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# BUCKLING BEHAVIOR OF PARTIALLY EMBEDDED REINFORCED CONCRETE PILES IN SAND

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## ABSTRACT
This paper aims to unify the structural and geotechnical aspects of the partially embedded slender reinforced concrete pile-soil system together, specifically under eccentric loading, where eccentricity is inevitable in actual practice. Seven reinforced concrete specimens partially embedded in sand as foundation medium were tested with the various critical combinations of unsupported length, loading eccentricity and coefficient of horizontal subgrade modulus of the sand medium. In this study, a simple approach to predict the buckling capacity of an eccentrically loaded partially embedded reinforced concrete pile in sand is formulated using the conventional Davisson and Robinson method combined with the ACI's flexural stiffness equation of the slender reinforced concrete column and also, introducing a reduction factor to account eccentricity. Comparison was also made between the theoretical predictions and the test results.

**Keywords**: pile, concrete, buckling, length, stiffness, sand, modulus.

## INTRODUCTION
Concrete piles are common structural foundation elements used to support superstructure. The situations for piles that are partially free-standing are frequently arising nowadays, where such piles are subjected to buckling because of the long unsupported length. The partially embedded pile is structurally more important than column due to the absence of lateral support or bracing along its unsupported length. With the continuing innovation in concrete technology, further leads to more application on slender members in which stability plays a vital role. These piles become more vulnerable because of an eccentricity induced due to pile installation [1], which is inevitable in actual practice, even under the best of the conditions. Though, supporting soil medium offers enough confinement along the embedded length, but not right from the top ground level. Hence, it is imperative that the study on stability of pile, specifically partially unsupported, is critical all together.

In the point of view of practicing engineers, the calculation buckling loads is always a major concern, either due to the complexity or due to the sparsely scattered studies. Most of the theoretical studies concentrate on geotechnical aspects [2-9]. On the other hand, experimental investigations concerns mainly on structural part of the pile purely as column [10]. However, little study is attempted combining both the geotechnical and the structural aspects together in the partially embedded pile-soil system, especially for concrete piles.

Aim of the present investigation is to formulate a simple approach for the analysis of partially embedded reinforced concrete pile.

## ANALYTICAL APPROACH

### Equivalent length of the pile
It is well known that the importance of the present study lies on the accurate determination of equivalent length of the pile ($L_e$), which is equal to unsupported length ($L_u$) plus the depth of fixity ($L_f$). Both AASHTO LFRD [11] as well as ACI committee 543 [12] adopts the standard and simplified formulas proposed by Davission and Robinson [4], to determine the depth of fixity ($L_f$), which is used in the proposed approach. For partially embedded piles in sand, $L_f$, measured from ground, is calculated from

$$L_f = 1.8\,[EI/n_h]^{0.20} \qquad (1)$$

Where EI is the flexural stiffness of the pile, and $n_h$ is the coefficient of horizontal subgrade modulus.

Equation (1) was based on beam-on-elastic-foundation theory, and is intended for partially embedded piles. The coefficient of 1.8 in equation (1) was suggested for simplification and compromise such that the equation is applicable to both bending and buckling behaviors. This equation is also included in the FHWA report [13], which deals with seismic design of highway bridges.

### Eccentricity
Euler load ($P_{cr}$) for an eccentrically loaded partially embedded reinforced concrete pile is:

$$P_{cr} = \Pi^2\,EI/(0.7\,L_e)^2 \qquad (2)$$

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.

In case of an eccentrically loaded slender member, it is well known that the buckling load will be always smaller than the Euler load irrespective to the magnitude of the eccentricity. Therefore, in order to account eccentricity, a reduction factor (α) is introduced in equation (2), as detailed by Venkatasubramani et al. [14], in which the value of α is readily available for practical applications. Hence, the modified Euler equation accounting eccentricity is:

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$$P_{cr} = \alpha \Pi^2 EI/(0.7 L_e)^2 \quad (3)$$

**Stiffness of the member**

For the determination of the flexural stiffness (EI) of the pile to be used in equation (3), the simplified equation permitted by ACI building code [15] (ACI 318-89 Eq. (10-11)) for a slender reinforced concrete column to short-time loads, is taken as:

$$EI = 0.4 E_c I_g \quad (4)$$

Where $E_c$ is the modulus of elasticity of concrete, and $I_g$ is the moment of inertia of the gross concrete cross section.

Equation (4) singly accounts various factors including slenderness effects. Considering the convenience, ACI building code allows equation (4) for practical applications.

