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Experimental Investigation on Buckling Behavior of Axially Loaded Prestressed Concrete Piles in Sand

P. Senthil Kumar, S.K. Arun Kamaraj and P. Parameswaran
Department of Civil Engineering, PSG College of Technology, Coimbatore, India

Abstract: This study aims to combine the structural and geotechnical aspects of the partially embedded slender prestressed concrete pile-soil system together to determine the buckling capacity of the pile. Three prestressed concrete specimens partially embedded in sand as foundation medium were tested with the combinations of unsupported length and coefficient of subgrade modulus of the sand medium under axial loading. In this study, a simple procedure to predict the buckling capacity of an axially loaded partially embedded prestressed concrete pile in sand is formulated using conventional Davisson and Robinson method combined with the ACI's flexural stiffness equation of the slender column. Comparison was also made between the theoretical predictions and the test results.

Key words: Partially embedded pile, prestressed concrete pile, axial load, flexural stiffness, coefficient of subgrade modulus, buckling capacity

INTRODUCTION

Piles are structural elements that are used to transfer the building loads to the foundation medium. Normally, the lateral support given to a pile, even by the weak foundation medium, is sufficient to prevent it from buckling under the applied building loads (Cummings, 1938; Glick, 1948). However, the situations for piles that are partially free-standing are frequently arising nowadays for offshore structures or bridges, where the unsupported section of pile behaves as a structural column and is more vulnerable to buckling (Klohn and Hughes, 1964; Lee, 1968; Ramsamooj, 1975; Senthil Kumar *et al*., 2006).

Several theoretical studies are currently available for analyzing buckling of fully embedded piles. Until recently, most of the theoretical studies on partially embedded piles concerns mainly on assessing the buckling capacity of the pile (Hetenyi, 1946; Francis, 1964; Davisson and Robinson, 1965; Gabr *et al*., 1994; Chen, 1997; Heelis *et al*., 1997; San-Shyan Lin and Chang, 2002; Baghery, 2004). On the other hand, full scale experimental investigations conducted earlier were to understand about the column strength of long reinforced concrete pile (Hromadik, 1961), ignoring the effect of surrounding foundation medium. At the same time, detailed studies made on partially embedded timber piles was covering well with the theory and the desirable field experiments (Klohn and Hughes, 1964), but its application is limited to such members only. Similarly, numerous laboratory investigations on piles in partially embedded condition with consistent foundation medium was carried out on steel as well as aluminum piles (Lee, 1968) and also on, brass piles (Ramsamooj, 1975). Senthil Kumar *et al.* (2006) indicated the importance of carrying out experimental investigations on partially embedded pile, in which the experimental study is limited reinforced concrete pile only. However, little investigation is attempted considering the effect of both the geotechnical aspects and structural aspects together for partially embedded prestressed concrete pile. It is well kwon that eccentricity of loading is inevitable in actual practice, even under the best conditions; however, the ideal case of axial loading is essential for analyzing the full capacity of the pile.

Hence, the present study aims to formulate a procedure for predicting the buckling capacity of axially loaded partially embedded prestressed concrete pile considering both geotechnical as well as structural aspects of the soil-pile system together. In order to understand the behavior of partially embedded pile, experimental investigation was carried out on consistently reproducible foundation medium at various required states of sand medium. The experimental results are compared to the theoretically predicted buckling load.

ANALYTICAL APPROACH

It is well known that the importance of the present study lies on the exact determination of equivalent length of the pile (L_e), which is equal to the sum of unsupported

Corresponding Author: P. Senthil Kumar, Department of Civil Engineering, PSG College of Technology, Coimbatore, India

Length (L_u) and depth of fixity (L$)._f$ Davisson and Robinson (1965) have proposed simplified formulas, to determine the depth of fixity (L_f), which is adopted by AASHTO LFRD (1994) as well as ACI committee 543 (2000). For the partially embedded piles in sand, L_f, measured from ground, is computed from:

$$L_f = 1.8\ [EI/n_h]^{0.20} \tag{1}$$

Where,

- E = Modulus of elasticity of the pile material
- I = Moment of inertia of the pile
- n_h = Coefficient of horizontal subgrade modulus.

