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Effect of raft and pile stiffness on seismic response of soil-piled raft-structure system

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Abstract. Soil-pile raft-structure interaction is recognized as a significant phenomenon which influences the seismic behaviour of structures. Soil structure interaction (SSI) has been extensively used to analyze the response of superstructure and piled raft through various modelling and analysis techniques. Major drawback of previous study is that overall interaction among entire soil-pile raft-superstructure system considering highlighting the change in design forces of various components in structure has not been explicitly addressed. A recent study addressed this issue in a broad sense, exhibiting the possibility of increase in pile shear due to SSI. However, in this context, relative stiffness of raft and that of pile with respect to soil and length of pile plays an important role in regulating this effect. In this paper, effect of relative stiffness of piled raft and soil along with other parameters is studied using a simplified model incorporating pile-soil raft and superstructure interaction in very soft, soft and moderately stiff soil. It is observed that pile head shear may significantly increase if the relative stiffness of raft and pile increases and furthermore stiffer pile group has a stronger effect. Outcome of this study may provide insight towards the rational seismic design of piles.

Keywords: seismic base shear; pile-raft-structure interaction; raft flexibility; flexibility of piles; pile shear; column shear

1. Introduction

Piled raft foundation is considered to be a well engineered solution for mainly high-rise buildings, towers, skyscrapers, bridges and nuclear structures in soft to medium soil. Conventionally, piles are designed as a load bearing foundation element as well as settlement reducer under gravity loading, while the role of raft as a foundation member is generally ignored (e.g., Horikoshi and Randloph 1998, Poulos 2001, Liang and Chen 2004). However, recent studies

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emphasize 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). On the other hand, seismic design of structures supported on such foundation system is traditionally carried out assuming fixed base condition. Some studies as well as few design guidelines (e.g., Gazetas and Mylonakis 1998, Mylonakis and Gazetas 2000, Dutta *et al*. 2004, FEMA 451 2005, FEMA 356 2000, Eurocode 8-Part 1 1998 etc.) have addressed the importance of consideration of soil structure interaction (SSI) indicating a possibility of detrimental response in structure which overrules the common notion of beneficial response due to SSI. In reality, foundation offers a partial fixity at structure base level due to deformable characteristics of soil, and thereby leads to a change in dynamic response of a structure as compared to fixed base idealization. This is known as inertial interaction (FEMA 440 2005). On the other hand, kinematic interaction between pile and soil, leading to relative movement between pile and soil, was found to be marginal in case of pile embedded in soft soil (FEMA 440 2005, Gazetas 1984). Hence, present study only considers inertial interaction which is also recognised as governing criteria for design of flexible piles embedded in homogenous soil (e.g., Gazetas 1984, Kaynia and Mahzooni 1996, Rovithis *et al.* 2009). However, a recent study by the authors (Saha *et al.* 2013) has primarily attempted to examine the influence of SSI on distribution of seismic design forces at different elements of a soil-pile raft-structure system. This study clearly indicates that relative acceleration of heavy raft and upper part of the pile with respect to the neighbouring soil attracts extra lateral force which may lead to considerable increase in pile head shear. Interestingly, looking at such phenomenon with common notion about SSI leading to period lengthening may appear to be a bit counter intuitive. Further, the change in modal coupling when a soil-pile raft-structure interaction is considered, may lead to increase in lateral shear in column as well as in pile. These issues act as a major motivation to study the problem in further detail identifying the combination of influential parameters increasing or decreasing to such design quantities. This issue seems to be more meaningful from the viewpoint of design. The design aspects involving response in element of such system is not given adequate attention though the intricacies of different level of rigour of modelling were extensively studied.

