Load Sharing Mechanism of Combined Pile-Raft Foundation (CPRF) under Seismic Loads

Ashutosh Kumar[1] and Deepankar Choudhury[2*]
[1]*PhD Research Scholar, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai-400076, India.*
[2*]*Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai-400076, India, Also Adjunct Professor, Academy of Scientific and Innovative Research (AcSIR), New Delhi, India.*
E-mail: ashusingh@iitb.ac.in, dc@civil.iitb.ac.in

ABSTRACT: In the present work, the load sharing mechanism under seismic loads for fully hinged (H) and fully rigid (R) connected Combined Pile-Raft Foundation (CPRF) have been studied by using three-dimensional finite element based geotechnical software. The importance of connection condition has been investigated in detail. After successful validation of experimental results of the proposed numerical model of CPRF, the same model has been analyzed under different earthquake loading conditions. Results of the present analyses show that connection rigidity had little influence on vertical settlement of CPRF but had pronounced response on the load sharing by foundation components. In the purview of seismic loading, lateral stiffness played a pivotal role in deciding the load-settlement, lateral displacement, bending moment in piles and inclination response of CPRF. The load sharing by foundation components is governed by mobilization of lateral displacement. Initially, raft shares higher proportion of seismic loads but reaches to limiting value at relatively smaller displacement thereafter piles bear the remaining load. CPRF-H reached the limiting value of inclination at 4% of normalized lateral displacement which is unlike the case for CPRF-R. The findings of the present study provide insight into the behavior of CPRF subjected to seismic loads and can be used for the seismic design of CPRF.

KEYWORDS: Pile-raft, Pseudo-static, Seismic, Settlement, Load sharing, Lateral displacement

1. INTRODUCTION

Recently, Combined pile-raft foundation (CPRF) has gained popularity and recognized as one of the efficient foundation alternatives in comparison to the unpiled raft and conventional group pile foundation for high-rise buildings. This has happened because of the utilization of the capacity of both components of CPRF i.e. pile and raft considering performance-based design approach resulted into controlling total and differential settlements by introducing few piles below raft foundation and by utilizing the capacity of the raft in conventional pile group foundation. The application of CPRF system having 64 piles beneath 256m high Messuturm Tower of Germany has proved its use as an economical foundation system with saving of approximately USD 5.9 million, over conventional group pile foundation (316 piles) (Katzenbach et al. 2005 and 2016). The concept of CPRF has been successfully applied in many Asian countries for several high rise buildings and observations were reported by Kakurai (2003), Yamashita et al. (2011), Yamashita et al. (2012) and Kumar et al. (2017). The performance of high-rise buildings founded on CPRF system was also assessed under various devastating earthquakes. The satisfactory performance of 22m tall custom Tower in 2001 Bhuj earthquake (M_w= 7.8) has proved the advantage of using raft foundation with piles that helped in controlling the risk of sudden catastrophic collapse of the entire building (Dash et al. 2009). The overwhelming response to 12 stories base-isolated building in Tokyo founded on CPRF in 2011 Tohoku earthquake (M_w= 9.0) boosted the confidence of geotechnical practitioners for the use of such foundation in seismically active areas (Yamashita et al. 2012). Architectural Institute of Japan (AIJ, 2001) published design code for CPRF and the guideline for the design and construction of CPRFs for different subsoil conditions when subjected to vertical load has been published by International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), which was edited by Katzenbach and Choudhury (2013).

However, the design framework for the CPRF subjected to combined vertical and seismic loads is not well established till date. In current practice, geotechnical practitioners still use conventional pile foundation under such loading considerations which ignore the load sharing by pile cap/raft even if they rest on competent soil strata which results into installation of more piles than actually required. The optimization in the design can be achieved by controlling displacement and load distribution response to an acceptable level rather than suppressed to a lower level than that a structure can withstand. Considering the recent trend towards performance-based design, the behaviour of CPRF subjected to additional seismic loadings in terms of horizontal load and moment should be rationally explained. Several researchers have investigated the response of CPRF by varying connection condition of piles with the raft. Horikoshi et al. (2003a) studied the behaviour of connection conditions between pile and raft component of piled raft foundation under static loading by using geotechnical centrifuge test. Horikoshi et al. (2003b) did a comparative study between the response of group piles and piled raft by using geotechnical centrifuge shaking table test. Matsumoto et al. (2004a) investigated the response of hinged and rigid connected CPRF subjected to combined loading i.e. vertical, lateral and moment load by using 1g experimental test under static loading condition. Matsumoto et al. (2004b) explained the influence of superstructure on the response of rigid connected CPRF using 1g shaking table tests for seismic loading condition. Sawada and Takemura (2014) performed centrifuge study to investigate the response of unpiled raft, pile group and CPRF foundation subjected to lateral and moment loads. Unsever et al. (2015) did experimental and numerical analyses to investigate the response of CPRF subjected to a static horizontal load. Kumar et al. (2015), Chatterjee et al. (2015a), Kumar and Choudhury (2016) and Kumar et al. (2016) investigated the pseudo-static and seismic behaviour of rigidly connected piles by using various numerical modelling techniques. However, these studies did not clearly explain the mechanism behind the effect of mobilization of lateral displacement on load sharing and inclination of CPRF under vertical and seismic loadings scenario for different connection rigidity.

