Nonlinear Rocking Stiffness of Combined Piled Raft Foundation

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Abstract. Rocking behavior of foundation during seismic excitation was recognized as an influencing mode of vibration on the dynamic response of structural system. Past research presented impedance expression for shallow and pile foundation considering rocking mode of vibration. Past proposals are found to be limited to linear stiffness. In this context, present study attempts to propose nonlinear dynamic rocking stiffness of combined piled raft foundation (CPRF) in non-dimensional form by performing three dimensional (3D) finite element analysis using *PLAXIS 3D* (2008). Nonlinear response of foundation is a well evidenced phenomenon during moderate to strong earthquake excitation and hence incorporation of nonlinear impedance of foundation in sub-structure based dynamic soil structure interaction (DSSI) analysis is required to assess accurately the seismic response of superstructure and foundation. On the other hand, 3D seismic analysis of CPRF supported structure is relatively complex and computationally expensive. Hence, the outcome of present study will offer a simplified solution to carry out seismic analysis of structure supported on CPRF and to frame design guideline for CPRF system.

Keywords: Nonlinear, DSSI, *PLAXIS 3D*, CPRF, Rocking, Seismic.

1 Introduction

Over the last few decades, extensive research has been conducted to derive extensive understanding on the role of soil–foundation–structure interaction (SFSI) on the seismic performance of structures (e.g., Jennings and Bielak 1973; Veletsos and Nair 1975; Kausel and Roesset 1975; Gazetas 1983; Tassoulas 1984; Wong and Luco 1985; Gazetas 1991; Gazetas and Mylonakis 1998). The main assumption in all these researches was the soil was assumed to behave as linearly elastic material. Such assumptions may be reasonable in order to determine the elastic response of foundation system. However, past failures of structure during Northridge (1994) and Kobe (1995) earthquakes (PGA 0.98g and 0.85g respectively) have shown the necessity of consideration of nonlinear inelastic action in soil and at soil foundation interface (Kourkolis *et al.* 2012; Gazetas *et al.* 2013). Such observations are also pertinent from some other seismic episodes like the 2006 Parkfield earthquake (M_w=6.0 and PGA= 1.8g) and 2011 Tohoku-oki (Japan) mega earthquake (M_w=9.0 and PGA= 3g). Apparently, under such mega seismic excitations the consideration of linear soil model may not be reasonable approach in design consideration of soil-foundation-structure system. Hence recent research suggests that soil–foundation nonlinear response may be beneficial and should be seriously considered in analysis and design (e.g., Paolucci 1997; Gazetas *et al*. 2003; Pecker 2003; Gajan *et al.* 2005; Mergos and Kawashima 2007; Harden and Hutchinson 2006; Gajan and Kutter 2008). The need for considering soil nonlinearity in designing foundations as a part of rehabilitation scheme is also presented in several normative documents (FEMA 2000). Nonlinearity in soil-foundation interface may induce rocking motion on foundation in which large rotation of foundation with partial uplifts and sliding could be observed (Gazetas *et al.* 2004). Several experimental and numerical studies are performed to verify the effect of rocking motion on foundation system. Paolucci *et al.* (2008) performed shake table tests to examine overturning moments at the soil-foundation interface. Tileylioglu *et al.* (2011) studied dynamic stiffness and damping of the shallow foundation from a field test using forced vibration. Further, Gajan *et al.* (2005) and Gajan and Kutter (2008) studied the variations of the nonlinear load-deformation relationship of foundations according to the type of loadings (cyclic and earthquake loadings). In the same context, Deng and Kutter (2012) found that the rocking foundation with small contact area is a good mix of energy dissipation and re-centering ability that produces good seismic performance for the soil-foundation-structure system. Gazetas and his group agreed with the concept of energy dissipation capacity and performed FEM analysis to determine the non-linear static rocking stiffness of shallow foundation for different plan shapes supported on a uniform layer of undrained clay (Gazetas *et al.* 2013).As such, the majority of the previous studies focused on linear and nonlinear response of shallow foundations (Ticof 1977; Butterfield and Gottardi 1994; Bransby and Randolph 1998; Ukritchon *et al.* 1998; Maugeri *et al.* 2000; Martin and Houlsby 2001; Gourvenec and Randolph, 2003; Gazetas and Aposolou 2004; Knappett *et al.* 2004; Gourvenec 2007). However studies on dynamic response of piled raft foundation incorporating nonlinearity at soil-foundation interface were not sufficient.

