Lateral displacement analysis for pile in clays using CPT-based p-y curve

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ABSTRACT

The p-y analysis methods are widely used for the displacement design of laterally loaded piles. In clays, the conventional p-y curves are given based on strength parameters such as the undrained shear strength (s_u) that can be obtained from sampling and laboratory tests. In this study, p-y curve methods based on the cone penetration test (CPT) were presented for both static and cyclic loading conditions. The consideration of continuous soil profiling using CPT is a unique feature of this method introducing the correlation between effective cone resistance and ultimate lateral soil resistance. Lateral displacements of piles were estimated using the CPT-based p-y curve method. The results were compared with the measured data from field load tests. The predicted results showed close matches to the measured results from the field load test.

Keywords: Laterally Loaded piles; p-y curve analysis; Clays; Cone Penetration Test; Cone Resistance

1 INTRODUCTION

For the displacement analysis of laterally loaded piles in clays, the p-y approach is widely used. It is based on the beam-on-elastic foundation (BEF) where the soils are considered as a series of discrete springs characterized by the relationship between the soil resistance (p) and the lateral displacement of pile (y) with depth (API 2000). The strength parameters including the undrained shear strength are required to establish the p-y curves. This requires that the undisturbed soil sampling and subsequent laboratory tests or relevant in-situ testing process. The in-situ testing methods, such as the Cone Penetration Test (CPT), have been preferred as an effective design tool because no sampling and laboratory testing procedure is necessary. In particular, the CPT-based p-y curve methods have been proposed, where the results of CPT are directly incorporated into the lateral displacement analysis (Kim et al. 2014, Kim et al. 2016).

In this study, the CPT-based p-y method for laterally loaded piles in clays subjected to cyclic loading is reviewed based on the work given in Kim et al. (2016). The continuous profiling characteristics of CPT are introduced directly into the p-y displacement function in terms of the effective cone resistance. The cyclic loading effect is considered with the number of loading cycle in the method. The field load test for case example is adopted to examine the validity of the CPT-based p-y method and compared with results from the conventional p-y methods.

2 CONVENTIONAL P-Y CURVES FOR CLAYS

There have been various p-y curve models for the nonlinear springs (Matlock 1970, Dunnavant and O'Neill 1989). The p-y curves are defined by the shape of the curve and the ultimate lateral soil resistance (p_u). The ultimate lateral soil resistance (p_u) for clays can be expressed in terms of the undrained shear strength (s_u) as follows:

$$p_u = N_c s_u D \tag{1}$$

where, p_u = ultimate soil resistance;
N_c = bearing capacity factor;
s_u = undrained shear strength;
D = diameter of pile.

The bearing capacity factor (N_c) depends on the depth and strength of clay. N_c increases linearly to the limit depth (z_r) where N_c remains the constant. Eq. (2) and (3) are the proposed equations for N_c of soft and stiff clay, respectively (Matlock 1970, Dunnavant and O'Neill 1989).

$$N_c = 3 + \frac{\gamma' z}{s_u} + \frac{Jz}{D} \le 9 \tag{2}$$

$$N_c = 2 + \frac{\gamma' z}{s_u} + 0.4\frac{z}{D} \le 9 \tag{3}$$

where, γ' = effective unit weight of soil;
z = depth from ground surface;
J = empirical parameter.

The characteristic shapes of the nonlinear p-y relationship are shown in Fig. 1. The hyperbolic equations of Matlock (1970) and Dunnavant and O'Neill (1989) are given respectively as:

$$\frac{p}{p_u}=0.5\left(\frac{y}{y_{50}}\right)^{1/3} \quad (4)$$

$$\frac{p}{p_u}=1.02\tanh\left[0.537\left(\frac{y}{y_{50}}\right)^{0.7}\right] \quad (5)$$

where, p = lateral soil resistance per unit length;
y = induced lateral displacement;
y_{50} = reference lateral displacement
= $2.5\cdot\varepsilon_{50}\cdot D$ (Matlock 1970);
= $0.0063\cdot\varepsilon_{50}\cdot D\cdot K_R^{-0.875}$ (Dunnavant and O'Neill 1989);
ε_{50} = reference strain corresponding to 50 % of failure stress in triaxial test;
K_R = relative pile-soil stiffness = E_pI_p/E_sL^4;
E_pI_p = flexural rigidity of pile;
E_s = soil modulus;
L = length of pile.

