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TECHNICAL NOTE

# Influence of Pile Diameter on Effective Pile Length under Earthquake Load

Ayothiraman R.[1] and Chandra Prakash G.[2]

Key words

**Abstract:** Piles installed in seismically active regions are predominantly subjected to lateral loads due to earthquakes. Design of laterally loaded pile is mainly governed by depth of fixity and/or effective pile length. Effective pile length under earthquake load may be amplified compared to static loads, and there are only few equations reported in the literature to determine the effective pile length under earthquake loads. These equations were developed based on parametric analysis, especially for a constant diameter and by varying pile length. However, influence of pile diameter on effective pile length has not been investigated so far and is accordingly carried out using 3-D finite element analysis, which is presented in this paper.

## Introduction

Investigation into the analysis of damages to civil engineering structures experienced during past and recent earthquakes reveals that the extent of damage to the structure is predominantly dependent on the type of foundation and soil condition, in particular to the behaviour of liquefaction and/or strain softening of cohesionless and cohesive soil respectively. Earthquake load is acting predominantly in the lateral direction, but the lateral capacity of pile is normally 10% of the vertical capacity of pile. Additionally the stiffness in the lateral direction is also very low in comparison to the vertical stiffness and hence the lateral capacity/stiffness of pile governs the design in most cases, in which the lateral loads such as earthquake loads are dominant.

The lateral capacity and stiffness is mainly dependent upon the characteristic of top soil layers within a few meters of depth, which mainly consists of weak deposits such as soft clay or loose sand. The zone of stressed soil mass under lateral within this top soil mass is function of pile diameter. Effective pile length or depth of fixity is an important parameter for design of piles subjected lateral loads. IS 2911 (Part-1&3) gives specification to find out the depth of fixity or effective pile length under static lateral loads. Also there are many well-established empirical equations reported to estimate the effective pile length under static lateral loads (Krishnanetal.1983; Velez et al. 1983). It is reported that effective pile length is amplified under dynamic lateral loads applied at the pile-head (Boominathan and Ayothiraman, 2007a). This implies that effective pile length might be amplified under earthquake loads also and IS code (IS 1893) does not specify how to determine the effective pile length under earthquake load. There are only few equations reported to determine the effective pile length under dynamic loads (Krishnan et al. 1983; Velez et al. 1983; Gazetas, 1984; Poulos & Hull, 1989; Boominathan and Ayothiraman, 2007b), especially under earthquake loads (Gazetas, 1991). The existing equations predict the effective pile length in a non-dimensional way, i.e. $L_e/d$, where $L_e$ is the effective pile length and $d$ is pile diameter, which means the effective pile length is function pile diameter. However, these equations were developed based on the studies carried out by varying the pile length only; not the pile diameter. It is very essential to investigate the influence of pile diameter rigorously on the effective pile length and pile behaviour under earthquake loads. This paper presents result of three-dimensional finite element analysis carried out to study the influence of pile diameter on pile behaviour in clay, in particular on the effective pile length.

