Behavior of pile-raft foundation under combined vertical lateral and moment loads: A parametric study

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ABSTRACT

Piled raft foundation is a rational solution for heavy and tall structures which are typically subjected to combinations of vertical, lateral and moment loadings resulting from the dead weight of superstructure, in addition to significant lateral loads and moments from soil pressures, seismic loading and wind loads.The interaction of lateral, vertical and moment load on piled raft foundation has not been well understood due to the complex interaction among raft, soil, piles and superstructure. The present study is an attempt to investigate the interaction of vertical (*V*), lateral (*H*) and moment (*M*) loads on the design response of an idealised piled raft foundation using 3D Finite Element Analysis. A parametric study is carried out due to the variation of different influential parameters to investigate the influence on capacity of pile-raft incorporating *V-M-H* interaction. The results indicate that *V-M-H* interaction have significant effect on lateral load carrying capacity of piled raft system. Present findings are useful as they may provide broader understanding of response of piled raft foundation system under combined *V-M-H* load and in framing design guidelines of piled raft foundation under various loading condition.

Keywords: Pile-Raft Foundation, Soil structure interaction, *V-M-H* interaction, Finite Element Analysis.

1 INTRODUCTION

Combined piled raft foundation is recognized as a rational solution for heavy and tall structures. Piles under the raft are acting as settlement reducer and while raft is able to provide reasonable measures for both stiffness and soil resistance (Poulos 2001). Recent studies emphasized on contribution of raft along with pile as a foundation element which attributes an optimum solution of design of piled raft system under gravity loading (Chow and Teh 1991, Clancy 1993). In this context, relative stiffness of raft with respect to soil is outlined as a controlling factor in design of such foundation (Horikoshi and Randloph 1998, Clancy 1993). Design of such foundation system therefore warrants the combined capacity of the pile and the raft and interaction under serviceability condition. State of the art research indicates that considerable effort has been given for the development of optimum design guideline of piled raft foundation system under static loading (Horikoshi et al. 1998, Poulos et al. 2011). In fact, the behavior of pile raft foundation is complicated due to combined action of vertical (*V*), horizontal (*H*) and moment (*M*) loading. Horizontal loading, such as, earthquake, wave loading and wind may lead to a significant horizontal forces and moment in addition to gravity loading to such foundation. Hence, sustainable design of piled raft foundation requires consideration of *V-M-H* interaction in obtaining response. A few experimental studies on piled-raft under seismic loading were reported in literature (Pastsakorn et al. 2002, Matsumoto et al. 2004a, 2004b) which are primarily focused on horizontal deformation of foundation by restricting the rotational behavior of foundation. However, the rocking of raft was reported to be an important behavior during seismic loading (Swada et al. 2014). Limited studies were reported on behavior of piled raft considering combined *V-H* and *M-H* loading (Hamada et al. 2012, Sawada et al. 2014, Matsumoto et al. 2004). Hence, the behavior of piled-raft foundation considering *V-M-H* interaction is required to frame seismic design guideline for the structures supported on piled raft foundation.

Present study is an attempt to investigate the behavior of piled raft foundation considering combined action of *V-M-H* load. The foundation system is considered to be embedded in sandy soil. A 3D finite element (FE) analysis considering nonlinear behavior of soil is performed. A parametric study due to the variation of different influential parameters, such as Young's modulus of pile and soil (E_p/E_s), length to diameter ratio of pile (*L/D)* and thickness of raft (t_r) is carried out to investigate the influence on the capacity of pile-raft incorporating *V-M-H* interaction.

2 MODELING AND METHODOLOGY

PLAXIS 3D V2 (2008) is used in 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 28m × 28m × 16m where the piled raft having a plan dimension of 4m × 4m × 1m is considered to be embedded at the middle of soil domain. The model is created using a 10-noded tetrahedral element. Mohr-Coulomb constitutive model is used to model sandy soil medium. The side boundaries of soil domain are constrained against horizontal direction and the bottom boundaries are constrained against both horizontal and vertical directions.

