PSUEDO STATIC ANALYSIS OF BUILDING FRAMES RESTING ON GRAVEL CUSHION CONSIDERING SPSI

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Abstract

Super structures are generally assumed to be rigid at the base during analysis and design. Soil-foundation system present beneath the base of the structure influences the seismic behaviour of buildings significantly. In this study, a numerical analysis (Pseudo-static method-Direct approach) using a finite element software Plaxis 3D is performed to determine the effect of Soil-Pile-Structure Interaction (SPSI) on seismic response of a 7-storey RC Moment Resisting Framed Structure. A sandy soil layer with relative density of 50% and a pile spacing of 5D is chosen for the study. Two nearfield (1979 Imperial, 1994 Northridge) and farfield (1995 Kobe, 1999 Chi-Chi) ground motions are applied to the models using Pseudo Static Method observing the storey displacement, inter-storey drift, pile bending moment, raft and pile settlement. A gravel cushion layer is provided as a countermeasure beneath the raft foundation for varying thickness. The behaviour of structure with and without cushion layer is compared with that of structure with rock base. The results showed that Soil Pile Structure Interaction has a great influence over the structure's response and the provision of cushion layer significantly lowered the pile bending moment, settlement and storey displacement with increase of cushion layer thickness.

Keywords: Soil Pile Structure Interaction; Plaxis 3D; Pseudo-static; seismic response.

1. Introduction

Bearing capacity of loose sandy soil such as in coastal areas is very low compared to denser soils. Hence pile foundation is preferred to withstand huge structures like dams, reservoirs, power plants, high rise structures, etc. Piles are capable of withstanding lateral loads arising from earthquakes, wave current, etc. Improper design of pile foundation system may lead to the failure of piles and thereby directly affecting the structure's response during a seismic event. Seismic events like Bhuj earthquake of 2001 and Kobe earthquake of 1997 emphasized the importance of proper design of pile foundation system considering Soil-Structure Interaction (SSI) effects.

The importance of SSI effects during a seismic event was accentuated by many researchers in the recent decades (George Mylonakis and George Gazetas 2000 [1], J.P Stewart et al. 1999 [2], Enrique Luco 1986 [3], Khalil et al 2007 [4], Ayedemir and Ekiz 2013 [5], Chen 2019 [6]). An experimental work on the SSI effect of a two-storey shear building was carried out by Chang and Kim 2019 [7], through which an effective method for a Pseudo-Dynamic Test was proposed that can simulate SSI in a shake table. Zhuang Haiyang et al 2019 [8], developed a new shake table test method to determine the effect of SSI on base isolated structures subjected to dynamic load and concluded that the efficiency of isolation layer decreases with increase in the PGA of input ground motion due to SSI. A direct approach method of numerical study was put through by Nguyen et al 2016 [9] to study the influence of SSI on the seismic response of MRF building with shallow foundation system. They observed that the reduction in size of foundation lengthened the natural period the structure thereby significantly reducing the base shear. Yong-Seok Kim et al.,[10] studied the non-linear effect of SSI of soft sand soil on the response of structure's foundation (Mat and Pile foundation). They conducted FEM analysis over 4 structures of varying height and foundation type. They illustrated the importance of nonlinear behaviour of soil on structure's response. In spite of these extensive studies, not many studies focus on Soil-Pile Structure Interaction (SPSI) effects during a seismic event. Some of the recent studies on SPSI effect on dynamic loading include Sharma et al 2018 [11], Chore and Ingle 2008 [12], Bozorgnia and Bertero 2004 [13].