## Seismic Soil-Pile Interaction

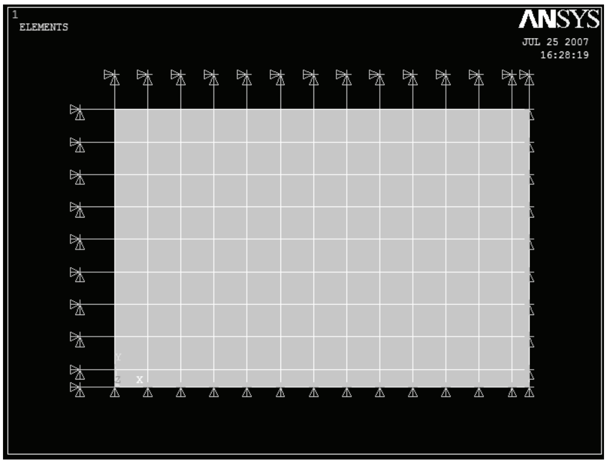
### Finite Element Modelling

Finite element method is well suited for analyzing problems, such as a pile/pile groups in layered soil, which is not easily handled with analytical or semi-analytical formulations. Also, hysteretic damping, Rayleigh damping and wave absorbing lateral boundaries conditions can be introduced to account for damping characteristics and appropriate boundary conditions. In the present study, 3D finite element formulation is considered to model the seismic soil-pile interaction using ANSYS. Soil is modelled as elastic-perfectly plastic material with Mohr-Column failure criterion. Pile is modelled as linear elastic. The soil has been discretized as eight-noded brick elements and pile as a beam element. Each of the 8 nodes has three translational degrees of freedom in the nodal x, y, and z

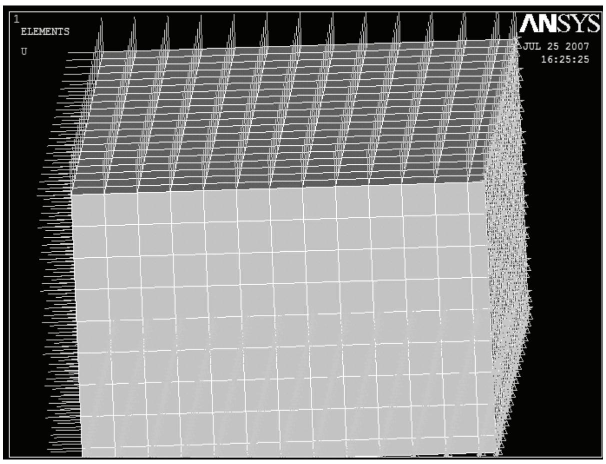
1 Assistant Professor, Department of Civil Engineering, IIT Delhi, New Delhi – 110016, Email: araman@civil.iitd.ac.in
2 Formerly PG Student, Department of Civil Engineering, IIT Guwahati, Guwahati–781039, E-mail: prakash267@yahoo.co.in

directions. The pile is completely embedded in the soil and pile head is assumed as free head. The developed 3-D FE model is shown in Figure 1.

To simulate an infinite soil medium, springs and dashpots are attached on the side walls of the foundation which provide the proper boundary conditions. It is noted that these are used in all three directions along the boundary. The coefficients of the springs and dashpots are derived separately for the horizontal and vertical directions based on the predominant frequency of loading. The constants of the springs and dashpots in the two horizontal directions were calculated using the solution developed by Novak and Mitwally (1988). This also simulates the radiation damping/wave absorbing conditions at the boundary. Material damping is considered in the analysis. Additional hysteretic damping may develop due to the nonlinearity, but dissipation of seismic energy through inelastic deformation tends to overshadow the dissipation of the energy through hysteretic damping and is therefore neglected.




a. Plan




b. Elevation

Fig.1 3D–Finite Element Model

## Validation of Model

The efficacy of the proposed model is demonstrated by comparing the predicted response of pile with the experimentally measured single pile response. Three well instrumented full-scale experiments are selected where the pile response was recorded beyond the elastic limit. Kramer et al. (1990) conducted lateral monotonic and cyclic tests on a cylindrical steel pile installed in the Mercer Slough peat near the eastern shore of Lake Washington in Bellevue, Washington. Jennings et al (1984) and Brown et al. (1988) conducted dynamic experiments on solid and hollow piles embedded in medium dense/dense saturated silty sand deposits. The soil properties and pile characteristics are summarized in Table 1, and these properties are used in the analysis to predict the pile response. The pile response, such as pile deflection behaviour at 120kN load and p-y curves at different depths is obtained from the analysis. The results are compared with the experimental data of the respective literature and the results of numerical analysis reported by Badoni and Makris (1996). Figure 2 & 3 show the comparison of predicted and measured pile response and it is found from the figures that the agreement of the prediction with the measured values is very good.