In the present work, an attempt has been made to present the complex nature of CPRF in a simplified way to broaden the understanding of the mechanism behind load sharing under seismic loading conditions by using finite element geotechnical software PLAXIS3D (version-5.10, 2011). The present study focuses on investigating the importance of connection rigidity on the response of CPRF which may help the geotechnical practitioners in establishing the guideline for the design and practice of this rational foundation system under both static and seismic loading conditions. The experimental results reported by Matsumoto et al. (2010) have been used for the validation of the present developed numerical model.

2. NUMERICAL SIMULATIONS AND VALIDATIONS

Matsumoto et al. (2010) performed a group of experimental tests and analytical studies to investigate the influence of connection condition on a model raft, piled raft and pile group foundations under static vertical and horizontal loading conditions at normal gravity (1g) level. Authors had applied vertical loads by placing steel plates on the top of the raft foundation and horizontal loads with the help of actuator as illustrated in Figure 1. The experiments performed by Matsumoto et al. (2010) on piled raft foundation are simulated in the present study by using PLAXIS3D finite element based geotechnical software. Numerical simulations are carried out for two extreme cases of connection conditions of piles with raft i.e. fully rigid and fully hinged, due to the limitation of PLAXIS3D in modelling intermediate connection conditions. The fully rigid and fully hinged connections of Combined Pile-Raft Foundation (CPRF) are named here as CPRF-R and CPRF-H, respectively. It is to be noted that in the case of CPRF, raft base is in direct contact with the soil surface and exerts pressure on the soil below the raft. Hence the raft in CPRF is different than the pile cap used in conventional pile group foundation, where contact of pile cap base to exert pressure on soil is not considered in the design.

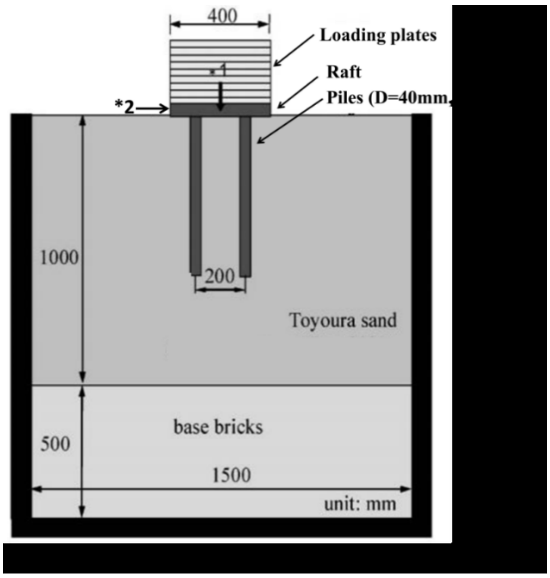


Figure 1 Sectional view of the experimental setup used by Matsumoto et al. (2010) which has been used for validation of present study (Modified after Matsumoto et al. 2010)

2.1 Numerical modelling methodology

Matsumoto et al. (2010) performed consolidated drained triaxial test on Toyoura sand and observed dependency of shear modulus on confining pressure as per Eq.(1):

$$G = G_{ref}\left(\frac{p_o}{p_{ref}}\right)^{0.5} \tag{1}$$

where, p_{ref} is a reference value of confining pressure (100 kPa), P_o is confining pressure and G_{ref} is the value of G at $p_0 = p_{ref}$. Similarly, Young's modulus will show similar variation with confining pressure as depicted by Eq. (2):

$$E = E_{ref}\left(\frac{p_o}{p_{ref}}\right)^{0.5} \tag{2}$$

The accurate prediction of soils strength and deformation parameters ensures the correct response of the foundation system in the numerical technique. Hardening soil model available in the standard library of PLAXIS3D is chosen in the present study to simulate the response of Toyoura sand given by Eqs. (1) and (2). This is based on the hyperbolic relation between axial strain and deviatoric stress. It incorporates stress dependency of soil stiffness which can be expressed as per Eq. (3):

$$E_{50} = E_{50}^{ref}\left(\frac{c\cos\phi - \sigma_3 \sin\phi}{c\cos\phi + p^{ref}\sin\phi}\right)^m \tag{3}$$

