SEISMIC BEHAVIOR OF HIGH-RISE STEEL BUILDING ON PILE GROUPS ACCOUNTING FOR SOIL-STRUCTURE INTERACTION EFFECTS ON SOFT SOIL

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ABSTRACT

Previous studies on the subject have identified seismic soil–structure interaction (SSI) as the important factors affecting structures response on soft soil during the earthquakes. In this paper, a three dimensional (3D) Finite Element Method (FEM) for the nonlinear behaviour of structure and soil are utilized. To investigate the effects of the SSI on the seismic response of the superstructures, a series of numerical simulations were conducted on 15-story building as well as six types of pile-raft foundations. The goal was to evaluate the effectives of using a piled raft and estimation of the required optimum number, location and configuration of the piles. In order to confirm the reliability of the numerical model, the validation was accomplished based on the data extracted from experimental shaking table results. Therefore, parametric studies have been conducted in order to obtain design strategies for an optimized design of piled rafts subjected to low-to-high intensity real earthquake records as input motions. The numerical results indicate a reasonable correlation between Shaking Intensity Rate (SIR) parameter and maximum interstory drift of structures. Furthermore, the performance level of structures on softened ground is a function of area replacement ratio, diameter, and length and space between piles and ground motion characteristic, so these important aspects are considered.

INTRODUCTION

The problem of soil-structure interaction (SSI) in the seismic analysis and design of structures has become increasingly important as it may be inevitable to build structures at locations without favourable geotechnical conditions in seismically active regions (Bagheri et al., 2018, Tabatabaiefar and Fatahi, 2014). According to Cuhna et al. (2001) who investigated the design alternatives for a piled-raft case history, the load distribution between piles is significantly affected by raft rigidity, pile stiffness, pile length-diameter ratio, and structural stiffness. They suggested that pile loads, as well as contact pressures, tend to decrease as the raft thickness increases, increase with the reduction of the number of the piles, and their maximum values are mainly dependent on the number and length of piles. Reul and Randolph (2004) studied parametrically the optimized design of a piled raft foundation and concluded that it clearly depends on subsoil conditions, the load configuration, and the load level. In this situation, mitigation strategies may be assessed in order to achieve economical and effective solution. Hokmabadi et al. (2014) utilized a three dimensional numerical model in order to better understand the SSPSI phenomena of three different cases of structures supports, namely fixed base, shallow foundation and floating pile foundations. Their investigations indicated that the floating pile foundations contribute to the reduction of lateral displacements due to the reduced rocking components in comparison with the shallow foundation case. Banerjee et al. (2014) studied seismic effects on fixed-head, end-bearing piles installed through soft clay, using centrifuge and numerical modeling concluded that for all piles, the pile head and soil masses have significant influence on the bending moment. In this research, the main objectives of the numerical parametric study are acquiring better understanding of key parameters (soil type and ground motion characteristics) which influence

SSI under seismic loads and capturing the effects of SSI in the seismic design procedure of regular high-rise moment resisting building frames to ensure design safety and reliability.

NUMERICAL SIMULATION

The numerical analysis is carried out to investigate various factors affecting the seismic response including configurations and length of the piles and characteristics of the ground motions. The structural and soil elements are modelled as an inelastic and an elastoplastic continuum material. The height of structure was chosen 15-story with the height of each level 3 m. Columns and beams of the models are box profiles which their size varies along the height of the building (Table 1). Furthermore, in order to do a realistic simulation of the buildings, the structure is ideally divided into three and five parts of homogeneous section properties for 15-story building. In order to accurately investigate the actual behavior of the structure under the effects of SSI, code Abaqus (V6.13.1) has been utilized for modeling and analyzing structures. Fig. 1 shows the 3D model of the 15-story building on soft clay. The beams and columns of the frames are capable of exhibiting inelastic behavior and such nonlinear behavior is introduced to the members by using elasto-plastic elements. Nonlinear shell elements are utilized for the floor diaphragms. The damping matrix is assumed to be of Rayleigh type with 5% material damping for both the structure and original soil materials. Column structural elements are a two-node linear beam in space, finite elements with six degrees of freedom per node comprising three translational and three rotational components. The embedded shallow foundation is represented by inelastic eight-node brick elements.