Equation 1 was based on the conventional beam-on-elastic-foundation theory and intended for partially embedded piles. The coefficient of 1.8 in Eq. 1 was suggested for simplification and compromise such that the equation is applicable to both bending and buckling. This equation is also included in the FHWA report (1987).

Therefore, Euler load (P_{cr}) for an eccentrically loaded partially embedded prestressed concrete pile is:

$$P_{cr} = \prod^2 EI/(0.7\ L_e)^2 \tag{2}$$

Equation 2 is applicable for the end conditions of the present study that is fixed at the base and pinned at the top. However, it can be solved for other top end conditions also.

For the determination of flexural stiffness (EI) of the pile to be used in Eq. 2, the simplified equation permitted by ACI building code (1989) [ACI 318-89 Eq. 10-11] for a slender reinforced concrete column to short-time loads, which is recommended for prestressed member also, is taken as:

$$EI = 0.4\ E_c I_g \tag{3}$$

Where,

- E_c = Modulus of elasticity of concrete
- I_g = Moment of inertia of the gross concrete section.

It is known that the flexural of a slender member depends on various factors. However, considering the convenience, ACI building code allows the Eq. 3 for practical applications.

MATERIALS AND METHODS

An experimental investigation was planned to study the behavior of the axially loaded partially embedded prestressed concrete piles using the method outlined by Senthil Kumar *et al*. (2006). Totally three tests were carried out by varying unsupported Length (L_u) and coefficient of horizontal subgrade modulus (n_h), as detailed in Table 1. Figure 1 shows the experimental set up used for the present study.

Table 1: Details of partially embedded piles

Specimen reference	f_{cc} (N mm^{-2})	L_u (m)	R.D (%)	n_h (kN m^{-3})
APP 1	43.02	1.0	30	9801
APP 2	24.42	1.1	50	12197
APP 3	26.04	1.1	70	19543

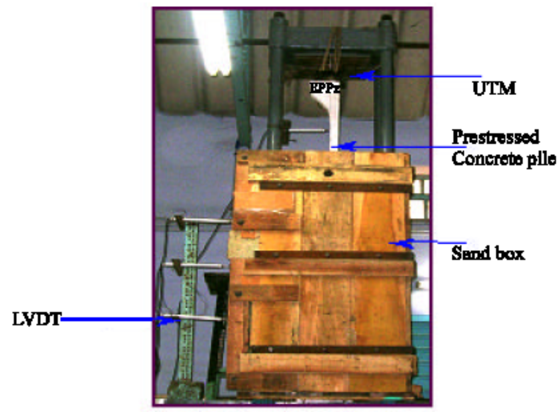

Fig. 1: Experimental setup

Test specimens: The pile specimens of size 40×50×2200 mm were cast with cement (53 grade), river sand and crushed aggregates of maximum size 6mm for the proposed mix of concrete grade M50, as per IS 10262 (1982) standards. Mild steel rod of four numbers of 4 mm diameter were used as complementary reinforcement with 3 mm diameter as lateral ties spaced at 40 mm center to centre. Additional reinforcement with suitable arrangement was provided at the ends of the pile for better distribution of load and to avoid anchorage failure.

Single HTS wire of diameter 4 mm with an ultimate tensile strength of 1660 MPa was used for prestressing. Pretensioning was done by Killick system of single wire prestressing using self-straining steel frame of 20 kN capacity as shown in Fig. 2. Prestressing force applied was 850 MPa (nearly, 50% of ultimate stress), which is less than IS 1343 (1980) standards.

Additional rods (deflection rods) were fixed during casting, to measure the lateral deflection in the embedded region. Control specimens were cast along with each pile specimen and cured under similar conditions of parent specimen. The values of concrete compressive strength (f_{cc}) are given in Table 1.

Foundation medium: Dry river sand was used as a foundation medium. The specific gravity and uniformity coefficient of the sand were 2.62 and 1.4, respectively. The limiting void ratios were e_{max} = 0.63, e_{min} = 0.47 corresponding minimum dry densities were 1.599 and 1.782 g/cc, respectively. The placement density for various relative densities was obtained by calculation.