## EXPERIMENTAL SETUP AND TEST PROCEDURE

An experimental investigation was planned to study the behavior of the eccentrically loaded partially embedded slender reinforced concrete piles using the method outlined by Senthil Kumar *et al.*, [16]. Totally seven tests were carried out by varying unsupported length ($L_u$), coefficient of horizontal subgrade modulus ($n_h$) and loading eccentricity (e), as detailed in Table-1. Figure-1 shows the experimental set up used for the present study.

**Test specimens**

The pile specimens of size 40mm x 50mm x 2200mm, 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 [17]. Mild steel rod of four numbers of 4mm diameter were used as main reinforcement with 3mm diameter as lateral ties spaced at 40mm 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. Additional rods (deflection rods) were fixed during casting, to measure the lateral deflection in the embedded region. Control specimen of 150mm x 150mm x 150mm cube was cast with each pile specimen and cured under similar conditions of parent specimen. The values of compressive strength of the concrete cube (fck) 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 1.599g/cc and 1.782g/cc, respectively. The placement density for various relative densities (R.D) 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 [18], using a very rigid concrete pile with square cross-section as recommended by Terzaghi [19]. The values of $n_h$ for various relative densities are presented in Table-1, which is based on the average of three test values.

**Table-1.** Details of partially embedded pile.

| Speci-men | $f_{ck}$ (N/mm$^2$) | $L_u$ (m) | e (mm) | R.D (%) | $n_h$ (kN/m$^3$) |
|---|---|---|---|---|---|
| E1 | 42.69 | 1.0 | 60 | 30 | 9801 |
| E2 | 29.11 | 1.0 | 40 | 30 | 9801 |
| E3 | 48.14 | 1.0 | 20 | 30 | 9801 |
| E4 | 29.93 | 1.2 | 40 | 30 | 9801 |
| E5 | 34.23 | 1.1 | 40 | 30 | 9801 |
| E6 | 18.39 | 1.1 | 40 | 50 | 12197 |
| E7 | 53.45 | 1.1 | 40 | 70 | 19543 |

**Test setup and procedure**

Amsler universal testing machine (UTM) of 1000kN capacity, suitably modified to allow a maximum specimen length of 2200mm, 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 (Figure-1) of size 0.6m x 0.6m x 1.5m to meet the current 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 150mm thickness, based on the placement density, was poured and uniformly compacted till achieving 150mm graduated level mark for each and every layer.

The deflection of the pile was measured using LVDTs at five locations, in which three were attached with deflection rods extending through the foundation medium.

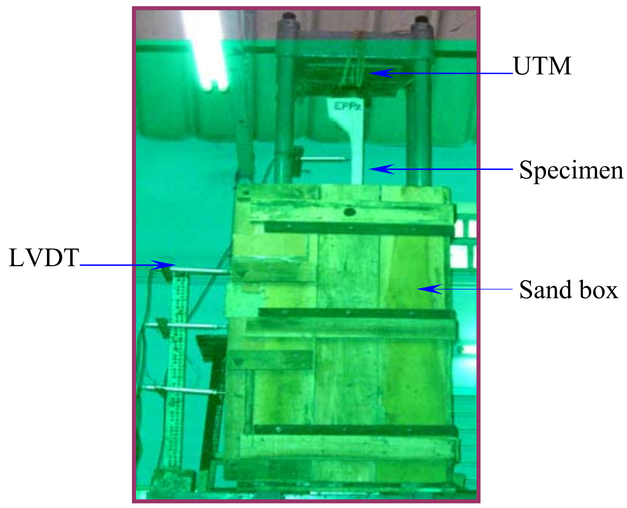


**Figure-1.** Experimental setup.

The loads were applied axially with desired eccentricity. In all the tests, an initial set load of 2kN 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.

## RESULTS AND DISCUSSION

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 Figures 3 to 9.

In general, in all the tested pile, the failure occurred above the foundation medium, as expected.

It was observed that all the tested specimens exhibits large lateral deformation followed by spalling of cover concrete in the compression zone and flexural cracks along the tension face, finally leading to buckling failure due to unbound deformation (Figure-2).