Soil medium beneath the structure greatly influences the seismic behavior and response of the structure, especially for the structures constructed on soft soils with shear wave velocity lower than 600 m/sec. Thus, in order to achieve reliable and accurate results, SSI effects are needed to be taken into consideration in dynamic analysis of the structures resting on softer soils. The Mohr–Coulomb model is used to simulate the nonlinear behavior of the soil. The failure envelope corresponds to a Mohr–Coulomb criterion shear yield with tension cutoff tension yield function. The mechanical characteristics of the soil are mentioned in Table 2. Model consists of a clay layer with a total thickness of 30m on bedrock.

Table 1. The typical sections of 15-story building

Level	Beam sections	Column sections
1-3	$IPE\,300$	$Box\,550\times25$
4-6	$IPE\,300$	$Box\,500\times20$
7-9	$IPE\,300$	$Box\,450\times15$
10-12	$IPE\,270$	$Box\,400\times12$
13-15	$IPE\,270$	$Box\,350\times10$

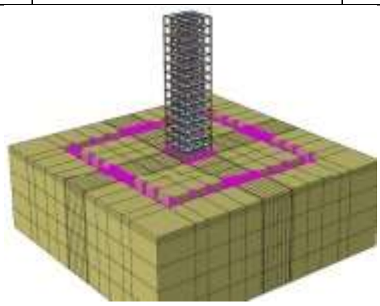

Figure 1. 3D view of steel moment resisting frame on soft soil

According to the Rayhani and El Naggar study, the horizontal distance of the soil lateral boundaries should be at least five times the width of the structure. In addition, by undertaking comprehensive numerical modeling and centrifuge model tests, Rayhani and El Naggar recommended 30 m as the maximum bedrock depth in the numerical analysis as the most amplification occurs within the first 30m of the soil profile. Therefore, the maximum bedrock depth is 30 m while the horizontal distance of the soil lateral boundaries is assumed to be 60 m. In the numerical model, the values of the interface stiffness properties used in the foundation simulations are calculated using the equation suggested by Whitman (1967). And finally, by performing a thorough investigation on finding appropriate values of soft clay parameters which are consistent enough with the measured structural deformations, a value of k_n=k_s=5 (MPa/m) has been selected for soft clay.

Table 2. Major modeling Properties of soft clay (Rahvar, 2009)

Model parameters	Soft clay
Soil type (AS 1170)	E_e
Unified classification (USCS)	CL
$\rho =$ Soil density (kg/m^3)	1470
$V_s =$ Shear wave velocity (m/sec)	150
$G_{max} =$ Maximum shear modulus (kPa)	33100
$\upsilon =$ Poisson's ratio (kPa)	0.4
$c' =$ Cohesion intercept (kPa)	20
$\phi' =$ Friction angle (degree)	12
Plasticity Index (PI)	15

Each model is subjected to four ground motion records selected from the PEER Strong Motion Database (Pacific Earthquake Engineering Research (PEER) Centre (2012)). The ground motions were selected to cover a range of intensities, durations, and frequency contents, in order to enable a comprehensive evaluation of SSI on softened ground. The PGA, PGV, and PGD values in Table 3 are the maximum absolute values of acceleration, velocity, and displacement for each ground motion. Two near field earthquakes including Kobe, 1995 and Northridge, 1994 and two far field earthquakes comprising El-Centro, 1940 and Hachinohe, 1968 are selected and utilized in time-history analysis.

Table 3. Earthquake data for the parametric analysis (PEER Centre, 2012)

Earthquake motion parameters	Northridge (USA)	Kobe (Japan)	El Centro (USA)	Hachinohe(Japan)
Date of occurrence	1994	1995	1940	1968
Magnitude of earthquake, M_w	6.7	6.8	6.9	7.5
Maximum horizontal acceleration, (g)	0.843	0.834	0.349	0.231
Predominant period, T_p (sec)	0.36	0.36	0.56	0.22
Significant duration, D_{5-95} (sec)	5.32	8.4	24.58	27.79
Time of MHA (t_p (sec))	4.2	8.52	4.1	4.18
$\mathrm{PGV}/\mathrm{PGA}$ (sec)	0.157	0.112	0.102	0.146
Arias intensity (m/sec)	5.004	8.389	1.758	0.899
SIR (m/sec/sec)	1.903	1.407	0.117	0.037
Energy flux (J.m^{-2}.sec^{-1})	8560.187	7649.179	2144.177	2409.691
Type	Near field	Near field	Far field	Far field
Hypocentral distance (km)	9.2	7.4	15.69	14.1

