength and failure strains. Also, the anistropic behaviour of soil are accounted for in this constitutive model by the ADP framwork, where the shear strength and failure strain parameters for active (A), direct simple shear (D), and passive (P) are specified as inputs.

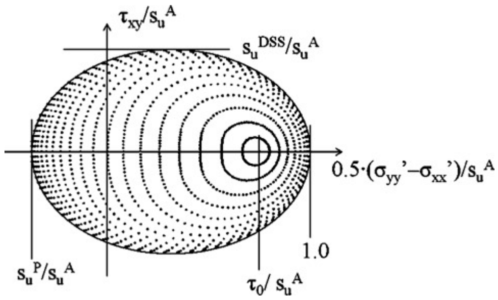

Figure 1. Typical deviatoric plane strain plot of NGI-ADP (Grimstad et al., 2012).

It should be noted that the undrained shear strength parameters obtained from triaxial tests are identical to those from plane strain conditions. However, as triaxial test is widely used in practice and provide slightly conservative strength values (Ladd et al., 1977), the strengths from triaxial tests are often adopted in place of the ADP framework, for example, using s_{uTXC} to represent s_{uA}.

The initial stress state is defined by the shear mobilization parameter τ_0/s_{uA} and the in-situ earth pressure at rest K_0. The initial stiffness of the stress-strain curve plays an important role in SLS analyses. The initial slope of the stress-strain curve is defined by G_0, which is denoted as unloading and reloading modulus G_{ur} in NGI-ADP.

3.2 *Model calibration based on index parameters*

Over the past few decades, NGI has conducted extensive research on high-quality Norwegian marine clay samples. Therefore, data from triaxial and direct simple shear test as well as odemeter test have been collected and corelations were proposed (Andersen, 2015).

The parameters required for NGI-ADP model could be reasonably calibrated given that the soil index data is available. For example, the strength parameters could be derived by:

$$s_{uD}/\sigma'_{v0} = 0.33(OCR)^{0.79} \quad (1)$$

$$s_{uD}/\sigma'_{v0} = 0.21(OCR)^{0.83} \quad (2)$$

$$s_{uE}/\sigma'_{v0} = 0.16(OCR)^{0.88} \quad (3)$$

Figure 2 shows the typical stress-strain relationships for Drammen clay of various OCR at Triaxial test and DSS test.

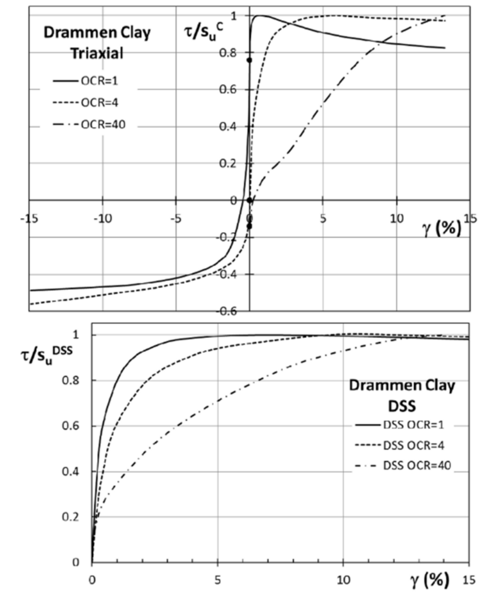

Figure 2. Stress-strains curves for clay at various tests (Andersen. 2015).

The elasticity is defined by ν_u and G_{ur}. In this study, ν_u is 0.495 to model the undrained response. The initial shear modulus G_{max} is used as G_{ur}, which can be estimated using the expression proposed by Andersen (2015), as given in Equation (4) and shown in Figure 3.

$$G_{max}/s_{uD} = \left(30 + \frac{300}{\mathrm{I_P} + 0.03}\right) \cdot OCR^{-0.25} \quad (4)$$

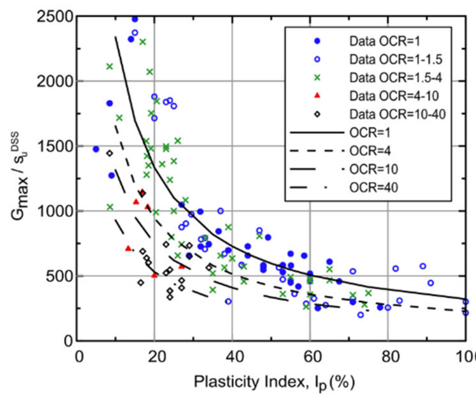

Figure 3. Normalized initial shear modelus versus OCR and Ip (Andersen. 2015).

