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Numerical investigation on seismic response of moment resisting RC building frames resting on sand considering soil-pile-structure interaction

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ABSTRACT: Buildings constructed in seismic prone areas must satisfy the limit state design criteria and inter-storey drift limitations. In recent years, importance of considering soil-structure interaction in the seismic analysis and design of building frames was addressed by various researchers. This study aims to investigate the effects of soil-pile-structure interaction on the behavior of moment resisting frames resting on sand. Numerical analysis was performed on a 10 storey midrise reinforced concrete building using a finite element program PLAXIS3D. The base shear was distributed to all storeys by using equivalent static method. Denseness of soil and spacing of piles were considered as parameters for the analysis. The elastic seismic response of the building in terms of storey displacement and inter-storey drifts was observed. The normalized storey lateral displacement and inter-storey drift values with fixed base structure were evaluated and presented in this paper. The results indicate that the inter-storey drift and storey lateral displacement are affected significantly by the considered parameters. Thus it is pertinent for the designers and practitioners to consider soil-pile-structure interaction for the analysis and design of building frames.

1 INTRODUCTION

The significance of considering soil-structure interaction (SSI) and soil-pile-structure interaction (SPSI) for the analysis and design of super structures situated on soft soils is studied by the various researchers. The soil lateral spreading and liquefaction resulted in settlement and tilting of buildings (Dash & Bhattacharya (2012)) and collapse of Hanshin Expressway bridge (Mylonakis et al. 2000). Similarly the failure of piles was primary reason for the collapse of Showa Bridge during 1964 Niigatta earthquake (Kerciku et al. (2008) and Bhattacharya et al. (2008)), building damages during 1995 Hyogen Nambu earthquake (Tokimatsu et al. (1996)). The response of structure under seismic excitation is complex in nature. The various factors such as ground motion, material non-linearity, foundation type, soil characteristics, etc. affect the response of the building structures. For earthquake analysis, the structures are generally considered to be fixed at the base level and the effects of soil-structure interaction are generally neglected. But in reality, the response of the structure is altered by the response of the soil and the response of the soil is affected by the response of the structure when the building is subjected to seismic forces. Mylonakis and Gazetas (2000) described the role of soil-structure interaction in the seismic response of structures using recorded ground motions and theoretical considerations. Gazetas et al. (1993) presented the formulas to obtain dynamic impedances of foundations with large number of piles. Furthermore, various researchers have studied the effects of SSI and SPSI on structural performance (Kim & Rosset (2004), Dutta et al. (2004), Bhattacharya et al. (2006), Dutta et al. (2007), Massumi & Tabatabaiefar (2007), (2008), (2010), Roy & Dutta (2010), Tabatabaiefar et al. (2010), (2013) and Carbonari et al. (2012)). The reduction in plasticity index of the soil decreases the base shear and the lateral deflections and inter-storey drifts get enhanced for the flexible base models (Fatahi & Tabatabaiefar (2014)). It was suggested by Tabatabaiefar & Fatahi (2014) that the dynamic soil structure interaction is significant for structures built on soft and very soft soils as the structures performance changes from life safety to near collapse level. Similarly, the importance of SPSI on the seismic analysis and design of tall buildings supported on pile foundations had been studied extensively by Yingcai(2002). Chore & Ingle (2008) and Chore et al. (2009) studied the response of single storey two bay framed building resting on pile foundations. It was concluded that the number, spacing and diameter of piles affect the super structure response considerably. Carbonari et al. (2008, 2011), performed linear finite element analysis with the effects of SSI and studied the performance of coupled wall frame structures founded on pile foundations. The estimated results show that the importance of SSI analysis is crucial for the accurate estimation of behavior of the systems. Hokmabadi et al. (2014) and Hokmabadi & Fatahi (2016) studied the performance of moment resisting frames experimentally and numerically considering material (soil and structure) non-linearity and geometric (uplifting, gapping and P-delta) non-linearity. Structures supported on shallow, piled-raft and floating pile foundations were compared with fixed base structure. It was found that ignoring SPSI effects in the analysis and design may lead to erroneous structural performance. Nguyen et al. (2017) investigated the effects of type and size of pile foundations resting on soft soil in high seismic region, on response spectrum, lateral deflection and response of the entire system. A fully non-linear time history method was adopted to study the dynamic response of soil, structure and foundation systems. By increasing the pile length, the structure undergoes maximum lateral deformation which leads to inter storey drift value exceeded to 1.5%, which is threshold value of life safety level. Understanding the seismic response of pile supported structure is challenging that involves the interaction among nonlinear behavior of structure, pile foundation, raft and the soil under strong earthquake motion. Experimental works and numerical studies are limited to plasticity index effects, raft and pile foundation sizes, soil flexibility, liquefaction of soil, etc. Similarly the major research outcomes are also limited to behavior of soil-pile system considering super structure as a lumped mass. Thus, due consideration of soil-pile-structure interaction during seismic analysis of structures resting on sandy soils is needed to ensure the safety of super structure. In this study, a finite element program PLAXIS 3D is used to address the effects of seismic soil-pile-structure interaction on the response of moment resisting reinforced concrete building frames resting on sand. The effects of spacing of piles and relative density of soil are considered for the evaluation of structural response.