$$SIR = I_{a(5-75)} / D_{(5-75)}$$

VERIFICATION

The results of the conducted experimental (Tabatabaeifar et al. 2014) investigation in this section are employed to verify 3D numerical models. The results show that the calculated response is in good agreement with the experimental counterpart. Accordingly, the scaled 15-story structure models with three different types of foundations, namely: (i) fixed-base structure representing the situation excluding the SSI, (ii) structure supported by shallow foundation, and (iii) structure supported by pile-raft foundation, are numerically simulated and their calculated results are compared with the experimental measurements (Fig. 2). The developed numerical nonlinear 3D model accounts for the various phenomena observed in SSPSI experimental study, providing further understanding on the influence of the SSPSI on the seismic response of the superstructure. The developed 3D numerical model is capable of simulating the behavior of the soil-pile-structure system with acceptable accuracy; therefore it would be a rational and appropriate tool for further studies of the SSPSI effects. Furthermore, few disparities observed between FEM predictions and experimental measurements in the lower levels of the shallow foundation and pile foundation cases can be due to the nature of the numerical method, adopting nonlinear elastic-perfectly plastic Mohr-coulomb model for the soil, assuming ideal rigid connection between the foundation and the pile caps, and unavoidable experimental uncertainties.

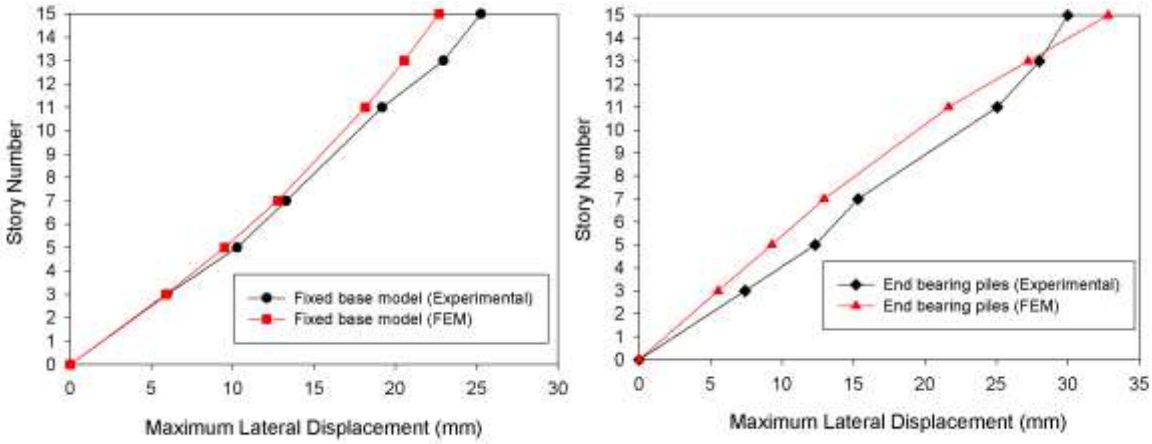

Figure 2. Comparison between maximum lateral displacement of the structure from shaking table tests and 3D numerical predictions for the fixed base, and pile-raft (end bearing) foundations under Northridge earthquake

RESULTS AND DISCUSSION

The results presented in this study outline crucial aspects that may be considered by engineers for the geotechnical and structural designs of such superstructures.

SEISMIC DEMAND

Ground motion characteristics also affect the influence of other parameters, such as pile performance, and structural H/W ratio on the deformation mechanisms. The Kobe motion was selected for its longer duration and slower rate of energy buildup compared to the Northridge motions. These motions have an approximately similar PGA. The significant durations (D5–95) of Northridge and Kobe events were approximately 5 sec and 8 sec, respectively, while their corresponding arias intensities were 5 m/sec and 8.4 m/sec. As shown in Fig. 3, structure underwent smaller lateral deflection during the Kobe earthquake, although they deformed for a longer time period. Although the arias intensity and significant duration of the Kobe event were, respectively, 1.67 and 1.58 time larger than those during the Northridge event, structures deformed less during the Kobe earthquake. Simpler ground motion measures, such as peak ground acceleration (PGA) and peak ground velocity (PGV), are even more deficient. By combining the effects of ground motion intensity, frequency content, and duration, the SIR of the ground motion better defines the seismic demand that identified through this study. As could be expected, much larger SIR values lead to increase in displacements for both of superstructures.