Table 1 Properties of Soil and Pile Considered

| Test/Year | Soil Properties | Pile Properties |
|---|---|---|
| Kramer et al. (1990) | $\nu_s = 0.49$<br>$V_{s(tip)} = 30$ m/s<br>$\rho_s = 1120$ kg/m$^3$<br>$C_u = 14.4$ kN/m$^2$ | L = 14.9 m<br>d = 0.20 m<br>$E_pI_p = 3.81 \times 10^3$ kN-m$^2$ |
| Jennings et al. (1984) | $\nu_s = 0.49$<br>$V_{s(tip)} = 125$ m/s<br>$\rho_s = 1600$ kg/m$^3$<br>$\phi' = 35^\circ$ | L = 6.75m<br>d = 0.45 m<br>$E_pI_p = 0.8 \times 10^5$ kN-m$^2$ |
| Brown et al. (1988) | $\nu_s = 0.48$<br>$V_{s(tip)} = 160$ m/s<br>$\rho_s = 1600$ kg/m$^3$<br>$\phi' = 38.5^\circ$ | L = 13.1 m<br>d = 0.273 m<br>t = 0.0093 m<br>$E_pI_p = 7.3 \times 10^3$ kN-m$^2$ |

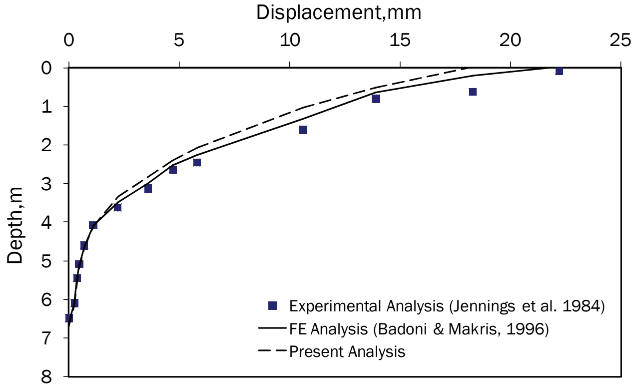



Fig. 2 Comparison of Predicted and Measured Pile Deflection for Lateral Force of 120kN

## Parametric Studies

Seismic analysis of single pile was performed by varying the different parameters like pile diameter (d = 0.3, 0.5, 0.7 & 1.0 m), L/d ratio of pile (10, 20, 30 & 40) and soil modulus (Es = 20, 40, 60 & 80 MPa) using the proposed FE model. A constant material damping of 20% is used in the analysis for all cases, whereas the radiation damping at the boundary of the model is modelled with springs and dashpots; their constants are calculated using Novak & Mitwally (1988). The seismic loading is applied at the base of the 3-D model, i.e. at the bottom face of the soil block/model as transient motion. For the transient motion, an acceleration time history of El Centro Earthquake 1940 (N-S Component), with peak ground acceleration equal to 0.32g was used.

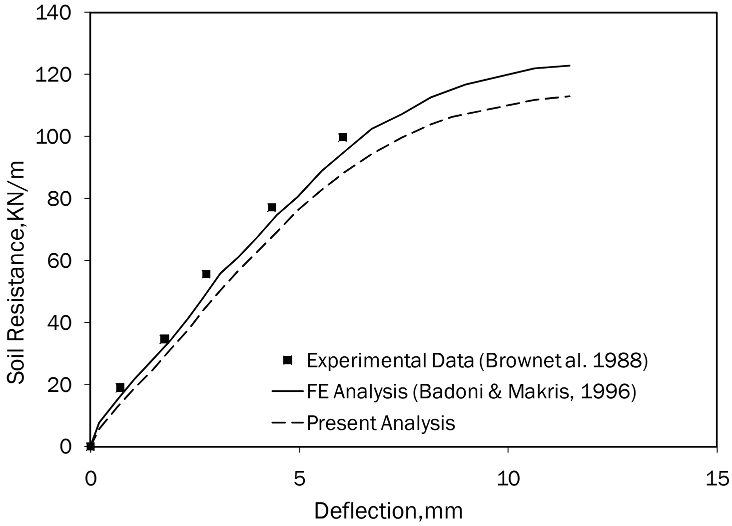



**Fig. 3 Comparison of Predicted and Measured p-y Curve at Depth, 1.22m**

## Pile Deflection

Pile deflection behaviour under the given seismic excitation has been predicted for different pile diameters: 0.3 m,0.5 m, 0.7 m and 1.0 m, for different length to diameter ratios of piles: *L/d* = 10 and 40 and different soil modulus values: $E_s$ = 20, 40, 60, and 80 MPa. The predicted pile deflection profiles are plotted against the normalized depth of pile (*z/d*), i.e. the ratio of desired depth along the pile (*z*) to pile diameter (*d*). the typical pile deflection profiles for *L/d* = 10 & 40 for $E_s$ = 20 and 40MPa are shown in Figures 4 and 5 respectively.

