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Behaviour of Combined Pile-Raft Foundation (CPRF) under Static and Pseudo-static Conditions using PLAXIS3D

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ABSTRACT

In this study, effect of pile head connection condition on the behavior of Combined Pile-Raft Foundation (CPRF) by using finite element based geotechnical program PLAXIS3D is investigated. The finite element model is first validated with experimental results from available literature. Thereafter, the responses of CPRF in terms of settlements, normalized bending moments (M/M_{max}) and normalized lateral displacements (u/D) under available input earthquake loadings, like 2001 Bhuj, 1989 Loma Prieta and 1995 Kobe are studied. Results show that connection condition has little influence on settlement under vertical load alone whereas load sharing by raft varies from 30% for hinged connection to 54% for rigidly connected CPRF model. Under the application of lateral load including various earthquake loads, raft mobilizes ultimate resistance at faster rate compared to pile irrespective of connection rigidity. Connection rigidity played an important role in bending moment variations, lateral displacements and rotations.

Introduction

Combined Pile-Raft Foundation (CPRF) has been widely recognized as economic and rational foundation for high rise buildings when subjected to vertical loading due to its effectiveness in load sharing by both raft and pile components. Adequate design of CPRF subjected to vertical load considering raft resistance reduces number, length or diameter of piles without compromising the safety of the foundation. This concept have been extensively used in Germany, Japan, UK and many other countries for its overwhelming performance under unfavorable ground condition (Katzenbach et al. 2000, Katzenbach et al. 2012, Mandolini et al. 2005 and Yamashita 2012). International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) published international guideline for CPRF design, construction and practice (Katzenbach and Choudhury (2013)). For seismically vulnerable areas, it is important to secure the safety of foundations during expected earthquake in the design process. One of the practical and conventional design techniques is the application of equivalent static horizontal loads at the top of CPRF to analyze the load sharing response and checking connection sensitivity by using different connection conditions between raft and piles. In the last decade, centrifuge modelling of CPRF subjected to static lateral loading and shaking, shaking table tests of small sized piled raft with and without superstructure, static lateral or cyclic loading test or large scale test (Horikoshi et al. 2003 (a,b), Matsumoto et al. 2004, Choudhury et al. 2006, 2008, Sawada and Takemura, 2014) and analytical studies (Kitiyodom and Matsumoto 2002, 2003,

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Hamada et al. 2011, Choudhury et al. 2015) have been carried out. These experiments and analyses results are available for various pile head connection conditions ranging from fully hinged to fully rigid and it has been observed that connection condition is one of the key factors affecting the behavior of CPRF during static, horizontal loading and shaking. However, design and analysis of CPRF having different connection condition when subjected to horizontal and seismic loading in addition to vertical load is not well understood till now due to complexities involved in the interaction of pile, soil and raft under such loading and connection considerations.

In this paper, effect of pile head connection condition on behavior of CPRF by using finite element based geotechnical program PLAXIS3D (Version-5.10, 2011) is investigated. The CPRF model is first validated with the experimental results of Matsumoto (2014), then the same model is analyzed under pseudo-static earthquake loadings of 2001 Bhuj, 1989 Loma Prieta and 1995 Kobe earthquake. The responses of CPRF in terms of bending moment, settlement and normalized lateral displacement (*u/D*) are presented. The present study findings are useful as it provide broader understanding of the response of CPRF for rigid and hinged connection condition under different loading cases.

Validation of present model by using PLAXIS3D

Modelling details

Matsumto (2014) performed 1g experimentation and conducted series of vertical and horizontal load tests on raft and CPRF with different connections at pile head in dry sand to examine the effect of connection condition on CPRF behavior. The experiments described are simulated in PLAXIS3D finite element based geotechnical computer program in the present study. Successful prediction of the response of foundations is highly dependent on the subsoil strength and deformation parameters. Matsumoto et al. (2010) performed consolidated drained triaxial test on Toyoura sand and observed shear modulus is dependent on confining pressure. Thus, Young's modulus will show similar variation with confining pressure as depicted by Equation 1:

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

where, p_{ref} is a reference value of confining pressure (100 kPa) and E_{ref} is the value of E at $p_0 = p_{ref}$.