PILE-RAFT FOUNDATION CONFIGURATIONS

According to the above-mentioned arguments, the results of the 3D numerical predictions for the maximum lateral deflections of the 15-story structure supported by the fixed-base, the shallow foundation, and several types of pile-raft foundation are summarized and compared in Fig. 4. As mentioned earlier, the 3D numerical model accounted for the inelasticity of the soil and the structure. To examine the effect of optimum number, location and piles configuration, six cases considered. The main reason for reducing the lateral displacement in pile-raft foundations in comparison to the shallow foundation case is the presence of stiff pile elements in the soft soil increases the equivalent stiffness of the ground and influences the dynamic properties of the whole system. It was predicted and evaluated in this investigation which the optimum design case for pile-raft foundation is model (III). Generally, this is a function of area replacement ratio, diameter, length, and space between piles. In summary, a comparison of the three cases (models IV, V, VI) during the Northridge event indicated similar pattern of responses for different pile-raft configurations. The aforementioned parametric studies have concluded that increasing the number of piles is beneficial for the foundation performance up to a certain point but not for every circumstance. According to the Fig. 4, displacement distribution throughout the height of building is nearly linear manner for all pile-raft systems, whereas in the other cases the response is non-linear. As Dimitra, has explained, allowing mobilization of failure mechanisms at the foundation level implies the development of a hinge below the footing which restrains the transmission of loading to the superstructure and, namely, isolating it from ground motion. As a result, the superstructure remains elastic during severe seismic loading and failure of the superstructure is avoided. Perhaps the nonlinearity of piles and the group effect are the reason behind the fact that the response of tall building is linear behavior during the ground motions.