Experimental determination of the coefficient of subgrade modulus for the foundation sand at a particular relative density was carried out separately, by the procedure outlined by Lee (1968), using a very rigid concrete pile with square cross-section as recommended by Terzaghi (1955). The values of n_h for various relative densities are presented in Table 1, which is based on the average of three test values.

Test setup and procedure: Amsler Universal Testing Machine (UTM) of 1000 kN capacity, suitably modified to allow a maximum specimen length of 2200 mm, was used to test the pile specimen. UTM keeps the assembly set up intact up to specimen failure, even under large deformations.

A specifically designed wooden box (Fig. 1) of size 0.6×0.6×1.5 m to meet the testing requirement, was placed in position to fill the sand after securing the position of the specimen between the ball-socket arrangements at both ends. Weighed mass of sand obtained for 150 mm thickness, based on the placement density, was poured and uniformly compacted till achieving 150 mm graduated level mark for each and every layer.

The deflection of the pile was measured along the whole length using Linear Variable Displacement Transducers (LVDT) at five locations that is 410 mm (LVDT-1), 1140 mm (LVDT-2), 1460 mm (LVDT-3), 1750 mm (LVDT-4) and 2180 mm (LVDT-5), where three (namely, LVDT-3, 4 and 5) among that were attached with deflection rods extending through the foundation medium.

The loads were applied axially with desired eccentricity. In all the tests, an initial set load of 2 kN was applied and then initial readings were observed. At every loading increment, the deflections were recorded carefully besides observation of failure and marking cracks simultaneously.

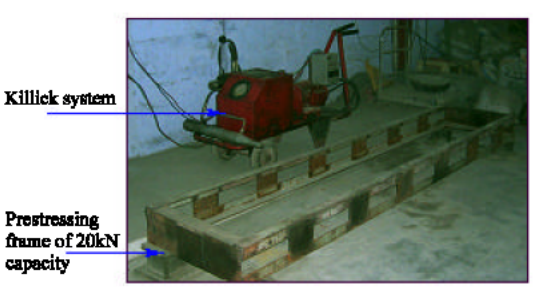

Fig. 2: Killick system of prestressing and prestressing steel frame

RESULTS AND DISCUSSION

Load-deflection diagrams: From the experimental results, the basic observations obtained such as applied load and lateral deflections are plotted as the lateral deflection curves along its length at various stages of loading for each pile, so as to understand the behavior of pile, as shown in Fig. 3-5.

In all the tested specimens lateral deformation was observed indicating the buckling of the piles. Flexural cracks were observed near the middle region of the unsupported length indicating the initiation of failure. Finally, the pile failed by crushing of concrete in compression with spalling of cover concrete. Further, in all the tested piles, the failure occurred above foundation medium.

From Fig. 3-5, it is clear to see that the deflection of the pile reverses direction during the test under continuous increasing loading. This may be due to the nonlinear relation between the deflections and the applied load.

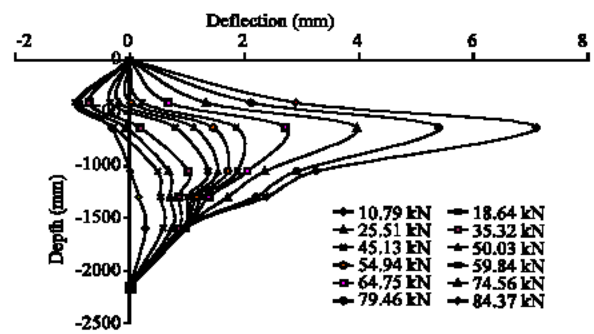

Fig. 3: Pile lateral deflection for APP 1 (L_u = 1.0 m, R.D = 30%)

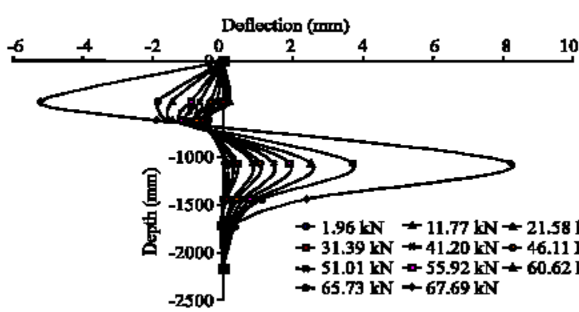

Fig. 4: Pile lateral deflection for APP 2 (L_u = 1.1 m, R.D = 50%)