where, E_{50}^{ref} is reference stiffness modulus corresponding to reference confining pressure p^{ref}. The actual stiffness depends on the minor principal stress σ_3 which is confining pressure in triaxial test and m is stress dependency factor. Janbu (1963) reported the value of m as 0.5 for silts and sand. In the present study, the stress level dependency factor is adopted as 0.5. The shear strength parameters such as Cohesion c and friction angle ϕ of soil are used as per Mohr-Coulomb failure criteria in the hardening soil model. Equations (1), (2) and (3) represent similar stiffness dependency with confining pressure hence, hardening soil model is the best suited for the present study. Soil model is divided into two layers, top 1m of Toyoura sand is modelled by using hardening soil model and remaining 1m brick base is modelled by using linearly elastic model. Thereafter, boundary conditions are assigned such that sides can move in the vertical direction but restricted to move laterally. The base of the soil model is restrained in all directions i.e. fixed base condition is maintained. A mesh optimization study is carried out to decide on the extents of the model boundaries, all of which help in reducing the computational effort and boundary effect.

The soil model having dimensions of 3m x 3m x 2m is developed by using 10-noded tetrahedral soil elements which is laterally two times bigger than the model dimensions considered by Matsumoto et al. (2010). The selection of the lateral boundary is based on the convergence of the numerical results, to eliminate boundary effects, simulations of the experimental load tests. A square raft of size 400mm x 400 mm and thickness 40mm is modelled using plate element. Four hollow piles with each of diameter 40mm, thickness 2mm, and length 600mm are modelled using embedded pile element. The pile spacing (s) to pile diameter (D) ratio, s/D is kept as 5. Figure 2 illustrates the developed numerical model of soil, pile and raft with the boundary.

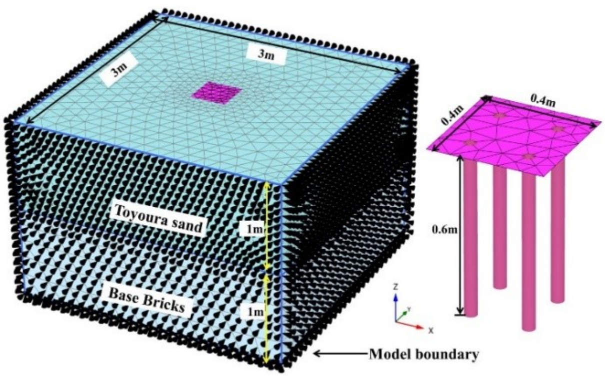


Figure 2 Three-dimensional view of chosen CPRF and soil model in PLAXIS3D

Connection condition between pile and raft has been established as fully rigid and fully hinged, available as an inbuilt program in PLAXIS3D. Analyses have been carried out for both connection conditions separately. The geotechnical and mechanical properties of soil, pile and raft are given in Table 1. The medium sized mesh is generated with 26622 numbers of soil elements and 39173 numbers of nodes having an average element size of 2.6 cm.

Table 1 Input soil parameters used in PLAXIS3D (modified after Matsumoto et al. 2010)

	Symbol (unit)	Values		
		Toyoura sand	Base Brick*	Raft and pile
Elastic modulus	E(kN/m^2)	-	6000000	70000000
Poisson's ratio	μ	0.3	0.2	0.3
Unit weight	γ (kN/m^3)	15.9	22	27
Angle of friction	(ϕ)	40	-	-
Confining stress dependent stiffness modulus	E_{50} (kN/m^2)	as per Eq. (3)	-	-
Reference stiffness modulus	E_{50}^{ref} (kN/m^2)	17000	-	-

Note: * Kaushik et al. (2007), - means data not required

2.2 Validation of developed numerical model subjected to vertical and horizontal loads

To validate the developed numerical model, a vertical load of 3.384kN is applied at the top of CPRF, thereafter horizontal loads of 1.92kN and 3.84kN are applied. Figure 3 illustrates the comparison of the load-settlement curve of CPRF for both the connection conditions as reported by Matsumoto et al. (2010) and finite element analysis.