To simulate actual Toyoura sand behavior under confinement, hardening soil model is chosen which also shows stiffness dependency with confining pressure as per Equation 2:

$$E_{50} = E_{50}^{ref}\left(\frac{c\cos\phi - \sigma_3\sin\phi}{c\cos\phi + p^{ref}\sin\phi}\right)^{m} \tag{2}$$

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= 0.5, where m is stress dependency factor. Cohesion (c) and friction angle (ϕ) are shear strength parameters used as per Mohr-Coulomb failure criteria.

Soil model is divided into two layers, top 1m Toyoura sand is modelled by using hardening soil model and remaining 1m brick base is modelled by using linearly elastic model. The model dimensions 3 m (L) x 3 m (B) x 2 m (H) is chosen for the present study which is laterally two times bigger than the soil model dimension proposed by Matsumoto (2014) to eliminate boundary effect, as shown in Figure 1. Square raft of size 400mm and thickness 40mm is modelled by using 6-noded plate element. Four hollow piles of diameter 40mm, thickness 2mm and length 600mm are modelled by using 10-noded tetrahedral embedded pile element. The geotechnical and mechanical properties of soil pile and raft is given in Table 1.

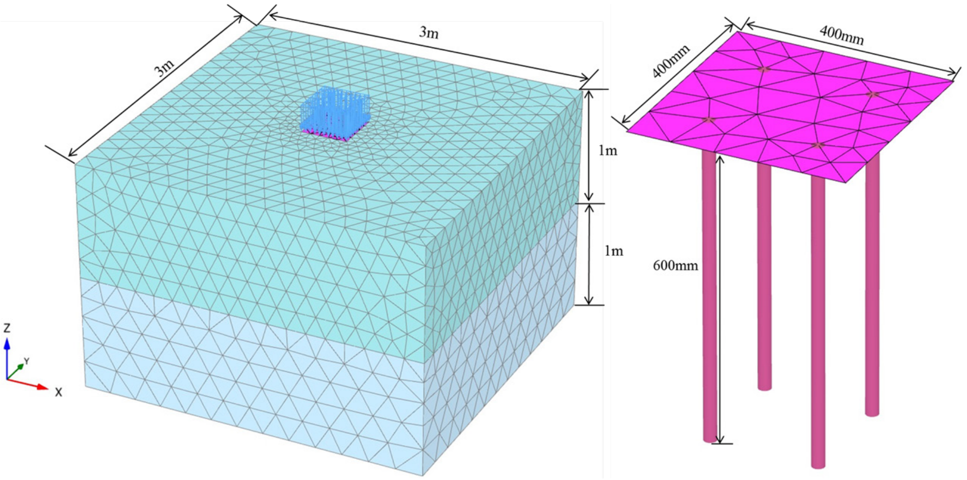

Figure 1. Three dimensional view of chosen CPRF and Soil model in PLAXIS3D

Table 1. Input soil parameters used in PLAXIS3D (Matsumoto, 2014)

	Symbol/unit	values		
		Toyoura sand	Base Brick*	Raft and pile
Young's 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	(°)	40	-	-
Confining stress dependent stiffness modulus	E_{50} (kN/m^2)	as per eqn. (2 & 3)	-	-
Reference stiffness modulus	E_{50}^{ref} (kN/m^2)	17000	-	-
Note: * Kaushik et al. (2007), - means data not required				

A total of three modelling and analyses cases viz. raft foundation alone (RF), pile raft with rigid connection (CPRF-R) and pile raft with hinged connection (CPRF-H) have been discussed. Medium sized mesh is generated with 26622 numbers of soil elements and 39173 numbers of nodes having average element size of 2.6 cm. Firstly, the vertical load of 3.384 kN is applied at the top of CPRF and then horizontal load of 1.92 kN and 3.84 kN are applied. The responses of CPRF are observed for above mentioned loading cases.

Results of vertical loading

Figure 2 illustrates the load-settlement relationship for the different cases of foundation as obtained by Matsumoto (2014) and PLAXIS3D which shows that the observed settlement in CPRF is less than settlement observed in raft foundation alone, indicating the resistance provided by raft in load sharing. It can also be noted that pile head connection condition has very little influence on settlement under application of vertical load.