2 SEISMIC BEHAVIOUR OF FIXED BASE AND PILE SUPPORTED STRUCTURE

2.1 *Description of fixed base model*

Equivalent static analysis was performed on a ten storey moment resisting reinforced concrete building frames as per IS1893:2016. SAP2000 V 20 software was used for the analysis and design of fixed base structure. Three bays ten storeys building of uniform width of 4 m and height of 3.5 m (Figure. 1) was selected for the analysis. The loading conditions were considered in accordance with IS 875:1987 (Part 1 and 2). The thickness of slab and wall was considered as 120 mm and 230 mm respectively. Floor finish and live load were considered as 1 kN/m^2 and 4 kN/m^2 respectively. Seismic parameters such as zone factor 0.36, importance factor 1.5, and response reduction factor 5 and damping of the building 5% were used for the simulation (IS 1893:2016). Grade of concrete and grade of steel used were M25 and Fe415 respectively. The fundamental time period of the structure was found to be 0.909 sec. The base shear obtained from both the equivalent static and response spectrum analysis was 2575 kN. The structural design was carried out as per IS 456:2000, in such a way that the conditions of limit state of collapse and serviceability were ensured. The inter storey drift of the fixed base building was evaluated and ensured that the values are within the permissible limit of 0.4%.

2.2 *Description of pile supported structure*

The raft and pile foundations were designed as per IS 456:2000 and IS 2911 (Part 1/Section 4):2010. Grade of concrete and steel were considered as same as that of the structure. The length, breadth and thickness of the raft were 15 m, 15 m and 0.7 m respectively. The length to diameter ratio of the pile foundation considered as 40. A pile group consisting of 16 piles