Table 1. Specification of pile, raft, superstructure and soil

Superstructure	Value
Material	Steel
Diameter (m)	0.5
Length (m)	3.0
Density (kN/m^3)	77
Poisson's ratio, υ	0.33
Young's modulus, E_b (kN/m^2)	2.0×10^8
Cross sectional Area, A_b (m^2)	0.196
Moment of Inertia, I_b (m^4)	0.003068
Raft	
Material	Aluminum
Raft Dimensions (m)	4 × 4 × 1
Density (kN/m^3)	27
Poisson's ratio, υ	0.35
Young's modulus, E_r (kN/m^2)	70×10^6
Shear modulus, G_r (kN/m^2)	2.593×10^7
Moment of inertia, I_r (m^4)	21.33
Pile	
Material	Steel
Pile Length, L (m)	9.0
Pile Diameter, d (m)	0.5
Density (kN/m^3)	77
Poisson's ratio, υ	0.33
Young's modulus, E_p (KN/m^2)	2.0×10^8
Cross sectional Area, A_p (m^2)	0.196
Moment of Inertia, I_p (m^4)	0.003068
Soil	
Soil type	Loose Sand, Medium Sand
Young's Modulus, E_s (kN/m^2)	7000, 13000
Poisson's Ratio, υ	0.3
Unit Weight, γ_{sat} (kN/m^3)	14, 20
Frictional Angle, ø	31˚
Dilation Angle, φ	1˚
Cohesion, c (kN/m^2)	0

A square raft of dimensions of 4m × 4m × 1m (thickness) is modeled using plate element. Two fixed headed piles of length 9 m and diameter 0.5m, having a centre to centre spacing of 4*D*, is modeled using beam element. 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.

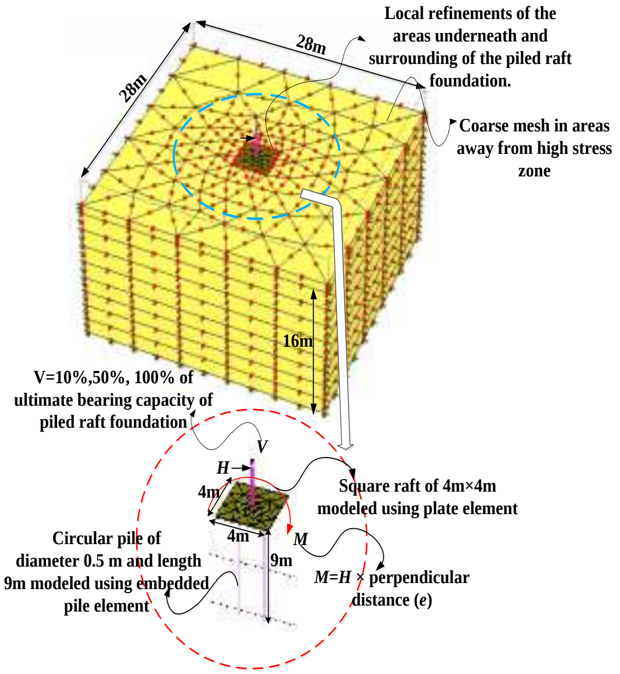

Fig 1: 3D finite element mesh of the piled raft superstructure foundation system.

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. The surface to surface contact method is used to model soil-raft interface. Two set of analyses are performed in present study. In the first set of analysis, horizontal load (*H*) is applied at the top central node of the raft surface under a constant action of vertical load (*V*) which may be considered a case of *V-H* interaction loading. Further in the second set 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, in order to make it a case of *M-V* interaction loading. The moment (*M*) thus generated is a product of the horizontal load (*H*) and the perpendicular height (*e*) of the superstructure. For all these cases, the vertical load is kept constant and is taken equal to 10%, 50% and 100% of the ultimate bearing capacity of the whole piled raft foundation system. In both the sets of analyses, the loads are applied in two stages. In the first loading stage, a prescribed vertical load is applied on the whole model. In the second loading stage, the vertical load is maintained constant and a horizontal load is applied at a specified vertical elevation from ground level in case of *M-V* loading case and on the top of raft surface for *V-H* loading case respectively. Both the horizontal and the moment load are monotonically increased until failure was reached.