The importance of soil-pile foundation-structure interaction is highlighted in previous studies (for e.g., Jeremic *et al*. 2004, Boulanger *et al*. 1999, Badoni and Makris 1992, Gazetas *et al.* 1993, Liyanapathirana and Poulos 2005, Rovithis *et al*. 2009, Giannakou *et al.* 2010, Chore *et al.* 2014). Several researchers proposed various approaches to simulate behaviour of soil-pile-structure interaction encompassing either coupled (e.g., Kagawa and Kraft 1980, Guin and Banerjee 1998, Curras *et al*. 2001, Rovithis *et al*. 2009, Jeremic *et al*. 2004, Hutchinson *et al*. 2004, Dode *et al.* 2014 etc.) or uncoupled analysis techniques (Gazetas *et al.* 1993, Liaranapathirana and Poulas 2005, Ghosh and Lubowski 2007) with a fair compromise between rigor and accuracy. In coupled analysis, beam on dynamic Winkler foundation (BDWF) idealization for SSI modelling was found to be relatively simplified and computationally less expensive than 3D-continuum analyses. While, the acceptability of BDWF approach was validated through experimental studies idealizing pile-soil deformation by nonlinear dynamic *p-y* curve (Boulanger *et al.* 1999, Curras *et al*. 2001, Chau *et al.* 2009). However, soil is also considered as linear material for obtaining the response of pile under low to moderate dynamic loading (e.g., Tajimi 1969, Novak *et al.* 1974, Pender and Satyawan 1996, Gazatas and Dobry 1984, Makris and Gazetas 1992). Further, a recent study (Mandal *et al.* 2012) based on elastic pile-soil continuum analysis proposed a simplified technique for evaluation of lateral capacity of pile. From the above viewpoint, it is observed that modelling intricacy has been studied in detail, while relatively less attention has been paid to the overall

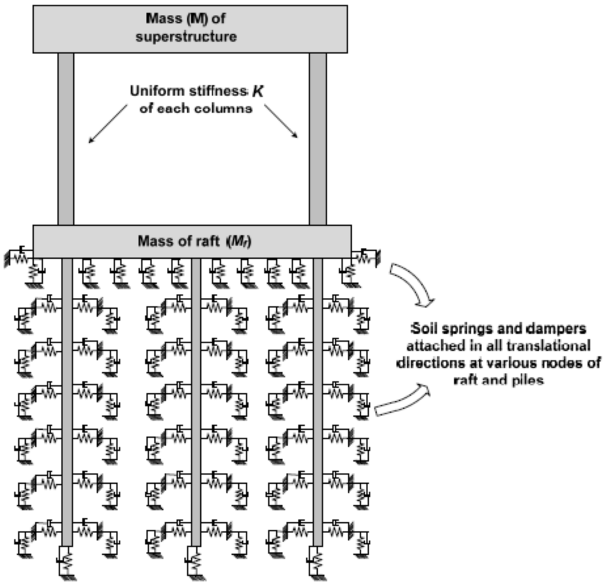

Fig. 1 Schematic representation of simplified model for soil-pile raft-structure system

seismic behaviour of soil-pile raft-superstructure system attributing change in design forces at various components (e.g., Curras *et al*. 2001, Rovithis *et al*. 2009, Jeremic *et al*. 2008 etc.). Furthermore, explicit seismic design guidelines are rather limited for structures supported on pile foundation incorporating SSI. The effect of various parameters pertaining to piled raft foundation, such as relative stiffness of raft and soil, relative stiffness of pile and soil, slenderness ratio of pile, spacing of pile and soil consistency were outlined as controlling factors in design of such foundation (e.g., Horikoshi and Randloph 1998, Hain and Lee 1978, Clancy 1993). The influence of such parameters was not explicitly investigated in previous study (saha *et al.* 2013) so that it may give an optimum seismic design guideline for soil-pile raft-structure system. These aspects are examined in this study.

Thus, the objective of the present study is to gaze the increasing effect on seismic forces due to extra inertia contributed by raft influenced by various influential parameters associated with piled raft system. Effect of soil-pile foundation-structure interaction on seismic response of structures (primarily of ground storey columns and piles) encompassing different associated parameters, viz., relative stiffness of raft (k_{rs}) and pile ($k_p=E_p/E_s$), length to pile diameter (L/d) ratios and pile spacing (s) to diameter (d) ratios (s/d) of pile is studied in the present scope of the paper. In order to examine the responses of the system incorporating various analysis techniques, namely, response spectrum analysis, equivalent static analysis and time history analysis are considered. A comparison of shear force obtained from different analysis methods at column and pile head of pile-raft-structure systems is also examined. Results are presented in the form of normalised design forces at column and pile head to the same obtained due to fixed base idealization. Pile-soil deformation is considered to be linear. Dynamic effect during seismic shaking is attempted to be captured considering an idealized one storey system supported by piled raft foundation. This parametric study may provide crucial inputs in refining design guidelines of soil-pile raft-superstructure system.

