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Estimation of Lateral Displacements for Offshore Monopiles in Clays based on CPT Results

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ABSTRACT

In this study, a CPT-based *p-y* analysis method for estimating lateral displacements of offshore monopiles in clays is presented. The cone penetration test (CPT) can be particularly effective to characterize the subsoil condition in offshore area were the sampling and other experimental process are limited. For the method presented in this paper, test results from CPT are directly introduced into the p-y analysis procedure as main input soil characteristics. The effective cone resistance was adopted in the *p-y* curve function. To validate the CPT-based method, the displacement analysis was performed using a case example selected from the literature. Close match was observed between results from field load test and CPT-based method.

1. INTRODUCTION

Monopiles are commonly used for offshore structures that are installed for water depths shallower than around 30 to 40 m. Lateral load response is key consideration for monopiles as wave and wind act as predominant load components (API 2010). To estimate the lateral load carrying capability of piles under working load condition, the displacement analysis based on beam-on-elastic foundation (BEF) with *p-y* relationship is often adopted (Matlock 1970, Dunnavant and O'Neill 1989). In this approach, the soils are assumed as a series of discrete elastic springs that characterize the relationship between soil resistance and pile displacement. While the *p-y* method is less rigorous than the full numerical analysis, it has been widely used for many applications in engineering practice due to its simplicity and reasonable accuracy.

Proper soil parameters should be obtained and introduced into the *p-y* analysis for the displacement analysis and design of offshore monopiles. The conventional sampling- and laboratory test-based approach can be subjected to various

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experimental uncertainties due to the offshore environmental condition. In-situ testing methods may be, therefore, more effective for offshore cases (Lee and Randolph 2011). The *p-y* methods using the results of pressuremeter test (PMT) and dilatometer test (DMT) were proposed by Briaud *et al*. (1985) and Gabr et al. (1994), respectively. PMT and DMT were adopted because of the similarity in the lateral loading mechanisms of the tests and laterally loaded piles. The CPT-based *p-y* curves for sands were also proposed (Dyson and Randolph 2001, Suryasentana and Lehane 2014, Kim et al. 2015) assuming that the cone resistance of cone penetration test (CPT) is governed by the horizontal stress as for laterally loaded piles (Schnaid and Houlsby 1991).

In this study, CPT-based *p-y* method for offshore piles in clays is presented based on the work given in Kim et al. (2014). The continuous profiling characteristics of CPT is utilized and soil layer profile data is introduced directly using the effective cone resistance into the method as described in Fig. 1. Case examples from the literature are selected to examine the validity of the CPT-based p-y method and used to compare with results from the conventional p-y method.

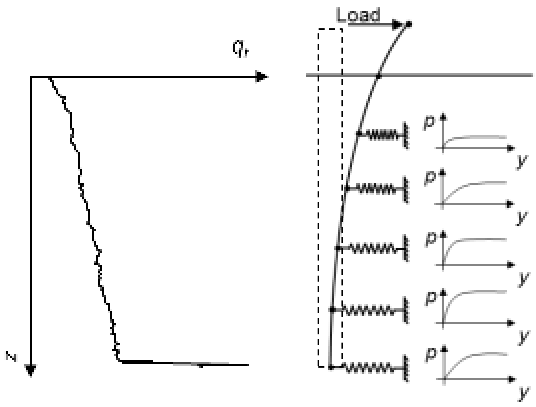

Fig. 1 Configuration of soil-spring model for laterally loaded pile.

2. DISPLACEMENT ANALYSIS USING p-y CURVES FOR PILES IN CLAYS

Matlock (1970) proposed *p-y* model based on the results of full-scale field load tests in soft clays, which was incorporated into the design specification for offshore monopiles in clays by American Petroleum Institute (API RP2A). The *p-y* curve by Matlock (1970) is shown in Fig. 2(a) and can be given by the following normalized form:

$$\frac{p}{p_u} = 0.5\left(\frac{y}{y_{50}}\right)^{1/3} \tag{1}$$

where p = lateral soil resistance; p_u = ultimate lateral soil resistance: y = lateral pile displacement; y_{50} = reference pile displacement defined as $2.5 \cdot \varepsilon_{50} \cdot D$; ε_{50} = strain corresponding to 50 % of failure stress in triaxial test; and D = pile diameter. The soil