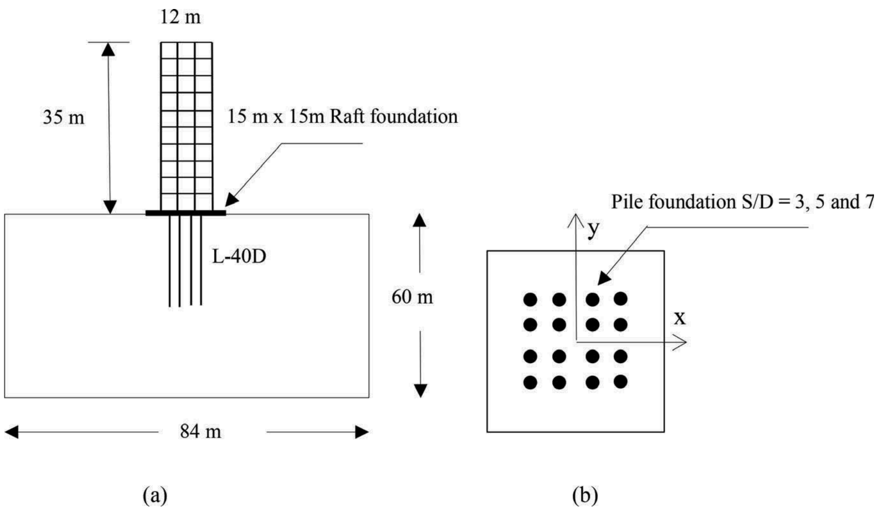


Figure 1. (a) Elevation and (b) Plan view of 4 x 4 Pile foundation arrangement

(4x4) with various relative densities of sand (30%, 50% and 70%) and various pile to pile spacing (3D, 5D and 7D) were used for this study. The diameters of the pile foundations designed as friction type were 550 mm, 500 mm and 450 mm for 30%, 50% and 70% soil relative densities respectively. The soil properties used for the analysis were considered from the research work carried out by Park et al. (2016).

A finite element program PLAXIS3D was used for the analysis of structure considering soil-pile-structure interaction. Mohr-Coulomb constitutive material model was used for modeling of soil. Elastic material model was used for super structure, raft and pile foundation in PLAXIS-3D. Poisson's ratio and interface between soil and pile (R_{inter}) were considered as 0.35 and 0.70 respectively. The boundaries of the soil were considered as seven times, three times and five times the width of the structure in x, y and z axis respectively as suggested by Kramer (1996). It was also indicated by Kumar et al. (2016) that the deformation attributable to vertical loading extended nearly 3 times from the raft boundary laterally and 1.5 times the pile length vertically. The pile, raft and super structure frame members were modelled using embedded beam, plate and beam elements respectively. The base shear obtained from the equivalent static analysis was converted into storey shear using parabolic distribution as per IS1893:2016 and assigned as point loads on the corresponding floors. Medium size meshing was used for modelling to save running time and to avoid convergence problems. The boundary conditions of the model were used as horizontally fixed in x and y directions and fully fixed in z direction respectively. The schematic representation of modelled soil-pile supported structure is shown in Figure 1.

3 RESULTS AND DISCUSSION

The behaviour of pile foundations and super structure under lateral loading was studied for various soil relative densities and spacing of piles. The effects of the considered parameters on the seismic response of the pile foundations and super structure storey lateral displacement and inter-storey drifts were discussed.

3.1 *Behaviour of pile foundation*

The normalized pile displacements (u/D) along lateral direction for varying relative densities and spacing of piles were plotted. The effect of relative densities of soil on the normalized horizontal displacement of pile foundation is shown in Figure 2 (a) for the row 1(R1) piles with the spacing of 3D. Similarly, the effect of spacing of piles on the normalized horizontal