Despite the fact that structural failure of pile group system can be avoided by proper design, the connection between the pile group and raft plays a vital role in carrying a horizontal dynamic load. This structural connection will attract large lateral force from the earthquake which leads to the mobilisation of the adhesive force in the interface of soil and raft (Wong et al 2000) [14] affecting the super structure's response. The bearing capacity of soil in the zone of pile raft connection is increased by placing a cushion layer made of flexible materials like gravel, soil and cement, etc, which thereby mobilises the forces acing over the pile-raft interface. Baziar et al. 2018[15], conducted centrifuge testing of Non connected Piled Raft System under dynamic loading. A cushion layer consisting of crushed sand was used between the raft and pile system to resist the lateral movement of raft and superstructure during dynamic loading. They proposed a foundation system that reduces the load transfer to pile thereby reducing the bending moment. However, very few studies are done on cushion layer in connected piled raft system. Ghalesari and Rasouli 2014 [16] performed a finite element analysis and centrifuge tests on the behaviour of piled raft system with a gravel layer to static loading. They concluded that the maximum and differential settlement of the piled raft foundation system is widely affected by the gravel layer thickness and the grain size.

A seismic analysis in which dynamic loading of the input earthquake shaking is represented by a static incremental lateral load (equal to the total weight of the building multiplied by the PGA of input ground motion) is called as Pseudo-Static Analysis. However, pseudo-static approach method neglects the effect of time period and frequency of the earthquake motion, oscillatory nature and phase difference in wave form. Woodward et al. 1996 [17] assessed the dynamic behaviour of retaining wall subjected to seismic loading by performing pseudo static and dynamic analysis. They found that the pseudo static method had good agreement with non-linear dynamic approach in terms of lateral earth pressure and displacement. Liyanapathirana and Poulos 2005 [18] analysed the effect of soil-pile-structure interaction on seismic response of piles using pseudo static approach. They suggested that pseudo static method can be used determine the pile bending moment and displacement in liquefiable soil. Basha and Babu 2010 [19], designed a bridge abutment subjected to earthquake load using pseudo-static method. Kumar et al 2016 [20] performed static, pseudo static and dynamic analysis on combined piled raft foundation using finite element software Plaxis 3D.

In this paper, Pseudo-Static analysis method is adopted to determine the seismic response of building frame resting on a gravel cushion layer considering the effects of soil-pile-structure interaction using Plaxis 3D. The response in terms of storey displacement, inter storey drift, pile displacement, bending moment and settlement is determined for the models with gravel cushion layer of thicknesses 0.5 m, 1 m, 1.5 m and the optimum thickness for cushion layer is determined.

2. Numerical Modelling

2.1 Validation

The centrifuge tests on piled raft foundation performed by Horikoshi et al 2003 [21] and numerical tests performed by Kumar et al [20], is used to validate the FE model in Plaxis 3D for its preciseness. A piled raft foundation of raft dimensions 80 x 80 mm (4 x 4m prototype scale) with 25mm thickness made of aluminium and piles of length 170 mm and 10mm diameter made of aluminium were modelled by Horikoshi et al. The performance of the piled raft foundation in dry Toyoura sand with relative density of 60% was assessed by applying static vertical load of 4.69kg. In Plaxis 3D, the piled raft foundation was modelled in the prototype scale (4m width and 1m thick raft, a 2 x 2 pile group of 9m length and 0.5 m diameter with pile spacing of 2m) for validation. The soil was modelled using Mohr-Coulomb soil with parameters as given in table 1. Kumar et al performed a pseudo static analysis using Plaxis 3D for the centrifuge test performed by Horikoshi et al.

Fig. 1 shows the displacement profile of the Toyoura sand under static vertical loading. The maximum vertical settlement of soil was measured as 15.4 mm which is in good agreement with the experimental result of 15 mm as per Horikoshi et al and Kumar et al numerical result of 21.2 mm. Fig. 2 shows the bending moment and lateral deflection of piles under pseudo static loading for 4 ground motions (El-Centro, Loma Prieta, Bhujm Sikkim), which is in good agreement with the numerical results of Kumar et al.