**Figure-2.** Failure pattern.

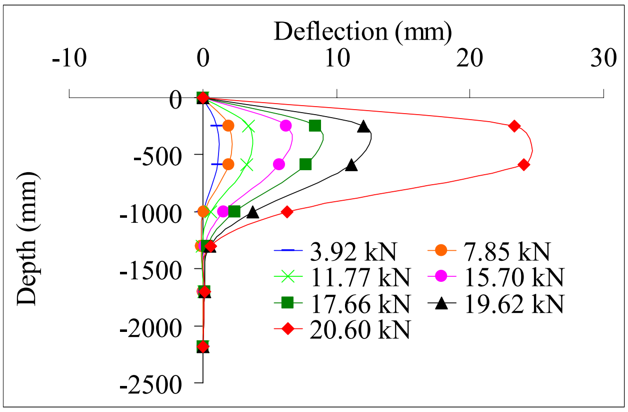


**Figure-3.** Pile lateral deflection for E1 ($L_u$ = 1.0m, e = 60mm and R.D =30%).

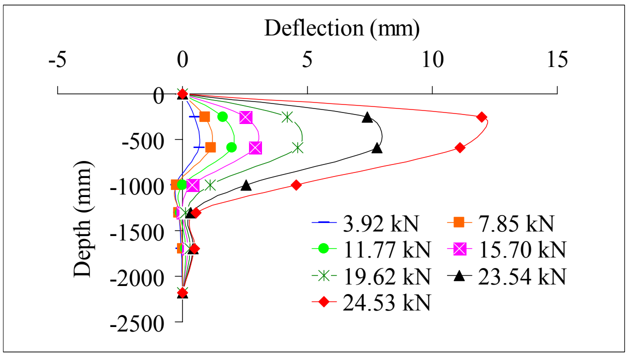


**Figure-4.** Pile lateral deflection for E2 ($L_u$ = 1.0m, e = 40mm and R.D =30%).

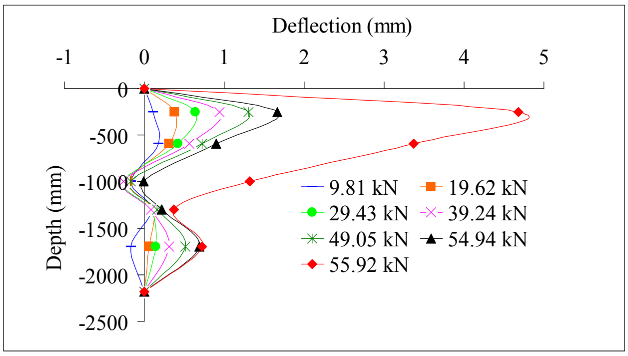


**Figure-5.** Pile lateral deflection for E3 ($L_u$ = 1.0m, e = 20mm and R.D =30%)

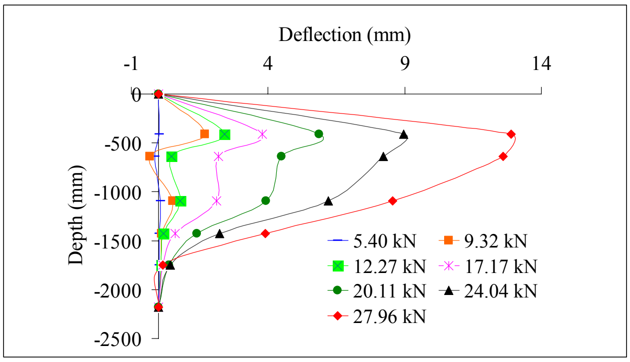


**Figure-6.** Pile lateral deflection for E4 ($L_u$ = 1.2m, e = 40mm and R.D =30%).

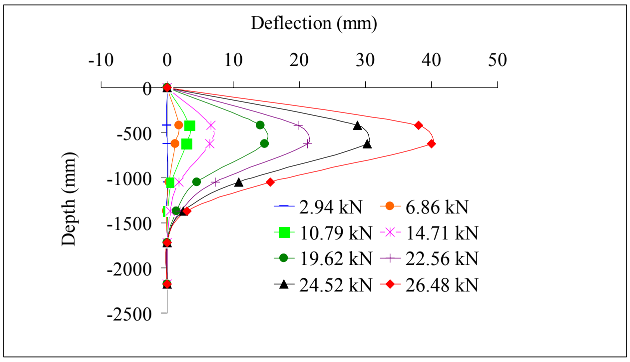


**Figure-7.** Pile lateral deflection for E5 ($L_u$ = 1.1m, e = 40mm and R.D =30%).

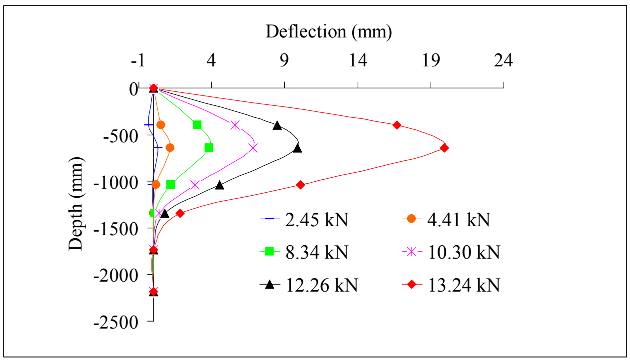


**Figure-8.** Pile lateral deflection for E6 ($L_u$ = 1.1m, e = 40mm and R.D =50%).

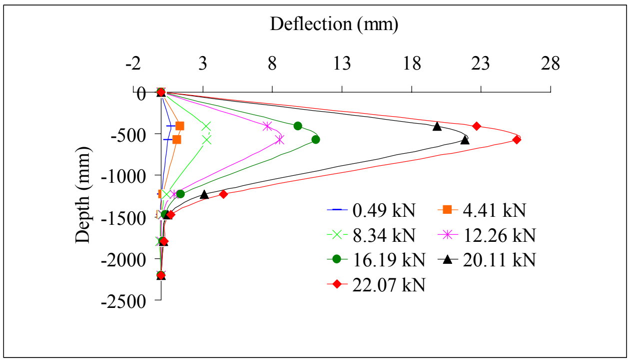


**Figure-9.** Pile lateral deflection for E7 ($L_u$ = 1.1m, e = 40mm and R.D =70%).

It is evident from Figures 3 to 9 that the general trend in the variation of deflection is high near the middle of unsupported length and it is insignificant in the embedded portion, comparing the deflection along the entire length of the pile. It is seen that the partially embedded pile, while progressing towards failure stage divides into two units clearly, one is the unsupported length slightly extending into ground with large deflection, and behaves as like column and other is the remaining embedded length with very small deflection. It is also noticed that the surrounding soil medium even in the loose state (R.D = 30%) offers enough support to the partially embedded pile. All 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.

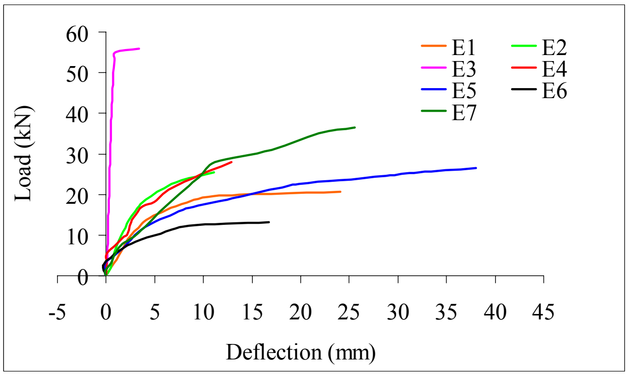


**Figure-10.** Load-deflection curves for different piles.

Figure-10 illustrates the load-deflection curves at middle of unsupported portion for the tested piles and it shows the typical eccentrically loaded column behavior of the partially embedded pile. Further, the curves show the ductile behavior of the partially embedded pile. Based on the experimental results, the following general features were also observed.

