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Pile induced filtering of seismic ground motion in homogeneous soil

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Pile induced filtering of seismic ground motion in homogeneous soil

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Abstract. The foundation input motion (FIM) that a structure experiences during an earthquake, is known to be different from the free field ground motion due to soil structure interaction (SSI) effects. Kinematic interaction in a single pile can also introduce a rotational component to the FIM. Conventionally, soil structure interaction is performed by applying the free field ground motion to the structure ignoring the effects of kinematic interaction. Deep foundation elements such as piles are known to suppress certain frequencies of ground motion which in turn induces kinematic bending moments in them. In this study, kinematic soil pile interaction is simulated using 3D numerical models using a coupled finite element-boundary element method. Single pile, group pile and piled raft models in a homogeneous soil profile are analysed for vertically propagating shear waves. Three earthquake time histories with varying frequency content are considered in this study. Transfer functions are then plotted together to analyse the effects of pile induced filtering of ground motion. The ratio of response spectrum at the foundation level and free field ground, for the pile group considered, is found to closely follow the behaviour of a fixed headed single pile. It is found that embedment of the pile cap, as in the case of a piled raft can result in further filtering of ground motion.

Keywords: soil structure interaction, pile foundation, piled raft, response spectrum

1. Introduction

Pile foundations are often employed to support structures when shallow soil layers are incompetent to carry foundation loads. Vertically propagating shear waves from an earthquake can result in bending moments are shear forces in pile foundations. Critical structures that are often founded on pile foundations include highway bride abutments, tall buildings, and heavy storage structures.

Seismic soil structure interaction can be considered to be a combination of a kinematic response and an inertial response. Kinematic response is fundamentally a result of the contrast in stiffness between foundation and soil stratum. Kinematic response is more prominent for embedded foundations than shallow foundations [1]. It has been proven that SSI does not always play a beneficial role in the seismic response of structures as often assumed [2]. The frequency dependent nature of SSI needs to be taken into account for any reasonable prediction of seismic response. The importance of considering SSI in the design of pile foundations has been highlighted by several studies from the past [3-5]. Kinematic response of pile foundations has been found to be significantly influenced by the pile soil stiffness contrast, and pile spacing [6].

Although a proper and rigorous nonlinear SSI analysis can simulate soil pile systems with a high degree of accuracy [7, 8], the computational effort and skill required is rather high for routine design. Simplified methods are therefore used depending on the importance of the structure. Simplified methods for estimate the FIM for pile foundations includes the use of transfer functions or spectral reduction factors, both considering the frequency dependent alteration in the free field ground motion [9, 10].

In the present study, finite element based models are developed for 3D SSI analysis using a substructuring based numerical method. A hypothetical 3x3 pile group in homogeneous soil layer is considered for the study. The kinematic response of single pile (SP), pile group (PG) and piled raft (PR) with an embedded pile cap is analysed for three different earthquake motion records with varying frequency content. The results are then presented in terms of transfer functions with respect to free field motion at the surface, as well as spectral ratios.

2. Soil Structure Interaction Analysis

2.1 Kinematic Response of Pile Foundations

It is well known that pile foundations filter out high frequencies from translational response while introducing a rotational component. Rotational component of foundation input motion can be detrimental depending on the structure soil system [11]. The rotational component diminishes with an increase in the number of piles along the direction of motion [10]. A vast majority of previous studies ignore the effect of an embedded pile cap. The assumption of loss of contact of pile cap and soil can be justified if the possibility of scouring or soil subsidence exists. However, piled rafts are chosen in situation where raft-soil contact loss is unlikely. Hence the evaluation of pile soil interaction considering embedment of pile cap becomes relevant for piled raft foundations.

