A study for the vertical stiffness of preboring precast concrete pile from field load tests

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ABSTRACT

In South Korea, apartment remodeling project involving two to three floor vertical extension is under beginning stage as of year 2018. In the point of foundation retrofitting and reinforcement, the vertical stiffness of 20~30 year old PC pile is the key parameter in the process of structural analysis. In this paper, the stiffness of the PC pile with various diameter and length was analyzed based on thirty eight field loading test results which were performed in 1990's. The analysis results show that the pile stiffness decreases with the increase of the length-diameter ratio (L/D). In addition, the coefficient 'a' for estimating pile stiffness proposed in references are compared to those obtained from the field loading tests. It shows that 'a' obtained through the estimation of the literature are very similar to the field test results in the range of $10 < \mathrm{L/D} < 50$.

Keywords: Vertical Pile stiffness, Pile reinforcement, PC pile, Apartment remodeling

1 INTRODUCTION

Many apartment remodeling projects are currently on-going with 2~3-story vertical extension in South Korea. In most cases, due to the floor increase (*i.e.,* load increase) and the application of enhanced seismic criteria, the bearing capacity of existing piles is insufficient and additional pile installation is required. In the case of the foundation reinforcement, the existing pile and the reinforced pile have different vertical stiffness due to the heterogeneous nature of their materials and bearing mechanism. Therefore, the load sharing is dominantly influenced by the stiffness ratio of the different piles.

The vertical stiffness of the pile can be estimated by the method described in Korea Highway Bridge Design Standard (KHS, 2008) and the Pile Foundation Design Guideline of Korea Railroad Corporation (KRC, 2012). This study presents the vertical stiffness analysis results of field load tests for SIP (Soil-cement Injected Precast Pile) PC piles installed between 1995 and 1997 and its comparison to the values estimated using analytical equations of KHS (2008) and KRC (2012).

2 VERTICAL STIFFNESS ANALYSIS OF PILE

Thirty eight field compression load test results for SIP-PC piles were used for analysis which were performed in 1995-1997 (KISTEC, 2017). The diameters of the test piles were 350mm, 400mm, and 500mm. The design loads (P_d) were Φ350: 40ton (392kN), Φ400: 50ton (490kN), Φ500: 65ton (642kN) which were denoted in the field test reports. The length of the pile varies depending on the field conditions. The length vs. diameter ratio (L/D) of the piles ranges from 12 to 41. The vertical stiffness K was estimated from P-δ curve of field loading test results as the secant slope at the pre-defined reference design load. K was obtained in two ways according to Eq. (1) and (2).

$$K_d = \frac{P_d}{\delta_d} \tag{1}$$

$$K_d^e = \frac{P_d}{\delta_d - \delta_d^p} = \frac{P_d}{\delta_d^e} \tag{2}$$

where K_d and K_d^e are vertical stiffness at the design load corresponding to total and elastic deflections of pile head, respectively. In other words, δ_d, δ_d^p and δ_d^e represent total, irrecoverable (plastic), and recoverable (elastic) vertical deflections, respectively.

Eq. (3) shows the pile vertical stiffness K estimation formula given by KHS (2008) and KRC (2012). The estimation equation is a function of the structural properties such as pure sectional area (A_p), length (L) and diameter (D) of the pile, and the elastic modulus (E_p) of the pile section, and reflects the effect of the pile construction method and material on the factor 'a'. If 'a' removes in Eq. (3), it is identical to the stiffness formula of the cantilever column subjected to axial load.

$$K = \mathrm{a}\frac{A_P \cdot E_P}{L} \tag{3}$$

In this study, Eq. (4) and Eq. (5) are used for estimating 'a' according to KHS (2008) and KRC (2012), respectively.

$$\mathrm{a} = 0.013(L/D) + 0.53 \tag{4}$$

$$\mathrm{a} = 0.011(L/D) + 0.36 \tag{5}$$

From Eqs. (3) to (5), it is denoted that the interpretation of the design guidelines of KHS (2008) and KRC (2012) are difficult to reflect the conditions and engineering characteristics of the pile installed. Therefore, it is suggested that obtaining the vertical stiffness from $P-\delta$ curve at the head of the pile is the most reliable when there is field loading test result (Bowles, 2012).