- The trend in the variation of deflection along the length of the pile is same.
- The deflection of the pile is high near the middle of the unsupported length and reduces while approaching the foundation medium and then dies out further below.
- The behavior of the piles is almost similar in loose (R.D = 30%), medium (R.D = 50%) as well as dense (R.D = 70%) states of sand.

Finally, comparison between the ultimate load for the test specimen ($P_u$), the experimental critical load ($P_e$) and the theoretically predicted critical load ($P_t$) was carried out as shown in Table-2. In which, the theoretical critical load were estimated based the present approach and the experimental critical loads were determined based on the procedure suggested by Kwon and Hancock [20].

**Table-2.** Summary and comparison of results.

| Speci-men | e/D ratio | $P_u$ (kN) | $P_t$ (kN) | $P_e$ (kN) | $P_e$/ $P_t$ |
|---|---|---|---|---|---|
| E1 | 1.5 | 20.60 | 15.94 | 19.24 | 1.207 |
| E2 | 1.0 | 24.53 | 23.25 | 23.51 | 1.011 |
| E3 | 0.5 | 55.92 | 48.13 | 55.13 | 1.145 |
| E4 | 1.0 | 31.39 | 18.06 | 27.96 | 1.548 |
| E5 | 1.0 | 26.48 | 21.81 | 26.48 | 1.214 |
| E6 | 1.0 | 19.13 | 16.91 | 19.13 | 1.131 |
| E7 | 1.0 | 36.50 | 28.62 | 36.50 | 1.275 |

As expected, the present approach is conservative, since the ACI equation for EI singly accounts many factors including slenderness effects and the use of most conservative (i.e., greatest) value (Lee, [20]) for the coefficient of the depth of fixity.

## CONCLUSION

Buckling capacity of the partially embedded slender reinforced concrete pile under eccentricity may be predicted conservatively using the proposed approach. Comparison between the predicted load and test results indicates the correctness in determining the effective length. Experimental investigations reveal the column behavior of the partially embedded pile along the unsupported length.

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