Kinematic soil-pile interaction, being a frequency dependent phenomenon is often quantified using transfer functions in translation (I_u) and rotation ($I_\emptyset$) defined as

$$I_u = \frac{u_P}{u_{ff}} \tag{1}$$

$$I_\emptyset = \frac{\emptyset_P . d}{u_{ff}} \tag{2}$$

where d is the diameter of pile, u represents displacement, and subscripts p, and ff represent the pile foundation and free field soil respectively. A dimensionless frequency parameter, a_o defined as in Eq. 3, is used in this study.

$$a_o = \frac{\omega d}{V_s} \tag{3}$$

In addition to transfer functions, the ratio of response spectrum ordinates of the foundation and free field soil has also been used to represent kinematic response of pile foundations [9]. The spectral ratio, is defined as

$$\xi = \frac{S_{a,p}}{S_{a,ff}} \tag{4}$$

where represents the response spectrum ordinate and subscripts p and ff represent the pile and free field respectively.

The spectral ratio has the advantage of direct and easier applicability for structural analysis. In the present study, both transfer functions and spectral ratio are extracted for the cases of single pile, pile group and piled raft.

2.2 Flexible volume substructuring method

The substructuring method in frequency domain that involves partitioning the soil foundation system into sub systems and then using the principle of superposition forms one of the most computationally efficient techniques for SSI analysis. In the present study, three dimensional SSI analysis is carried out using the FEM-BEM based program ACS SASSI program [12,13]. The soil-foundation system is partitioned into three subsystems namely free field site, excavated soil, and structure or foundation as presented in Fig. 1. The foundation and near field soil are modelled using 3D finite elements whereas the far field soil is taken into account using the Thin Layer Method [14]. The free field soil is represented in terms of impedances defined at each interaction nodes. The equation of motion in frequency domain can be expressed as

$$[C]\{U\} = \{Q\} \tag{5}$$

where C is the total stiffness matrix which can be expressed as a function of the complex stiffness matrix [K], mass matrix [M} and frequency ω as

$$[C] = [K] - \omega^2[M] \tag{6}$$

The equations of motion for the Flexible Volume Sub-structuring Method (FVSM) method are formed by combining the equation of motion of the structure and those of soil in the frequency domain.

$$\begin{bmatrix} C_{ss} & C_{si} \\ C_{is} & (C_{ii} - C_{ff} + X_{ff}) \end{bmatrix} \begin{Bmatrix} u_s \\ u_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ X_{ff} u_f' \end{Bmatrix} \tag{7}$$

In equation (7) the subscripts *s, i and f* refer to degrees of freedom at the superstructure, basement and excavated soil nodes respectively. In the FVSM technique, all finite element nodes of the excavated soil volume are treated as interaction nodes, which leads to a rigorous and computationally expensive analysis. The soil profile consists of viscoelastic horizontal layers. Material damping is introduced by complex moduli which includes an effective damping ratio. Evaluation of the methodology against published centrifuge shaking table test results as well as analytical results have been reported by different authors [15-18] and is not repeated for brevity.

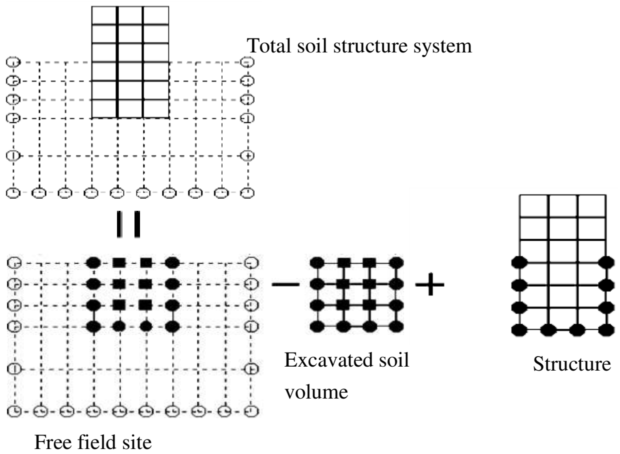

Figure 1. Partitioning of the total system into substructures in the Flexible Volume Method