2. Modeling of soil- pile raft- structure interaction

A simplified model shown in Fig. 1 is considered to represent the soil-pile raft-structure system. The modeling of whole pile raft-soil-superstructure system is presented separately for (i) superstructure (ii) interaction between raft and soil and (iii) interaction between pile and soil.

2.1 Modeling of superstructure

Superstructure is considered as a three dimensional space frame structure which consists of four column members supporting a rigid deck slab resembling single storey single degree of freedom (SDOF) system. Elastic beam-column element is used for columns and their stiffness values are achieved by assigning sectional properties. Rigid diaphragm element is used to define the slab through which mass is defined. Structural fixed base condition is achieved by restraining all degrees of freedom at all column supports. Present study considers fundamental periods of 0.25 sec, 0.50 sec, 1.0 sec, and 2.0 sec of such equivalent SDOF systems which represent typical short, medium and long period structures respectively. Note that, fundamental periods are obtained by adjusting the mass and stiffness properties of the SDOF system.

2.2 Raft-soil interaction model

A square raft is modeled using four noded plate elements discretised into square meshes with thickness equals to the raft thickness. Mesh sensitivity analysis is performed to achieve the convergence in the response. Raft-soil interaction is modeled using distributed linear springs and dashpots connected to each node of entire raft in all translational degrees of freedom. Dutta *et al.* (2009) described that this particular concept may capture raft-soil interaction more rationally as compared to the use of equivalent springs located at centroid of a foundation for each degrees of freedom as suggested by Gazetas (1991). In fact, Dutta *et al.* (2009) showed that distributed spring over the entire raft gives a realistic stress distribution in raft itself with due consideration of soil flexibility. Furthermore, incorporation of vertical springs in raft takes care of coupled lateral-rocking mode of vibration (Gazetas 1991). Raft slab is discretised into $n \times n$ plate elements. Hence, springs are attached to each of the $(n+1)\times(n+1)$ nodes in all degrees of freedom. Stiffness of distributed lateral springs in three mutually perpendicular directions (lateral (K_{x1}), longitudinal (K_{x2}) and vertical (K_y)) are given below as prescribed in well accepted literature (Dutta *et al.* 2009)

$$K_{x1} = K_{xG1} / n^2 \tag{1a}$$

$$K_{x2} = K_{xG2} / n^2 \tag{1b}$$

$$K_y = \frac{K_v}{(n^2 + 2)} \tag{2}$$

where K_{xG1}, K_{xG2} and K_v are the overall lateral, longitudinal and vertical stiffness values of soil spring (see Table 1) proposed by Gazetas (1991), G is the shear modulus of soil, L_R is the half length of raft and v is the Poisson's ratio of soil. Formulae for K_{xG1}, K_{xG2} and K_v are presented in Table 1 for arbitrary shaped footing. However, the calculated values of K_{xG1} and K_{xG2} are equal for square raft considered in this study. The shear modulus of soil (in t/ft^2) is given by (Ohsaki and Iwasaki 1973)

Table 1 Stiffness of equivalent springs along various degree of freedom (Gazetas 1991)

Degrees of freedom	Stiffness of equivalent soil spring
Vertical (K_v)	$(2GI_R/(1-v))(0.73+1.54\chi^{0.75})$
Horizontal (K_{xG1}) (lateral direction)	$(2GI_R/(2-v))(2+2.54\chi^{0.85})$
Horizontal (K_{xG2}) (longitudinal direction)	$(2GL_R/(1-v))(0.73+1.54\chi^{0.75}) -(0.2/(0.75-v))GL_R(1-(B/L_R))$

Table 2 Typical Soil parameters considered for study as used in Bhattacharya *et al*. (2004).