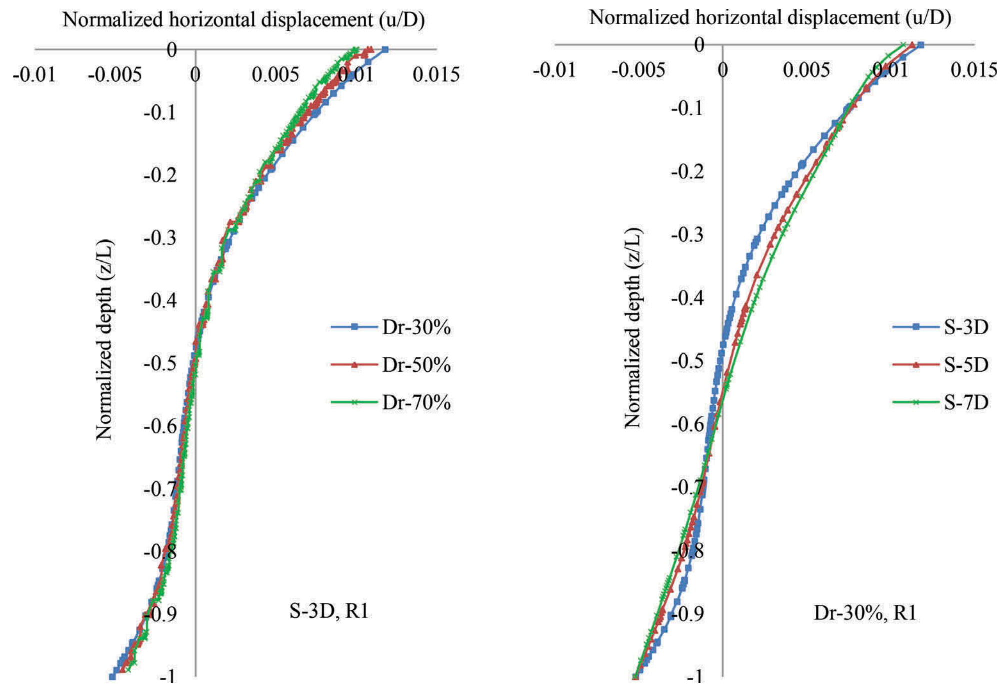


Figure 2. Normalized lateral pile displacement for varying (a) Relative densities and (b) Pile spacing

displacement of pile foundation for the R1 piles with relative density of 30% is shown in Figure 2 (b). It was noted from the plots that, the pile head deflection was observed to be maximum of 6.5 mm for the R1 piles modelled in loose soil deposit with relative density of 30% with spacing of 3D whereas the pile foundations modelled in dense soil with relative density of 70% with the same spacing was found to be 4.5 mm. Similary, the spacing of piles also affects the lateral displacement of pile foundation. It was found that the maximum lateral displacement at pile head was obvserved in pile foundations modelled with the spacing of 3D. The results clearly indicate that the pile lateral displacements are affected by denseness of soil and spacing of the piles. Although pile lateral displacements are observed to be less in magnitude, they affect the structural displacment significanty. The effcets of spacing of piles and soil relative densities on structural response are explained hereafter.

