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Seismic Response of Soil-Pile Foundation-Structure System

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ABSTRACT

This paper presents an initial effort to investigate seismic response of soil-pile-structure system considering soil-structure interaction effect. In general, structure and pile foundation under seismic load are designed estimating base shear considering fixed base condition. However, soil flexibility may result significant changes in the response of soil-pile foundation-structure system. Soil-pile-structure system is considered to have an idealised one storey system consisting of a mass in the form a rigid deck supported by four columns. This in turn rests on raft foundation with pile. The piles are modelled by beam-column element supported by laterally distributed springs. A parametric study encompassing feasible variations of parameters is made under spectrum consistent ground motion. A significant change in shear force carried columns and that transmitted to soil is observed as compared to what obtained in fixed base condition due to the soil-structure interaction effect. Summarily study indicates that the column shear may be overestimated while total shear transmitted to soil may be underestimated if the base shear in fixed base condition is considered. The total shear transmitted closely reflects the design shear force to be carried by pile. Hence, there is a possibility of an over-safe column design and unsafe pile design from fixed base assumption. The issue needs further detailed investigation for modifying relevant clauses of design standards.

1. INTRODUCTION

Traditionally a structure is considered to be fixed at base for seismic design. However, the recent researches in this direction have also prescribed to consider equivalent soil springs to account for the flexibility at base of the structure due to presence of soil. This approach is found to give satisfactory results for all feasible varieties of shallow foundations (Bhattacharya and Dutta 2004). However, limited studies are available on seismic response of structure incorporating the effect of soil flexibility if foundation consists of raft supported on pile group.

In general, structural design considers fixity at base level in a soil-pile foundation-structure system. Likewise, pile head is considered to be fixed for seismic design of pile raft. Hence, seismic design of structure and pile raft is performed by computing structure base shear force for a known weight and natural period of vibration of superstructure in fixed base condition. However, in reality, due to deformable characteristics of soil, foundation offers a partial fixity at structure base level and thereby alters natural period and response of the system. In contrast, design of foundation is directed by the amount of load transferred from the structure to the soil, based on extent of fixity offered by the soil. This interdependent behaviour of soil and structure changing overall response of the structure is termed as soil-structure interaction (SSI). Limited numbers of studies pertaining to the effect of soil structure interaction on the response of soil-pile foundation-structure system has been carried out in previous research work. A few of them are as follows. Boulanger *et al.* (1999) assessed validity of dynamic *p-y* analysis in seismic soil-pile-structure interaction using dynamic centrifuge model tests. Guin and Banerjee (1998) investigated that the distribution of structural loading transferred to the pile changes considerably for a coupled soil-pile-structure under seismic load due to soil-structure interaction. Gazetas *et al.* (1993), Markis and Gazetas (1992) conducted a parametric study for pile groups considering soil-pile-structure. The study reveals that the cross-interaction between piles controls the dynamic response of pile group under seismic inertial loading at pile head. Gazetas (1984) developed pile head displacement interaction curves for end-bearing single piles supporting a superstructure mass under seismic load and various soil and pile parameters. Relatively lesser efforts have been diverted towards studying effects of soil-structure interaction on soil-pile-structure system facilitating design of pile, raft and structure incorporating the effect of soil flexibility. The present study is an initial effort in this direction.

The objective of the present study is to highlight the effect of soil-structure interaction on seismic response of soil-pile foundation-structure system for feasible variations of soil consistencies, pile length to diameter ratios and natural periods of superstructure. The dynamic effect during seismic shaking is attempted to be captured through the consideration of a idealised one storey system supported by foundation. The piles are considered to be supported laterally by compression-only distributed linear springs. Spectrum consistent seismic ground motions are used to make the results more meaningful and realistic.

2. SYSTEM MODELLING

Idealisation of Superstructure

Seismic response of soil-pile-structure system is obtained by idealising a one storey system supported by a pile raft. To resemble a single degree freedom system (SDOF), superstructure is considered as three dimensional space frame structure which consists of four column members along with a rigid deck slab. Structural fixed base condition is idealised by restraining all possible degrees of freedom at all column supports. A schematic diagram of idealised system considered for fixed base and soil-pile foundation-structure is shown in Fig 1. Young's modulus of soil (E_s) is considered not vary with depth (z) as considered in well accepted literature (Gazetas 1984). Since, fundamental natural period of vibration varies with height of a building, present analysis considers four representative natural period of vibration, namely, 0.25 sec, 0.50 sec, 1.0 sec, and 2.0 sec to represent short, medium and long period structure respectively. The different period of structures are attained through changing the ratio of mass of superstructure and its stiffness. Column stiffness can be attributed by assigning appropriate sectional properties. Maximum base shear force is obtained for the selected range of values of natural period of vibration of superstructure (T).