The effects of the degradation for lateral soil resistance due to cyclic loading were characterized as shown in Fig. 1. In cyclic loading condition, the softening behavior is expressed after the peak soil resistance whereas the p-y curve is the same as the static loading condition within the initial range. Matlock (1970) proposed the maximum lateral soil resistance equal to $0.72p_u$ at $3y_{50}$ by considering the effect of cyclic loading. The residual soil resistance (p) remains a constant of Eq. (6) beyond $15y_{50}$.

$$\frac{p_r}{p_u}=0.72\left(\frac{z}{z_r}\right) \quad (6)$$

where, p_r = residual soil resistance.

Dunnavant and O'Neill (1989) proposed the p-y parameters that take into account the number of loading cycle. The cyclic load envelop are defined as follows:

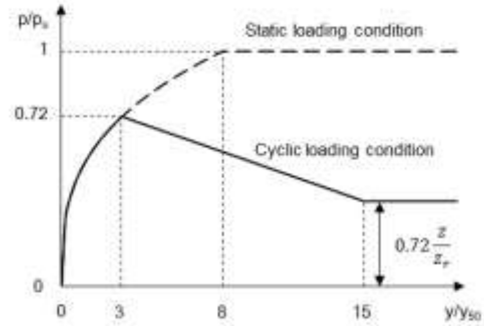
$$p_{cm}=N_{cm}s_uD \quad (7)$$

$$\left(\frac{N_{cm}}{N_c}\right)_n=1-\left(0.45-0.18\frac{z}{z_0}\right)\log n\le 1 \quad (8)$$

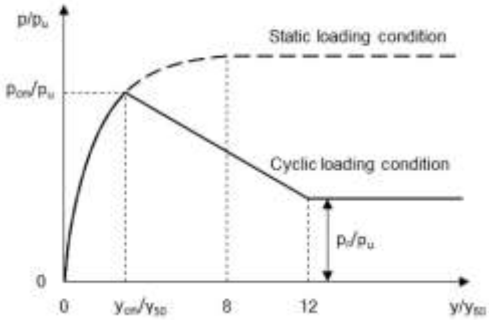
$$\left(\frac{p_r}{p_{cm}}\right)_n=1-\left(0.25-0.07\frac{z}{z_0}\right)\log n\le 1 \quad (9)$$

$$y_{cm}=2.43y_{50}\left[\tanh^{-1}\left(\frac{0.98p_{cm}}{p_u}\right)\right]^{1.428} \quad (10)$$

where, n = number of loading cycle.



(a) Matlock (1970)



(b) Dunnavant and O'Neill (1989)

Fig. 1. Characteristic shapes of p-y curves for clays.

N_{cm} = bearing capacity factor under cyclic loading condition;
p_r = residual soil resistance corresponding to n;
p_{cm} = peak soil resistance under cyclic loading condition;
z_0 = reference depth = 1 m;
y_{cm} = reference displacement under cyclic loading condition.

3 CPT-BASED p-y CURVE ANALYSIS FOR CLAYS

3.1 Introduction of p-y curve using CPT-results

The undrained shear strength (s_u) is a governing variable to establish the p-y relationship and the ultimate lateral soil resistance in clays. The lateral load carrying capacity is well correlated to the cone resistance which is dependent on the effective stress of soil. In order to utilize the results of CPT, the correlation of the undrained shear strength and the cone resistance was adopted as given by (Lee et al. 2010):

$$s_u=\frac{q_t-u_0}{N_e}=\frac{q_e}{N_e} \quad (11)$$

where, s_u = undrained shear strength;
q_t = cone resistance;
u_0 = hydrostatic pore pressure;
N_e = effective cone factor $\cong$ 16;
q_e = effective cone resistance.