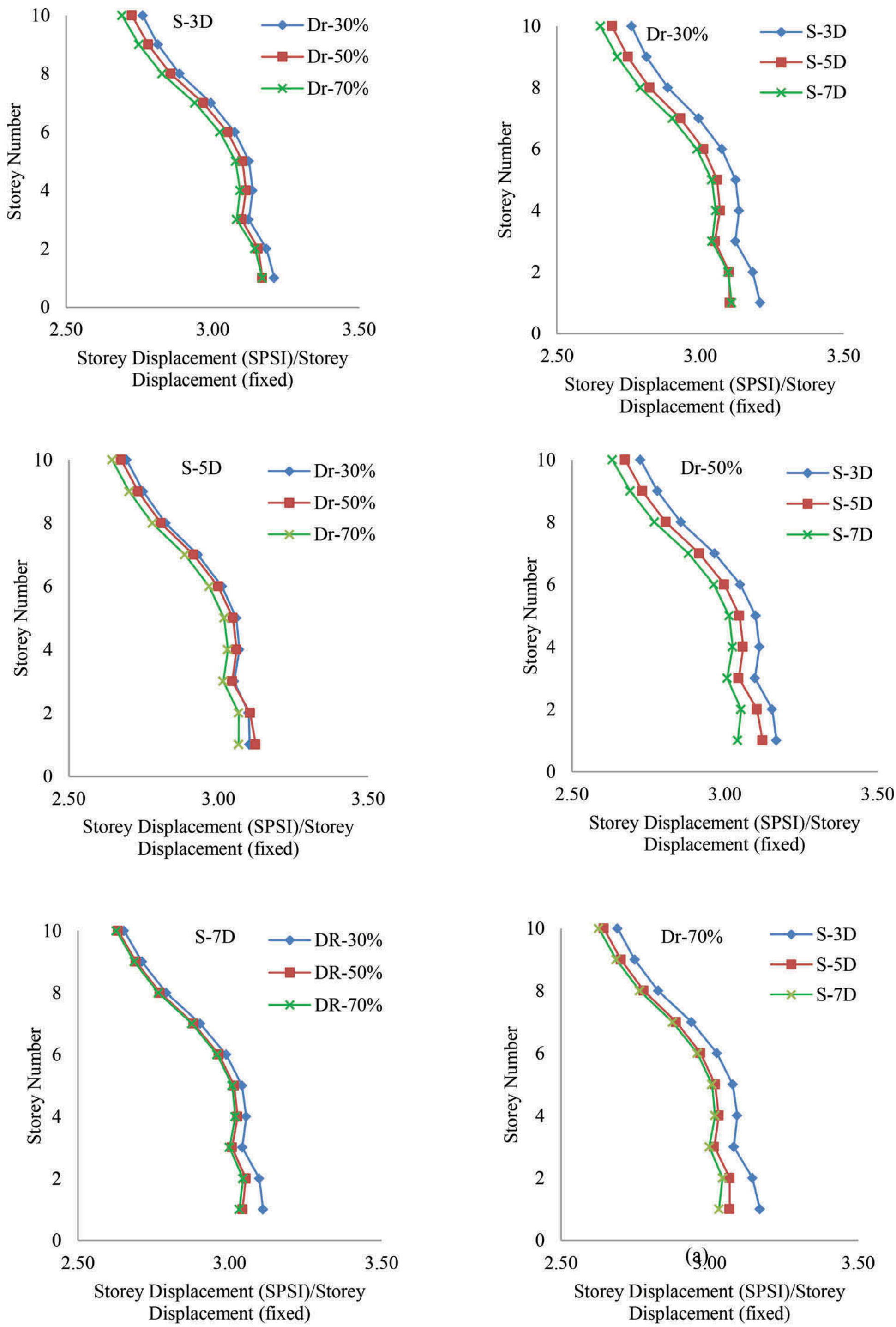
3.2 *Behaviour of super structure*

3.2.1 *Effect of denseness of soil*

Various relative densities of 30%, 50% and 70% were used for the parametric study. Storey lateral displacements were calculated from the seismic analysis by subtracting the foundation displacement in all stories. As expected, storey lateral displacements were amplified for loose soil with the value of 293 mm whereas for fixed base structure 108 mm was observed.

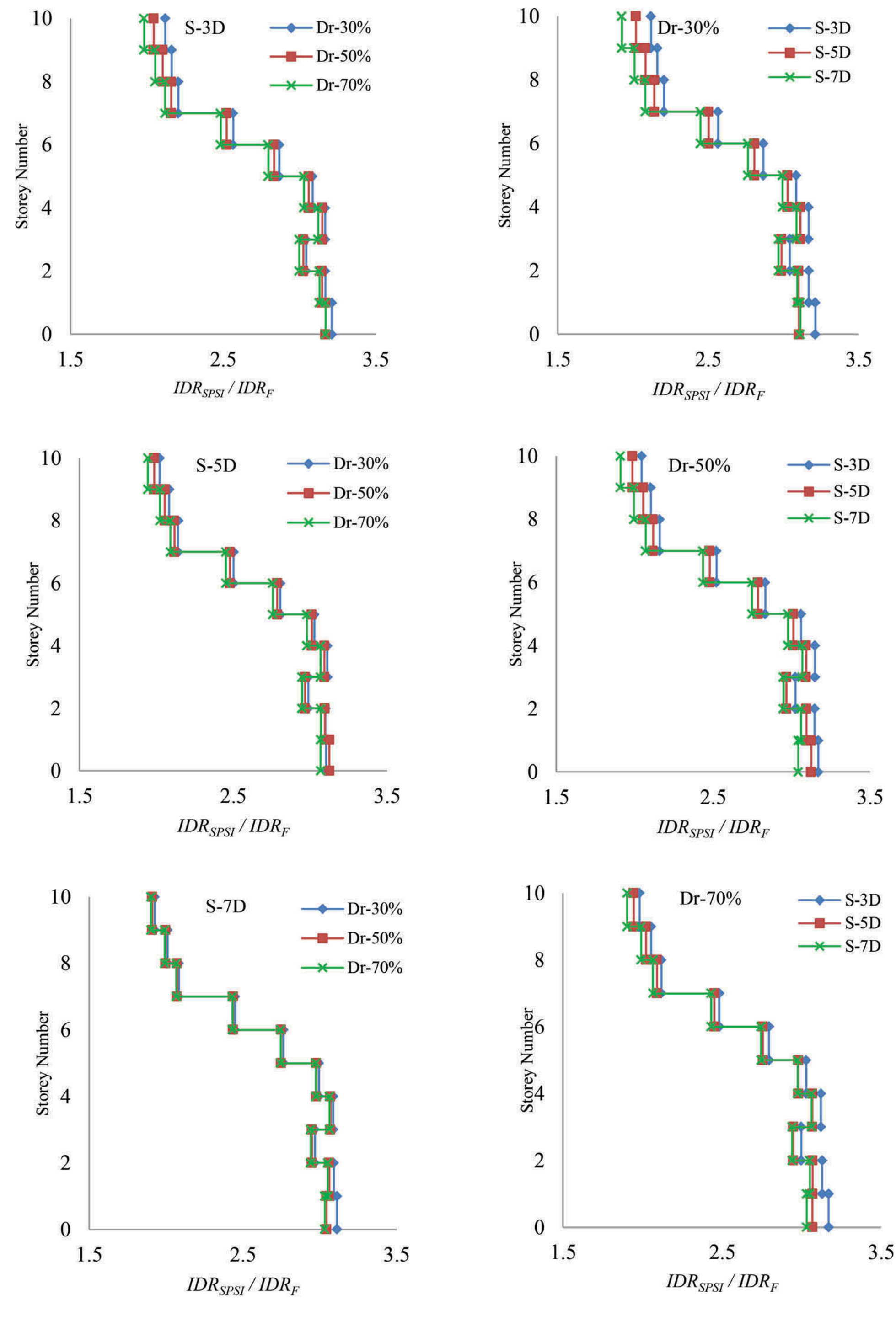
Similarly displacements of pile supported structure in x direction were normalized with displacements of fixed base structure. The results of normalized displacements for various relative densities of soil are shown in Figure 3 (a). It is observed that the normalized displacements are found to be maximum in 30% relative density with the value of 3.21.