It is observed from above Figures 4 and 5 that the pile deflection is reducing with an increase of pile diameter and *L/d* ratio for all soil modulus. This is due to fact that the passive resistance zone increases with an increase of pile diameter and pile length. It is also noticed from these figures that increase of soil modulus causes reduction of pile deflection, because the increase of soil modulus cause increase in the stiffness of the soil which ultimately resist the pile against deflection.

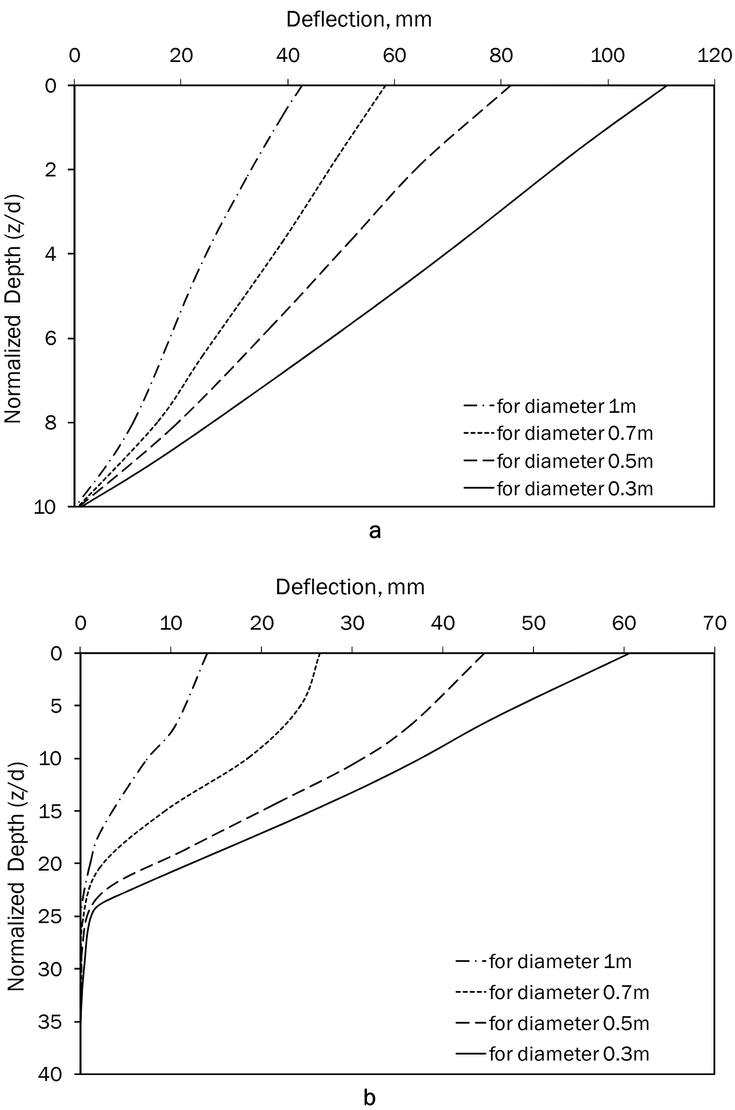



**Fig. 4 Pile Deflection Vs Normalized Depth Curves for Different Pile Diameters and for Es = 20MPa: (a) L/d=10 ;( b) L/d=40**

## Effective Pile Length

The effective pile length is defined as a pile length from the ground surface at which the pile deflection is zero. The effective pile length values, i.e. the normalized depth of zero deflection were obtained from the pile deflection profiles and are refereed as normalized effective pile length.