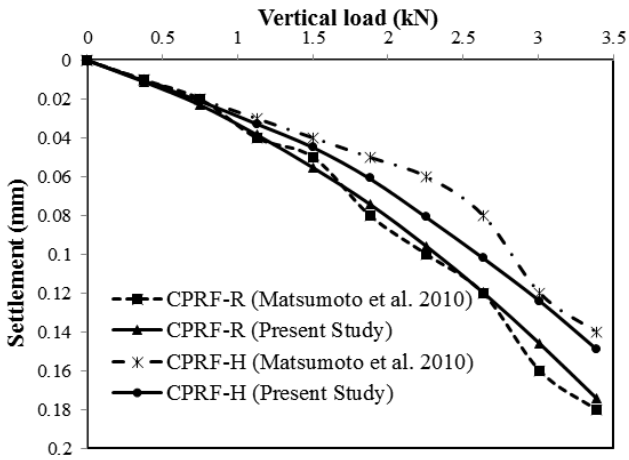


Figure 3 Comparison of load-settlement curves as obtained in present study with those reported by Matsumoto et al. (2010)

The curves indicate maximum vertical settlement of 0.043% and 0.037% of the raft width (B) in CPRF-R and CPRF-H cases respectively, showing little influence of connection condition. However, load sharing by piles under the influence of vertical load at similar settlement level in CPRF-R and CPRF-H are 46% and 70% respectively, shows the importance of connection condition, as illustrated in Figure 4. These values bear close resemblance with Kakurai (2003) who proposed a typical range of 40% to 70% of load sharing by pile by field monitoring of actual building foundation. The load sharing by piles in CPRF as reported by Yamashita et al. (2011) lies between 54% to 93%. It is to be noted that raft carries a lesser proportion of the applied load during initial loading stage for both connection conditions which may be due to poor soil-raft interaction at an earlier stage. This resulted-in higher load sharing by piles at the initial stage which decreases non-linearly with an increase in settlement and stabilizes as proper soil-raft interaction gets established. This decrease is also attributed to early mobilisation of pile resistance.

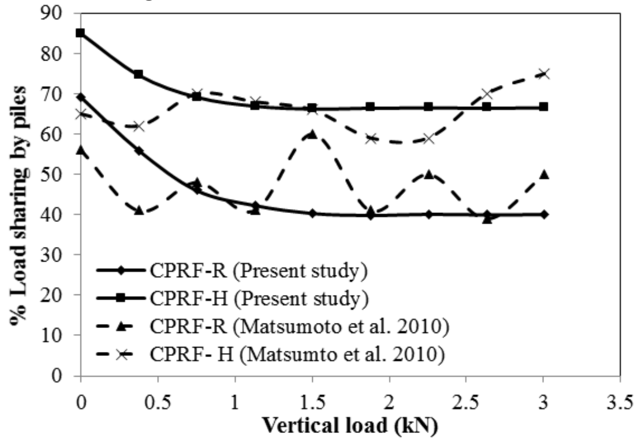


Figure 4 Comparison of load sharing by piles in CPRF as obtained in present study with those reported by Matsumoto et al. (2010)

After successful validation with vertical load, horizontal loads of 1.92kN and 3.84kN are applied at the level of raft in combined pile-raft foundation system. It was noted that piles shared 77% and 69% of the total horizontal load of 1.92kN in the case of CPRF-R and CPRF-H respectively. The load sharing by piles increased further under the horizontal load of 3.84kN for both connection conditions. It is observed that the pile head connection rigidity dictated the horizontal load carried by raft in CPRF. Similar load sharing behavior was obtained by Horikoshi et al. (2003a). The bending moment variations along pile length under the application of 3.84 kN horizontal load for both cases of connection conditions is shown in Figure 5.

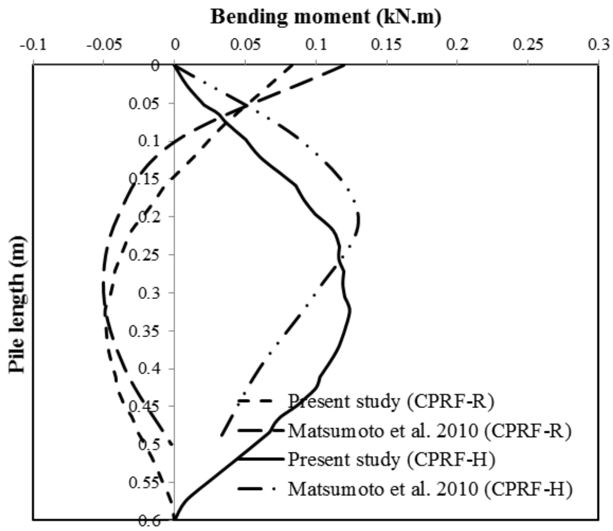


Figure 5 Comparison of bending moment variations along pile length as obtained in present study with those reported by Matsumoto et al. (2010)

It can be seen that bending moment variation along pile length is nearly matching with Matsumoto et al. (2010). The analyses outcome of Matsumoto et al. (2010) and finite element analysis by using PLAXIS3D are in good agreement which shows a validation of the present numerical model, as mentioned in Table 2. Hence, the proposed numerical model can be used for further analysis of CPRF.