The maximum inter-storey drift ratio (IDR) values were also obtained for varying soil relative densities. It was found that the maximum IDR value was observed to be 0.011 for 30% relative density of soil. The SPSI amplifies the IDR values more than the permissible value for which the building was designed. The normalized IDR values (IDR_{SPSI}/IDR_F) are presented in Figure 4 (a). The maximum value of 3.21 is observed for 30% relative density in lower



(a) (b)

Figure 3. Normalized storey displacements for varying (a) Relative densities and (b) Pile spacing



(a) (b)

Figure 4. Normalized inter-storey drifts for varying (a) Relative densities and (b) Pile spacing

stories. The decrease in lateral deflection and drift values is due to lateral resistance offered by the soil thus reducing the lateral movement of pile foundations (Figure 2 (a)). It is clear from the Figure 3 (a) and 4 (a) that the denseness of soil influences the structural performance. As the soil relative density increases, the structural drift and lateral displacement reduces.

3.2.2 *Effect of spacing of pile*

The pile to pile spacing is the predominant factor controlling the behavior of pile groups. Since increase in pile spacing increases the group efficiency of pile foundation, it is pertinent to investigate its influence on seismic response of super structure. Various pile to pile spacing of 3D, 5D and 7D were used for this study. The response of the structure in terms of storey lateral displacement and inter-storey drift of pile supported structures are compared with fixed base structural response. Figure 3 (b) clearly illustrates that the super structure modelled with pile to pile spacing of 3D experiences maximum storey lateral displacement in all types of soils. Pile supported structure with spacing of 3D amplifies storey displacement to the value of 293 mm. The normalized displacement value of 3.21 in lower stories and 2.76 in upper stories are obtained. It is also noted from Figure 3 (a) that the structure designed for 7D spacing provides almost same response in all types of soil.

The maximum inter-storey drift ratios were plotted in Figure 4(b) for varying spacing of piles. The maximum IDR value recorded for the pile supported structure is 0.011 for the pile to pile spacing of 3D. The maximum normalized IDR values (IDR_{SPSI}/IDR_F) observed is 3.21 for 3D spacing and less value is 3.03 for 7D spacing in lower stories. The resistance offered by the soil between the larger spacing piles increases the group efficiency (Figure 2 (b)) is the primary reason for the reduction in movement of pile foundations when it is subjected to lateral loads. This resulted in reduced structural lateral displacement and inter-storey drift values. Therefore, spacing of piles significantly affects the structural performance.

