A study on the effect of pile cap on the vertical impedance of a single pile

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ABSTRACT

Pile foundations are employed used to support Impedance functions for pile foundations in various modes of vibration, forms an important step in Soil Structure Interaction (SSI) analysis of pile supported structures. Most of the available expressions for vertical impedances, originating from analytical, and numerical models, ignore the effects caused by a pile cap bearing with the ground. However, in many practical situations, the pile cap-soil interaction is congruent with pile-soil interaction. This paper presents a substructuring based numerical study on effects of a ground contacting pile cap on the vertical impedance of a single pile in multilayered and homogeneous soil profiles. A free vibration test conducted on a full scale pile in Hazira, India is simulated using the Flexible Volume Substructuring Method (FVSM) in the ACS SASSI program. The damped natural frequency of the pile was estimated with a fair degree of accuracy. The 3D model is then extended to study the influence of ground contacting pile cap on vertical impedance of the single pile, in a parametric study. The presence of a rigid massless pile cap is found to have negligible influence on the stiffness coefficient. However radiation damping of the system is found to be enhanced by the pile cap-soil contact. The increase in damping is however significant at higher frequencies.

Keywords: pile impedance; pile cap; SASSI

1 INTRODUCTION

Pile groups are frequently used in situations where shallow soil layers are incapable of supporting superstructural loads. Under static loads the presence of an embedded pile cap generally improves the load carrying capacity and reduces settlement of the pile foundation. Studies on pile cap-soil interactions (Butterfield & Baerjee 1971; Ottaviani 1975; Chow & Teh 1991; Rollins & Sparks 2002) have shown that the presence of a pile cap can alter the system stiffness as well as the pile-soil load transfer mechanism. The piled raft design concept takes advantage of the additional stiffness, and reduction in total and differential settlement, resulting in economic foundation design. However, the inherent conservatism in ignoring the effect of pile cap for static loads, may not hold true for dynamic loads. The dynamic vertical and horizontal stiffness of pile groups with pile cap embedded in the ground can be less than that of those with free standing pile caps at certain frequencies (Emani & Maheswari 2009; Liu & Ai 2017).

To assess the influence of a ground contacting pile cap on vertical impedance of a single pile soil system, a numerical study using 3D finite element based substructuring method is carried out in the present study. A free vibration test conducted on a full scale pile embedded in cohesionless soil strata, in Hazira, India is simulated to validate the methodology adopted. The developed model is then extended to study the influence of a circular pile cap on the vertical impedance of the pile.

2 EXPERIMENTAL SETUP

The field test on single pile was conducted at a site in Hazira in the Gujarat State of India. The site consisted of intermittent layers of silty sand and clayey sands, with relatively hard stratum occurring at 15 to 20m depths. To characterize the subsoil, the standard penetration test, together with seismic cross hole tests

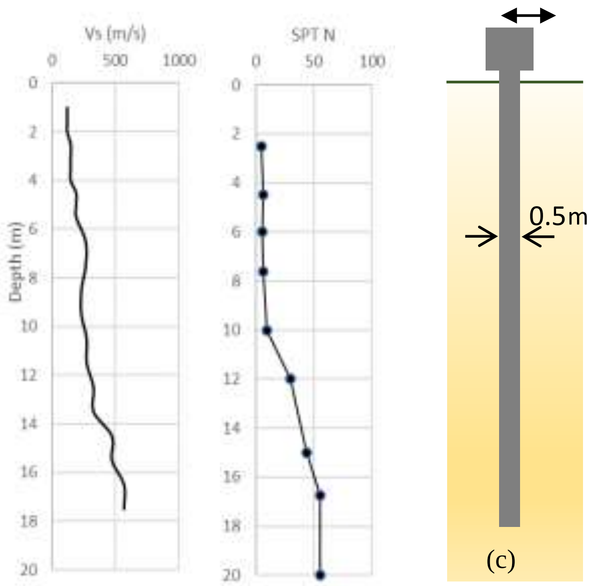


Fig.1 (a) Shear wave velocity and (b) SPT N profile at the site and (c) schematic diagram of the pile was conducted at the site. The shear wave velocities obtained from the test and a typical SPT N profile are presented in Fig. 1 (a) and (b).