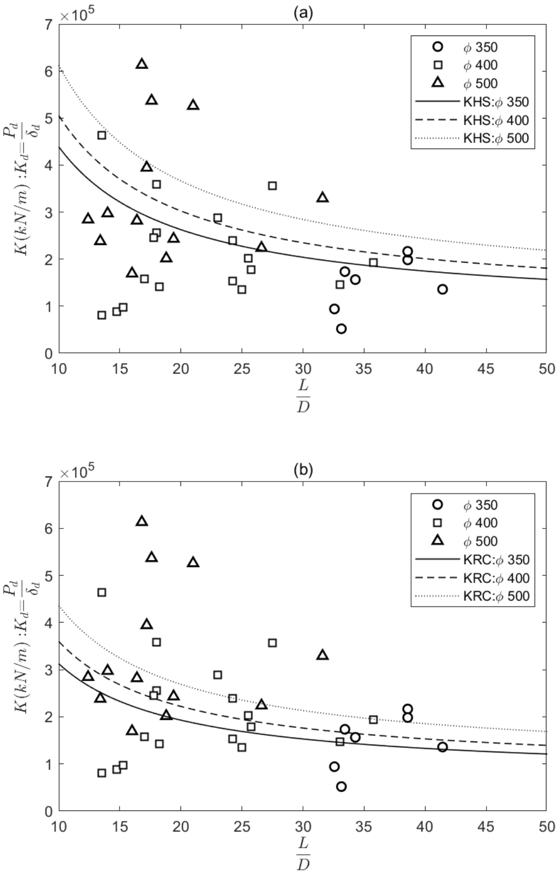

Fig. 1. K_d vs. L/D; (a) Comparison with KHS (2008) and (b) Comparison with KRC (2012).

Figures 1 and 2 show K_d (K with total settlement) and K_d^e (K with elastic settlement) at design load along to the variation of length to diameter ratio (L/D), respectively. In each figure, '○', '△', and '△' are K of the field compression loading tests corresponding to Φ350, Φ400 and Φ500, respectively.

Three solid and dotted lines in (a) and (b) of figures show the estimated K from KHS (2008) and KRC (2012), respectively. Since KHS (2008) and KRC (2012) are generally applied when L/D is more than 10, the graphs are appropriately scaled.

From the results, it can be seen that the K according to the two ways of estimation tends to decrease as L/D increases, but it is noted that the field test results are widely distributed. Therefore, it is difficult to find the ideal relation between K and L/D by regression analysis for each diameter based on the field test data. In addition, it is shown that $K_d < K_d^e$. From the visual observation of the results, it is noted that K_d is closer to the estimation of KHS (2008) and KRC (2012) than K_d^e at the design load of the pile.

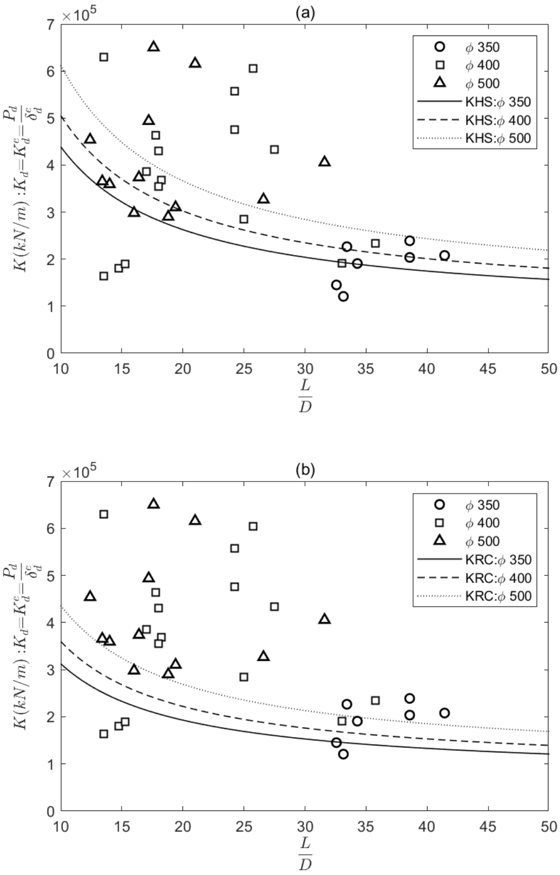

Fig. 2. K_d^e vs. L/D ; (a) Comparison with KHS(2008) and (b) Comparison with KRC(2012).