The initial stress state parameter K_0 is assumed following the correlation from (Karlsrud et al., 2005). The initial shear mobilization τ_0/s_{uA} is calculated from K_0.

$$K_0 = 0.53\,OCR^{0.47} \quad (5)$$

$$\tau_0/s_{uA} = 0.5(1-K_0)\left(\frac{\sigma_{v0}}{s_{uA}}\right) \tag{6}$$

The τ_0/s_{uA} is set to be zero when the value calculated by Equation (6) is negative.

3.3 *Model setup*

The monopile is 32 m in length, 8 m in diameter, and assumed wished in place. Wall thickness is 0.1 m, and Young's modulus E of steel is 210 GPa. The soil domain is 200 m × 160 m × 80 m, which is considered large enough to avoid boundary effects. Since this is a symmetrical problem, only half of the soil volume is considered. The parameters of NGI-ADP required for each case are detailed in Table 2.

Table 2. Input of the NGI-ADP model

Parameters	Unit	Case 1	Case 2	Case 3	Case 4	Case 5
γ'	kN/m^3	8	8	8	8	8
G_{ur}/s_{uA}	/	655	490	404	1488	463
s_{uA_ref}	kPa	1	1	1	1	1
s_{uA_inc}	kPa/m	2.64	7.89	16.28	2.64	2.64
s_{uP}/s_{uA}	/	0.64	0.64	0.64	0.64	0.64
s_{uDSS}/s_{uA}	/	0.48	0.55	0.60	0.48	0.48
γ_A	%	1.5	6	18	1.5	1.5
γ_P	%	7	12	18	7	7
γ_{DSS}	%	3.5	8.5	18	3.5	3.5
K_0	/	0.53	1.02	1.56	0.53	0.53
τ_0/s_{uA}	/	0.71	0	0	0.84	0.84
R_{inter}	/	0.65	0.47	0.38	0.58	0.65

An interface defined by the Mohr-Column model is used to simulate pile-soil interaction and possible gapping between the monopile and soil. The degradation factor R_{inter} for interface for each case is assumed based on OCR and Ip (Andersen & Jostad, 2014). In general, soil disturbance could have a greater effect in high OCR conditions, contributing to lower R_{inter} values.

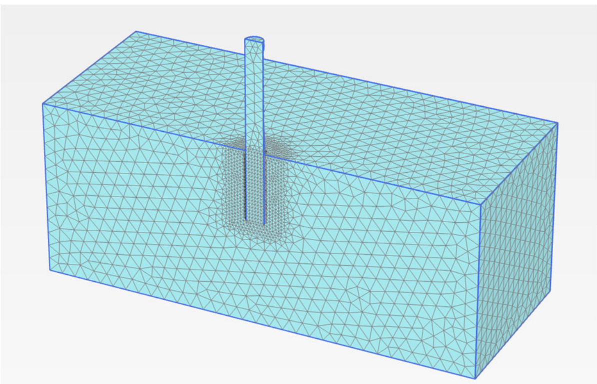

Figure 4. Model in Plaxis.

The mesh around the pile is densified, and 39687 elements are generated in total. Each case is subjected to lateral loading from zero up to failure, which is defined as a lateral displacement of 0.1D.

4 CPT-BASED P-Y CURVES

4.1 *CPT-based p-y formulas from the literature*

Three aforementioned CPT-based p-y curves from literature, Guo and Lehane (2014), Truong et al. (2017), Ebrahimian et al. (2015), are selected for comparison. Correspondingly, they are referred as CPT-A, CPT-B, and CPT-C for convenience. A short description of each method is shown in Table 3.