The bored cast in situ test pile constructed, had a length of 18m, and a diameter of 0.5m. The pile was casted with M35 grade concrete with 10 numbers of 16mm longitudinal reinforcement bars bundled with 8mm helical reinforcement. A free-standing pile cap of 0.75mx0.75mx0.75m was cast on top of the pile for experimental fixtures. A schematic diagram of the pile is presented in Fig. 1(c). The pile can be categorized as flexible, according to the criteria by Dobry et al. (1982) and Poulos & Hull (1989). The free vibration test was conducted by applying a lateral force using a reaction pile, followed by a sudden release. The lateral load was applied to the pile by rotating a pulling screw and then suddenly releasing the load with the help of a clutch type attachment, as recommended by Indian Standard IS: 9716-1981. The vibration of the pile was recorded by acceleration pickups placed on the pile surface, below the pile cap as shown in Fig. 2.

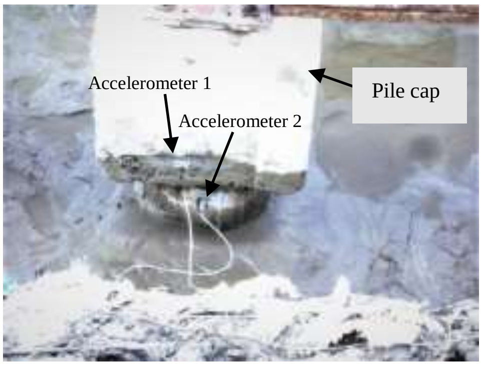


Fig. 2. Photograph showing the pile and pile cap

3 NUMERICAL ANALYSIS

3.1 Methodology

Numerical analyses in the present study is carried out using the finite element based substructuring technique implemented in frequency domain.

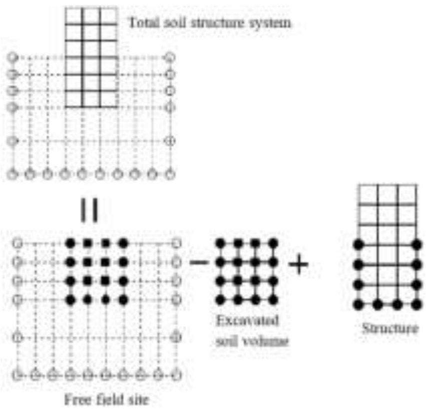


Fig. 3. Partitioning of the soil structure system in FVSM method (modified from Ostadan & Deng, 2010)

The Flexible Volume Substructuring Method (FVSM) wherein the soil foundation system is partitioned as shown in Fig. 3 is implemented in the ACS SASSI program (Lysmer et al 1981; Ghiocel 2013).

The methodology involves a FEM-BEM coupling wherein finite elements are used to model the foundation and near field soil, while a formulation based on the use of fundamental Green's functions, for layered media (Kausel, 1986), is utilized to model the free field soil. The FVSM method considers all nodes in the embedded part of foundation as interaction nodes. The simplified equation of motion can be expressed as

$$\begin{bmatrix} C_{ss} & C_{si} \\ C_{is} & (C_{ii} - C_{ff} + X_{ff}) \end{bmatrix} \begin{Bmatrix} u_s \\ u_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ X_{ff} u_f{}' \end{Bmatrix} \quad (1)$$

where C is the complex frequency dependent stiffness matrix and subscripts *s*, *i* and *f* refer to degrees of freedom for nodes at the superstructure, basement and excavated soil, respectively. The analysis is essentially linear in nature.

3.2 Simulation of a lateral free vibration test

A 3D finite element model was developed for the FVSM method of analysis as shown in Fig. 4. Eight noded brick elements were used to model the pile, pile cap, and near filed soil elements. The near field soil elements were extended up to five pile diameters from the pile. Considering the shear strains observed during trial runs, the shear modulus assigned to soil elements within one pile diameter from the pile periphery, were reduced to accommodate for the degradation caused during the construction and testing.