3 ANALYSIS OF COEFFICIENT 'a'

Figure 3 shows the results of comparing 'a' of Eq. (3) analyzed from the field test results with the coefficient 'a' of KHS (2008) and KRC (2012). Figure 3(a) and (b) are analysis results based on K_d and K_d^e, respectively. The 'o' symbol is the field load test result and the solid black line is the linear regression analysis of each data. The black dashed line shows the ± standard deviation of the error that occurs when a value is predicted according to L/D ratio using the linear regression analysis formula (Mathworks, 2017). In addition, the gray solid line and the gray dotted line represent the value of ‘a’ according to Eq. (4) and Eq. (5) along L/D ratio. The ‘a’ obtained from K_d is comparable to those of Eqs. (4) and (5) while the ‘a’ from K_d^e is relatively over estimated by looking at the coefficients of linear regression polynomial and the band size of ± standard deviation error.

The error analysis of the test results showed that ‘a’ is estimated to be similar to the field load test results within the L/D range of 10~50. In other words, when a value is predicted through the interpretation of KHS (2008) and KRC (2012), it is found that it is within the range of 50% probability of the actual load test result.

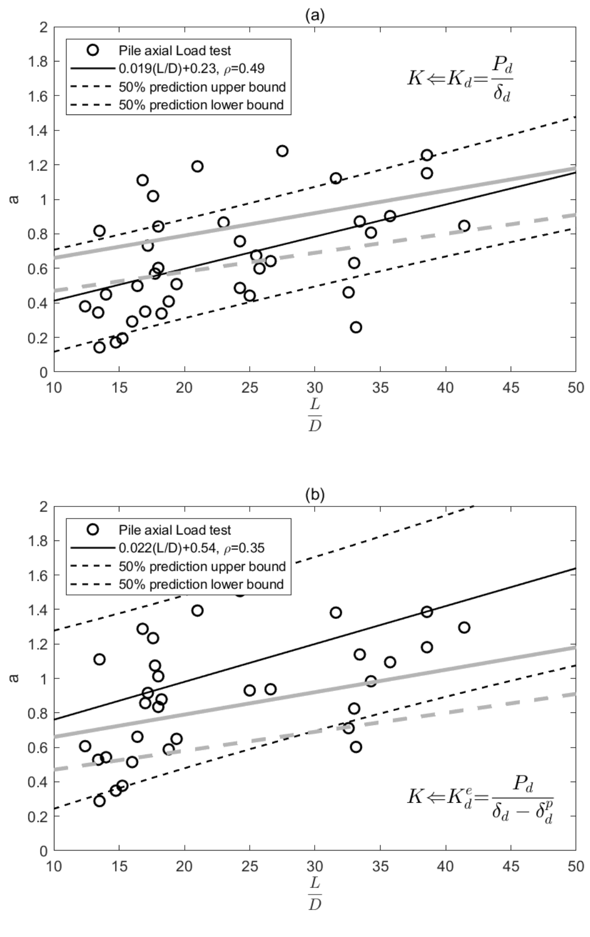

Fig. 3. Coefficient ‘a’ vs. L/D ; (a) ‘a’ from K_d and ‘a’ from K_d^e.

4 CONCLUSION

In this paper, the vertical stiffness of pile was analyzed with 38 cases of SIP-PC pile constructed in 1995-1997. In addition, the field test results were compared to the stiffness estimate methods of the pile foundation design guidelines of Korea Railroad Corporation (KRC, 2012) and Korea Highway Bridge Design Standard (KHS, 2008). The results of the study are as follows.

1. The vertical stiffness (K) from field test results were calculated by two methods. They are the secant slopes of p-δ curve at design load with i) total settlement and ii) elastic settlement. From the results of the analysis, it can be seen that K value decreases with the increase of L/D. It is not easy to find the ideal relation of $K\ vs. \frac{L}{D}$. At least, it is surely shown that $K_d < K_d^e$ and K_d^e is better related to the K estimation from KHS (2008) and KRC (2012) based on the visual observation.
2. The coefficient ‘a’ of the field test results which reflects the effect of pile type and construction method for stiffness estimation were compared to the equations suggested in KHS (2008) and KRC (2012). From the comparison, ‘a’ obtained from K_d is more comparable with the literatures than that from K_d^e. The error analysis showed that ‘a’ from KHS (2008) and KRC (2012) appropriately estimate the values in the range of $10 < \frac{L}{D} < 50$. When ‘a’ value is predicted through KHS (2008) and KRC (2012), it is within the range of 50% probability of the field load test results.

This study has focused on the vertical stiffness of SIP (Soil-cement Injected Precast pile) from field loading tests. The vertical stiffness of the SIP-PC pile analyzed in this study might be used as a reference value for remodeling structural analysis which is a key parameter to obtain the distribution of load for existing and reinforcing piles. In addition, this study is expected to be a basic data to understand the limits and applicability of the estimation formula presented in KHS (2008) and KRC (2012).

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