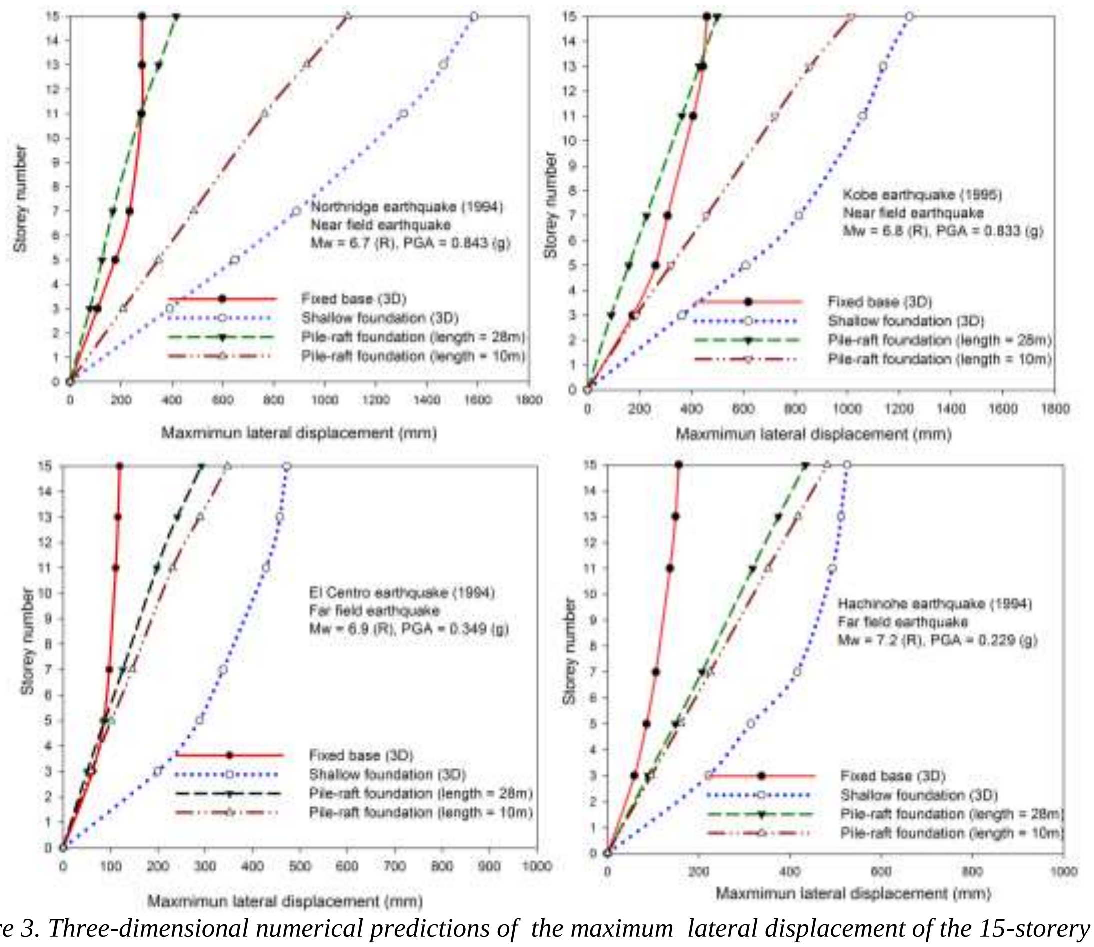

Figure 3. Three-dimensional numerical predictions of the maximum lateral displacement of the 15-storery model structure under the influence of following records: (a) Northridge earthquake; (b) Kobe earthquake; (c) El Centro earthquake; (d) Hachinohe earthquake.

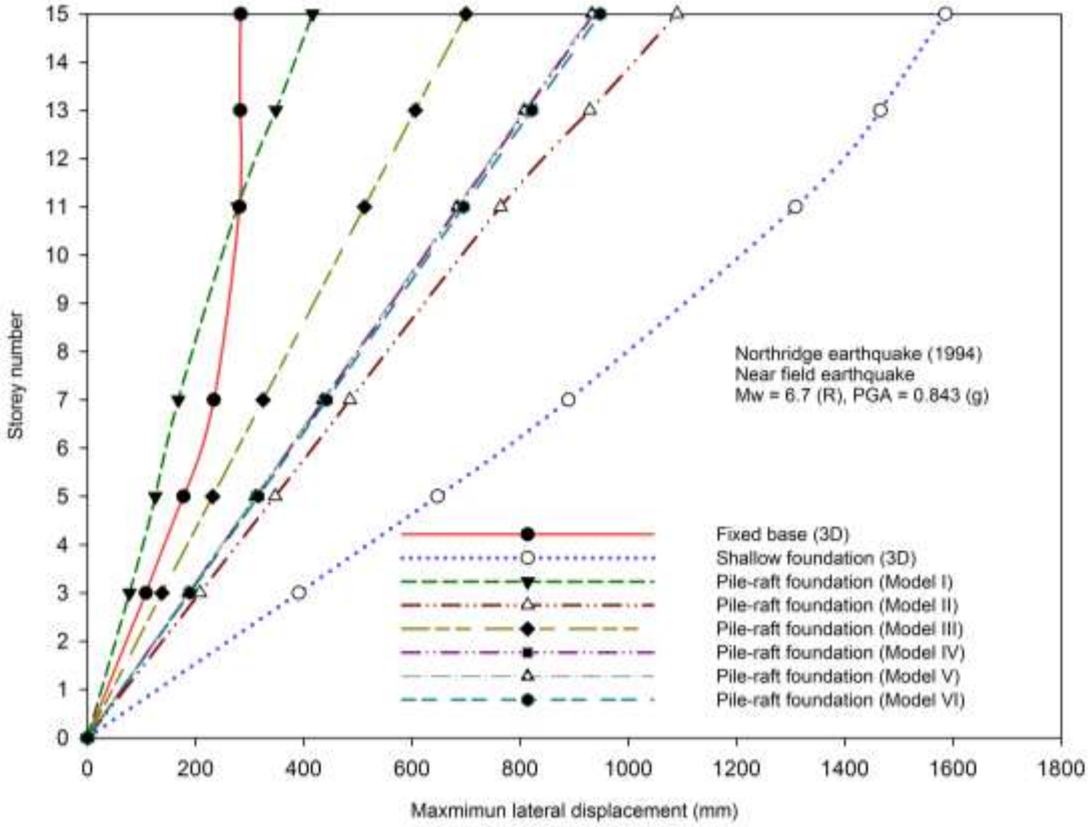

Figure 4. Comparison of maximum lateral displacement versus number of story for different models during the Northridge earthquake