Table 2 Comparison of present study results with the previous researcher

	Vertical settlement (mm) V= 3.384kN		% Vertical load sharing by raft V=3.384kN		Bending moment (kN.m) H=3.84kN	
	CPRF-R	CPRF-H	CPRF-R	CPRF-H	CPRF-R	CPRF-H
Present study	0.17	0.15	54.04	30.19	0.083	0.14
Matsumoto et al. (2010)	0.18	0.14	52.67	34	0.12	0.13
% difference	-5.56	7.14	2.60	-11.21	-30.83	7.69
'V' and 'H' indicate vertical and horizontal load						

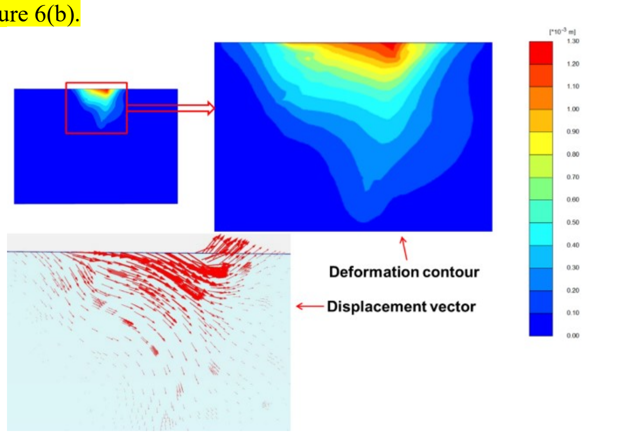
3. CPRF RESPONSE UNDER PSEUDO-STATIC LOAD

The pseudo-static load is defined as the equivalent static horizontal load which is obtained by multiplying the seismic coefficient with a total vertical load acting on the foundation unit. This is one of the conventional design approach following by several researchers Liyanapathirana and Poulos (2005), Phanikanth et al. (2013 a,b) and Phanikanth and Choudhury (2014) to investigate the response of pile in liquefying soil deposits. In the present study, the pseudo-static load is obtained for Bhuj 2001, Loma Prieta 1989 and Kobe 1995 earthquakes and is applied at the level of raft component of CPRF and the response of CPRF has been noted for both connection rigidities. Table 3 shows the brief description of peak ground acceleration (PGA), input pseudo-static load, the output of the results in terms of load sharing by piles and raft, maximum bending moments and lateral displacements in piles and rotation in CPRF.

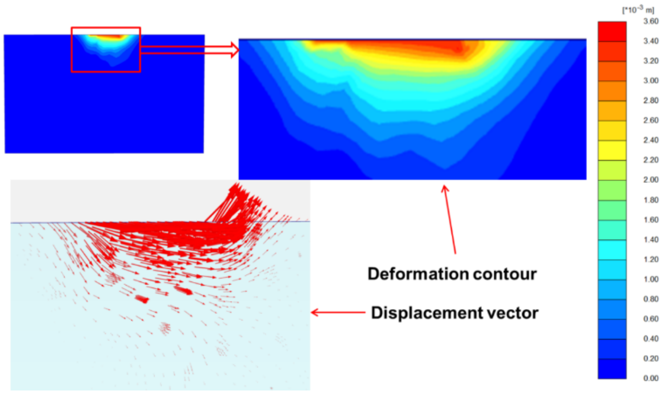
Table 3 Seismic input parameters and results of pseudo-static loading

Earthquake	2001 Bhuj	1989 Loma Prieta	1995 Kobe
Peak Ground Acceleration (g)	0.106	0.279	0.834
Max. pseudo-static load (kN)	0.358	0.944	2.82
Load sharing by raft in CPRF-R (%)	49	42	13
Load sharing by raft in CPRF-H (%)	82	76	14
Max. bending moment in pile in CPRF-R (kN.m)	0.003	0.011	0.063
Max. bending moment in pile in CPRF-H (kN.m)	0.001	0.005	0.085
Lateral deflection in pile in CPRF-R (mm)	0.03	0.094	1.05
Lateral deflection in pile in CPRF-H (mm)	0.034	0.126	3.394
Rotation in CPRF-R (rad)x10^{-3}	0.547	1.206	16.794
Rotation in CPRF-H(rad)x10^{-3}	0.114	0.213	5.616

Figures 6(a) and 6(b) illustrate the displacement contour and displacement vector diagram of CPRF system under 1995 Kobe pseudo-static seismic load for fully rigid and fully hinged connection conditions respectively. Simultaneous rotation and displacement in the foundation components can be observed for CPRF-R case whereas displacement component is predominant in the case of CPRF-H case. The reason for this phenomenon may be attributed to the differences in connection rigidity of piles with the raft. In the case of CPRF-R, front piles try to laterally displace and move-in along with raft which displaces soil below it in a downward direction thereby displacing the soil surrounding raft in an upward direction, as shown in Figure 6(a). On the contrary, lateral displacement in CPRF is more pronounced in CPRF-H case due to lesser restrain thereby laterally displacing entire foundation under lateral load with minor downward displacement as shown in Figure 6(b).