2.3 Pile soil system

The problem of kinematic foundation soil interaction is often studied by analysing massless foundations subjected to vertically propagating shear or compressional waves [2, 19]. The assumption of massless shallow foundation can be compensated by considering foundation mass in the inertial interaction stage of SSI analyses. In the present study, kinematic response of a fixed head single pile, a 9 pile group and a corresponding piled raft foundation in a homogeneous viscoelastic soil stratum with elastic modulus of 30 MPa, and damping ratio of 5% overlying rigid stratum were analysed. The piles were of diameter of 0.5 m and length of 10 m spaced at 8 pile diameters in the longitudinal direction and 4 pile diameters in the transverse direction as presented. A homogeneous soil layer of thickness 20 m overlying rigid stratum is considered in the analysis. Three-dimensional finite element models of a single pile (SP), pile group (PG) and piled raft (PR) were created with vertical mesh size restricted to one fifth of the shortest wavelength to satisfy the wave passage criteria. Figure 2(a)-(c) presents schematic diagrams of the three cases considered. The fixity of the single pile was ensured by applying rotational restraint at the pile head nodes. The pile group model presented in Fig. 2 (b) was adopted from the hypothetical model considered in Poulos [20]. The model with a ground contacting pile cap or raft, will be referred to as piled raft (PR) in the following sections. The piled raft model with raft thickness (*t*) of 0.5 m corresponding to one pile diameter was considered in this study. The raft was assigned close to zero mass to avoid inertial interaction effects in the PG and PR models.

In order to rigorously capture pile-soil-pile and raft-soil-pile interactions, near field soil elements are defined between the piles. The analysis in frequency domain is essentially linear. In the present study soil is modelled as a viscoelastic solid and the foundation elements are assigned linear elastic properties. Nonlinear response such as pile soil slip and strain dependent shear modulus and damping of soil are not considered in this study. Eight noded brick elements were used to model the pile, raft and near field soil respectively.

