PHC 항타말뚝에 대한 CPT 선단지지력 공식의 적용성 분석
Applicability of CPT-based Toe Bearing Capacity of Driven PHC Piles

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개요 : CPT 시험은 지난 30여년 동안 지반조사 분야에서 널리 이용되어 왔다. CPT 콘의 근입은 항타말뚝의 근입방법과 유사하기 때문에, CPT 콘의 선단저항력을 이용하여 말뚝의 지지력을 산정하려는 연구가 많이 수행되어 왔다. 본 연구의 목적은 기존에 제안된 CPT 선단지지력 공식의 적용성을 분석하는 것이다. 이를 위해 낙동강 하구 대심도 연약지반에서 수행된 항타 PHC 말뚝에 대한 총 172개의 PDA 시험자료와 80개소의 CPT 자료를 수집하였다. PDA시험의 CAPWAP분석에서 얻어진 선단지지력과 각 CPT 지지력 공식에서 산정된 선단지지력을 비교함으로써 각 공식의 적용성을 분석하였다. 분석에 이용된 CPT 지지력 공식은 Aoki 방법, Meyerhof 방법, Penpile 방법, Philpponnat 방법, LCPC 방법, Schmertmann 방법, Zhou 방법, ICP 방법, Eslami & Fellenius 방법, 그리고 UWA-05 방법의 총 10가지이다. 분석결과, Aoki 방법, Phillipponnat 방법, ICP 방법 그리고 LCPC 방법 순으로 그 적용성이 높은 것으로 나타났다.

Key words: Cone penetration test (CPT), Pile Driving Analyzer (PDA), CAPWAP, toe bearing capacity, PHC piles, soft deposit

1. INTRODUCTION

The cone penetration test (CPT) has been used for more than 30 years for soil exploration purposes. The test method of CPT is similar with the installation of driven piles, so the cone tip resistance of the CPT can be closely related to the toe and the shaft resistances of the pile. Until now, many CPT based method for evaluating pile capacity have been suggested. Therefore, it is important for the practical purpose to evaluate the applicability of the CPT based methods.

In the Nakdong river deltaic area, a large number of CPT and PDA tests for driven PHC piles were performed for the design of apartment complex. The data include 172 PDA tests at EOID for the piles with 0.5m and 0.6m in diameter and 80 CPT data. The CAPWAP analysis were performed to evaluate the shaft and the toe resistances from the PDA tests. Usually, the shaft resistance at EOID is significantly underestimated due to the soil disturbance during pile driving. However, the toe resistance at EOID showed the reliable estimation of toe resistance. Therefore, the applicability of the CPT based toe bearing capacity methods were analyzed by comparing the calculated toe resistance(Q_p) from the CPT based method and the estimated toe resistance(Q_m) from the CAPWAP analysis.

The analyzed CPT based toe bearing capacity methods include the ten methods of Aoki and

De Alencar (1975); LCPC(Bustamante and Gianeselli, 1982); ICP (Jardine et al., 2005); Eslami and Fellenius (1997); Meyerhof (1951, 1976); Penpile(Clisby et al 1978); Philipponnat (1980); Schmertmann(1978); UWA-05 (2005); Zhout et al (1982) method.

2. SITE CONDITION AND SELECTION OF DATA

The study site was Myeongji site in the Nakdong river deltaic area. Figure 1 shows soil stratification and Figure 2 shows the combined CPT results in Myeongji site. The fill of about 5 m thick was placed on the ground surface and followed by loose silty sand, soft silty clay, silty sand seamed with silty clay and sandy gravel on bed rock.