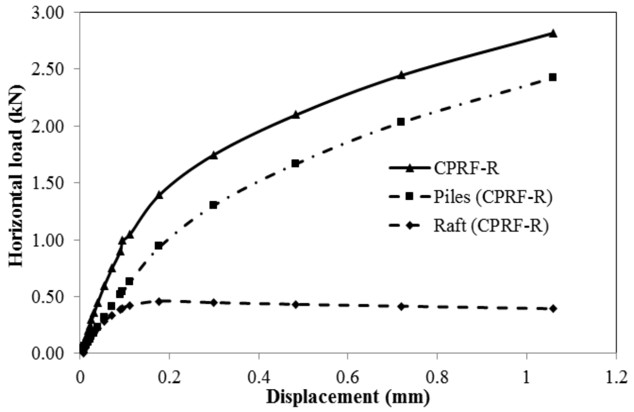
(a)



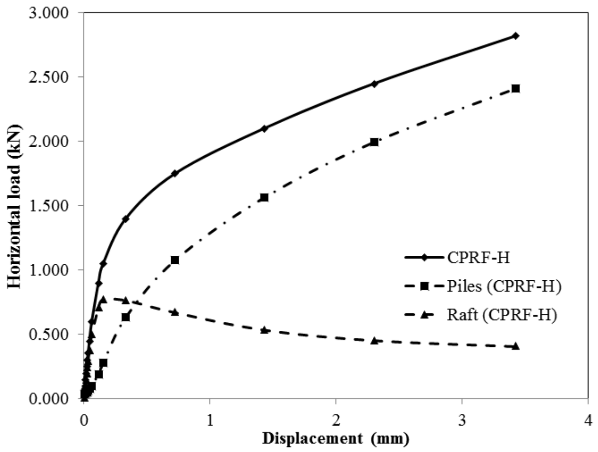
(b)

Figure 6 Lateral displacement contour and displacement vector for (a) CPRF-R, (b) CPRF-H under 1995 Kobe earthquake motion simulated as pseudo-static load

Figures 7(a) and 7(b) illustrate the horizontal load carrying capacity of CPRF with its components for fully rigid and fully hinged connection respectively. It can be observed from the figures that CPRF-R undergoes lesser displacement as compared to CPRF-H. The reason for this may be due to the lesser stiffness of the connection conditions. For comparison, lateral stiffness for both the connection conditions is calculated at the lateral load of 1.7kN which is 50% of the vertical load. The lateral stiffness of 6296kN/m and 2575kN/m are obtained for CPRF-R and CPRF-H, respectively. It is to be noted that CPRF-R carries 59% more lateral stiffness as compared to CPRF-H which is similar to the findings of Horikoshi et al. (2003) who reported almost 50% more lateral stiffness for CPRF-R. It is interesting to note that raft component of CPRF attained its limiting resistance value nearly at the same level of displacement for both types of connection conditions (0.025% of the raft width, *B*) which conveys that ultimate resistance of raft is independent of connection rigidity with piles. It can also be observed that raft mobilizes the ultimate strength at a faster rate in case of CPRF-H as compared to CPRF-R. The lesser stiffness of connection rigidity in CPRF-H allows displacement of the raft with lesser restrains which helps raft in gaining ultimate strength at a faster rate. After mobilization of raft resistance, the additional lateral loads are taken by piles leading to attainment of ultimate resistance in piles at higher displacement.



(a)

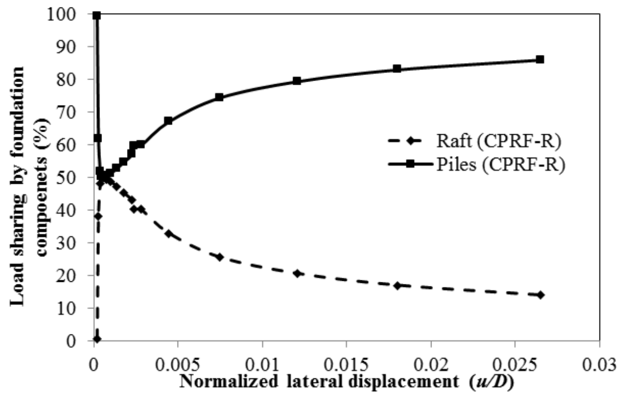


(b)