From the viewpoint, the present study is a humble attempt to propose nonlinear static rocking stiffness of piled raft foundation system for different factors of safety (F_s). The piled raft foundation system is assumed to be embedded in soft clay deposit. A three dimensional analysis using *PLAXIS 3D* has been done to model the piled raft foundation embedded in homogeneous clay deposit. Results are given in the form of simple non-dimensional curves as a function of angular deformation of piled raft system which can be readily used in the equivalent linear analysis.

2 Modeling of piled raft foundation

PLAXIS 3D V2 (2008) is used in the present study to model the 3D soil-piled raft foundation system. The piled raft arrangement is completely embedded in ground with the top surface of the raft being at same level with the ground surface. The 3D soil domain is assumed to have a dimension of 30m × 30m × 20m where the piled raft having a plan dimension of 10m × 10m × 1m is considered to be embedded at the middle of soil domain. The model is created using a 10-noded tetrahedral element.

The soft soil creep model available in *PLAXIS 3D* (2008) is used to model the clayey soil media. The Soft Soil Creep model is suitable for materials that exhibit high degrees of compressibility and exhibit significant creep behavior. Hence computations with creep models are desirable for foundation embedded in clayey soil media. The features that are considered in this model are stress-dependency of stiffness; distinction between primary loading and unloading-reloading, time dependent compression, memory of pre-consolidation stress, shear strength following the Mohr-Coulomb (MC) failure criterion, creep yield surface adapted from the Modified Cam-Clay model with an associated flow rule. The side boundaries of soil domain are constrained against lateral movement while the bottom boundary is constrained for both lateral and vertical movement. A square raft of size of 10m (length)×10m (width)×1m (thickness) is modeled using plate element. 2×2 concrete pile group of length 14m and diameter 0.7m and having centre to centre spacing of 5*D* is rigidly attached to the raft. The piles are modeled as embedded pile elements available in armory of *PLAXIS 3D* (2008). Sufficient distance at around fourteen times the diameter of pile is kept between the edge of the foundation system and the soil boundary in order to minimize the effect of boundary on response of the foundation. A rigid vertical cylindrical section of height of 3m and diameter 0.5m representing superstructure is modeled by fixed connection at the top of the raft surface in order to create a vertical dead load over the top of the piled raft foundation system and to develop a moment load (*M*) at the top of the raft surface. The rigid bar is modeled using a 3D beam element. The structural elements are considered as elastic and non-porous material. Detailed parameters of soil, pile, raft, and superstructure used in present study are presented in Table 1. A typical 3D mesh discretization generated in present study is shown in Fig.1.

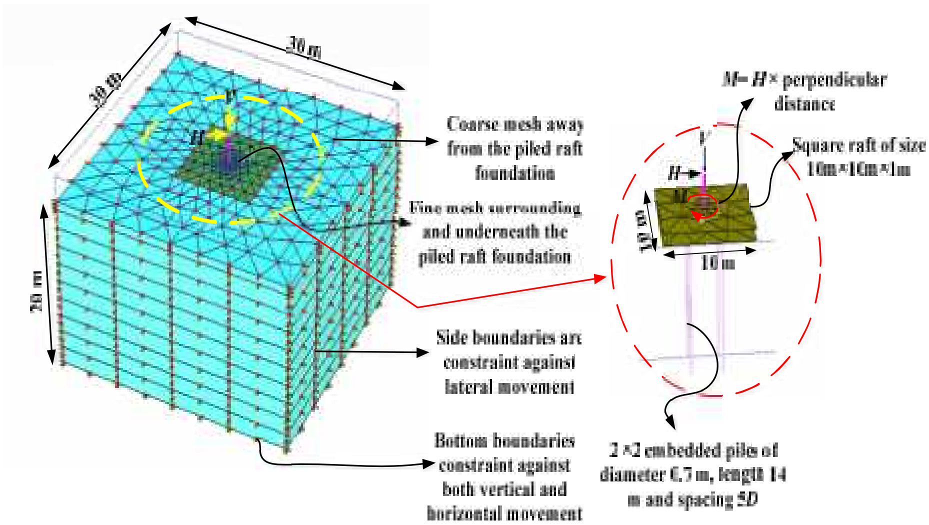

Fig. 1. Three dimensional model of piled raft foundation under combined *V-M-H* loading

Variable mesh density is employed to achieve acceptable accuracy maintaining the computational efficiency of the solution. Finer and coarser mesh is considered near to the piled raft system and away from the system respectively. Total no of nodes and elements are used as 3135 and 1056 to create the 3D FEM model. The surface to surface contact method is used to model the soil-raft interface. The roughness coefficient in the form of strength reduction factor (R_{inter}) is used for interface modeling of both raft and pile with soil. This factor represents interface strength to the soil strength. Present study considers R_{inter}= 0.7 for soft clay soil as proposed elsewhere (*PLAXIS 3D* (2008)).