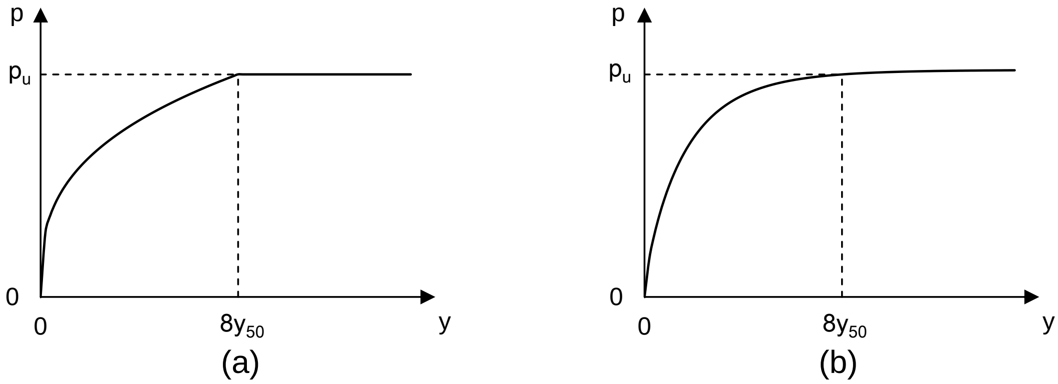

Fig. 2 *p-y* curves in clays by (a) Matlock (1970) and (b) Dunnavant and O'Neill (1989).

resistance (p) converges to the ultimate soil resistance (p_u) beyond the lateral pile displacement of $8 \cdot y_{50}$. p_u is obtained as follows:

$$p_u = N_c s_u D \tag{2}$$

where s_u is the undrained shear strength and N_c is the bearing capacity factor given as:

$$N_c = 3 + \frac{\gamma' z}{s_u} + \frac{Jz}{D} \le 9 \tag{3}$$

where γ' is the effective unit weight of soil, z is the depth from ground surface, J is the empirical parameter equal to 0.5 and 0.25 for soft and stiff clays, respectively.

For piles embedded in stiff clays, Dunnavant and O'Neill (1989) proposed the *p-y* relationship derived from the results of a series of full-scale lateral load tests. The *p-y* curve function proposed by Dunnavant and O'Neill (1989) is given as the following hyperbolic tangent equation:

$$\frac{p}{p_u} = 1.02 \tanh[0.537(\frac{y}{y_{50}})^{0.7}] \tag{4}$$

where y_{50} is the reference pile displacement obtained as $0.0063 \cdot \varepsilon_{50} \cdot D \cdot K_R^{-0.875}$, K_R is the relative pile-soil stiffness defined as $E_p I_p / E_S L^4$, $E_p I_p$ is the flexural rigidity of pile, E_s is the elastic modulus of soil, and L is the pile embedded length. Eq. (4) plots the *p-y* curve as shown in Fig. 2(b). The value of p equals to p_u beyond the lateral displacement of $8 \cdot y_{50}$. p_u is obtained using Eq. (2) similarly to Matlock Method (1970). The bearing capacity factor (N_c), however, is calculated differently by the following relationship:

$$N_c = 2 + \frac{\gamma' z}{\bar{s}_u} + 0.4 \frac{z}{D} \le 9 \tag{5}$$

where $\bar{s}_u$ is the average undrained shear strength over the depth z.

3. LOAD TRANSFER ANALYSIS BASED ON CPT RESULTS

3.1 CPT-based p-y Curve

The undrained shear strength (s_u) is an important soil variable that characterizes the ultimate soil resistance (p_u) and the shape of *p-y* curve for clays. If CPT is introduced and utilized, the continuous and detailed depth profile of soil condition can be obtained, which can be effectively used to identify seabed soil conditions. To estimate s_u from CPT, the effective cone factor method proposed by Lee et al. (2010) is introduced given as the follow:

$$s_u = \frac{q_t - u_0}{N_e} = \frac{q_e}{N_e} \tag{6}$$

where q_t is the cone resistance, u_0 is the hydrostatic pore pressure, q_e is the effective cone resistance defined as q_t - u_0, and N_e is the effective cone factor equal to 16 ± 3. The correlation of Eq. (6) is quite straightforward and simple to apply as u_0 can be readily obtained from CPT results. Using Eq. (2) and the effective cone factor N_e of Eq. (6), the p_u correlation can be obtained as:

$$p_u = \frac{N_c}{N_e} q_e D \tag{7}$$

While N_e was proposed constant, N_c given by Eq. (3) varies with depth. This yields that N_c/N_e increases linearly from 0.1875 to 0.5625 with depth. Introducing the CPT-based p_u equation of Eq. (7) into Eq. (1), the *p-y* function by Matlock (1970) can be modified in terms of the effective cone resistance q_e given as follows (Kim et al. 2014):

$$p = 0.5 q_e D (\frac{N_c}{N_e})(\frac{y}{y_{50}})^{1/3} \tag{8}$$

As CPT-based *p-y* function of Eq. (8) utilizes the continuous depth profile of CPT, the detailed variation of soil characteristics with depth can be taken into account for the *p-y* analysis without further assumption or simplification from in-situ soil profiles.