3.0 RESULTS AND DISCUSSION

3.1 Influence of thickness of raft

Present study investigates the influence of relative stiffness of raft, i.e. flexible to rigid behavior on piled raft foundation under coupled *V-H* and *V-M* loadings. Varying raft thickness of 0.1m, 0.5m and 1m are considered to represent flexible, moderately rigid and rigid behavior respectively. Lateral displacement 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. 2(a) and 2(b) presents the lateral load deformation behaviour of pile raft foundation system with increase in thickness of raft from t_r= 0.1m, 0.5m and 1m respectively under action of *V-H* and *V-M* loading respectively. It is observed from Fig. 2(a) and 2(b) that the lateral load carrying capacity increased significantly with the increase in thickness of raft. For instance, the lateral resisting capacity increased by a value of 41.66% for t_r =1m compared to t_r =0.1m as observed in Fig. 2(a). Similarly, in case of *V-M* loading, from Fig. 2(b), it is observed that for 50% vertical load (i.e. *V*=50%) at a deformation of 0.3m, the lateral moment resisting capacity increased by 23.33% for t_r =1m with respect to t_r =0.1m. Further, it can also be observed from Fig. 2(a) and 2(b) that the lateral and moment resisting capacity increases with application of combined *V-H* and *V-M* loading cases if compared to sole horizontal or moment load (i.e. *V*=0%) irrespective of raft thickness(t_r). The lateral capacity curve for a particular t_r in case of *V-H* and *V-M* loading cases is observed to be increasing with increment of vertical loading i.e., *V*=10%, 50% and 100%. For instance, considering the case of *V-H* loading with raft thickness t_r = 0.1m, it can be seen from Fig. 2(a) that the lateral load resisting capacity increased from 1500 kN at *V*=0% to 2000 kN at *V*=10% and then increased to 3000 kN at *V*=50% and 3250 kN at *V*=100% at same lateral deformation of 0.3 m. Further, with raft thickness t_r =1m, the capacity increased from 2000 kN at *V*=0% to 5000 kN at *V*=100%. Similar observations are noticed in case of moment resisting capacity from Fig. 2(b).

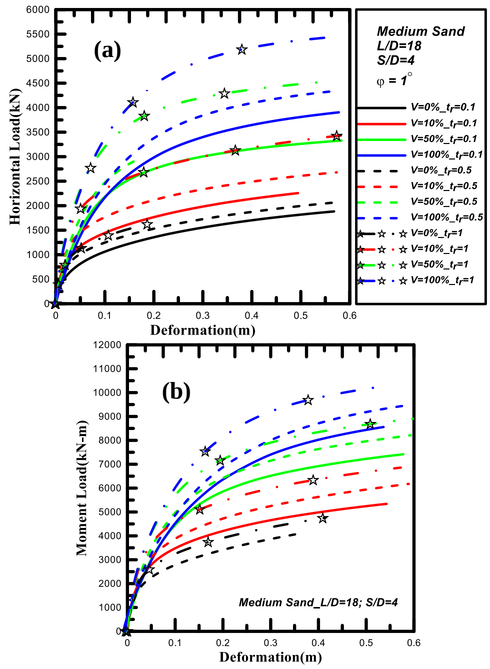

Fig.2: Lateral load deformation behavior of pile raft foundation system with varying raft thickness under action of (a) *V-H* loading and (b) *V-M* loading

3.2 Influence of pile length to raft width ratio (*L/B*)

The effect of flexible and stiff behavior of pile on lateral load capacity of piled raft foundation under combined action of *V-M-H* load is investigated and presented in Fig. 3 (a) and (b) for *V-H* and *V-M* loading respectively. Three values of slenderness ratios (*L/B*) of 1, 2.25 and 5 are chosen to incorporate the effect. *L/B* ratio of 1 indicates rigid behavior of pile. However, *L/B* ratio of 2.25 and 5 indicates flexible behavior of pile.

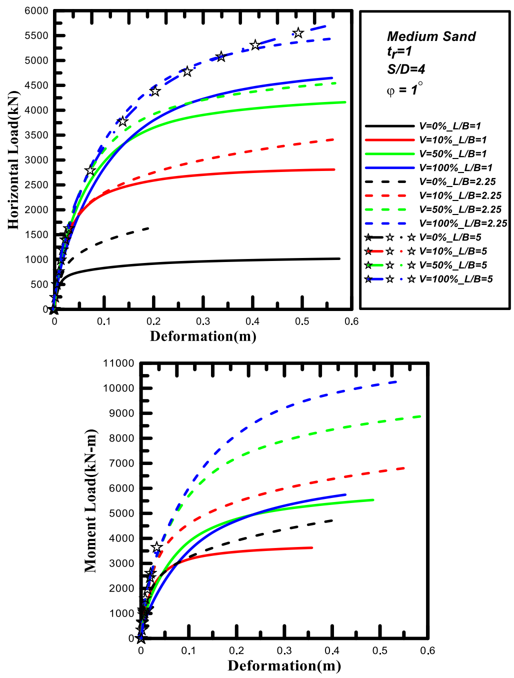

Fig.3: Lateral load deformation behavior of pile raft foundation system with varying length to width ratio (*L/B*) under action of (a) *V-H* loading and (b) *V-M* loading