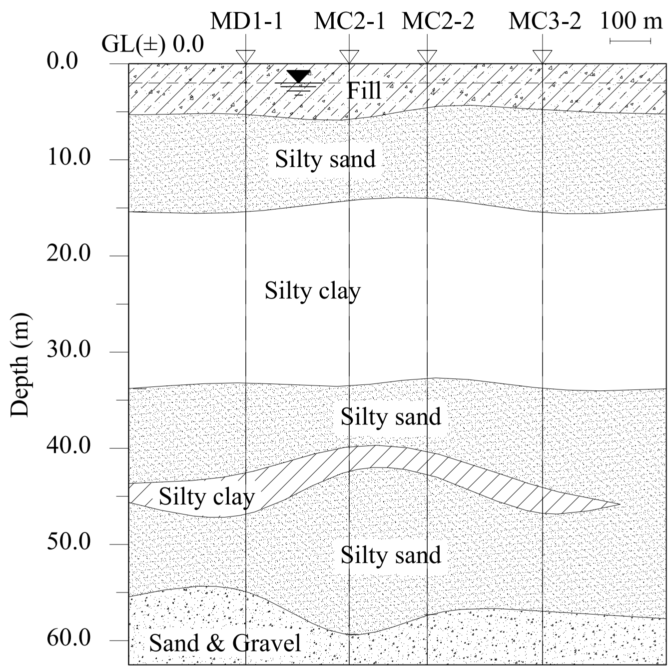


Figure 1 Soil stratification

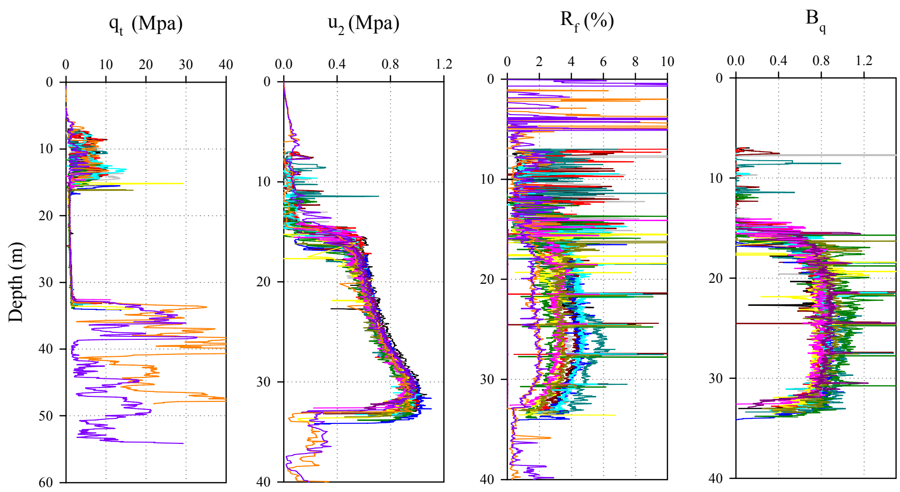


Figure 2 Typical CPT profiles in Myeongji site

Beofore calculating the toe bearing capacity from CPT data, the inclination of cone rod during the penetration was corrected by Equation 1.

$$L_1 = \sum_{i=1}^{L} \cos\alpha_i . L_i \quad (1)$$

where, L_1= corrected depth of CPT data; α_i= measured inclination angle between vertical direction and cone rod at the i-th depth number; L_i= penetrated depth of CPT at i-th depth number.

The closest CPT data from PDA testing locations were selected as the analysis set with the corresponding CAPWAP results. To improve the correlation between the calculated and the measured resistances, the data with large variation were removed by Equation 2. The data, which satisfied Equation 2, were used for the analysis. After applying Equation 2, a total of 130 PDA test data were selected.

The following equation was used:

$$\frac{\bar{x}}{s^2} \le \left(\frac{Q_p}{Q_m}\right)_i \le \bar{x}.s^2 \quad (2)$$

$$s = \exp\left(\left[\frac{1}{n-1}\sum_{i=1}^{n}\left[\ln\left(\frac{x_i}{\bar{x}}\right)\right]^2\right]^{\frac{1}{2}}\right) \quad (3)$$

where: $\bar{x}$ = geometric average of ratio Q_p/Q_m; s = standard deviation of ratio Q_p/Q_m; $x_i = (Q_p/Q_m)_i$; n= number of ratio Q_p/Q_m .

3. CPT-BASED METHODS OF TOE BEARING CAPACITY OF PILES

A summary of the CPT-based method is presented in Table 1.

Table 1 Summary of CPT-based methods

CPT-based methods	Unit toe bearing capacity, r_t
Aoki and De Alencar (1975)	$r_t = q_{ca}/F_b \le$ 15 MPa F_b depends on pile type; 1.75 for PHC driven piles q_{ca}= average cone tip resistance (q_c) of zone in 8D above and 4D below pile toe; D is the pile diameter.
LCPC (Bustamante and Gianeselli, 1982)	$r_t = k_b q_{eq}$ k_b = 0.15-0.6 depends on soil type and installation procedure. q_{eq} = equivalent average of q_c values in zone of 1.5D above and 1.5D below pile toe
ICP (Jardine et al, 2005)	*In clay:* $r_t = k.q_{ca}$ k: =0.8 for drain loading; =1.3 for undrain loading. *In sand:* $r_t = \left[1 - 0.5\log\left(\frac{D}{D_{CPT}}\right)\right].q_{ca}$ D_{CPT}=diameter of CPT cone rod. q_{ca} = same with LCPC method.
Meyerhof (1951, 1976,	r_t= C1.C2.q_{ca}