3.2 Calculation Algorithm

The governing differential equation for the equilibrium condition of a segment of pile under lateral loading is given by:

$$E_p I_p \frac{d^4 y}{dz^4} + Q \frac{d^2 y}{dz^2} - p + W = 0 \tag{9}$$

where E_pI_p is the flexural rigidity of pile, Q is the axial load on the pile, p is the soil reaction per unit length, and W is the distributed load along the length of the pile. Eq. (9)

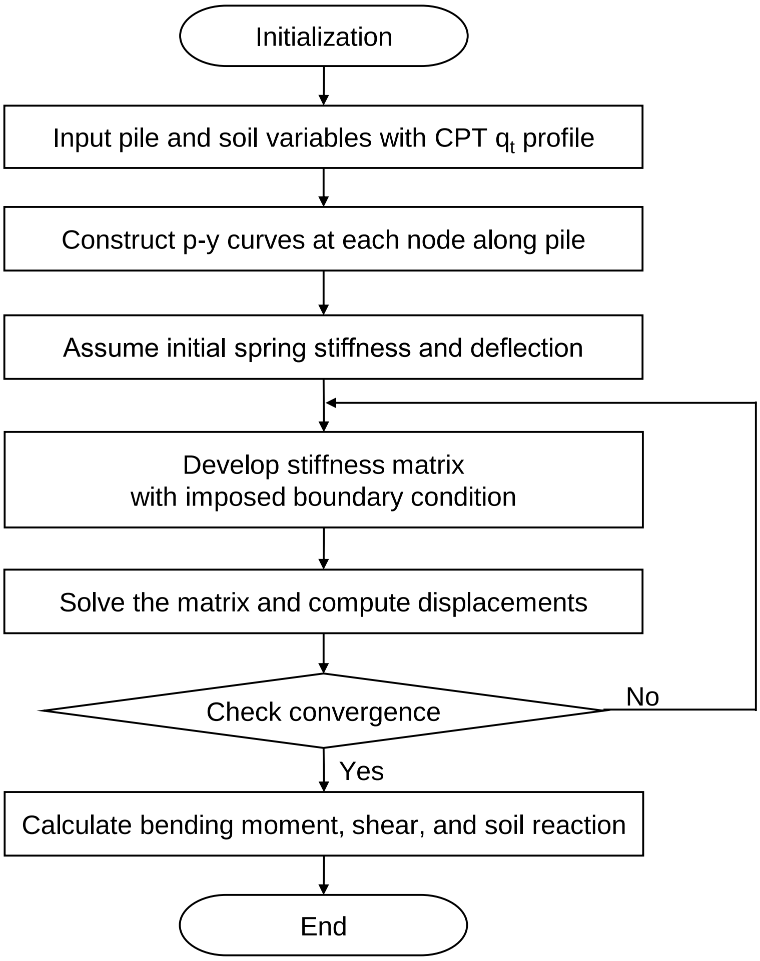

Fig. 3 Flow chart for CPT-based p-y analysis.

can be solved by applying the finite difference scheme with equations of boundary conditions at pile head and tip. For this purpose, the CPT-based p-y analysis described previously was programmed using the commercial programming software MATLAB. The main flow of the program is shown in Fig. 3 and the program includes (1) inputting of q_t profile as soil variable, (2) iterative calculation for solving the stiffness matrix, and (3) outputting results of analysis.

4. CASE EXAMPLE

To check the validity of the CPT-based p-y analysis for monopiles in clays, a case example was selected from the literature and compared with calculated results from other p-y analysis methods. The selected example was a field lateral load test conducted at the Incheon bridge construction in Korea (Kim and Jeong 2010). Fig. 4 shows the depth profile of soil layers and CPT cone resistance at the test site. Clay layers were observed down to the depth of 22.0 m and the values of s_u were typically in the range between 18 and 60 kPa. The water table was located near the ground surface during the load test. A steel pipe pile of 1.0-m diameter, embedded to the depth of 26.6 m with vertical load eccentricity of 0.5 m above the ground surface, was installed and tested.