Table 1. Properties of Soil, pile, raft, superstructure used in the present study

Soil properties	Value
Soil consistency	Soft Clay
Cohesion, *c* (KN/m^2)	14.5
Saturated unit weight (KN/m^3)	17
Unsaturated unit weight (KN/m^3)	14
Modified swelling index, © *	0.015
Modified compression index, a*	0.052
Modified creep index, ɜ *	0.005
Pile properties	
Material	Concrete
Length of pile (m)	14
Diameter of pile (m)	0.7
Young's modulus, E_p (KN/m^2)	2.5×10^7
Unit weight (Kn/m^3)	24
Raft properties`	
Material	Concrete
Raft dimension (m)	10×10×1
Unit weight (KN/m^3)	24
Young's modulus, E_r (KN/m^2)	2.5×10^7
Poisson's ratio, μ	0.12
Superstructure properties	
Material	Concrete
Diameter (m)	0.5
Area (m^2)	0.196
Young's modulus, E_c (KN/m^2)	2.5×10^7
Unit weight (KN/m^3)	24
Moment of inertia, *I* (m^4)	0.003068

3 Method of analysis

Two phases of analyses are performed in the present study. In the first loading phase, a prescribed vertical load is applied to the whole model. Further in the second phase of analysis, under a constant action of vertical load (*V*), the horizontal load (*H*) is applied at a height equal to the height of rigid superstructure which develops a moment load (*M*) at the top of the raft surface. The moment (*M*) thus generated is a product of the horizontal load (*H*) and the perpendicular height (*e*) of the superstructure. Both horizontal and moment load are monotonically increased until failure was reached. For both the phases, the vertical load is kept constant and is taken equal to 10%, 25%, 50%, 75% and 100% of the ultimate bearing capacity (V_{max}) of the whole piled raft foundation system. Fig. 1 presents the application of combined *V-M-H* load on the top of piled raft foundation system. The moment load (*M*) acting on the top of piled raft foundation system under constant action of vertical load (*V*) will develop a rotational angle (θ) with the leveled surface as shown in Fig. 2.

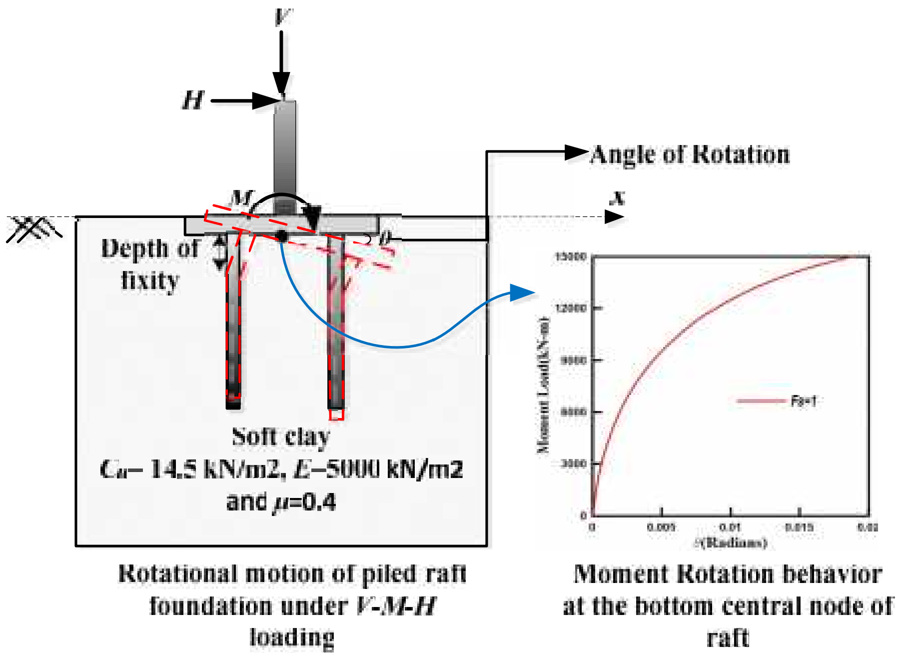

Fig. 2 Rotation of pile raft foundation subjected to *V-M-H* loading

This *M-θ* response of piled raft foundation under action of vertical load (*V*) will initiate a nonlinear rotational stiffness (K_R). This nonlinear rotational stiffness (K_R) of piled raft is the ratio of the applied moment, *M*, to the resulting rotation, ¯ , as recorded at the central node of the raft. Hence this nonlinear rotational stiffness (K_R) of the pile group can be calculated as,

$$K_R = \frac{M}{\theta} \tag{1}$$

This K_R is a function of shear modulus (G), width of the foundation (B), Poisson's ratio (μ) , undrained shear strength (c_u), Factor of safety ($Fs=V_{max}/V$) and angle of rotation (θ) and can be written as non-dimensional expression as mentioned by Gazetas *et al.* (2013).