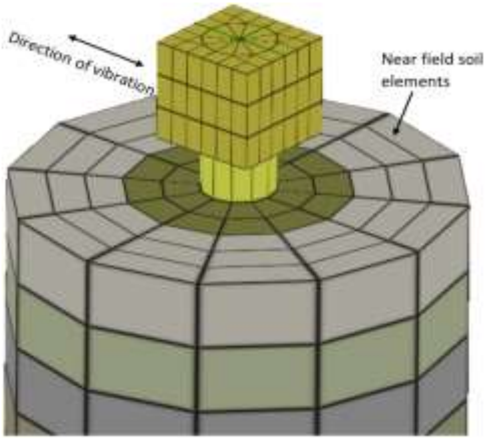


Fig. 4. Finite element mesh of the pile soil system

The soil properties used in the analysis are tabulated in Table 1. The pile and pile cap elements were assigned an Elastic Modulus value of 29.6 GPa, a Poisson's ratio of 0.25 and a unit weight of 25 kN/m^3.

To simulate the free vibration test, an impulse of 100Ns was applied at the face of the pile cap. The displacement time history at the node corresponding to the location of accelerometer 2 was extracted.

3.3 Parametric study

A parametric study was conducted to study the influence of a ground contacting pile cap on vertical impedance of the single pile. Circular pile caps were modelled over the single pile, using rigid massless solid elements touching the ground surface.

Table 1. Soil layer properties used in the numerical model

Thickness of layer (m)	V_s (m/s)	Unit wt (kN/m^3)
2	121	16.0
2	148	16.7
2	191	17.5
2	266	18.5
2	232	18.0
2	275	18.5
2	328	19.0
2	473	20.0
2	568	20.5

The diameter of pile cap to diameter of pile (d_c/d_p) was varied in multiples of pile diameters, from 2 to 5. The diameter ratio of 1 refers to the single pile without a pile cap. Fig.5 presents the FE mesh for the model with d_c/d_p=4. The pile-soil elastic modulus ratio (E_p/E_s) for the soil profile considered is close to 50. In this study, the frequency (ω) dependent complex vertical impedance is expressed in the form

$$S(\omega) = K_z(\omega) + i\omega C_z(\omega) \quad (2)$$

The coefficients K_x and C_x are calculated using the response of the foundation soil system to a unit vertical harmonic load using the expression

$$F_z = (K_z + i\omega C_z)(U_{real} + iU_{comp}) \quad (3)$$

where F_x is the applied load, and U_{real} and U_{comp} are the components of complex displacement. A dimensionless equivalent damping ratio, ($D_z = \omega C_z/2K_z$) is used to express damping. A frequency range of 1 to 60Hz is considered in the present study.

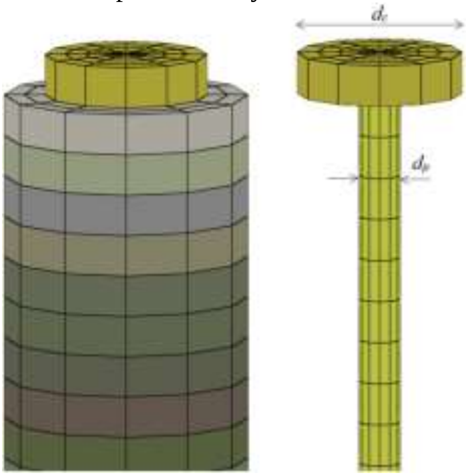


Fig. 5. Finite element mesh of the pile cap-pile-soil system with and without near field soil elements for d_c/d_p=4

4 RESULTS & DISCUSSION

The acceleration time history recorded from the lateral free vibration test, and the displacement time history from the simulation is presented in Fig. 6(a) and (b). As a comparison of the damped natural frequency (f_D) of the pile soil system is intended, the acceleration-displacement conversion is ignored.