Fig. 5 shows the comparison of the measured and calculated pile head displacements of the test monopile. It is seen that the calculated lateral load response using the CPT-based method is in close agreement with the measured result. The calculated results from Dunnavant and O'Neill method (1989) were also quite close to the measured data within the range of test load level while overestimated lateral displacements were observed beyond the load level of 700 kN. The Matlock method (1970) based on the simplified s_u-profile overestimated the displacement around twice the measured values. It is indicated that the resolution of depth profile near the ground surface for the input parameters is important for the *p-y* analysis and significantly affects calculated load responses.

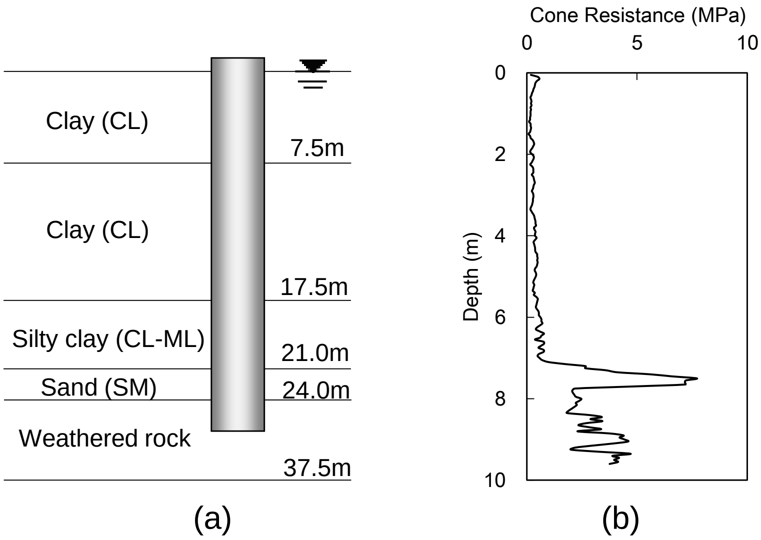

Fig. 4 Site condition and CPT results: (a) soil layer condition and (b) CPT profile.

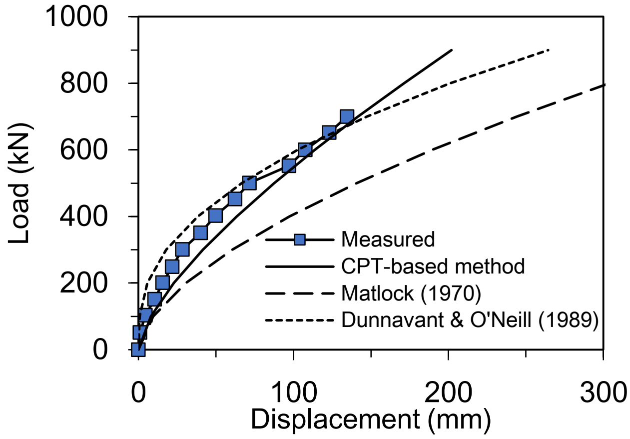

Fig. 5 Measured and calculated lateral load–pile head displacement curves.

5. SUMMARY AND CONCLUSIONS

In this study, the lateral displacement analysis method for offshore monopile using CPT-based *p-y* method was presented. The detailed soil profiling capability of CPT was utilized and incorporated into the CPT-based *p-y* curve without simplification or assumption for soil properties as input parameter for analysis. The experimental difficulties in characterizing soil parameters by additional sampling and testing procedure under offshore conditions can be excluded by adopting CPT results.

The correlation of the ultimate lateral soil resistance (p_u) in terms of the effective cone resistance was formulated by introducing the effective cone factor which does not require any further procedure for estimating the overburden total stress at con tip level. Introducing the ultimate soil resistance (p_u) with the effective cone factor, the CPT-based p-y function was presented. The detailed depth profile of soil characteristics can be considered readily by the *p-y* function using CPT results.

To validate the CPT-based p-y analysis method, the calculated lateral load responses were compared with the measured results of field lateral load test in the literature. For this purpose, the procedure of lateral displacement analysis based on CPT results was programmed using the commercial programing software MATLAB. Good agreement was observed between the results measured and calculated using the presented CPT-based p-y method. It was indicated that the detailed depth profile for input parameters is important for the adequacy of calculated load responses in the p-y analysis.

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