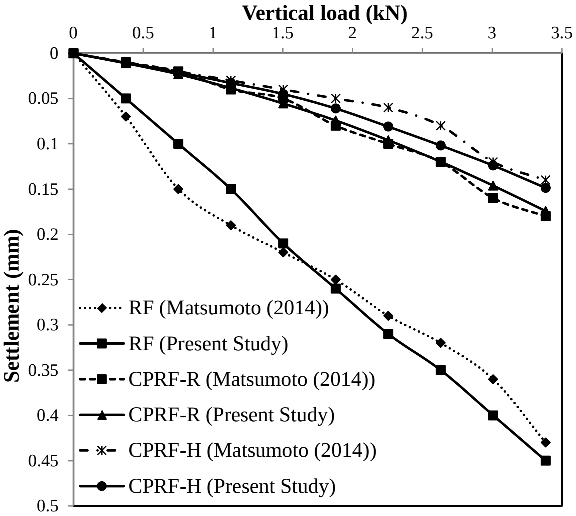

Figure 2. Comparison of load-settlement curve obtained as by Matsumoto (2014) and PLAXIS3D

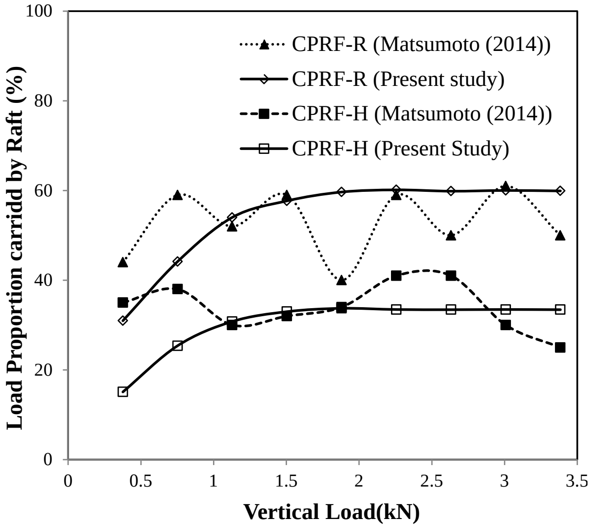

Figure 3. Comparison of load-proportion carried by raft as obtained by Matsumoto (2014) and PLAXIS3D

Figure 3 shows the vertical load proportion shared by raft with increase in vertical load calculated by subtracting axial forces carried by piles from total load applied on the raft. The average load shared by raft is about 30% for CPRF-H and 54% for CPRF-R which indicate the importance of the connection condition in load sharing. These values bear close resemblance with Kakurai (2003) who proposed typical range of 30% to 60% of load sharing by field monitoring of actual building foundation. It can also be observed that piles carry majority of the applied load during initial loading stage for both connection conditions. This may be due to poor soil-raft interaction at an earlier stage but proportion of load carried by piles decreased gradually with loading advancement and became constant as raft mobilized its ultimate resistance.

Results of horizontal loading

Horizontal load carried by raft is estimated by subtracting horizontal load carried by piles from total horizontal load applied. Raft shares 23% and 31% of the total horizontal load of 1.92kN in case of CRPF-R and CPRF-H. The load shared by raft further decreases under the horizontal load of 3.84kN for both connection conditions. It is observed that the horizontal load carried by raft is influenced by pile head connection rigidity and load sharing by the raft decreases with increase in horizontal loading. Similar load sharing behavior is obtained by Horikoshi et al. (2003a). Figure 4 illustrates the bending moment variations along pile length under the application of 3.84 kN horizontal loads for both cases of connection conditions. It can be seen from Figure 4 that normalized bending moment (M/M_{max}), where, M_{max} is the peak bending moment, variation along pile length is nearly matching with Matsumoto (2014). Figure 5 shows the normalized lateral displacement (u/D), where, u is the lateral displacement and D is the diameter of pile, along the pile length and is observed that piles in CPRF-R case displace less as compared to piles in CPRF-H because of the rigidity of the connection condition. Piles in CPRF-R have undergone 63% and 67% less displacement as compared to piles in CPRF-H under lateral load of 1.92kN and 3.84 kN, respectively. Maximum lateral displacement of 0.9% to 2.5% of pile diameter for CPRF-R to CPRF-H is observed in case of 1.92kN horizontal load which further increases with increases in load to 3.84 kN. The analyses outcome of Matsumoto (2014) and PLAXIS3D are in well agreement which shows good validation of the present numerical model, as mentioned in Table 2. Hence, the same model can be used for further seismic analysis.