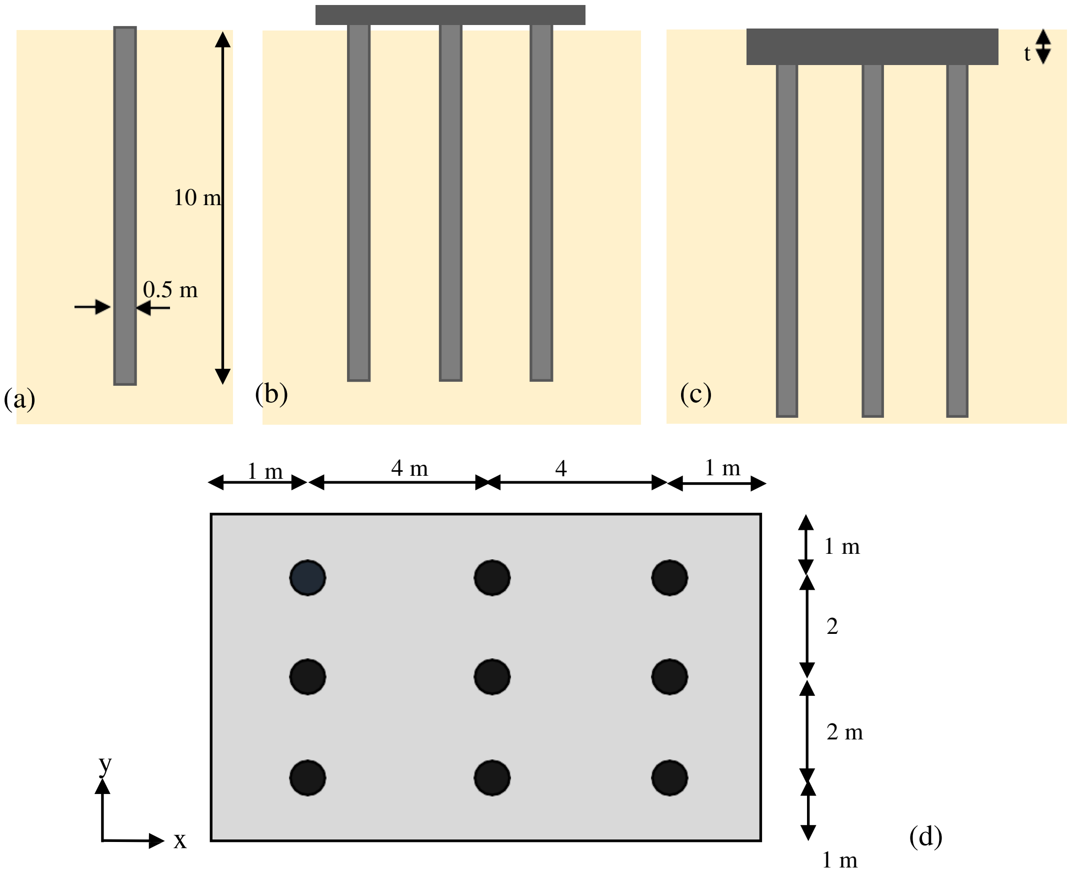

Figure 2. Schematic diagram showing (a) the single pile (b) pile group, (c) piled raft and (d) pile layout in PG and PR models

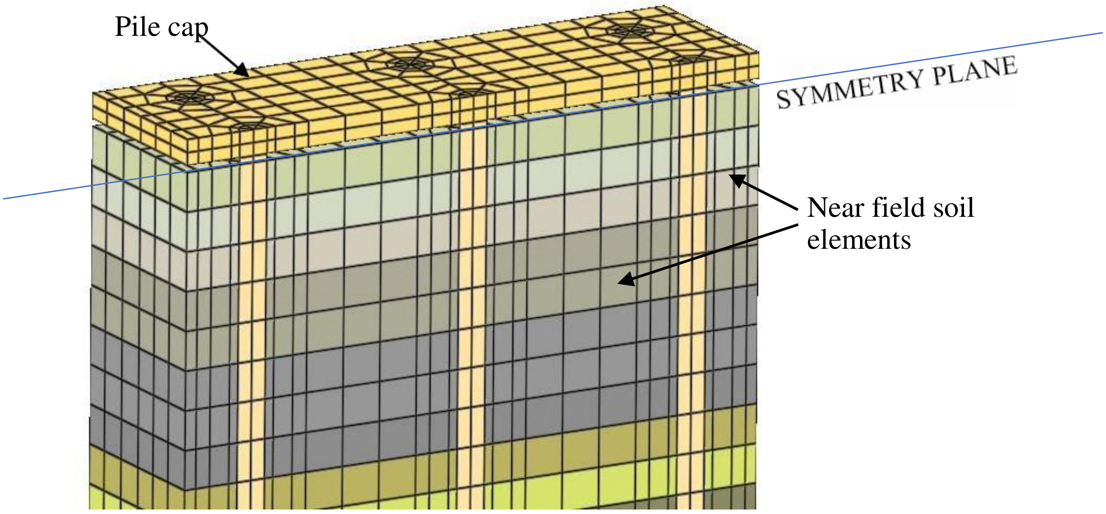

Figure 3. The finite element mesh of the pile group half model

Table 1. Transient ground motion considered in the study

Earthquake	Year	Recording Station	PHA (g)	M_w
Central Mexico	2017	UNAM	0.054	7.1
Ferndale	2014	Ferndale Fire Station	0.062	6.8
Valparaiso	2017	Curacavi	0.083	6.9

Taking advantage of symmetry in the PG and PR models, half models were defined with symmetry plane parallel to the x axis. For nodes along the symmetry plane, the translational degrees of freedom perpendicular to the plane were restrained. The finite element mesh of the half model of the pile group is presented in Fig. 3.