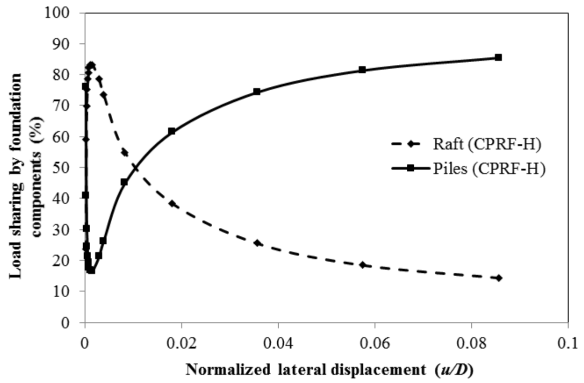
Figure 7 Variation of horizontal load with displacement for (a)-CPRF-R, (b)- CPRF-H

Figures 8(a) and 8(b) illustrate the percentage of load sharing by piles and raft components of CPRF for both types of connections. It can be observed from both the figures that horizontal load sharing by foundation components is dependent entirely on the mobilized lateral displacement. At the initial stage of lateral displacement, the total lateral load is shared by raft components but with advancement in loading and after complete mobilization of raft resistance, the pile took the lateral load which increases the load sharing by piles at larger displacement. It can also be noted from Table 3 that the load sharing by raft component of CPRF decreases with increase in pseudo-static load because raft mobilizes resistance at a faster rate initially but reaches its limiting value at smaller displacements as compared to the pile. Thus, an initial contribution of raft in load sharing is more than that of the pile. However, connection condition plays a crucial role for the lesser magnitude of the seismic load which can be seen from load sharing by raft or piles for CPRF-R and CPRF-H as reported in Table 3. However, for 1995 Kobe earthquake load, sharing of load by raft is nearly same for both connection conditions indicating its little influence of connection rigidity at higher earthquake loading.

Figure 9 illustrates the bending moment profile along the pile length for both connections rigidity. For rigidly connected pile, major part of bending moment is developed near pile head which further changes from positive to negative and then to zero along pile length. Poulos and Davis (1980), Gazetas (1984) and Choudhury et al. (2015) have also observed similar variation in bending moment along pile length. For hinged pile head connection, bending moment starts from zero and attains maximum value and then reduces to zero. Hence, active pile length which contributes to significant bending moment is dependent upon connection rigidity.



(a)



(b)

Figure 8 Loading sharing by foundation components (a)- CPRF-R, (b)-CPRF-H

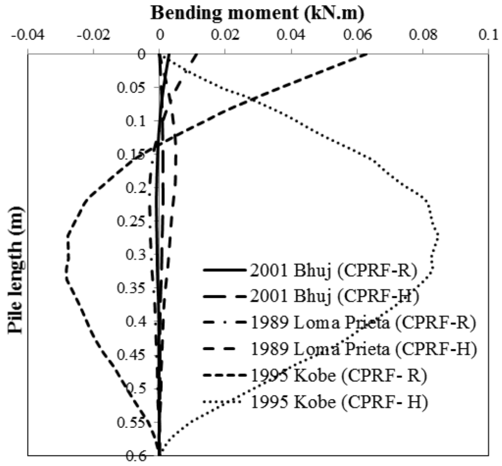


Figure 9 Normalized bending moment profile for different earthquake loads

Figure 10 illustrates lateral displacement along pile length for both connection conditions. It can be observed from both the figures that bending moment and displacement response in piles are more in the case of 1995 Kobe earthquake load which is due to the higher magnitude of 1995 Kobe as compared to 2001 Bhuj and 1989 Loma Prieta earthquake loads. It can be stated that lateral displacement in foundation system increases with increase in the magnitude of the lateral load which is also reported by Phanikanth et al. (2013 a,b) and Chatterjee et al. (2015b). It is to be noted that lateral displacement in the majority of the cases is higher than the prescribed limit of 0.01D provided by the guideline of highway bridge of Japan (JRA, 2002).