The variation of normalized effective pile length with *L/d* ratio of pile for different diameters at $E_s$ = 20 MPa and 80 MPa is shown in Figure 6. It is inferred from the figure that the effective pile length increases with pile length for all soil modulus conditions, but the rate of increase is high for low soil modulus. This is because that the almost full length of pile undergoes vibration

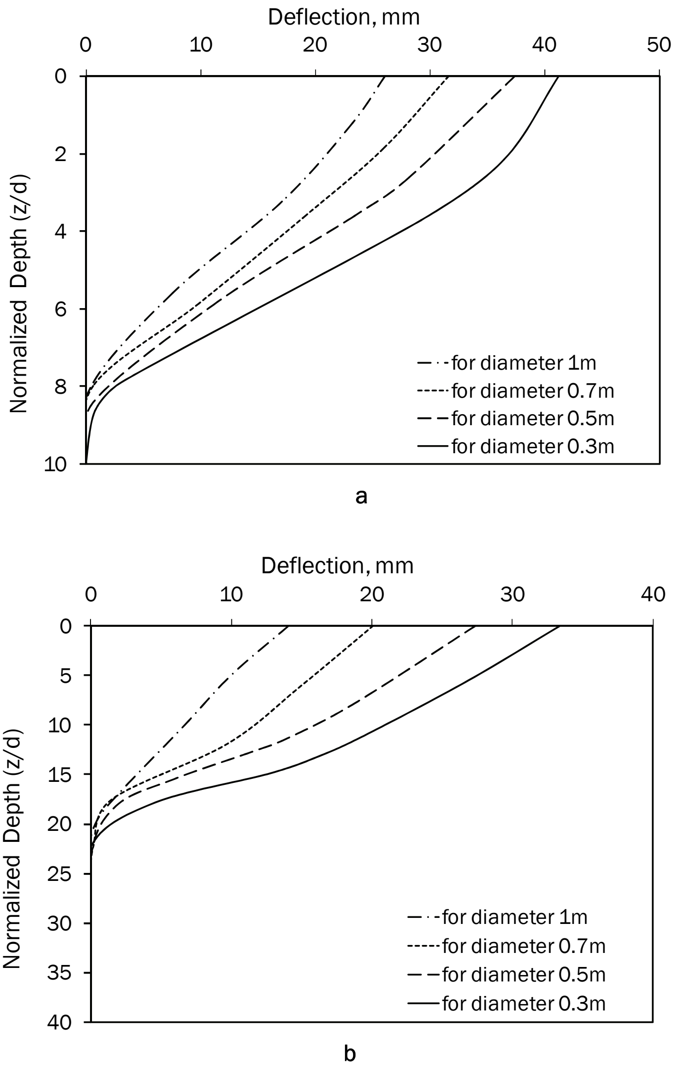



**Fig. 5 Pile Deflection Vs Normalized Depth Curves for Different Pile Diameters and for $E_s$ = 40 MPa at (a) *L/d*=10; (b) *L/d*=40**

during seismic shaking for piles embedded in very soft clay having low soil modulus. It is also inferred from Figure 6 that the pile diameter does not have significant effect on the effective pile length of short piles (*L/d*<20), but has a significant effect for long piles (*L/d*>30) embedded in all soil modulus conditions considered in the analysis. Moreover, the effective pile length is an important parameter for long piles only, i.e. for *L/d*>30, which is significantly affected by the pile diameter.