2.4 Seismic SSI analysis
The response of the soil foundation system is evaluated for vertically propagating shear waves. The ground motion is defined at the ground level. Response to harmonic loads, or transfer functions are evaluated at the bottom of the pile cap and raft for PG and PR models respectively. Transient response of the system is evaluated for three different earthquake time histories with varying frequency content. The earthquake motion is defined by a time history of acceleration and is introduced at the first layer i.e., ground level. Details of the three input time histories are presented in Table 1. The analyses were carried out for a total of 34 frequencies covering a frequency range of 0.01 Hz to 22 Hz considering the frequency content of the input motion. Fig. 4 (a)-(f) presents the acceleration time history and Fourier spectra of the input motions.

3. Results and Discussion

3.1 Harmonic response
The harmonic response of the three cases are often presented in terms of transfer functions in translation and rotation [21]. Fig. 5 presents the transfer function in translation for single fixed headed pile, pile group and piled raft cases. The responses of pile group and piled raft models are found to deviate from that of a single pile, and the deviation is found to vary with frequency. It is evident that an embedded pile cap plays an important role in the translational response of the system. For the pile group-soil system studied, the embedment effect is found to cause up to 25% decrease in translational response at a dimensionless frequency value of 0.28. However, at a_o values above 0.4, the trend is

found to reverse, with an embedded pile cap resulting in a higher response in comparison with the case of pile group.

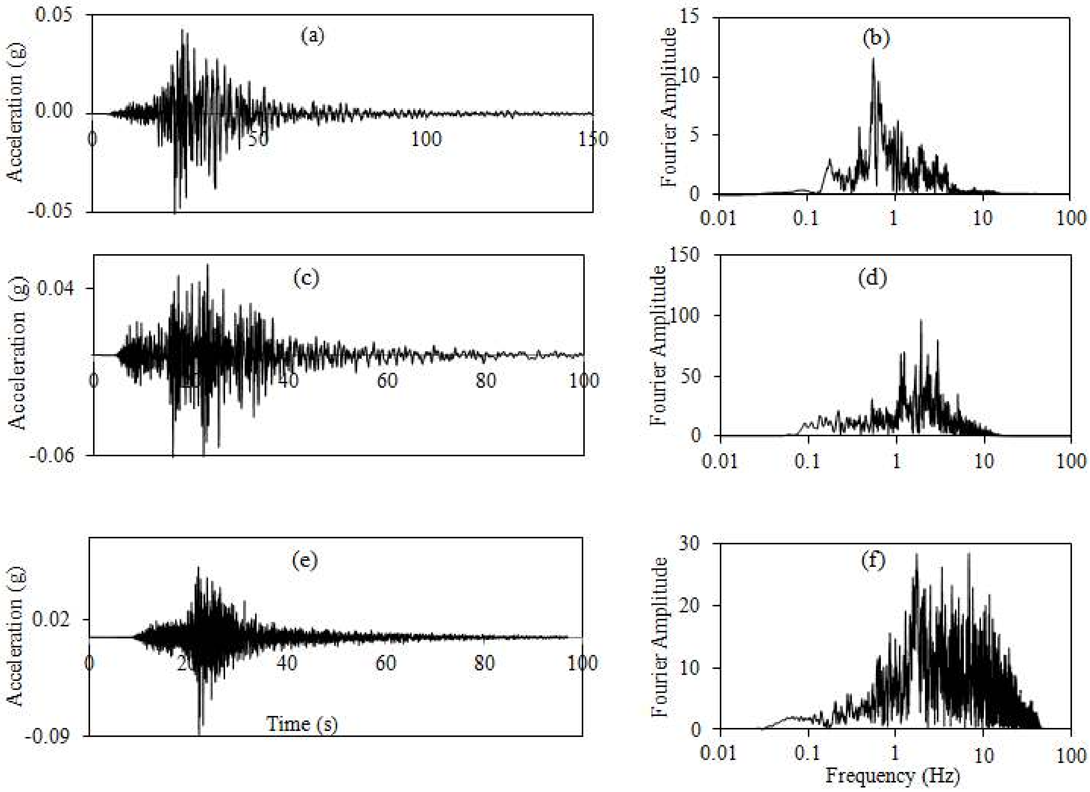

Figure 4. Acceleration time history and Fourier spectra of (a)-(b) Central Mexico 2017, (c)-(d) Ferndale 2014, and (e)-(f) Valparaiso 2017 ground motions