Table 3. CPT-based p-y formulas in the literature

Methods	*CPT-A*	*CPT-B*	*CPT-C*	*API*
Test type	Centrifuge	Numerical	Statistical	Field
Soil OCR	1-2	1-2	1-7	/
Pile type	Rigid	Rigid	/	Slender
Reference	Guo & Lehane (2014)	Truong (2017)	Ebrahimian et al. (2015)	API (2014)

The CPT-A method uses following expression to construct p-y curves:

$$\frac{P}{P_u} = tanh\left[8.80\left(\frac{z}{D}\right)^{-0.30}\left(\frac{y}{D}\right)^{0.68}\right], 0 < z < 3D \tag{7}$$

$$\frac{P}{P_u} = \tanh\left[6.34\left(\frac{y}{D}\right)^{0.68}\right], z > 3D \tag{8}$$

Where, P_u is the ultimate resultant soil pressure distributed along pile depth z, and could be derived from a factor named N_{pq}:

$$N_{pq} = \frac{P_u}{q_{net}} = 0.2 + tanh\left(0.3\frac{z}{D}\right) \tag{9}$$

The CPT-B method is proposed by Truong(2017), incorparating Rigid Index (I_r):

$$\frac{P}{P_u} = tanh\left[(0.26I_r + 3.98)\left(\frac{y}{D}\right)^{0.85}\left(\frac{z}{D}\right)^{-0.5}\right], \quad 0 < z < 3D \tag{10}$$

$$\frac{P}{P_u} = \tanh\left[(015I_r + 2.3)\left(\frac{y}{D}\right)^{0.85}\right], \quad z > 3D \tag{11}$$

Where N_{pq} is calculated also based on I_r:

$$N_{pq} = \left(\frac{3}{4.7 + 1.6\,ln\,I_r}\right) + [1.5 - 0.14\,ln\,I_r]\,tanh\left(0.65\frac{z}{D}\right) \tag{12}$$

It should be noted that, in Ebrahimian et. al. (2015), 6 models are given for estimating ε_{50}. There is one model that only requires q_{net} data for input and gives comparable accuracy:

$$\varepsilon_{50} = 0.85q_{net} + 0.1 \tag{13}$$

So, this model is chosen to estimate ε_{50} for API formulas and is referred to as CPT-C.

4.2 *CPT data and index parameters*

For the 5 cases listed in Table 1, with the given OCR and IP for each case, the empirical N_{kt} could be estimated, based on correlations developed for Norwegian marine clay (Karlsrud et.al. 2005). As metioned in section 2.3, the hypothetical s_u profile along the depth have been decided, the q_{net} could be obtained to construct the p-y curves for methods listed in Table 3.

$$N_{kt} = 7.8 + 2.5 \cdot log\,OCR + 0.082I_P \tag{14}$$

$$q_{net} = N_{kt} \cdot s_u \tag{15}$$

4.3 *1D analysis of pile-soil interaction*

The applicability of Timoshenko, Euler–Bernoulli and rigid beam theories matters in the analysis of laterally loaded monopiles and piles. Figure 5 shows the sketches of different beam theories (Gupta & Basu, 2018). It is found that the rigid theory should only be used for a quick initial estimate of pile head displacement, and Timoshenko or Euler–Bernoulli beam theories are both adequate for accurate prediction of pile head response.

In this study, the Euler–Bernoulli beam on a Winkler foundation is considered. No additional springs, but only horizontal p-y curves, are considered.

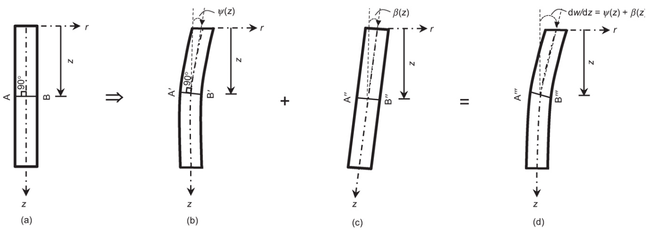

Figure 5. Beam deformation: (a) undeformed configuration of beam; (b) bending deformation (Euler–Bernoulli beam); (c) shear deformation; (d) total deformation (Timoshenko beam)

5 RESULTS AND DISCUSSION

5.1 *Comparison of pile displacement*

The pile displacements at mudline under different load levels obtained from 1D CPT-based p-y analyses are compared with those from 3D FEM. For reference, the results calculated from API (2014) reccomendations are also presented. Figure 6 and Figure 7 shows the result of Case 1, where the OCR is 1 and I_P is 27%.