4 CONCLUSIONS

To investigate the effects of soil-pile-structure interaction, denseness of soil and spacing of piles on the response of super structure, a 10 storey moment resisting reinforced concrete building frame was simulated in PLAXIS3D software and equivalent static analysis was performed. The results of normalized storey lateral displacements and inter-storey drifts were evaluated and discussed. The following conclusions are drawn from the parametric study.

- The soil-pile-structure interaction amplifies the structural lateral displacement and thus increases the inter-storey drift values.
- The soil denseness and spacing of piles play an important role in seismic behavior of super structure. By increasing the relative density of soil and spacing of piles, the resistance to lateral movement of pile foundations is increased which results into reduction in storey lateral displacement and inter storey drift values.
- The normalized lateral displacement and IDR results indicate that the pile supported structure lateral displacement and IDR values increased by 3 times the fixed base structure values. Therefore, proper care must be taken while designing the super structure for serviceability requirements.

REFERENCES

Bhattacharya, S., Dash, S.R. &Adhikari, S. 2008.On the mechanics of failure of pile-supported structures in liquefiable deposits during earthquakes. Current Science 94(5): 605-611

Bhattacharya, K., Dutta, S.C. & Roy, R. 2006. Seismic design aids for buildings incorporating soil-flexibility effect. Journal of Asian Architecture and Building Engineering 5(2): 341-348.

Carbonari, S., Dezi, F., Gara, F. & Leoni, G. 2008. Effects of soil-pile-structure interaction on the nonlinear seismic response of coupled wall-frame systems. The 14th World Conference on Earthquake Engineering. Beijing, China.

Carbonari, S., Dezi, F. & Leoni, G. 2011. Linear soil-structure interaction of coupled wall-frame structures on pile foundations. Soil Dynamics and Earthquake Engineering 31: 1296-1309.
Carbonari, S., Dezi, F. & Leoni, G. 2012. Nonlinear seismic behavior of wall-frame dual systems accounting for soil-structure interaction. Earthquake Engineering and Structural Dynamics 41: 1651-1672.
Chore, H.S. & Ingle, R.K. 2008. Interaction analysis of building frame supported on pile group. Indian Geotechnical Journal 38(4): 483-501.
Chore, H.S., Ingle, R.K. & Sawant, V.A. 2009.Building frame-pile foundation-soil interactive analysis. Interaction and Multiscale Mechanics 2(4): 397-411.
Dash, S.R. & Bhattacharya, S. 2012.Mechanism of failure of three pile-supported structures during three different earthquakes. The 15th World Conference of Earthquake Engineering, Lisbon.
Dutta, S.C., Bhattacharya, K. & Roy, R. 2004. Response of low-rise buildings under seismic ground excitation incorporating soil-structure interaction. Soil Dynamics and Earthquake Engineering 24: 893-914.
Dutta, S.C., Roy, R., Das, P.K., Roy, R. & Reddy, G.R. 2007. Seismic safety of structures: Influence of soil-flexibility, asymmetry and ground motion characteristics. Journal of Sound and Vibration 307: 452-480.
Fatahi, B. & Tabatabaiefar, S.H.R. 2014. Effects of soil plasticity on seismic performance of mid-rise building frames resting on soft soils. Advances in Structural Engineering 17(10): 1387-1402.
Gazetas, G., Fan, Ke. & Kaynia, A. 1993. Dynamic response of pile groups with different configurations. Soil Dynamics and Earthquake Engineering 12: 239-257.
Hokmabadi, A.S. & Fatahi, B. 2016. Influence of foundation type on seismic performance of buildings considering soil-structure interaction. International Journal of Structural Stability and Dynamics 16: 1550043-1-29.
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.
IS: 456-2000. Plain and Reinforced Concrete – Code of Practice. Bureau of Indian Standards. New Delhi, India. 2000.
IS: 875 (Part 1)-1987. Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures: Part 1 Dead loads – Unit weights of building materials and stored materials. Bureau of Indian Standards. New Delhi, India. 1989.
IS: 875 (Part 2)-1987. Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures: Part 2 Imposed loads. Bureau of Indian Standards. New Delhi, India. 1989.
IS: 1893 (Part 1)-2016. Criteria for Earthquake Resistant Design of Structures: Part 1 General Provisions and Buildings. Bureau of Indian Standards. New Delhi, India. 2016.
IS: 2911 (Part 1/Sec 4)-2010. Design and Construction of Pile Foundations – Code of Practice: Part 1 Concrete Piles - Section 4 Precast Concrete Piles in Prebored holes. Bureau of Indian Standards. New Delhi, India. 2010.
Kerciku, A.A., Bhattacharya, S., Lubkowski, Z.A. &Burd, H.J. 2008. Failure of Showa bridge during the 1964 Niigata earthquake: Lateral spreading or buckling instability. The 14th World Conference on Earthquake Engineering. Beijing, China.
Kim, Y. & Roesset, J.M. 2004. Effect of nonlinear soil behavior on inelastic seismic response of a structure. International Journal of Geomechanics 4(2): 104-114.
Kramer, S. L. 1996. Geotechnical Earthquake Engineering, Prentice-Hall, New Jersey.
Kumar, A., Choudhary, D. & Katzenbach, R. 2016. Effect of earthquake on combined pile-raft foundation. International Journal of Geomechanics 16(5): 04016013-1-16.
Massumi, A. & Tabatabaiefar, H.R. 2007. Effects of soil-structure interaction on seismic behavior of ductile reinforced concrete frames. World Housing Congress, Terrangganu, Malaysia.
Massumi, A. & Tabatabaiefar, H.R. 2008. A criterion for considering soil-structure interaction effects in seismic design of ductile RC-MRFs according to Iranian codes. The 14th World Conference on Earthquake Engineering. Beijing, China.
Mylonakis, G., Gazetas, G., Nikolaou, S., & Michaelides, O. 2000. The role of soil on the collapse of 18 piers of the Hanshin expressway in the Kobe earthquake. The 12th World Concference on Earthquake Engineering (1074). Auckland, New Zealand.
Mylonakis, G. & Gazetas, G. 2000. Seismic soil-structure interaction: Beneficial or detrimental? Journal of Earthquake Engineering 4(3): 277-301.
Nguyen, Q.V., Fatahi, B. & Hokmabadi, A.S. 2017. Influence of size and load bearing mechanism of piles on seismic performance of buildings considering soil-pile-structure interaction. International Journal of Geomechanics 04017007: 1-22.