Table 1 - Input Properties in Plaxis 3D

Parameters	Soil	Raft	Pile
Elastic Modulus (GPa)	0.04	41.7	70
Poisson’s ratio	0.3	0.2	0.35
Cohesion (kPa)	10	-	-
Unit Weight (kN/m^3)	16.3	24	27
Friction angle	31	-	-
Dilatancy angle	1	-	-

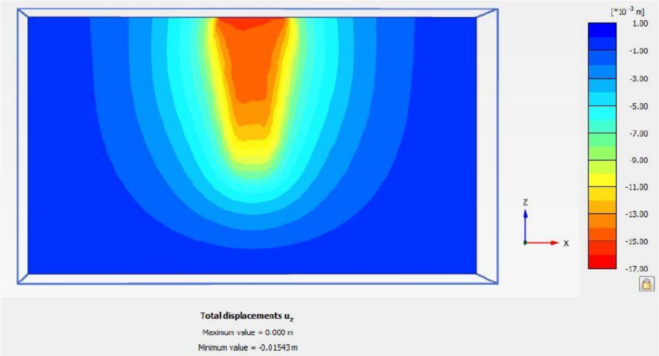


Fig. 1 – Soil Displacement contour

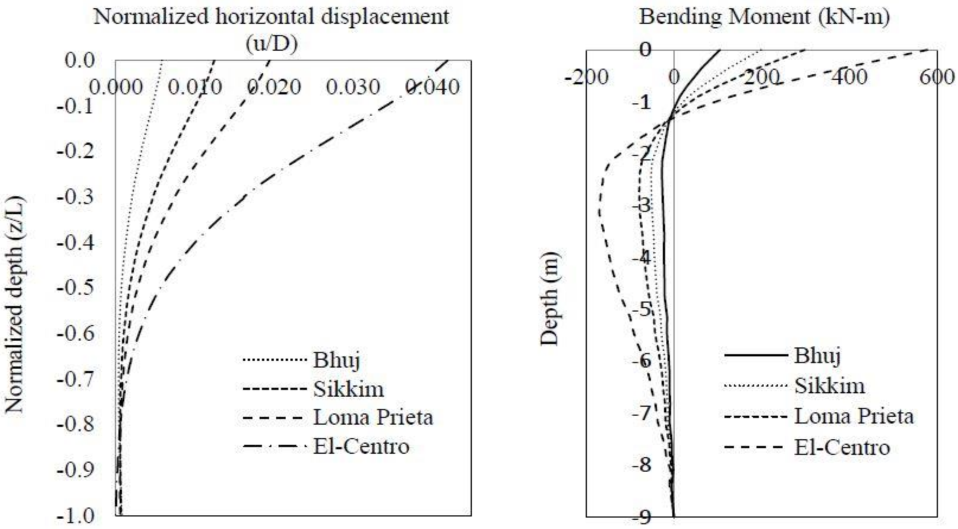


Fig. 2 – Lateral deflection and bending moment profile of pile

2.2 Parametric Study

A 7 storey RC moment resisting framed structure of 2 bays in both x and y directions with a bay length of 4m each and storey height of 4m is modelled. A uniform column and beam size of 450 x 450 mm and 230 x 400 mm respectively is adopted for the structure with a slab thickness of 125 mm. As per IS 456 [22], concrete grade of M30 and steel grade of Fe415 is provided for the structural members of the building. A total dead load of 16.56 KN/m is given to each beam and a live load of 3KN/m^2 is provided to the slabs. Response spectrum and equivalent static analysis is carried out on the 5 storey RC moment resisting frame with fixed base and designed using SAP 2000 v20 software as per IS 1893 Part 1 [23]. Table 2 shows the seismic parameters adopted in SAP 2000.

Table 2 - Seismic Parameters as per IS 1893 Part 1 [23]

Seismic Zone	V
Zone Factor	0..36
Importance factor	1.5
Response reduction factor	5
Time Period	0.509 s

For a base shear of 1800 KN and total vertical load of 67399.256 KN, a 12 x 12 m raft foundation of 0.7m thickness is designed using conventional design procedures as per IS 2950 part 1 [24] and IS 456 [22]. M30 grade concrete and Fe500 grade steel is provided for the raft foundation system with young’s modulus E of 27.38 GPa and Poisson’s ratio of 0.3. The net ultimate bearing capacity of the raft foundation is calculated to be 239.6 KN/m^2 using the procedure suggested by Rollins et al 2005 [25]. A 3 x 3 pile group is designed with pile diameter of 0.48m and length of 20 m. Ultimate load carrying capacity of 9 piles is found to be 23065 KN.