$$\frac{K_R}{K_{Relastic}} = f(\theta, F_s, \frac{G_0}{c_u}, \frac{G}{G_0}) \tag{2}$$

where G_0 represents the shear modulus at very small shear strain. It is observed from past studies (Gazetas *et al.* 2013) that G/G_0 and G_0/c_u plays a negligible role in rotational stiffness K_R. Hence equation 2 can be modified as a function of F_s and θ,

$$\frac{K_R}{K_{R_{elastic}}} = f\left(F_s, \theta\right) \tag{3}$$

It is assumed pile and raft act as spring mass system and rigidly connected to each other in a series combination. The elastic rotational stiffness ($K_{Relastic}$) of piled raft foundation is thus assumed as combined elastic rotational stiffness of pile and raft individually. Rotational stiffness of raft ($K_{Relastic(raft)}$) is calculated following a proposed relationship of Pender (1994),

$$K_{Relastic(raft)} = 0.3 E_s L_r^{\,3} \tag{4}$$

Where E_s is Young's modulus of soil, L_r is length of raft foundation. Further, elastic rotational stiffness of a single pile ($K_{Relastic(pile)}$) embedded in homogeneous clayey soil having uniform soil profile is determined by a relationship proposed by Gazetas (1984),

$$K_{Relastic(pile)} = \left(0.16\left(\frac{E_p}{E_s}\right)^{0.75}\right) \times d^3 E_s \tag{5}$$

Where E_p and E_s are Young's modulus of pile and soil respectively and d is the diameter of pile. However, the rotational stiffness of the group pile is obtained by multiplying stiffness of single pile using equation 5 with the number of piles in a pile group. In present study, since four numbers of piles are modeled, therefore rotational stiffness of 2×2 pile group may be given by equation 6,

$$K_{Relastic(pile)} = 4 \times \left(0.16\left(\frac{E_p}{E_s}\right)^{0.75}\right) \times d^3 E_s \tag{6}$$

The combined stiffness $K_{R_{elastic\ piledraft}}$ can be found out using the following formula,

$$\frac{1}{K_{R_{elastic(piled-raft)}}} = \frac{1}{K_{R_{elastic(raft)}}} + \frac{1}{K_{R_{elastic(pile)}}} \tag{7}$$

4 Result and Discussion

4.1 *M*-*θ* behavior of piled raft foundation for different factor of safety (F_s)

The present study investigates the influence of varying F_s on moment rotation behavior of piled raft foundation subjected to *V-M-H* load. Rotation is recorded at the central node on the bottom surface of the raft with the increase in lateral and moment load under constant vertical load. Fig. 3 presents the moment rotation (*M-θ*) behavior of pile raft foundation system with increase in factor of safety from F_s= 1, 1.33, 2, 4, 10 respectively. It is observed from Fig. 3 that moment load carrying capacity increases considerably with increase in F_s. For instance, at a rotation angle of 0.005 radians a maximum increase in moment load carrying capacity is observed in order of 26.08%, 32.60%, 47.82%, 54.34% when F_s changes from 1to 1.33, 1to 2, 1 to 4 and 1 to 10 respectively. The observations are contradictory to the observations made by Gazetas *et al.* (2013) for shallow foundation. The reason for such observation may be because of the nonlinear range of deformation of soil due to increase in rotational amplitude for piled raft foundation with decrease in F_s. Further, the increase in F_s also increases the moment load carrying capacity which indicates that the piled raft foundation can sustain purely moment load with presence of small amount of vertical loading whereas as the vertical load increases the soil attains sufficient amount of nonlinearity which in turn decreases the load carrying capacity of piled raft foundation, when the foundation system is being subjected to *V-M-H* load.