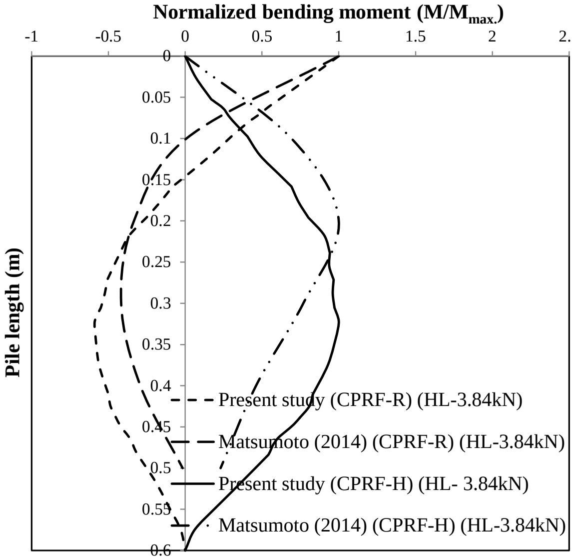

Figure 4. Bending moment variation along pile length

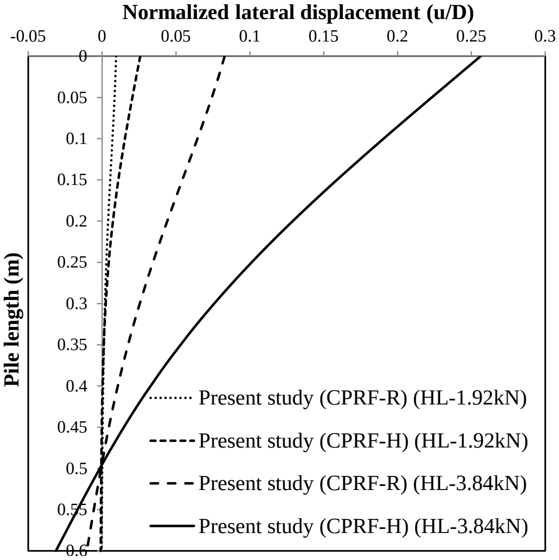

Figure 5. Lateral displacement along the pile length

Table 2. Comparison of present study results with previous researcher

	Settlement (mm)			% Load sharing by raft			Bending moment (kN.m)			
							H-1.92kN		H-3.84kN	
	Raft	CPRF-R	CPRF-H	Raft	CPRF-R	CPRF-H	CPRF-R	CPRF-H	CPRF-R	CPRF-H
Present study	0.45	0.17	0.15	100	54.04	30.19	0.036	0.041	0.083	0.14
Matsumoto (2014)	0.43	0.18	0.14	100	52.67	34	0.03	0.04	0.12	0.13
% difference	4.65	-5.56	7.14	0.00	2.60	-11.21	20.00	2.50	-30.83	7.69

Behavior of CRPF model under pseudo-static loading conditions

Seismically induced load is replaced with equivalent static horizontal load, equal to seismic coefficient times the vertical load. Seismically induced loads are applied at the level of raft and is named as pseudo-static horizontal load in the present study. Table 3 shows the details of seismic input parameters and corresponding Pseudo-static load applied to CPRF model.

Table 3 Seismic input parameters and horizontal load applied to CPRF model

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

Results of pseudo-static loading condition

It can be noted from Table 3 that loading sharing by raft 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 pile. Thus, initial contribution of raft is more than that of pile. However, connection condition plays crucial role up to lesser magnitude of seismic load only. The load sharing by raft under 1995 Kobe earthquake is nearly same for both connection conditions which indicate its little influence at higher earthquake loading. Maximum bending moments are developed near pile head in case of hinged and rigid pile head connection, increases with increase in lateral load, as shown in Figure 6 and Table 3. In addition, positive and major part of bending moment is developed near pile head which progressively reduces to negative and then to zero at the bottom of the pile limiting the contribution of overall length of pile.