2.2.1 Finite Element Modelling

The designed soil-foundation-structure system is the modelled in a three-dimensional finite element program Plaxis 3D V20 [26]. It is specially designed to perform a wide range of geotechnical applications like nonlinear dynamic analysis, flow and stability analysis. Wobbes et al. 2017 [27], Bhatnagar et al. 2015 [28], Ashutosh et al 2016 [20], Mercado et al. 2018 [29] and Monslave et al. 2017 [30], are some of the researchers who performed seismic analysis using Plaxis 3D software.

Mohr-Coulomb model which is a linear elastic and perfectly plastic model is used to model the Toyoura sand layer. The Mohr-Coulomb model is a combination of Hooke’s law of elasticity and Mohr-Coulomb failure criterion theory. 3-node beam element is used to model the beams and columns in the building, while 6-node plate element is used to model the slabs and raft foundation. They are modelled with elasto-plastic behavior. An embedded beam element is used to model the piles of diameter 0.5m and spacing of 5D. The input material parameters for the structural elements is given in Table 3. A damping of 5% is provided to the building using Rayleigh coefficients. 12-node interface elements are created in the vertical boundaries of x direction to simulate free-field boundary condition which absorbs the reflected secondary waves. A compliant base boundary condition is provided along Z_{min} boundary to have minimum reflection at the bottom boundary. Fig. 3 shows the diagrammatic representation of the model.

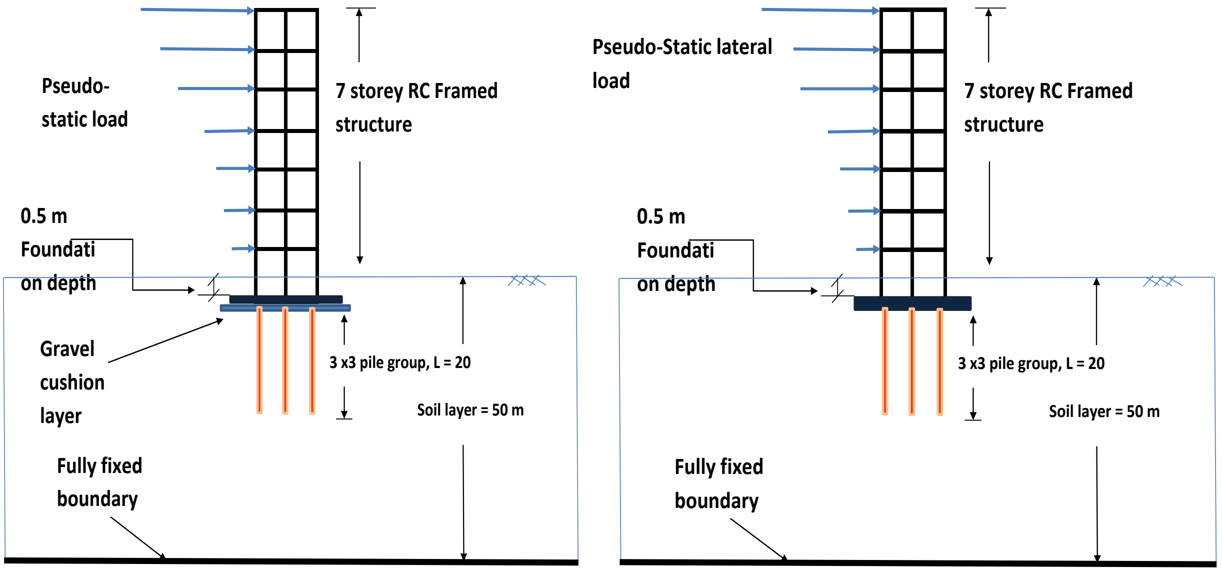


Fig 3 – Diagrammatic representation of the model with and without cushion layer subjected to pseudo-static load