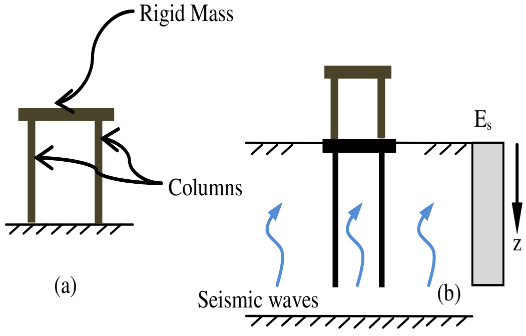

Fig. 1: Schematic Diagram of the Idealized System Considered (a) Fixed Base (b) The SSI System

Idealisation of Soil-Foundation System

Raft foundation is modelled by four noded plate elements discretised into square meshes with consideration of adequate slab thickness. Each node of the plate is considered to have three degrees of freedom (two mutually perpendicular horizontal directions and one perpendicular direction) and it employs a hybrid element formulation. Pile foundation is modelled using two noded beam-column element with uniform sectional property. Raft-soil interaction is modelled by using distributed springs of equal stiffness values over the entire area of raft. Translations of raft are considered in two mutually perpendicular horizontal directions and vertical direction in the present study. Stiffness properties of distributed springs in each direction are computed by using empirical expressions prescribed in literature (Dutta *et al*. 2008). Stiffness of vertical spring is assigned as suggested by Gazetas (1991) to simulate coupled lateral rocking mode of vibration. Stiffness values of all such vertical springs are assumed to be equal with suitable modification for those at corners and periphery (proportional to influence area). It can be noted that the raft spring idealisation indicates a better judgement of stress distribution over the raft area taking care soil flexibility (Dutta *et al.* 2009). The distributed stiffness values of each spring along lateral direction and vertical direction for raft are given by Eq. (1) and (2) (Dutta *et al*., 2009),

$$K_{xD} = K_{xG} / n^2 \tag{1}$$

$$K_{yD} = 5.4/(n^2+2)*(GL/1-\nu) \tag{2}$$

where, K_{xG} is the overall lateral stiffness (Gazetas 1991), n is the no. of elements for raft, G is the shear modulus of soil ($G = 120N^{0.8}$ t/ft^2, Ohsaki and Iwasaki 1973), N is the SPT value of soil, L is the length of raft and υ is the Poisson's ratio of soil.

Distributed Lateral springs are introduced along the pile length to incorporate the effect of soil flexibility. Subgrade modulus approach (Bowles 1997) is adopted for idealization of those springs under plane strain condition which are connected at various nodal points of modeled pile foundation. Vertical spring is introduced at the of pile tip to account for tip resistance. Equivalent stiffness values of linear springs are calculated by end-area theory based on the value from Eq. (3) and introduced orthogonally at equally spaced nodal points along the pile length. Homogeneous soil medium is considered and which is attributed by constant value of Young's modulus (E_s) over the soil depth (z). Horizontal modulus of subgrade reaction is calculated using the following expression (Bowles 1997),

$$K_S = A_S + B_S z^n \tag{3}$$

$$A_s = C\left(cN_c S_c + 0.5\gamma N_\gamma S_\gamma\right) \tag{4}$$

$$B_s = C\left(\gamma N_q S_q\right) \tag{5}$$

where, K_s is the subgrade modulus of soil, A_s is the constant for either horizontal and vertical members, B_s is the coefficient for depth variation, z is the depth of interest below ground, n is the exponent to give best fit K_s and C is a calibration factor based on allowable bearing capacity. Other factors attributed from standard bearing capacity equation from Terzaghi and Hansen approach (Bowles 1997).

Dobry and Gazetas (1986) reported that the values of equivalent spring vary significantly with excitation frequency for long piles embedded in soft clay. Gazetas (1991) described that the inertia force exerted by a time varying ground excitation imparts a frequency dependent behaviour which seems to be more conveniently incorporated in stiffness in the equivalent sense. Stiffness of equivalent spring is dependent on deformable characteristics of soil. Inertial force is influenced by frequency of ground excitation. Hence, assumption of frequency independent springs is deemed to be appropriate.

Damping

Velez *et al.* (1991) reported that 5% damping of soil medium would be a realistic assumption for understanding the behaviour of pile-raft system. IS-1893 (2002) suggests 5% of critical damping is reasonable for concrete structures, hence, 5% of critical damping in each mode is considered irrespective of fixed base condition or support flexibility.

Ground Motion

The effect of SSI on single degree freedom idealised structure is studied under a type of ground motion. Two uncorrelated artificially generated earthquake acceleration histories consistent with IS 1893 (1984) specified design spectrum, having PGA (peak ground acceleration) of 0.1g, are used in the present analysis.