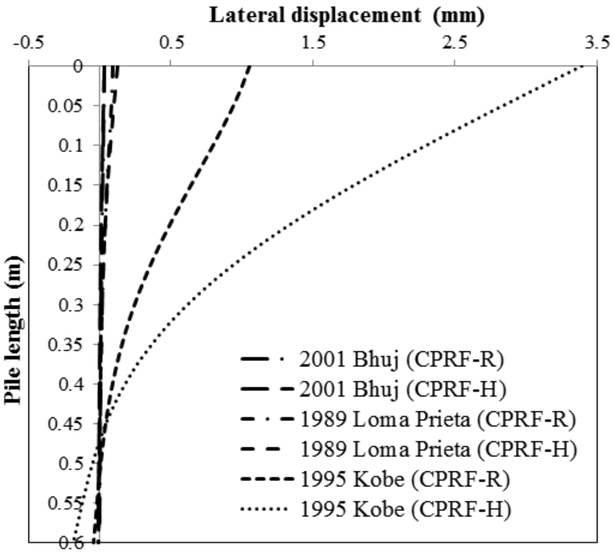


Figure 10 Lateral displacements along pile length for different earthquake loads

Figure 11 illustrates the schematic representation of obtaining the inclination of CPRF for both connections rigidity. Figure 12 shows the CPRF inclination under lateral displacement for both connection conditions. The inclination of CPRF is obtained by dividing the differential settlement (difference of vertical settlements obtained at two extreme edges of raft) by raft width, expressed with Eq. (4):

$$\text{Inclination}=\frac{\delta_B-\delta_A}{\text{Raft width}}=\frac{\delta_{BA}}{\text{Raft width}} \tag{4}$$

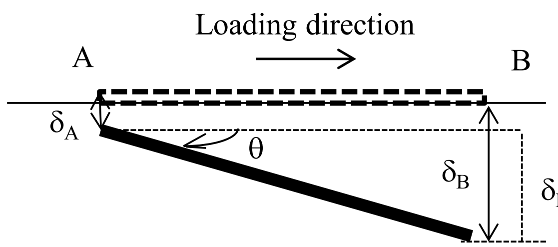


Figure 11 Schematic representation of inclination of CPRF under lateral load

It can be observed from Figure 12 that inclination in raft increases with increase in lateral displacement. In the case of CPRF-H, raft reaches to the ultimate value of inclination at smaller displacement. But, in case of CPRF-R, the ultimate value of inclination is not observed. The inclination in raft continues to increase with an increase in lateral displacement. This response of CPRF is due to the fact that lateral loads are resisted by passive resistance provided by surrounding soil in addition to the stiffness of connection. Hence, CPRF-R having more stiffness undergoes simultaneous rotation and displacement under the influence of lateral load which is unlike the case of CPRF-H where inclination reaches to limiting value after 4% of normalized lateral displacement (u/D). This observation may be pivotal in deciding the mobilization of lateral displacement for reaching to a certain value of inclination depending on the tolerance of the structure.

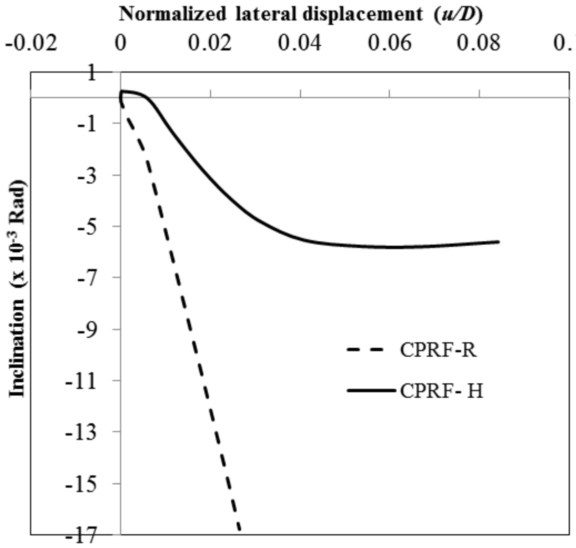


Figure 12 Inclination of raft with normalized lateral displacement for both CPRF connections

4. CONCLUSIONS

The present study investigated numerically the combined effects of vertical and lateral loadings for two extreme cases of connections rigidity of CPRF with the help of finite element based geotechnical commercial software. After successful validation of the presently developed numerical model with available experimental results under static vertical and horizontal loading conditions, the same model of CPRF was analyzed under different pseudo-static loads. It was observed that the connection rigidity had little influence on a vertical settlement under application of vertical load alone. However, it had a significant impact on load sharing between foundation components where raft shared 30% to 54% of total load depending on the connection rigidity. Load sharing by piles decreased non-linearly with an increase in vertical settlement until raft mobilizes its limiting resistance, showed the establishment of soil-raft interaction and early mobilisation of pile resistance.

In the case of lateral loading, mobilization of lateral displacement and stiffness of connection rigidity (59% more in CPRF-R as compared to CPRF-H) played an important role in load sharing, lateral displacement, the bending moment in piles and inclination response of CPRF. The lateral load sharing response of CPRF was unlike the case of vertical load sharing response where raft shared lesser load as compared to piles due to early mobilisation of ultimate lateral resistance in raft. The attainment of ultimate resistance in raft was independent of connection rigidity. The inclination of CPRF response in case of CPRF-H depicts full mobilization of lateral displacement and passive resistance provided by surrounding soil which is not the case for the CPRF-R.

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