Table 3 – Input Parameters in Plaxis 3D

Parameter	Raft	Pile	Beam, Column, Slab	Soil	Rock	Gravel Cushion
Unit Weight (kN/m$^{3)}$	25	25	25	16.7	27	20
Elastic Modulus (GPa)	28	28	28	0.03	40	0.08
Poisson’s ratio	0.3	0.3	0.3	0.3	0.3	0.3
Cohesion (kPa)	-	-	-	0	0	0
Angle of friction	-	-	-	35	40	35

2.2.2 Pseudo-Static Loading

Four input ground motions – two nearfield (1979 Imperial valley, 1994 Northridge) and two farfield (1995 Kobe, 1999 Chi-Chi) motions are assigned by pseudo static method. Table 4 shows the Peak Ground Acceleration (PGA) and the lateral static load applied for each earthquake data.

Table 4 – Input Ground Motion properties

Ground motion	PGA in g	Lateral load in kN
Imperial Valley	0.28	2863
Northridge	0.47	4805
Kobe	0.16	1636
Chi-Chi	0.22	2249

3. Results and Discussion

3.1 Storey displacement

Fig. 4 shows the storey displacement of the building with rock base, without and with cushion layer. A maximum lateral displacement of 0.66 m, 0.42 m, 0.63 m, 1.42 m for Imperial, Chi-Chi, Kobe and Northridge ground motions respectively are recorded for the model without any cushion layer. This shows a 55%, 47%, 13%, 69% increase in displacement for Imperial, Chi-Chi, Kobe and Northridge ground motions respectively when compared to the building with rock base model. Provision of cushion layer reduced the lateral displacement with increase in the cushion thickness but not to a great extent. A maximum reduction of 12% is achieved for Imperial ground motion.

3.2 Pile Lateral Displacement and Settlement

Fig. 5 shows the pile lateral displacement of the building with rock base, without and with cushion layer. The Northridge ground motion resulted in a maximum lateral pile displacement of 34 mm, while Imperial, Chi-Chi and Kobe resulted in a displacement of 12.6mm, 5.3mm, 8.4mm in the direction of the input ground motion without any cushion layer. Gravel cushion provided reduced the lateral displacement to a great extent upto 105% for Northridge earthquake. The increase in cushion thickness 1m, 1.5m, 2m showed a steady decrease in pile displacement. A maximum pile settlement of 7.35 is recorded for Imperial ground motion without cushion layer. Upto 32% reduction in pile settlement is observed with the provision of gravel cushion. Table 5 shows the pile settlement for various ground motions.