As the relationship of the effective cone resistance (q_e) and undrained shear strength (s_u) of Eq. (11) was introduced, the ultimate lateral soil resistance (p_u) was expressed in terms of the q_e with effective cone factor (N_e) as follows (Kim et al. 2014):

$$p_u = \frac{N_c}{N_e} q_e D \quad (12)$$

where, p_u = ultimate soil resistance;
N_c = bearing capacity factor;
D = diameter of pile.

The nonlinear p-y relationship is expressed in terms of the q_e by modifying the function proposed by Matlock (1970). The depth profile of CPT can be directly introduced into the p-y analysis method as an input parameter using Eq. (13) (Kim et al. 2014).

$$p = 0.5 q_e D \left(\frac{N_c}{N_e}\right)\left(\frac{y}{y_{50}}\right)^{1/3} \quad (13)$$

The characteristic shape of Eq. (13) corresponds to the curve for n = 1 in Fig. 2. The reference displacement (y_{50}) can be calculated directly from q_e by Eq. (14).

$$\varepsilon_{CPT} = 0.185\left(\frac{q_e}{p_A}\right)^{-1.124} \le 0.02 \quad (14)$$

where, ε_{CPT} = reference strain calculated using q_e;
p_A = reference stress = 100 kPa.

Eq. (14) was proposed by the regression estimation to utilize CPT results fully. The fitted values of Eq. (14) were set to maintain the consistency with the discrete values of ε_{50} specified in the method of Matlock (1970).

3.2 Application of cyclic loading condition

The cyclic loading effect was incorporated by modifying the degradation function reported by Dunnavant and O'Neill (1989). The degraded lateral resistances p_c and p_r can be obtained according to the number of loading cycle as Eq. (15) and Eq. (16), respectively (Kim et al. 2016):

$$p_{c,n} = \left(\frac{N_c}{N_e}\right)\left[1-(0.45-0.18\frac{z}{z_0})\log n\right] q_e D \le p_u \quad (15)$$

$$p_{r,n} = p_{c,n}\left[1-(0.25-0.07\frac{z}{z_0})\log n\right] \le p_{c,n} \quad (16)$$

where, n = number of loading cycle;
$p_{c,n}$ = peak soil resistance at loading cycle n;
$p_{r,n}$ = residual soil resistance at loading cycle n.

The p_c and p_r vary with the number of loading cycle (n). As n increases, p_c, p_r decrease logarithmically at the shallow depth where soil remolding and softening occurs by cyclic loading. The degradation effects due to cyclic loading are not considered at a deep depth.

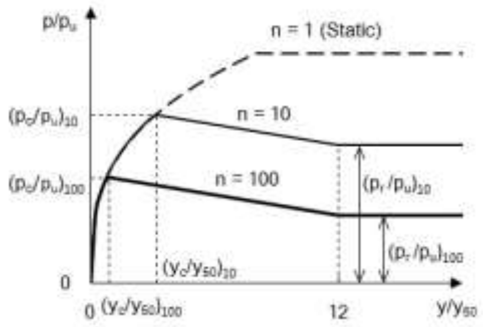


Fig. 2. Characteristic shape of CPT-based p-y curve (Kim et al. 2016).

The cyclic reference displacement y_c corresponding to p_c in Fig. 2 can be derived from Eq. (13) as follows:

$$y_c = 20\varepsilon_{CPT} D\left(\frac{p_c}{p_u}\right)^3 \quad (17)$$

As shown in Fig. 2, the lateral soil resistance decreases linearly from p_c to p_r at the displacement of $12y_{50}$. Depending on the number of loading cycle, the decreases in cyclic reference displacement (y_c), peak and residual soil resistance (p_c and p_r) indicate the degradation effect while the initial portion of the p-y curve is the same as that for the static condition.