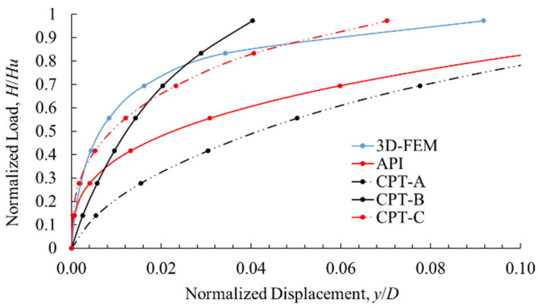

Figure 6. Load-displacement at mudline of Case 1, ULS

Usually, the load at 0.1D would be considered for the ultimate bearing capacity and commonly used as the boundary for ULS. Within this range (Figure 6), the CPT-B and CPT-C methods have better agreement with FEM results, while CPT-A gives larger displacements, similar to those observed with the API method.

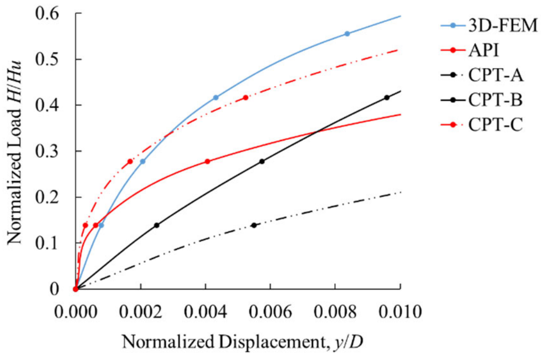

Figure 7. Load-displacement at mudline of Case 1, SLS

For SLS conditions, stiffness within 0.01D is more relevant. Figure 7 shows the displacement in this range. CPT-C agrees most with the FEM results, with a difference from 11% to 70%, while others have lager differences up to almost seven times of the displacement from FEM. Since this is typically the governing aspect for the design of monopiles, only the SLS displacement is focused on in the following parts

5.2 *Results of various OCR*

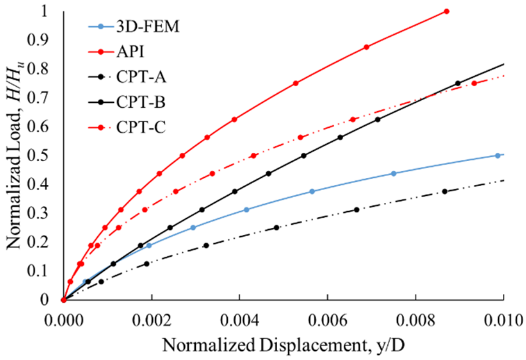

Figure 8. Load-displacement curve of Case 2, OCR=4

For Case 2, with an OCR of 4 representing medium OC clay, the CPT-B method agrees most with the FEM results, showed in Figure 8. In contrast, for Case 3, which involves high OC clay, the CPT-A method agrees better (Figure 9). This shift in performance highlights the influence of overconsolidation on method suitability and underscores the importance of an appropriate approach to consider soil conditions when deriving p-y curves.

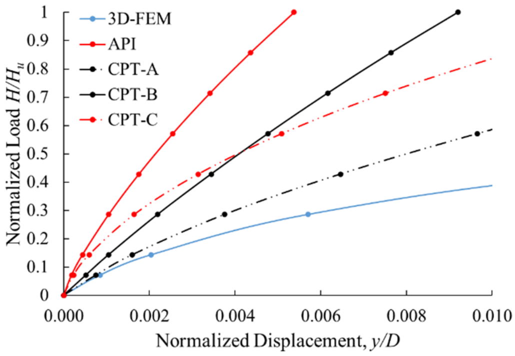

Figure 9. Load-displacement curve of Case 3, OCR=10

It is also important to note that, in over consolidated soil, all the CPT-based methods underestimate pile displacement, which may lead to non-conservative outcomes in design.

5.3 *Results of various Ip*

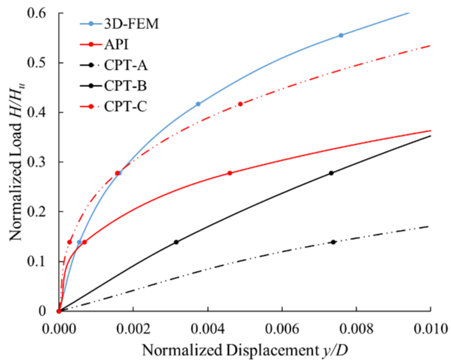

Figure 10. Load-displacement curve of Case 4, Ip=10%

With the OCR held constant, Cases 4 (I_P=10%) and 5 (I_P=40%) are designed to evaluate the performance of CPT-based methods in clays with differing plasticity, representing low and high plasticity soils, respectively.