ASSESSMENT OF PERFORMANCE LEVELS OF PROPOSED MODELS

Performance levels describe the state of structures after being subjected to a certain hazard level, and based on FEMA273/274 are classified as: fully operational, operational, life safe, near collapse, or collapse. Overall lateral deflection, ductility demand, and inter-story drifts are the most commonly used damage parameters. The above mentioned five qualitative levels are related to the corresponding quantitative maximum inter-storey drifts (as a damage parameter) of: <0.2%, <0.5%, <1.5%, <2.5%, and >2.5%, respectively. According to Fig. 5, model (III) experiences less inter-storey drifts in comparison to the structure supported by the shallow foundation. For example, the maximum recorded inter-storey drift of the fixed base structure is measured to be 1.28%, while the corresponding value for model (III) and shallow foundation cases are 1.67% and 4.38%, respectively. In other words, effects of SSPSI and SSI induce 30% and 242% increase in the recorded inter-storey drifts, respectively. As a result, the SSPSI may affect the performance level of the structure and shift the performance level of the structure from life safe zone to near collapse or even collapse levels. The key conclusion from this work is that the proposed system has advantages over typical pile-raft foundation in seismic zones in terms of having a cost-effective construction process and capable of exploiting the benefits of the nonlinear response during strong motion.

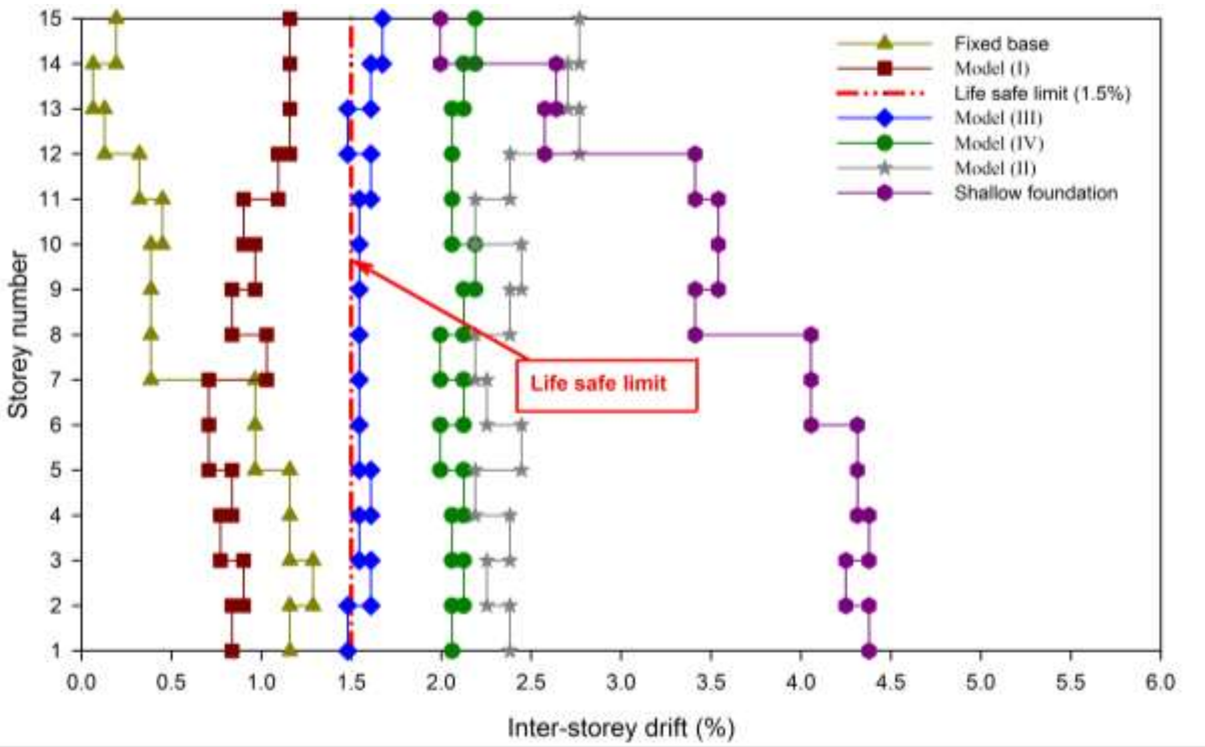

Figure 5. Comparison of simulation 15-story model showing the variation of maximum lateral displacement versus story number during the Northridge earthquake