4 COMPARISON WITH FIELD LOAD TEST

The field load tests conducted by Rollins et al. (2003) were compared with the predicted results to check the validity of the displacement analysis using the CPT-based p-y curve reviewed in this study. The test site was in Salt Lake City, US. The detailed soil properties were given in table 1 and used for the conventional s_u-based p-y curve analysis while the CPT profile given in Fig. 3 was adopted for the CPT-based p-y method. The groundwater table was located at 1.07 m. The API curve was adopted for the calculation within sand layers. The pile properties were given in Table 2, and the load eccentricities were 0.38 m and 0.49 m for case 1 and 2, respectively.

Table 1. Soil properties at test site.

Depth (m)	Soil type	γ (kN/m^3)	s_u (kPa)	ϕ (°)
0.0 – 1.3	Clay	14.9	70	-
1.3 – 1.7	Sand	16.5	-	36
1.7 – 3.0	Clay	16.5	105	-
3.0 – 3.5	Sand	16.5	-	36
3.5 – 4.1	Clay	16.5	105	-
4.1 – 5.2	Sand	16.5	-	38
5.2 – 9.8	Clay	14.9	35	-
9.8 – 15.0	Clay	16.5	105	-

Table 2. Properties of steel pipe piles.

Test pile	Diameter (m)	Embedded length (m)	Thickness (mm)
Case 1	0.324	11.5	9
Case 2	0.610	11.2	12.7

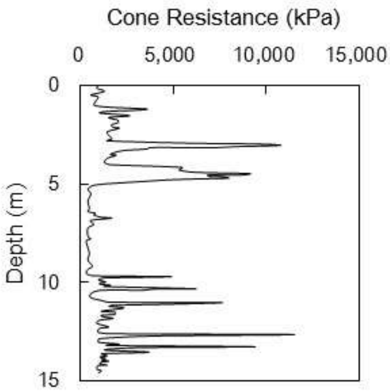
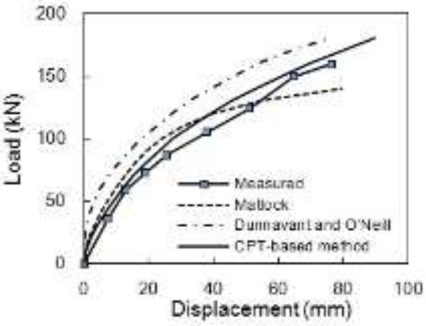
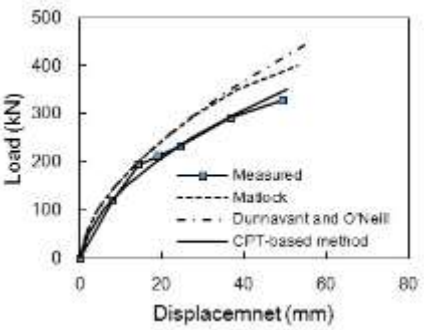


Fig. 3. Cone resistance profile at Salt Lake City site.



(a) Case 1



(b) Case 2

Fig. 4. Measured and predicted lateral load-displacement curves for 15-cycle-loading.

The results under 15-cycle-loading were compared as presented in Fig. 4. The calculated results using the CPT-based p-y curve method were in good agreement with the measured results in both case 1 and 2. Matlock's p-y method overestimated the displacement at a higher load level for case 1. The results from Dunnavant and O'Neill's p-y method were somewhat underestimated than the measured displacements.

5 SUMMARY AND CONCLUSION

The CPT-based p-y curve methods for clays under the static and cyclic loading conditions were presented. The continuous soil profile based on CPT was utilized in the method by introducing the effective cone factor into the p-y curve function. For the lateral displacement analysis, the CPT results can be considered directly by the correlation between the ultimate soil resistance and the effective cone resistance.

The results predicted using the CPT-based p-y method were compared with those obtained from the field load test and s_u-based p-y methods. In the case examples, the calculated lateral load responses showed close matches to the measured data for 15-cycle -loading. The results represent the effectiveness of the CPT-based method considering the detailed depth profile with the number of loading cycle as input parameters to evaluate the load responses in the p-y analysis.

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