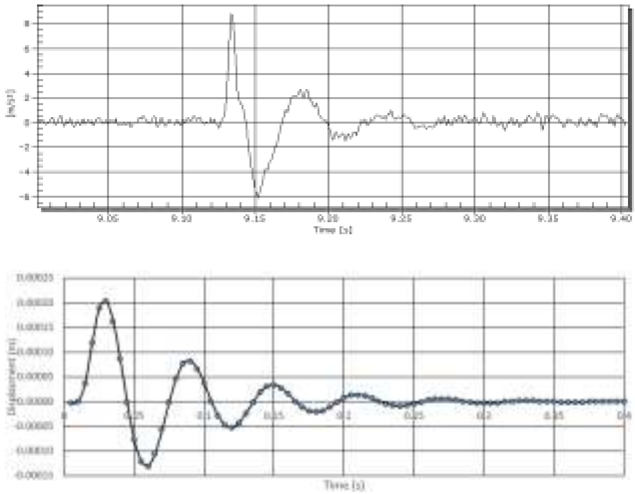


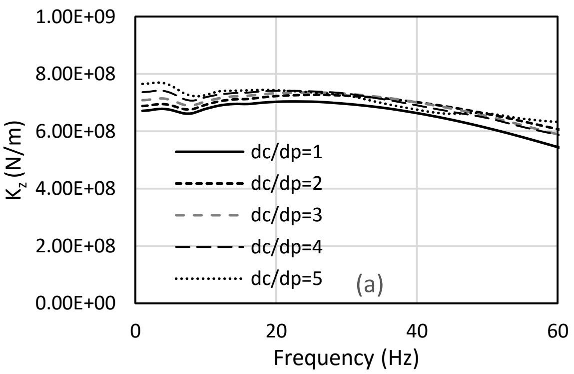
Fig. 6. Free vibration response recorded from the (a) experiment and (b) simulation

A comparison of the damped natural frequency of the pile soil system from the experiment and simulation is tabulated in Table 2. The numerical model was able to estimate the value of f_D with a fair degree of accuracy.

Table 2. Comparison of natural frequency from experiment and simulation

f_D from experiment (Hz)	f_D from numerical model (Hz)	Error (%)
18.57	16.66	11.46

The variation of stiffness and damping coefficients with increasing d_c/d_p ratio is presented in Fig. 7 (a) and (b). It is evident the presence of a pile cap does not influence the stiffness of the single pile-soil system. However, increase in the damping coefficient is observed as the pile cap diameter increases. The increase is prominent



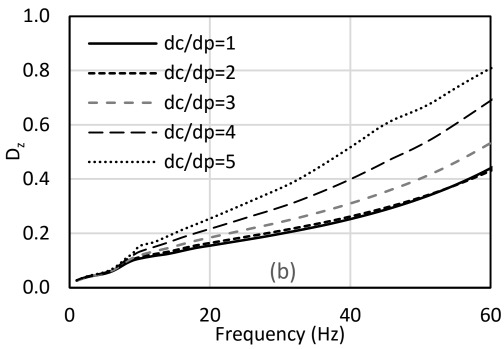


Fig. 7. (a) Stiffness coefficient and (b) equivalent damping ratio for various pile cap dimensions

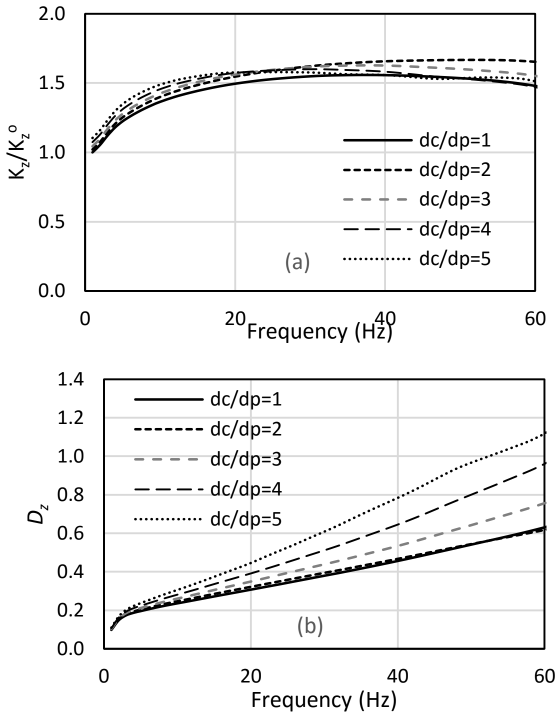


Fig. 8. Normalized (a) Stiffness coefficient and (b) damping ratio for various pile cap dimensions for E_p/E_s=500