The variation of normalized effective pile length with modulus ratio ($E_p/E_s$), for different *L/d* ratio of pile and constant diameter of pile of 0.5 m is given Figure 7. It is noticed from the figure that the effective length significantly reduces with decrease of modulus ratio, i.e. with an increase of soil modulus for all *L/d* ratios. The effective length estimated using existing analytical and semi-analytical expressions suggested by various authors (Krishnan et al. 1983; Gazetas, 1984; Poulos & Hull, 1989; Gazetas, 1991; Ayothiraman & Boominathan, 2008) for any kind of dynamic loads are also presented in Figure 7. It is found from Figure 7 that these equations highly underestimate the effecting pile length of long flexible piles under earthquake loads. In other words, one can say that the effective pile length under earthquake load is significantly amplified even compared to other dynamic loads. Hence an equation is developed by performing multiple regression analysis to estimate the effective pile length of long piles under earthquake load as given in Eqn. 1.

$$\frac{L_e}{d} = 2.20\left(\frac{E_p}{E_s}\right)^{0.345} \qquad (1)$$

In which, $L_e$ = Effective pile length under earthquake load, *d* is pile diameter, $E_p$ is Young's modulus of pile and $E_s$ is Young's modulus of soil. The regression analysis gives a correlation coefficient of 0.9465. The proposed equation can be used to find out the effective length or depth of fixity of single piles subjected to earthquake load, which is useful in design

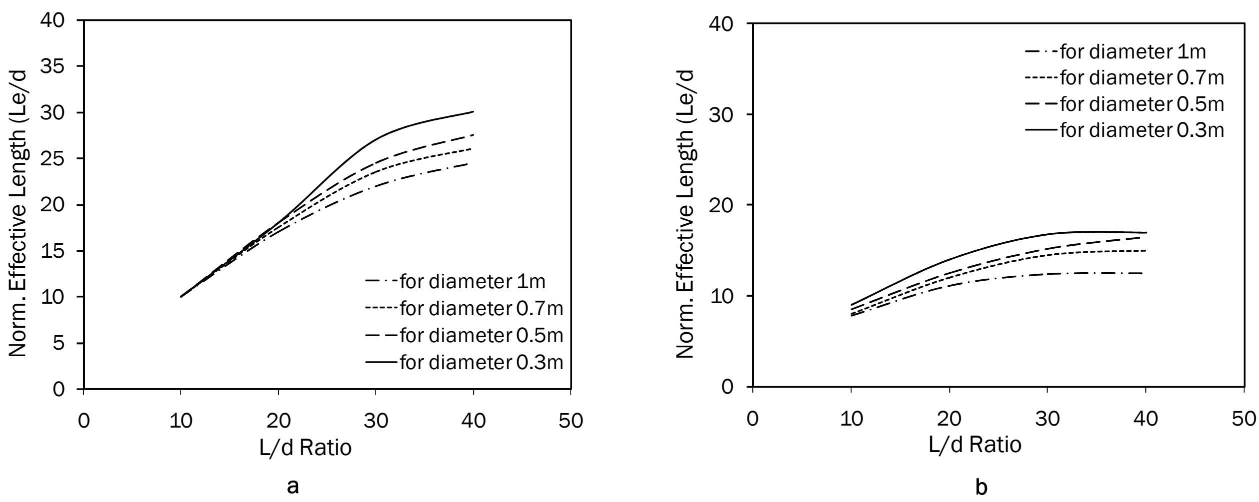



**Fig. 6 Normalized Effective Pile Length Vs *L/D* Ratio For Different Diameters at (a) Es = 20MPa and (b) Es = 80MPa**

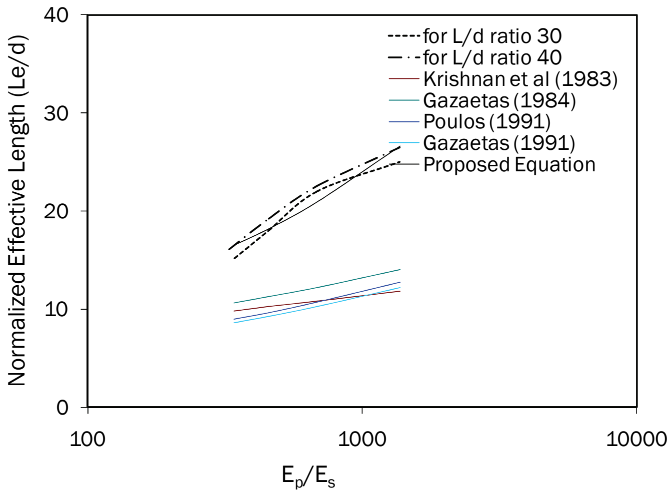



**Fig. 7 Normalized Effective Pile Length Vs Modulus Ratio**

of piles subjected to dynamic lateral loads. It is also to be noted that effect of ground motion characteristics by considering different earthquake motions are not taken in to account in the above equation, which requires further study. In the further study, the effect of fixed pile head could also be carried out. Effective pile length of single pile in a pile group could also be a scope for further study.