Table 5 – Pile Settlement for various cushion thickness and ground motions

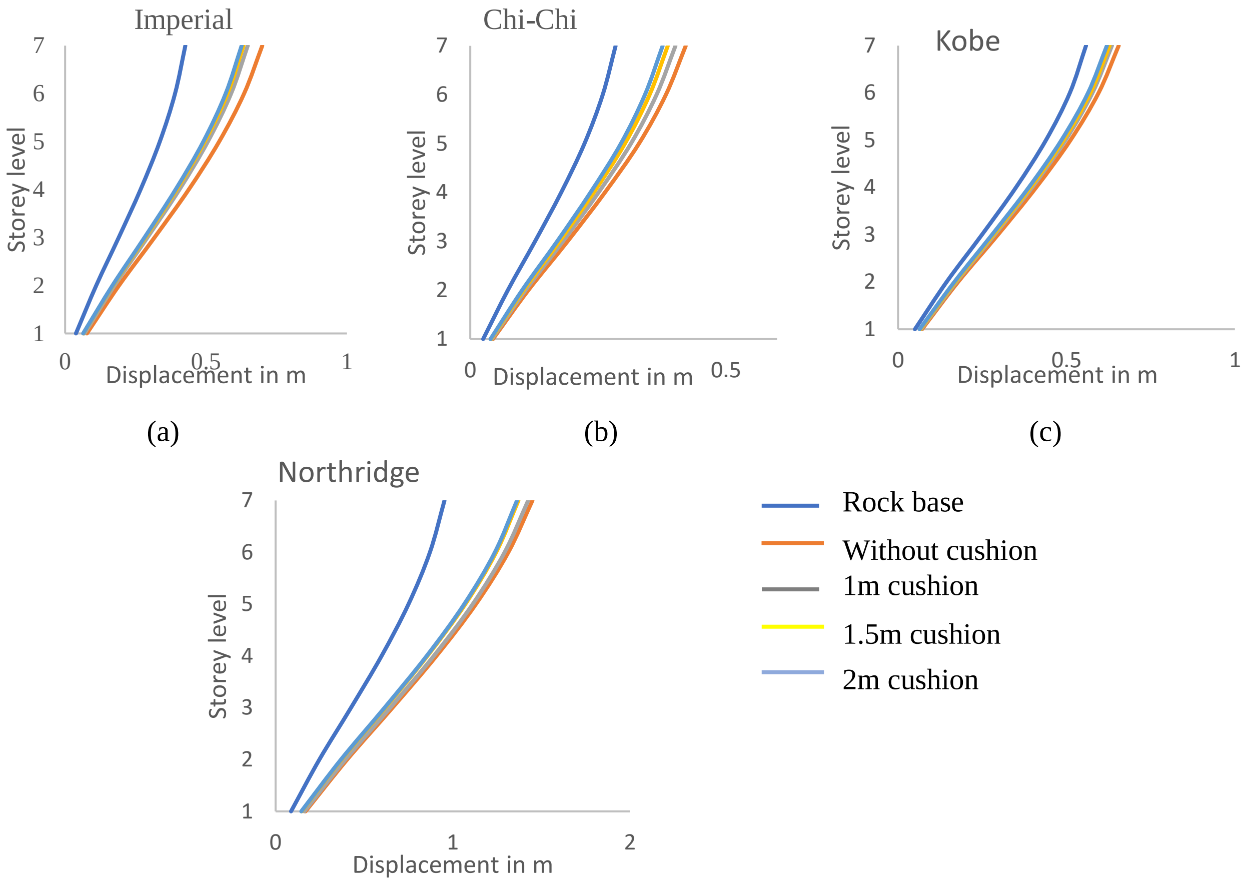
Ground motion	Pile Settlement (mm)			
	Without cushion	1 m cushion	1.5 cushion	2 m cushion
Imperial Valley	7.35	7.05	6.7	5.6
Northridge	6.42	5.9	4.75	3.61
Kobe	8.76	8.58	7.46	7.11
Chi-Chi	13.4	12.8	11.7	10.2

3.3 Pile Bending Moment

Fig. 6 shows the bending moment diagram of pile for various ground motions applied. A maximum of 149 kNm is observed for model without cushion during the Northridge earthquake. The results show that gravel cushion layer resulted in the reduction of bending moment upto 100% (Kobe) at the top of pile. A gradual decrease in the bending moment with increase in cushion layer thickness is observed. For 2m cushion thickness the bending moment has reduced from 80 kNm to 40 kNm for Kobe ground motion.