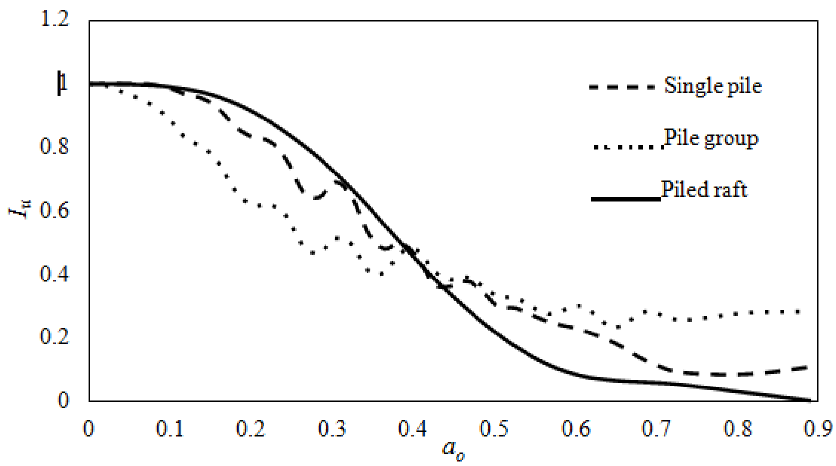

Figure 5. Transfer function in translation for the three foundation cases.

3.2 Transient response

The transient responses of the three foundation systems were evaluated for three different earthquake input motions described in Table 1. The input motions were defined at the ground level. The kinematic SSI effects are quantified using the spectral ratio, as defined in equation (4). The spectral ratios for the three input motions, obtained from the analyses are presented in Fig. 6. It was found that the spectral ratio for pile group closely follows the fixed head single pile behaviour. The piled raft model however was found to exhibit a considerable deviation from the behaviour of the pile group.