3. DETAILS OF CASE-STUDIES

Primarily, the study attempts to see the effect of soil-structure interaction on superstructure under seismic excitation for different natural time period, namely, 0.25 sec., 0.5 sec., 1.0 sec., and 2.0 sec. Two different types of soil consistency, namely, soft and medium are considered in the present analysis. The Poisson's ratio (υ) of soil is considered to be equal to 0.5 for all types of clay (IS: 5249,1992). Various soil parameters considered for the present analysis are given in Table 1. A plan area of 8.5 m × 8.5 m is taken for raft and superstructure floor area to calculate gravity loading accounted for design of floating piles. It is assumed that the superstructure weight is taken by raft based on its allowable bearing capacity, and the remaining part is assumed to be carried by pile foundation. A feasible range of L_p/D_p ratios are selected and, length and diameter of pile are obtained by trial and error approach. In some cases, unrealistic values of length and diameter of pile are observed to maintain feasible range of L_p/D_p ratios. However those values are considered in the present analysis for academic interest. It can be noted that for group of piles area ratio is considered to be same as single piles. Equivalent spring stiffness values are calculated for different soil consistency values. A typical case study of soil-pile-structure idealised system is presented in Table 2.

Table 1: Typical Soil Parameters Considered for Study (Bhattacharya and Dutta, 2004)

Parameters	*Consistency of Clay*	
	Very Soft	*Medium*
SPT N value	1.0	6.0
c_u (kPa)	9.8	36.8
γ_{sat} (kN/m^3)	13.5	18.5
Compression index (C_c)	0.279	0.135
Void ratio (e_0)	1.20	0.72
Young's Modulus, E_s (MPa) (Bowles 1997)	5.0	30.0

4. RESULTS AND DISCUSSION

The total shear in ground storey columns ($V_{B,col}$) and the total shear transmitted to soil ($V_{B,ssi}$) are obtained for soil-pile raft-structure system considering selected range of parameters. These base shear forces are normalised by the base shear ($V_{B,fixed}$) obtained in fixed base condition. Normalised base shears ($V_{B,ssi}/V_{B,fixed}$ and $V_{B,col}/V_{B,fixed}$) are plotted as a function of period of structures at fixed base condition in Fig. 2. Fig. 2(a), (b), (e) and (f) show that the ratio of $V_{B,col}/V_{B,fixed}$ values are less than 1.0 for very soft and medium soil which indicates that shear force in columns are less if soil-pile-structure interaction has been considered, as compared to the shear forces estimated from fixed base condition. For example, the value of $V_{B,col}$ is about 40% of $V_{B,fixed}$ for very soft soil, when natural period of fixed base structure is about 0.5 sec. Further the scenario seems to be other way round for the lateral shear carried by piles. The shear carried by piles is close to the total lateral base shear $V_{B,ssi}$ transmitted by the entire system to soil. Fig.

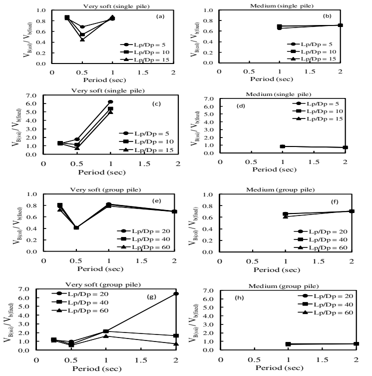

Fig. 2: Variation of Normalised Base Shear with Consistency of Soil, L_p/D_p Ratios, Pile Configuration for Different Periods of Superstructure

Table 2: Cases of Soil-pile Foundation-Structure Systems Considered

Case	*Soil*			*Pile*				*Raft*	*Superstructure*	
	Consistency	c_u *(kPa)*	K_s *(KN/m^3)*	D_p *(m)*	L_p *(m)*	L_p/D_p	*Pile Configuration*	*Size (m × m)*	*No. of Storey*	T_{fixed} *(Sec.)*
A	Very soft	9.8	5784	1.20	6	5	Single	8.5 × 8.5	2	0.25
				1.00	10	10				
				0.80	12	15				
				0.30	6	20	Group			
				0.25	10	40				
				0.20	12	60				

2(c) and (g) show that the shear forces in the pile embedded in soft soil may be as high as 5 times the shear forces obtained in fixed base case as the additional effect due to inertia force absorbed in heavy foundation is included. However, shear forces in the pile seems to be lower than the fixed base condition for medium soil as is evident from Fig. 2(d) and (h). Perhaps, the effect is much subdued in medium soil due to lesser soil flexibility. In fact, soil pile raft structure system experiences two primary effects. One is a tendency of reduction in base shear resulting from period lengthening while the other is a possibility in increase in the same due to additional inertia force attracted by the moving mass of the pile raft foundation. For soft soil, the foundation itself has a very heavy mass and thus overrules the former effect while vice versa takes place in case of medium soil.

Present study indicates that, the shear force in the pile may increase significantly or decrease marginally as compared to base shear force in fixed base condition due to the soil-structure interaction effect. This aspect is not adequately incorporated in available design standard. However, a detailed investigation in this aspect considering feasible range of soil and structural parameters is necessary.

5. CONCLUSION

This limited study indicates that columns may be overdesigned while pile may be underdesigned for structure supported on raft pile system in soft soil if a fixed base condition is considered. However, this is an indicative study which points out the need of making a further detailed study in this direction to avoid oversafe column design and unsafe pile design. This issue particularly becomes important after observing pile failure in 1964 Niigata Earthquake (Bhattacharya *et al.*, 2002).

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