3.4 Raft Settlement

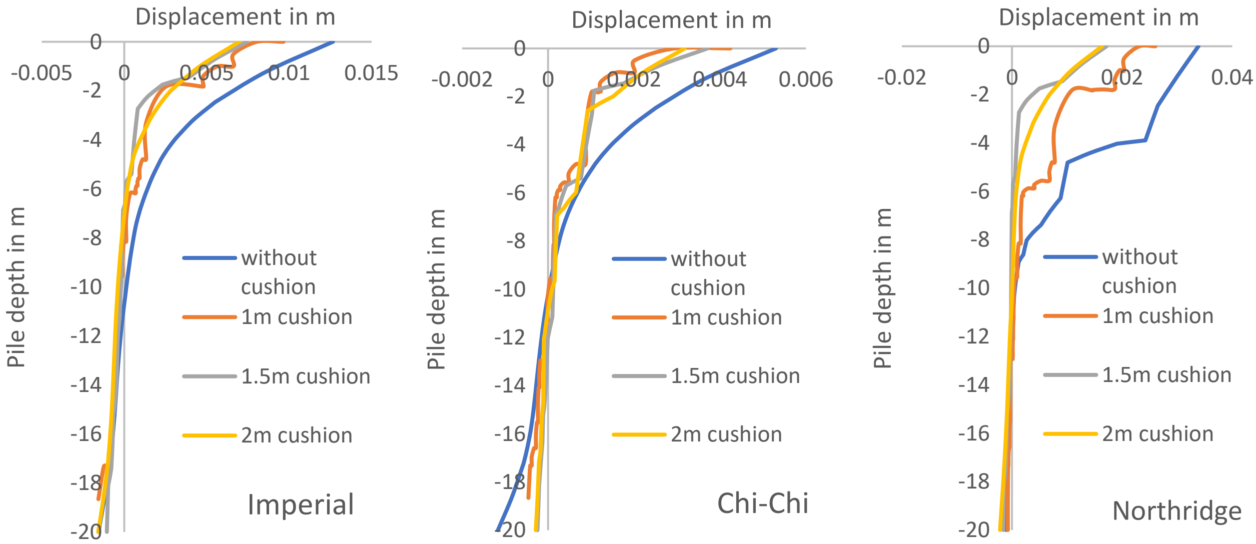
A raft settlement of 23.7mm, 33.7mm, 29.06mm, 58.27mm is obtained for Chi-Chi, Imperial, Kobe and Northridge ground motions respectively for models without any cushion layers. Cushion layer reduced the raft settlement upto 27% due to the increase in the stiffness of soil layer below the raft foundation.



(a) (b) (c)

(d)

Fig. 4 (a), (b), (c), (d) – Storey Displacement for various ground motions



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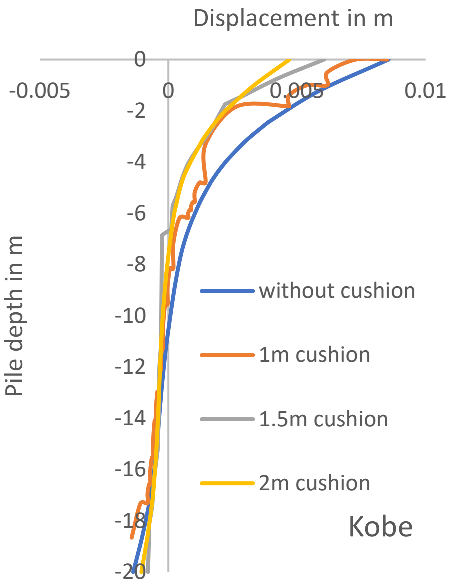