It is observed from Fig. 3 (a) and (b) that the lateral load resistance increases with the increase in slenderness ratio (*L/B*) of the foundation system. The increase in lateral capacity is more predominant while combined *V-H* and *V-M* loading are applied. For example, referring to Fig. 3(a) for *L/B* ratio of 1, the lateral load resistance increases from 1000 kN at *V*=0% to 2500 kN at *V*=10% considering deformation of 0.2m. The lateral resistance capacity further increased to a value of 3500 kN at *V*=50% and 3750 kN at *V*=100% respectively. Furthermore with the increase in *L/B* to 2.25, the lateral load resisting capacity increased from a value of 1500 kN in case of *V*=0% to a value of 4500 kN at *V*=100%. However, the capacity is found to be similar for *L/B* ratio of 5 as it is observed for *L/B* ratio of 2.25. The reason of this similarity may be due to the fact that both pile group exhibits flexible nature and pile length beyond depth of fixity marginally influence the capacity curve. A similar trend in lateral resistance is observed from Fig. 3 (b) for *V-M* load case.

3.3 Influence of varying *Ep/Es* ratio

Lateral load deformation behavior of piled raft foundation system with E_p/E_s ratio of 28,570 and 15,380 representing loose and medium sand respectively under *V-H* and *V-M* loading cases are presented in Fig. 4 (a) and (b) respectively.

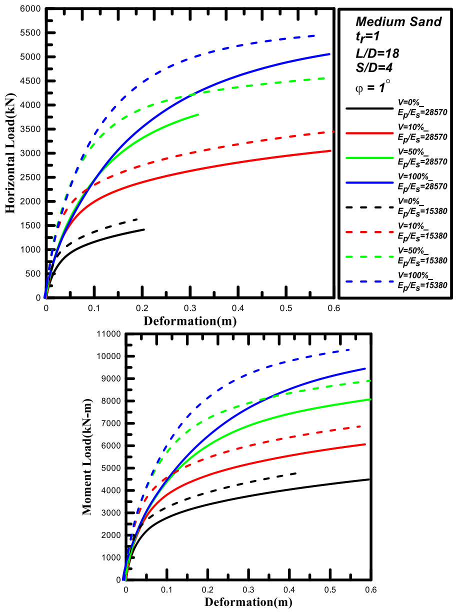

Fig.4: Lateral load deformation behavior of pile raft foundation system with varying E_p/E_s ratio under action of (a) *V-H* loading and (b) *V-M* loading

In both *V-H* and *V-M* loading conditions, increase in lateral capacity is noticed with the increase in stiffness of sand. For instance in Fig. 4(b) at a deformation of 0.3m and *V*=50%, the lateral load capacity increased by 15.38% for E_p/E_s =15,380 with respect to E_p/E_s =28,570. However, the capacity increases significantly if combined *V-M* loading is considered on the piled raft foundation system as compared to individual loading. For example, fig. 4 (b) presents that lateral moment resisting capacity of the piled raft foundation system at *V*=100% and E_p/E_s =15,380 is 2.07 times the capacity of what is obtained at *V*=0% at deformation 0.3m. The results show that with the increase in stiffness of soil the load resisting capacity of the foundation increased under combined *V-M-H* loading.

4. SUMMARY AND CONCLUSIONS

In summary, the present study presents interaction effect of combined *V-M-H* loading on lateral load carrying capacity of piled raft foundation using 3D finite element based numerical analysis. Numerical parametric analysis results on prototype structure indicate that lateral load resistance is significantly influenced due to *V-M-H* interaction. It is observed that variation of raft thickness from flexible to rigid behaviour may cause a maximum increase in lateral resistance of piled raft foundation in order of 43% and 24% for *V-H* and *V-M* loading respectively when *V*=100%. On the other hand, variation in *L/B* and E_p/E_s ratio may cause a maximum increase of lateral capacity in order of 80% and 20% respectively in case of *V-M* loading. 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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