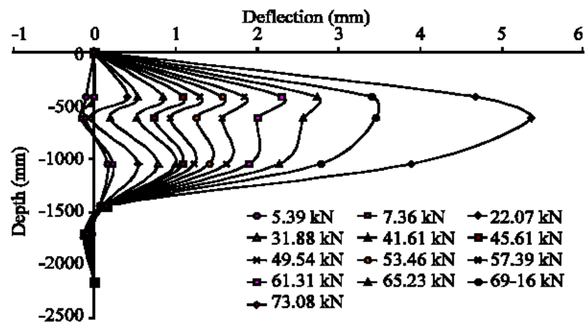

Fig. 5: Pile lateral deflection for APP 3 (L_u = 1.1 m, R.D = 70%)

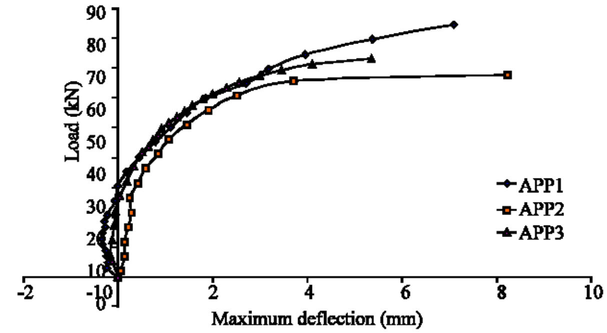

Fig. 6: Load-deflection curves for different pile specimens

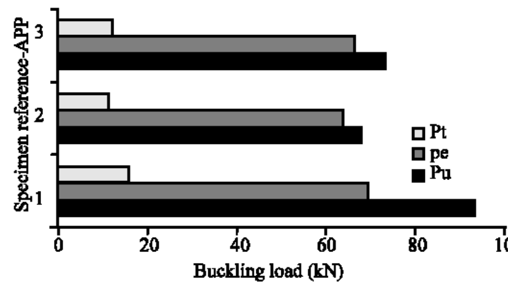

Fig. 7: Comparison of results

Further, it is noticed that the general trend in the variation of deflection is high at the middle of unsupported length and it is small along the remaining potion of the pile. It is seen that the partially embedded pile, while nearing the failure stage divides into two units clearly, one is the unsupported length slightly extending into ground with large deflection and behaves like column and other is the embedded length with insignificant deflection laterally supported by foundation medium. This confirms the column behavior of the pile in the unsupported length as well as its influence over the soil-pile system and ultimately its load carrying capacity.

Figure 6 illustrates the load-maximum deflection curves for the testes piles and it shows the typical axial loaded column behavior of the partially embedded pile under varying relative densities of the sand medium. Based on the experimental results, the following general features were also observed:

- The deflection of the pile is high at the middle of the unsupported length and reduces significantly in the foundation medium.
- The behavior of piles is similar in loose (R.D = 30%), medium (50%) as well as dense (70%) states of sand.

Finally, comparison between the ultimate load for the test specimen (P_u), the experimental critical load (P_e) and theoretically Predicted critical load (P_t) was carried out as shown in Fig. 7. In which, the theoretical critical loads were estimated based on the present procedure and the experimental critical loads were determined based on the procedure suggested by Kwon and Hancock (1992).

As expected, the present approach is highly conservative for prestressed concrete pile under axial loading condition, since the effect of prestressing is not accounted in the ACI code. Apart from that the ACI equations for EI singly accounts many factors including slenderness effects and the use of most conservative (i.e., greatest) value (Lee, 1968) for the coefficient of the depth of fixity in the Davisson and Robinson (1965) equation.

CONCLUSION

In this study, an attempt is made to unify the structural and geotechnical aspects of partially embedded prestressed concrete pile under axial loading. Buckling capacity of the partially embedded slender prestressed concrete pile may be predicted conservatively using the proposed procedure. Experimental investigation reveals the column behavior of the partially embedded pile along the unsupported length.

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