CONCLUSIONS

In this research, nonlinear 3D FE analysis model supported with different foundations on soft soil was conducted. The results were compared both quantitatively and qualitatively, investigating the effect of SSPSI on the seismic response of the high-rise steel moment frame. These comparisons provided valuable physical insights into the dynamic behavior of pile-raft foundation. Some of the key conclusions are as follows:

- The maximum displacement of the 15-storey model (I) structure subjected to the Northridge and Hachinohe earthquakes were measured to be 416.28 mm and 433.81 mm, respectively, while the corresponding value for model (II) case was 1089.74 mm and 481.86 mm, respectively. In comparison to the fixed base structure, the maximum lateral deflection of the model (III) increases by 22%, 28%, and 60% based on the 3D numerical predictions, while the maximum lateral deflection of the structure in model (III) is decreased by 65%, 63%, and 56% in comparison to the results obtained from the shallow foundation in 3rd, 7th, and 15th levels, respectively. It was predicted which the optimum design case for pile-raft foundation is model (III). Generally, this is a function of area replacement ratio, diameter, and length and space between piles. In summary, a comparison of the three cases (models IV, V, VI) during the Northridge event indicated similar pattern of responses for different pile-raft configurations. The aforementioned parametric studies have concluded that increasing the number of piles is beneficial for the foundation performance up to a certain point but not for every circumstance.
- It can be seen that further increases in the length of pile likely have a marginal impact on building displacements, especially in tall buildings. Therefore, pile-raft foundation alone cannot provide the required safety factors; it is possible to enhance its performance with the addition of piles, change in pile configurations and diameters.
- As could be expected, for the ground motions considered, much larger SIR values lead to increase in displacements for both of superstructures. The numerical results indicate a reasonable correlation between SIR parameter and maximum inter-story drift of structures.

REFERENCES

ABAQUS user's manual-version 6.13-1. Pawtucket, RI: Hibbit, Karlsson & Sorenson, 2013.

Bagheri, M., Ebadi Jamkhaneh, M., & Samali, B. (2018). Effect of Seismic Soil–Pile–Structure Interaction on Mid and High-Rise Steel Buildings Resting on a Group of Pile Foundations. *International Journal of Geomechanics, 18*(9), 04018103.

Banerjee, S., Lee, F.H., & Goh, S.H. (2014). Earthquake-induced bending moment in fixed-head piles in soft clay. *Ge´otechnique*, *64*(6), 431-446.

Cunha, R.P., Poulos, H.G., & Small, J.C. (2001). Investigation of design alternatives for a piled raft case history. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(8), 635–641.

Dimitra, B. (2010). 3D seismic response of pier foundation piles: Towards a new design concept. MSc thesis in civil engineering, National Technical University of Athens (NTUA).

FEMA 273 (1997). NEHRP Guidelines for the Seismic Rehabilitation of Buildings. prepared by the Applied Technology Council for FEMA, Federal Emergency Management Agency , Washington, D.C.,USA.

Hokmabadi, A., Fatahi, B., & Samali, B. (2014). Physical Modeling of Seismic Soil-Pile-Structure Interaction for Buildings on Soft Soils. *International Journal of Geomechanics, 15*(2), 04014046.

Hokmabadi, A.S., Fatahi, B., & Samali, B. (2014). Assessment of soil–pile–structure interaction influencing seismic response of mid-rise buildings sitting on floating pile foundations. *Computers and Geotechnics*, *55*, 172-186.

Pacific Earthquake Engineering Research (PEER) Center. (2012). *PEER Ground Motion Database*. Univ. of California, Berkeley, CA.

Reul, O., & Randolph, M.F. (2004). Design strategies for piled rafts subjected to non-uniform vertical loading. *Journal of Geotechnical and Geoenvironmental Engineering*, *130*, 1-13.

Tabatabaiefar, H., & Fatahi, B. (2014). Idealization of soil–structure system to determine inelastic seismic response of mid-rise building frames. *Soil Dynamics and Earthquake Engineering*, *66*, 339–351.

Tabatabaiefar, H., Fatahi, B., & Samali, B. (2014). Numerical and Experimental Investigations on Seismic Response of Building Frames under Influence of Soil-Structure Interaction. *Advances in Structural Engineering, 17*(1), 109-130.

Whitman, R.V., & Richart, F.E. (1967). Design Procedures for Dynamically Loaded Foundations. *Journal of the Soil Mechanics and Foundations Division*, *93*(6), 169-193.