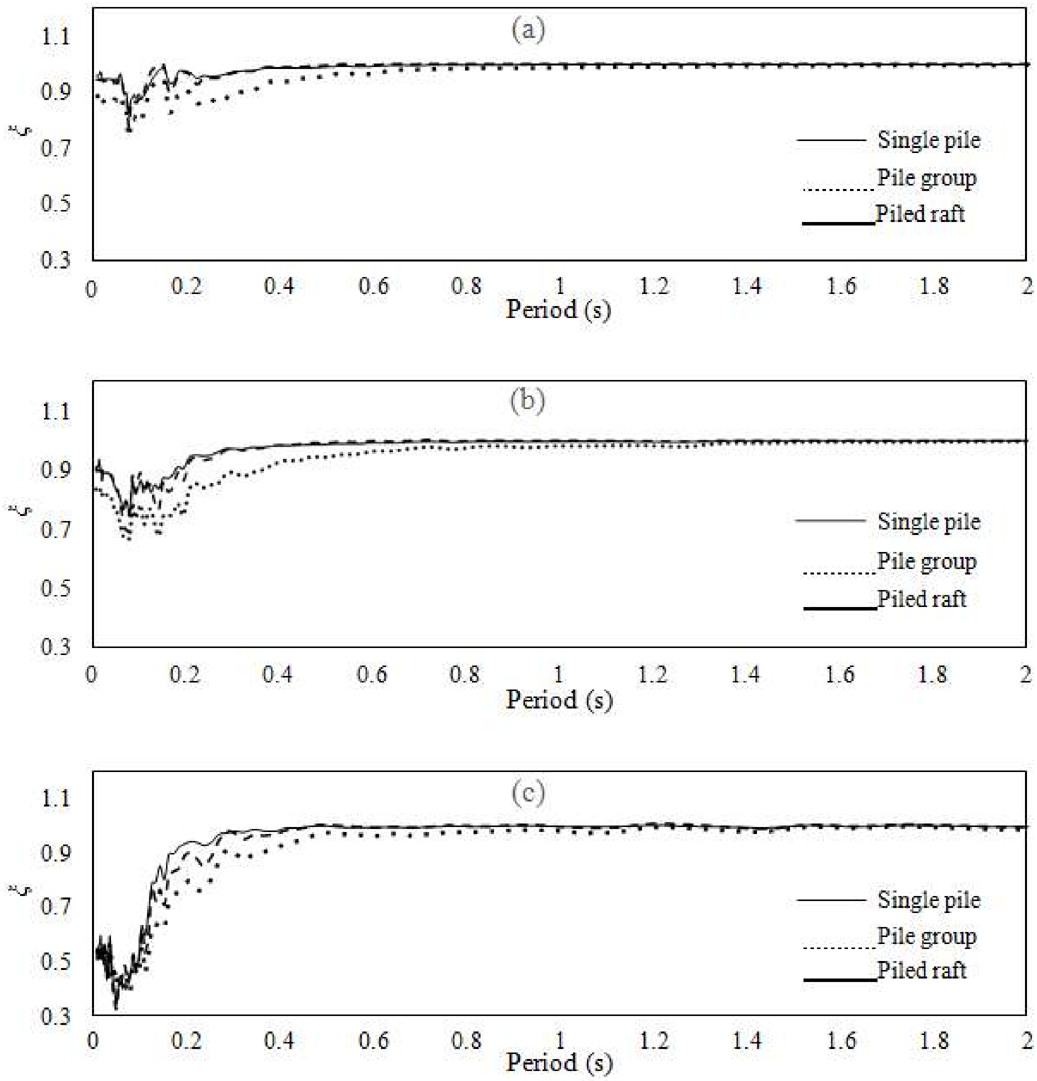

Figure 6. Spectral ratio for (a) Central Mexico 2017, (b) Ferndale 2014, and (c) Valparaiso 2017 ground motions

The peak acceleration observed at the top of the piled raft was observed between 8-9% lower than that of the pile group, for Central Mexico 2017 and Ferndale 2014 input motion with low and intermediate frequency content respectively. Another significant effect of pile cap embedment is the characteristic period at which the spectral ratio reaches unity. Available empirical relationship for spectral ratio such as those proposed by Di Laora and de Sanctis [9] do not consider this effect. Findings from this study point to the necessity of developing improved spectral ratio functions for piled raft foundations.

4. Conclusions

The kinematic response characteristics of a single pile, pile group and piled raft models are studied by carrying out three-dimensional soil structure interaction analyses employing a finite element based numerical method. Harmonic and transient response of the foundation models are evaluated for vertically propagating shear waves. The foundation input motion is characterized by plotting transfer function in translation as well as spectral ratios with respect to free field ground motion. The variation in transfer functions of pile group and piled raft is found to be frequency dependent. Embedment of the pile cap is found to result in a reduction of translational response by up to 25% at certain frequencies. From the spectral ratios evaluated for the three foundation types, it was found that embedment of pile cap results in a decrease in low period amplitude as well as an increase in the characteristic period at which the filtering effect can be ignored.

Reference

[1] Stewart J, Crouse, C B, Hutchinson, T C, Lizundia, B., Naeim, F., & Ostadan, F 2012 *Soil-structure interaction for building structures* (No. Grant/Contract Reports (NISTGCR)- 12-917-21).

[2] Mylonakis G, & Gazetas, G 2000 Seismic soil-structure interaction: beneficial or detrimental?. *Journal of Earthquake Engineering*, *4*(3), 277-301.

[3] Makris N, Gazetas G, & Delis, E 1996 Dynamic soil—pile—foundation—structure interaction: records and predictions. *Géotechnique*, *46*(1), 33-50.

[4] Stewart J P, Fenves G L, & Seed R B 1999 Seismic soil-structure interaction in buildings. I: Analytical methods. *Journal of Geotechnical and Geoenvironmental Engineering*, *125*(1), 26-37.