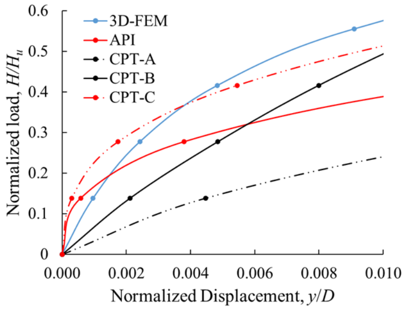

Figure 11. Load-displacement curve of Case 5, Ip=40%

Similar to observed for Case 1, the relative difference between displacement computed from 3D and CPT methods are notable in both Case 4 (Figure 10) and Case 5 (Figure 11).

5.4 *Discussion*

With increasing OCR, the performance of the CPT-based methods differs, likely due to their limited ability to account for OCR effects. Nevertheless, their overall displacement predictions show better agreement with the FEM results compared to the API method.

Within the SLS range of the analyzed cases, displacement differences relative to FEM results range from 11% to 70%, in some cases reaching nearly seven times the FEM-predicted values. These discrepancies may arise because the CPT-A and CPT-B methods are based on limited datasets—primarily kaolin clay and soils with OCR values between 1 and 2—which do not adequately represent the conditions studied here. For the CPT-C method, the differences may be attributed to the derivation of its ε_{50} correlation, which also depends on the original data sources and statistical approach used.

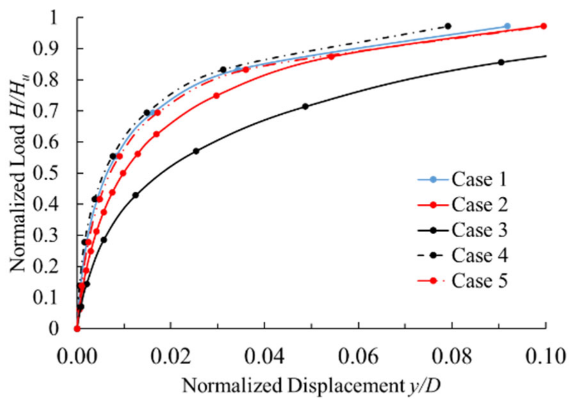

Figure 12. Load-displacement of all cases from FEM

Compared to OCR, the FEM results indicate that I_P has less effect on pile response (Figure 12). This leads to that the the pile response predicted by the CPT-based formulas remains consistent.

6 CONCLUSIONS

In this study, the monopile push-over in clay is numerically simulated, and several existing CPT-based p-y formulas in the literature are examined. The stress-strain relationships for 3D FEM analyses are derived from soil index parameters based on the data set of Norwegian marine clay. Further, the uncertainties of CPT-based p-y springs are illustrated by parametric studies, by varying OCR and I_P. The conclusions include:

- It is feasible to numerically investigate CPT-based p–y curves using stress–strain relationships from the Norwegian marine clay database, provided that specific soil index parameters such as OCR and I_P are available.
- The results show notable discrepancies between CPT-based p-y analyses and 3D-FEM simulations, particularly in the Serviceability Limit State (SLS). Nevertheless, the CPT-based formulas outperform the API-based recommendations in most cases.
- Among the evaluated methods, performance differs for various OCR conditions. For clay with low, medium, and high OCR in the 3 cases, CPT-C, -B, and -A agrees best with FEM results, respectively. This indicates that site-specific correlation is required. The performance of CPT-based methods remains consistent under varying I_P levels, and FEM results indicate that I_P has less effect on pile response. Caution is necessary when applying them to clays of higher OCR, as the pile displacements may be underestimated, leading to non-conservative design.
- The above findings highlight the need to refine CPT-based methods and emphasize the importance of incorporating soil index parameters when deriving p–y curves for monopiles in clay.
- In addition, the effect of cyclic loading in the design of monopile foundations should be accounted for, which is beneficial to be included in future studies.

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