1983) method	q_{ca} = average cone tip resistance of zone in 1D above and 4D below pile toe ; C_1=modification factor of scale effect; C_2=modification for penetration into dense strata
Penpile (Clisby et al 1978)	*In clay:* $r_t=0.25q_{ca}$ *In sand:* $r_t=0.125q_{ca}$ q_{ca} :the average of the three cone tip resistances close to the pile tip.
Philipponnat (1980)	$r_t=k_b.q_{ca}$ q_{ca}= average cone tip resistance in zone of 3D above and 3D below pile toe; k_b= depends on soil type. In this study, k_b =0.4 was used.
Schmertmann (1978)	$r_t= (q_{c1}+q_{c2})/2 \leq 15$ MPa q_{c1}=minimum of the average q_c values in zone of 0.7 to 4D below pile toe; q_{c2}= average of minimum of q_c values within 8D above pile toe.
UWA-05 (2005)	*For opened-ended piles:* $r_t = \left[0.15 + 0.45\left(\frac{D^2{}_{int}}{D^2}\right)\right].q_{ca}$ *For closed-ended pile:* $r_t=0.6q_{ca}$ q_{ca} = same with Schmertmann (1978) method.
Zhoul et al (1982)	$r_t=\alpha.q_{ca}$ q_{ca}= average cone tip resistance in zone of 4D above and 4D below pile toe; a=modification factor accodring to soil type.
Eslami and Fellenius (1997)	$r_t=C_t.q_{eg}$ q_{eg}= geometric average of q_e in zone of 8D above and 4D below pile toe; q_e = corrected cone tip resistance; C_t = 1/3D.

4. APPLICABILITY OF CPT-BASED METHODS

The rank index (RI) of Equation 4 suggested by Murad et al(2004), was introduced to quantify the overall performance of each CPT method. The RI value is defined as the sum of each rank. The lower RI value means the better performance of the method. The analyzed results of each CPT based methods are summarized in Table 2.

$$RI = R1+ R2 + R3 + R4 \quad (4)$$

where R1=rank by slope of best-fit line for Q_p vs Q_m relation and corresponding coefficient of determination (R^2); R2= rank by arithmetic mean (μ) and standard deviation (σ) of Q_p/Q_m values; R3= rank by probability within $0.8 \leq Q_p/Q_m \leq 1.2$ in log-normal and histogram distributions of Q_p/Q_m ; R4=rank by Q_p/Q_m values corresponding to 50% and 90% cumulative probabilities.

The first criterion R1 ranks each method by using the slope of the best-fit line for the predicted (Q_p) vs. the measured resistances (Q_m) curves and the corresponding coefficient of correlation(R^2) as shown in Figure 3(a). In Table 2, A and B are the ranks by the slope criterion and coefficient of correlation, respectively and R1 value is the average of A and B values. The applicability is better if the slope and the coefficient of correlation are closer to unity. The results showed that every method except Meyerhof method underestimated the toe capacity.

In the second criterion R2, the arithmetic mean (μ) and the standard eviation (σ) of Q_p/Q_m values are used. The applicability is better if the μ value is closer to unity and σ value is closer to zero. C and D are the ranks by the μ and σ values, respectively. R2 value is the average of C and D values.

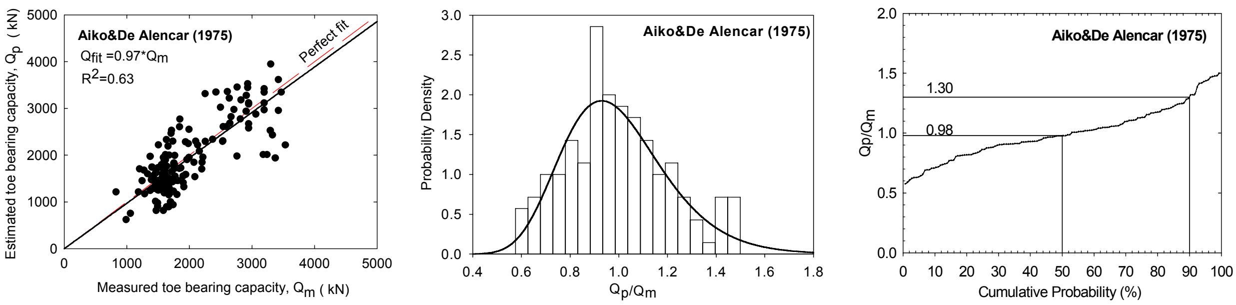
In the third criterion R3 suggested by Briaud and Tucker (1988), the log-normal distribution and histogram of Q_p/Q_m values are drawn as shown in Figure 3(b) and the probabilities within $0.8 \le Q_p/Q_m \le 1.2$ are calculated. The higher probability means the better applicability of methods. E and F are the rank from log-normal distribution and histogram distribution, respectively.