Park, D., Park, D. & Lee, J. 2016. Analyzing load response and load sharing behavior of piled rafts installed with driven piles in sands. Computers and Geotechnics 78: 62-71.

Roy, R. & Dutta, S.C. 2010.Inelastic seismic demand of low-rise buildings with soil-flexibility. International Journal of Non-linear Mechanics 45: 419-432.

Tabatabaiefar, H.R. & Fatahi, B. 2014. Idealisation of soil-structure system to determine inelastic seismic response of mid-rise building frames. Soil Dynamics and Earthquake Engineering 66: 339-351.

Tabatabaiefar, H.R., Fatahi, B. & Samali, B. 2010. Seismic behavior of steel moment resisting buildings on soft soil considering soil-structure interaction. The 14th European Conference on Earthquake Engineering, Ohrid, Republic of Macedonia.

Tabatabaiefar, S.H.R., Fatahi, B. & Samali, B. 2013. Seismic behavior of building frames considering dynamic soil-structure interaction. International Journal of Geomechanics 13(4): 409-420.

Tabatabaiefar, H.R. & Massumi, A. 2010. A simplified method to determine seismic response of reinforced concrete moment resisting building frames under influence of soil-structure interaction. Soil Dynamics and Earthquake Engineering 30: 1259-1267.

Tokimatsu, K., Mizuno, H. & Kakurai, M. 1996. Building damage associated with geotechnical problems. Special Issue of Soils and Foundations, Japanese Geotechnical Society: 219-234.

Yingcai, H. 2002. Seismic response of tall buildings considering soil-pile-structure interaction. Earthquake Engineering and Engineering Vibration 1(1): 58-64.