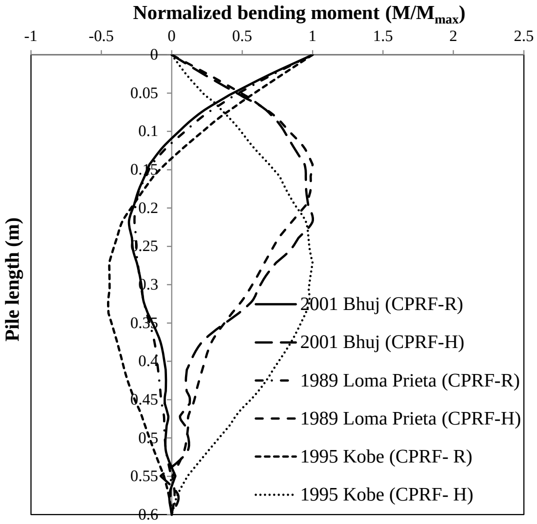

Figure 6. Bending moment along pile length for different earthquake load

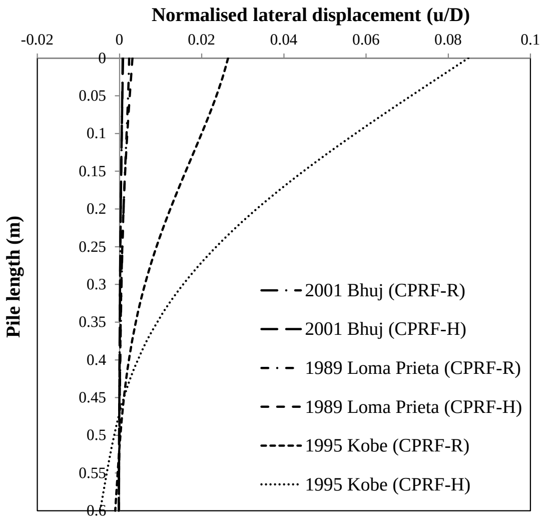

Figure 7. Lateral displacement along pile length different earthquake load

This observation is similar to that reported by Poulos and Davis (1980), Randolph (1981), Gazetas (1984) and Nikolau (2001). For hinged pile head connection, bending moment starts from zero and attains maximum value then reduces to zero, as shown in Figure 6. Hence, active pile length which contributes to significant bending moment is dependent upon connection rigidity. It is observed from Figures 5 and 7 that lateral displacement increases with increase in the lateral load which is same as observed by Phanikanth et al. (2013). It is to be noted that lateral displacement in majority of the cases is higher than the prescribed limit of 0.01*D* provided by guideline of highway bridge of Japan. CPRF-H undergoes less inclination as compared to CPRF-R which may be because of reduction in rotation due to flexibility of the connection condition. This observation is similar to that reported by Horikoshi et al. (2003 a,b), Matsumoto et al. (2004) and Matsumoto et al. (2010).

Conclusions

In the present study, series of modelling and analyses of raft foundation alone, CPRF-H and CPRF-R were carried out by using PLAXIS3D. The numerically obtained results simulated the experimental results both quantitavely and qualitatively which validates the present numerical model. It was observed that pile head connection condition had little influence on vertical settlement under application of vertical load alone. However, it was noted that connection condition played an important role in load sharing between foundation components where raft shared 30% to 54% of total load depending on connection rigidity. Load sharing by raft decreased with increase in horizontal load and corresponding displacement, it became nearly constant at higher load because of faster mobilization of raft resistance to its ultimate value. This phenomenon was observed irrespective of connection rigidity which is unlike the case of bending moment variations. It was also observed that piles in CPRF-H experience more lateral displacement when compared with piles in CPRF-R. CPRF-R undergoes more inclination as compared to CPRF-H case and varies in proportion to the lateral displacement. This may be due to flexibility of the connection condition in reducing rotation.

Accurate estimation of horizontal displacement, bending moment and rotation under designed load is very important to evaluate the induced stresses in the foundation components. It is seen that connection condition is an important factor influencing the load sharing, lateral displacement and bending moment distribution. It is also noted that vertical settlement under vertical load shows little variation but this loading scenario is unlikely to occur. For optimization of the design, maximum possible load sharing should be obtained from raft foundation. This leads to the use of lesser number of piles result into economic foundation system keeping the lateral displacement and rotation of the foundation components under permissible limit.

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