The fourth criterion R4 was suggested by Alsamman(1995) and Long and Wysockey(1999). The concept of this criterion is to list the ratio Q_p/Q_m in ascending order (number 1, 2, 3…n) and a cumulative probability, P, is calculated by Equation (5). P_{50} and P_{90} are defined as the values of Q_p/Q_m corresponding to 50% and 90% of cumulative probability as shown in Figure 3(c). The P_{50} and P_{90} values closer to unity means that thebetter applicability of methods.

$$P = \frac{i}{(n+1)} \tag{5}$$

where, i=ascending order of value considered in P; n = number of data

The analysis results showed that the applicability of Aoki method, Phillipponnat method, ICP method and LCPC method was higher in order. The Penpile method, however, was ranked as the worst method because this method showed a value of "zero" percent for both of the log-normal and histogram distribution criterion.



a) b) c)

Figure 3. Evaluation of rank index for Aoki and De Alenca method
(a) best-fit line; (b) log-normal and histogram distributions; (c) cumulative probabilities

Table 2. Evaluation of applicabilty of CPT-based methods

CPT- based method	Best fit calculations of Qp/Qm					Arithmetic Calculations of Qp/Qm					± 20% Accuracy (%) of Qp/Qm					Cumulative probability of Qp/Qm					Index (RI)	Rank
	Slope	r^2	A	B	R1	μ	σ	C	D	R2	Log-Normal	Histogram	E	F	R3	P_{50}	P_{90}	G	H	R4		
Aoki and De Alencar	0.98	0.63	1	3	2.0	0.98	0.23	1	5	3.0	65.34	64.70	1	1	1.0	0.98	1.30	1	6	3.5	9.5	1
Philipponnat	0.81	0.64	5	1	3.0	0.82	0.18	5	3	4.0	48.68	47.60	3	3	3.0	0.82	1.10	6	3	4.5	14.5	2
ICP	0.91	0.52	2	5	3.5	0.93	0.25	2	7	4.5	50.63	47.76	2	2	2.0	0.93	1.30	2	7	4.5	14.5	2
LCPC	0.90	0.63	3	3	3.0	0.87	0.24	2	6	4.0	44.74	47.42	4	4	4.0	0.86	1.20	4	5	4.5	15.5	4
Schemrtmann	0.88	0.45	4	7	5.5	0.90	0.28	2	8	5.0	39.58	41.79	5	5	5.0	0.87	1.28	3	8	5.5	21.0	5
Zhou et all	0.65	0.64	7	1	4.0	0.67	0.12	7	2	4.5	15.66	14.70	8	8	8.0	0.67	0.83	7	2	4.5	21.0	5
Eslami and Fellenius	0.81	0.26	5	10	7.5	0.84	0.35	5	9	7.0	27.92	33.30	6	6	6.0	0.84	1.40	5	10	7.5	28.0	7
UWA-05	0.53	0.43	8	8	8.0	0.54	0.18	9	3	6.0	10.61	9.41	9	9	9.0	0.52	0.79	8	4	6	29.0	8
Meyerhof	1.60	0.35	9	9	9.0	1.30	0.77	7	10	8.5	22.44	17.62	7	7	7.0	1.62	2.10	9	9	9	33.5	9
Penpile	0.30	0.48	10	6	8.0	0.29	0.11	10	1	5.5	0.00	0.00	10	10	10.0	0.30	0.45	10	1	5.5	29.0	10

Note: RI= R1+R2+R3+R4; R1= (A+B)/2; R2=(C+D)/2; R3=(E+F)/2; R4=(G+H)/2; R^2=correlation coefficient; μ=arithmetic mean; σ=standard deviation; P_{50} and P_{90}= Q_p/Q_m values corresponding to cumulative probability of 50% and 90%, respectively.

6. CONCLUSION

The cone penetration test (CPT) has been used for more than 30 years for soil exploration purposes. The test method of CPT is similar with the installation of driven piles, so the cone tip resistance of the CPT can be closely related to the toe resistance and the shaft resistance of the pile. The objective of the research is to analyze the applicability of the existing CPT based toe bearing capacity method. For this purpose, the qc profiles of CPT, which performed at 80 locations in the Nakdong river deltaic areas, were compared with the toe resistance from the CAPWAP analysis for 172 PHC piles with 0.5 and 0.6 diameter.

The analyzed CPT based toe bearing capacity methods include the ten methods of Aoki method, Meyerhof method, Penpile method, Philpponnat method, LCPC method, Schmertmann method, Zhou method, ICP method, Eslami &Fellenius method, and UWA-05 method. The comparison between the predicted toe capacity of the methods and the toe capacity from the CAPWAP analysis showed that the reliability of Aoki method, Phillipponnat method, ICP method and LCPC method was higher in order.

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