## Conclusions

Based on the comprehensive parametric studies carried out using the developed 3-D finite element model, the following major conclusions are arrived at, particularly on the influence of pile diameter on the effective pile length:

> The effective pile length is significantly influenced by the soil modulus and pile diameter, especially for long/flexile piles.

> An equation is proposed to estimate the effective pile length under earthquake loads for single pile for free head condition.

These results were obtained from the numerical studies on piles embedded in clay. The proposed empirical equation may be verified further and modified accordingly as and when a more reliable experimental data is made available based on either centrifuge or full-scale experiments on instrumented piles subjected to earthquake loads.

## References

Ayothiraman, R. and Boominathan, A. (2008): 'Dynamic bending behaviour of piles in clay', *Journal of Geomechanics and Geoengineering,* Under Review.

Badoni, D., and Makris, N. (1996): 'Nonlinear response of single piles under lateral inertial and seismic loads', *Soil Dynamics and Earthquake Engineering*, 15, 29–43.

Brown, D. A., Morrison, C. & Reese, L. C. (1988): 'Lateral load behavior of pile group in sand', *Jl. Geotechnical Engineering*, ASCE, 144, 30-45.

Boominathan, A. and Ayothiraman, R. (2007a): 'An experimental study on static and dynamic bending behaviour of piles in soft clay',*Geotechnical and Geological Engineering,* 25(2), 177–189.

Boominathan, A. and Ayothiraman, R. (2007b). Measurement and analysis of horizontal vibration response of pile foundations. Shock and Vibration, 14(2), 89-106.

Gazetas, G. (1984): 'Seismic response of end-bearing piles', *Soil Dynamics and Earthquake Engineering*, (3), 82 – 93.

Gazetas G. (1991): 'Foundation vibrations', *Foundation Engineering Handbook*, 2nd Edition, Van Nostrand Reinholds, 553-593.

IS: 2911 (Part-1): Indian Standard for design and construction of pile foundations: *Concrete piles*. Bureau of Indian Standards, New Delhi.

IS: 2911 (Part-3): Indian Standard for design and construction of pile foundations: *Under reamed piles*. Bureau of Indian Standards, New Delhi.

IS: 1893: *Indian Standard for criteria for earthquake resistant design of structures*, Bureau of Indian Standards, New Delhi.

Jennings, D. N., Thurston, S. J. and Edmonds, F. D. [1984]: 'Static and dynamic lateral loading of two piles', *Proc 8th WCEE*, San Francisco, CA. (3), 561-68.

Kramer, S. L., Satari, R. and Kilian, A. P. (1992): 'Evaluation of in situ strength of a peat deposit from laterally loaded pile test results', *Transportation Research Record No. 1278*, Transp. Res. Board, Washington, D.C., 103-109.

Krishnan, R., G. Gazetas, and A. Velez. (1983): 'Static and dynamic lateral deflection of piles in non-homogeneous soil stratum', *Geotechnique*, 33, 307 – 325.

Novak, M., and Mitwally, H. (1988): 'Transmitting boundary for axisymmetrical dilation problems', *Journal of Engineering Mechanics*, ASCE, 114(1): 181–187.

Poulos, H. and Hull, T. (1989): 'The role of analytical geomechanics in foundation engineering. In Foundation Engg' *Current Principles and Practices, ASCE*, 2, 1578-1606.

Velez, A., Gazetas, G. and Krishnan, R. (1983): 'Lateral dynamic response of constrained head piles', *Journal of Geotechnical Engineering*, ASCE, 109(8), 1063–1081.