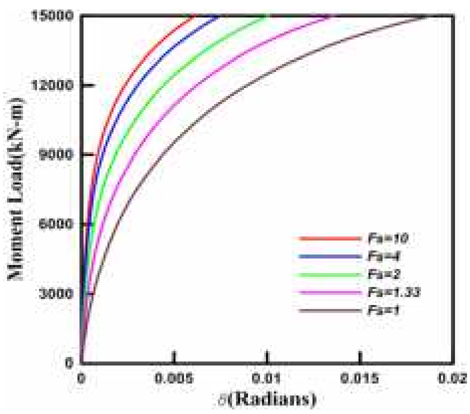

Fig. 3. *M-θ* behavior of piled raft foundation for different F_s=1,1.33,2,4,10 respectively

Furthermore, the influence of the assumed thickness of the soil domain on rotational stiffness of piled raft foundation is also investigated in present study. Fig. 4 presents the M-θ response of piled raft foundation for $F_s = 2$ considering two different depths, 20 m and 30 m respectively. It is observed that the increase in the thickness of soil domain from 20 m to 30 m has not influenced the rotational amplitude of piled raft for $F_s = 2$.

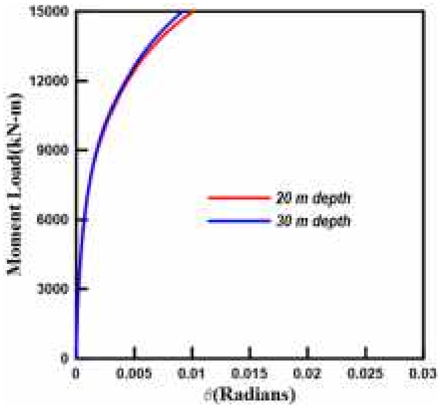

Fig.4. M-θ behavior of piled raft foundation for soil thickness of 20m and 30m for F_s=2

4.2Non-dimensional rotational stiffness with respect to rotation angle (θ) for different factor of safety (F_s)

Present study further tried to investigate the behavior of nonlinear static rotational stiffness of piled raft foundation system for different factor of safety (F_s). The nonlinear rotational stiffness K_R (θ, F_s) is normalized with linear rotational stiffness $K_{R\ elastic}$ as mentioned in the previous section. Fig.5 represents the non-dimensional rotational stiffness (K_R (θ, F_s)/$K_{R\ elastic}$) of piled raft foundation with different rotational amplitude for increasing amount of F_s=1, 1.33, 2, 4, 10 respectively. Two types of observation could be noticed from Fig.4. First, it has been seen that for a point of rotation non-dimensional rotational stiffness (K_R (θ, F_s)/$K_{R\ elastic}$) increases considerably with the increase in F_s. Further, for particular F_s, the rotational stiffness is higher for initial rotational amplitude and remains constant with the increase in rotation. For example, at rotational amplitude of 0.0001 radians the maximum increase in dimensionless rotational stiffness is 50%, 150%, 225%, 375% when F_s increases from 1 to 1.33, 1 to 2, 1 to 4, 1 to 10 respectively. However at rotational amplitude of 0.001 radians, K_R (θ, F_s)/$K_{R\ elastic}$ has almost become constant for all values of F_s.

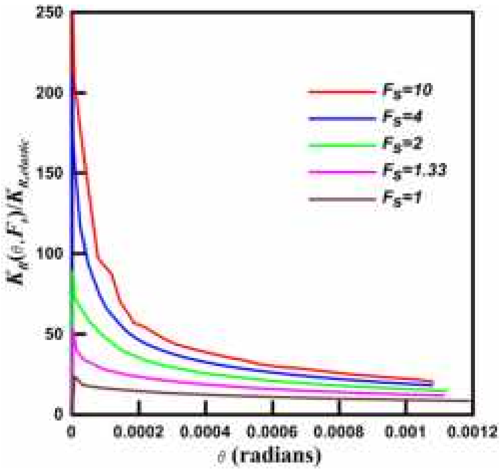

Fig. 5. Non-dimensional rotational stiffness with respect to rotational amplitude and different factor of safety for piled raft foundation

5 Summary and conclusions:

Present study presents nonlinear rotational stiffness of CPRF embedded in homogenous soft clay deposit for different factor of safety (F_s) by performing 3D FEM analysis. Non-dimensional graphs are presented for ease computation of rotational stiffness of piled raft foundation. It is observed that the piled raft foundation can sustain purely moment load with the presence of small amount of vertical loading whereas the vertical load increases the soil attains sufficient amount of nonlinearity which in turn decreases the load carrying capacity of piled raft foundation. Further, it is observed that for particular F_s, the rotational stiffness is higher for initial rotational amplitude and remains constant with the increase in rotation. However, present study is attempted for a limited number of cases. But a number of parametric studies will help in understanding the behavior of piled raft system under this loading condition and may strengthen the design approach that is presented in this text. Hence, present study offers valuable inputs for revamping design of piled raft foundation and indicates necessity of detailed study in this direction encompassing other influential parameters.

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