at higher frequencies. The study is also extended to the cases of single pile embedded in homogeneous soil stratum with E_p/E_s=500. For this case, the unit weight of soil was assumed to be 16kN/m^3 and a uniform soil damping ratio (β) of 0.05 was assigned.

The impedances for models with E_p/E_s=500 are normalized with the static (zero frequency) stiffness coefficient of the cap less single pile model and are presented in Fig. 8 (a) and (b). The same trend observed for the soil profile at Hazira, is observed for the homogeneous soil profile. The presence of a pile cap with d_c/d_p =5 increases the area of contact at ground level by 4.9 times. Even though load settlement behavior of a single pile is known to be affected by even a small circular cap (Viggiani 2014), the dynamic stiffness coefficient is not observed to be significantly altered. Radiation damping from foundations is known to be influenced by the area of contact with soil. The pile cap is observed to amplify energy radiation with the additional contact at its base.

5 CONCLUSION

A free vibration test conducted on a full-scale pile is simulated by the FVSM technique. The analysis method is found to predict the damped natural frequency of the pile soil system to a fair degree of accuracy. The influence of a pile cap on vertical impedance of a single pile is studied. A ground contacting pile cap is observed to increase radiation damping in the system, while having little influence on stiffness. The increase in damping coefficient for pile cap diameter ratio of 5, varies from 1.2 to 2.0 times the damping coefficient for cap less pile, within the frequency range considered.

REFERENCES

BIS (Bureau of Indian Standards). (2003). Guide for lateral dynamic load test on piles. IS. 9716: 1981

Butterfield, R., & Banerjee, P. K. (1971). The problem of pile group–pile cap interaction. Geotechnique, 21(2), 135-142.

Chow, Y. K., & Teh, C. I. (1991). Pile-cap-pile-group interaction in nonhomogeneous soil. Journal of Geotechnical Engineering, 117(11), 1655-1668.

Dobry R, Vicente E, O'Rourke M.J, Roesset J.M (1982) Horizontal stiffness and damping of single piles. J Geotech Eng Div ASCE 108:439–459

Emani, P. K., & Maheshwari, B. K. (2009). Dynamic impedances of pile groups with embedded caps in homogeneous elastic soils using CIFECM. Soil Dynamics and Earthquake Engineering, *29*(6), 963-973.

Ghiocel, D. M. (2017). ACS SASSI Version 3.0-An Advanced Computational Software for 3D Dynamic Analyses Including Soil Structure Interaction. Ghiocel Predictive Technologies, Rochester, New York, January.

Kausel, E. (1986). Wave propagation in anisotropic layered media. International Journal for Numerical Methods in Engineering, 23(8), 1567-1578.

Liu, C. L., & Ai, Z. Y. (2017). Vertical harmonic vibration of piled raft foundations in layered soils. International Journal for Numerical and Analytical Methods in Geomechanics, 41(17), 1711-1723.

Lysmer, J., Tabatabaie-Raissi, M., Tajirian, F., Vahdani, S., & Ostadan, F. (1981). SASSI: A system for analysis of soil-structure interaction.

Ostadan, F., and Deng, N. (2012). SASSI 2010 Version 1.0 User's Manual.

Ottaviani, M. (1975). Three-dimensional finite element analysis of vertically loaded pile groups. Geotechnique, 25(2), 159-174.

Poulos H, Hull T (1989) The Role of Analytical Geomechanics in Foundation Engineering. In: Foundation Engg: Current Principles and Practices, Vol 2. ASCE, pp 1578–1606

Viggiani, C., Mandolini, A., & Russo, G. (2014). Piles and pile foundations. CRC Press.