[5] Nikolaou S, Mylonakis G, Gazetas G, & Tazoh T 2001 Kinematic pile bending during earthquakes: analysis and field measurements. *Geotechnique*, *51*(5), 425-440.

[6] Mylonakis G, Nikolaou A, & Gazetas, G 1997 Soil–pile–bridge seismic interaction: kinematic and inertial effects. Part I: soft soil. *Earthquake Engineering & Structural Dynamics*, *26*(3), 337-359.

[7] Pitilakis D, Dietz M, Wood D M, Clouteau D, & Modaressi, A 2008 Numerical simulation of dynamic soil–structure interaction in shaking table testing. *Soil dynamics and earthquake Engineering*, *28*(6), 453-467.

[8] Zhang L, Goh S H, & Liu, H 2017 Seismic response of pile-raft-clay system subjected to a long-duration earthquake: centrifuge test and finite element analysis. *Soil Dynamics and Earthquake Engineering*, *92*, 488-502.

[9] Di Laora R, & de Sanctis, L 2013 Piles-induced filtering effect on the foundation input motion. *Soil Dynamics and Earthquake Engineering*, *46*, 52-63.

[10] Di Laora, R, Grossi, Y, de Sanctis, L, & Viggiani G M. 2017 An analytical solution for the rotational component of the Foundation Input Motion induced by a pile group. *Soil Dynamics and Earthquake Engineering*, *97*, 424-438.

[11] Sextos A G, Mylonakis, G. E, & Mylona, E. K. V 2015 Rotational excitation of bridges supported on pile groups in soft or liquefiable soil deposits. *Computers & Structures*, *155*, 54-66.

[12] Lysmer J, Tabatabaie-Raissi M., Tajirian, F, Vahdani, S, & Ostadan, F 1983 SASSI. *System for Analysis of Soil Structure Interaction, UC Berkeley, Dept. of Civil Engineering, Berkeley, CA*.

[13] Ghiocel PredictiveTechnologies 2014 *ACS SASSI:An Advanced Computational Software for 3D Dynamic Analysis Including Soil-Structure Interaction* Ghiocel Predictive Technologies, Inc., Pittsford, NY,USA

[14] Kausel E, and Roesset J M 1975 Dynamic stiffness of circular foundations.‖ *Journal of the Engineering Mechanics Division*, ASCE, 101(6), 771–785.

[15] Boominathan A, Varghese R, & Nair, S K 2018 Soil–Structure Interaction Analysis of Pile

Foundations Subjected to Dynamic Loads. In *Geotechnics for Natural and Engineered Sustainable Technologies* (pp. 45-61). Springer, Singapore.

[16] Varghese R, Boominathan A, & Banerjee S 2019 Kinematic Response Characteristics of a Piled Raft Foundation. *Proceedings of the 43rd Annual Conference on Deep Foundations, Anaheim, California*

[17] Varghese R., Boominathan A, & Banerjee S 2019 Seismic response characteristics of a piled raft in clay. *Journal of Earthquake and Tsunami*, *13*(01), 1950005.

[18] Varghese R, Boominathan A, & Banerjee, S. 2019 Numerical Analysis of Seismic Response of a Piled Raft Foundation System. In *Soil Dynamics and Earthquake Geotechnical Engineering* (pp. 227-235). Springer, Singapore.

[19] Wong H L, & Luco, J E 1986 Dynamic interaction between rigid foundations in a layered half-space. *Soil Dynamics and Earthquake Engineering*, *5*(3), 149-158.

[20] Poulos H G 1997 Comparison of some methods for analysis of piled rafts. In *Proc. 14th ICSMGE, Hamburg* (Vol. 2, pp. 1119-1124).

[21] Fan K, Gazetas G, Kaynia A, Kausel E, & Ahmad S 1991 Kinematic Seismic Response of Single Piles and Pile Groups Journal of Geotechnical Engineering, Vol. 117, No. 12 1860-1879