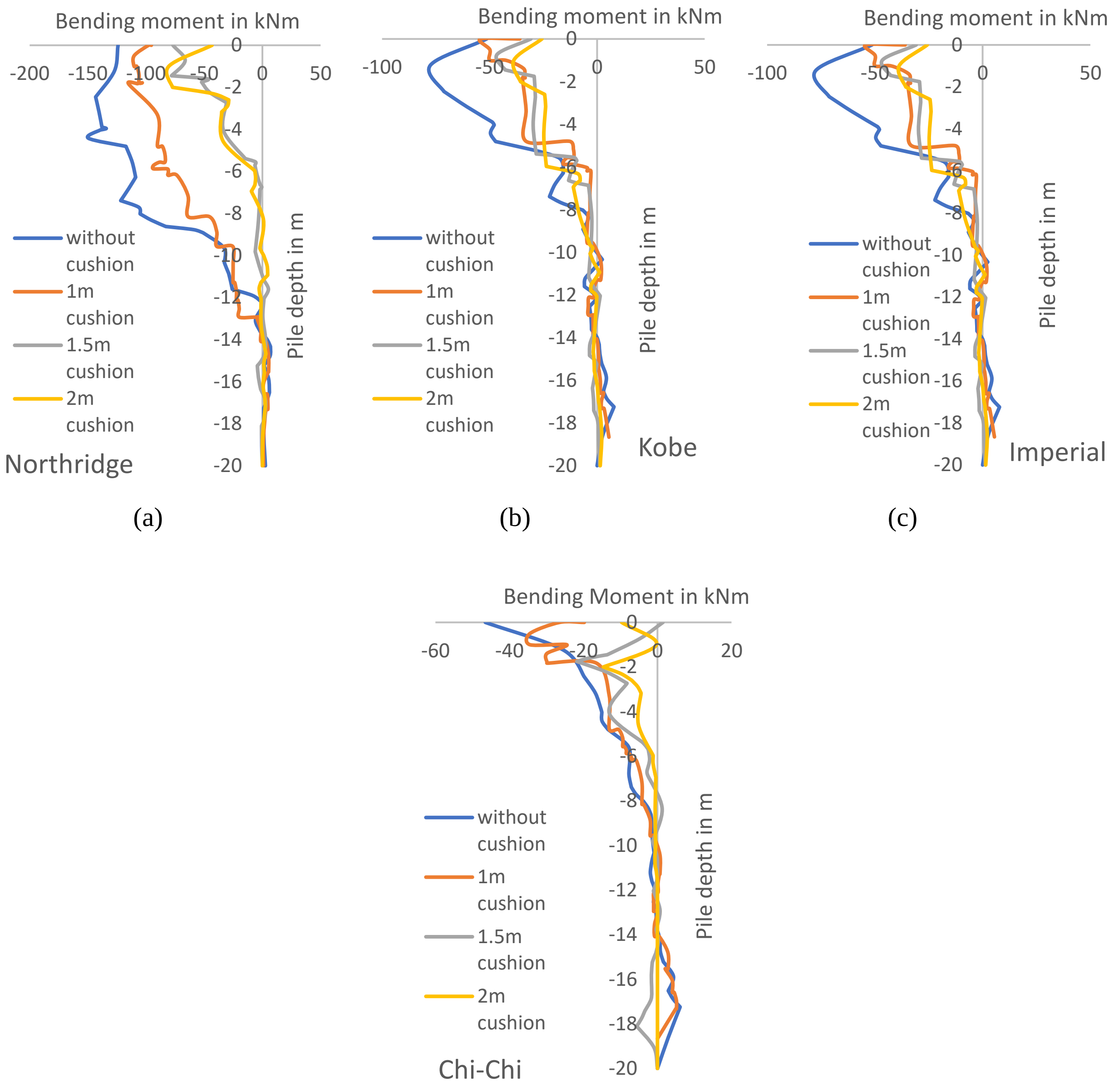
(d)

Fig. 5 (a), (b), (c), (d) – Pile Lateral Displacement for various ground motions

4. Conclusion

The current study suggests a numerical procedure to evaluate the seismic response of structure with piled raft foundation embedded in a soil stratum with a gravel cushion layer. The importance of soil structure interaction is clearly depicted from the following conclusions:

- The lateral storey displacement increased upto 69% with the inclusion of Soil Structure Pile Interaction (SSPI) effects when compared to rock base model.
- The farfield ground motions with PGA of 0.16 g and 0.22 g is found to have greater effect on the building with larger storey displacement upto 1.4m.
- Gravel cushion layer below the raft increased the soil stiffness and its bearing capacity in that region and hence resulted in the reduction of pile and raft settlement.
- Bending moment of piles showed a maximum value in the top portion of the pile without cushion layer due to the adhesive force developed from the applied lateral load.
- Application of cushion layer resulted in the reduction of bending moment in the top portion of pile by mobilizing the forces around the pile-raft interface region.
- The bending moment is reduced upto 100% for the center pile thereby reducing the horizontal displacement of pile upto 105% when compared to model without cushion layer.
- Increase in thickness of the cushion layer further increased the bearing capacity of soil and thereby reduced the pile displacement and bending moment.
- However, the presence of cushion layer below the raft didn’t greatly influence the superstructure’s response. Only a minimal amount of 12% reduction in storey displacement is observed with the inclusion of cushion layer.



(a) (b) (c)

(d)

Fig. 6 (a), (b), (c), (d) – Pile Bending moment diagram for various ground motions

5. References

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