Stiffness of clay	N value	Shear strength, S_u (kN/m^2)	ϕ (degree)	γ_{sat} (kN/m^3)	Compression Index, C_c	Void Ratio (e_0)	Young's Modulas, E_s (MPa) (Bowles 1997)
Very Soft	1	9.80	0	13.50	0.279	1.200	2.5
Soft	3	18.50	0	17.0	0.189	0.90	5.0
Moderately stiff	6	36.80	0	18.50	0.135	0.720	15.0

$$G = 120N^{0.8} \tag{3}$$

where $\chi=A_b/4L_R^2$, A_b is the area of the foundation considered; B and L_R are half width and half length of a rectangular foundation, respectively; G is shear modulus of soil and ν is the Poisson's ratio of soil.

where N is the SPT value of soil. Shear modulus of soil is calculated on the basis of reference SPT-N value as given in Table 2. Three different types of soil consistency, namely very soft, soft and moderately stiff are considered and their representative SPT-N values along with other parameters assumed are presented in Table 2. The G values for all three different soil types are estimated, and subsequently spring stiffness values are estimated using Eqs. (1) and (2) and assigned to raft nodes according to their influence area. Note that, raft-soil spring action is modelled following the study on dynamic stiffness of shallow foundation (Gazetas 1991), which is assumed to be valid for piled-raft, since these spring stiffness values primarily depend upon soil shear modulus which is an intrinsic property of soil.

Through distributed spring approach adopted in the present study as suggested in Dutta *et al*. (2009), the compressibility characteristics of soil as well as different mode of movements of raft can well be simulated. Stiffness values are observed to be dependent on the frequency of forcing function and as a result of which a frequency dependent multiplier is generally used to obtain their dynamic counterpart (Gazetas 1991). This multiplying factor was addressed as a function of a non-dimensional parameter a_0 where $a_0=\omega B/V_s$ (Gazetas 1991). Here, ω is the frequency of forcing function, B is the half of the width of the footing and V_s is the shear wave velocity in soil medium. However, a real earthquake contains pulses with different frequencies. Hence, it is difficult to adopt any particular frequency dependent factor in terms of a_0. Due to this reason, few studies (Parmelee *et al.* 1969, Prakash and Puri 1988) have ignored such factor. From this viewpoint, present study considers such multiplier as unity throughout the analysis.

Behaviour of piled-raft essentially depends on flexibility of raft expressed as the relative stiffness of raft and soil, k_{rs} (Clancy and Randolph 1996, Horikoshi and Randolph 1998), given by

$$k_{rs} = \frac{4}{3\pi} \frac{E_r \times B_r \times t_r^{\,3}(1-\nu^2)}{E_s L_r^{\,4}(1-\nu_r^{\,2})} \tag{4}$$

where E_r and E_s are the Young's modulus of raft and soil respectively, L_r and B_r are the raft length and breadth respectively, t_r is the raft thickness, ν_r and ν are the Poisson's ratio of raft and soil, respectively. The value of k_{rs} decides whether a raft behaves as a flexible or rigid element. According to Horikoshi and Randolph (1997), increasing order of k_{rs} indicates the raft behaviour changes from flexible behaviour to a rigid one. Hence, present study incorporates recommended values of k_{rs} to represent the flexible to rigid behaviour of raft.

2.3 Pile-soil interaction model

Pile-soil interaction is modeled using classical beams on dynamic Winkler's foundation (BDWF) where discrete soil springs are considered to be attached at pile nodes in all translational degrees of freedom. Pile is modeled using two noded linear beam-column elements (in which three translations in three mutually orthogonal axis and three rotations about same three axis per node are the nodal degrees of freedom). Soil is idealized with springs having linear behaviour. Stiffness values of such discrete springs are calculated on the basis of projected tributary area of contact between pile and soil. Gapping action between soil and pile under tension is not considered, since gapping effect seems to be marginal in case of fixed head pile (Pender and Satyawan 1996). Pile is divided into sufficient number of elements to obtain a reasonable accuracy in results.

Stiffness of horizontal soil springs proposed by Roesset and Angelides (1980) is considered in present study as given below

$$k_x(z) = \delta E_s(z) \tag{5}$$

where δ is a constant, k_x and E_s are spring stiffness (unit in kN/m^2) of soil and Young's modulus of soil respectively. Typical values of δ for various soils may vary from 1.0-1.2 for fixed-head pile (Gazetas and Dobry 1984). A fixed value of δ=1.2 is considered for the present analysis as recommended by Mylonakis and Gazetas (2002), Gazetas *et al.* (1993), Markis and Gazetas (1992).

Vertical springs are connected to pile tip representing tip resistance. Further, vertical springs attached at pile shaft represent frictional resistance offered at pile shaft. The equivalent spring stiffness of soil connected to each of the pile nodes are calculated based on Young's modulus of soil and tributary area of pile shaft (see Appendix A for details). Note that, soil spring stiffness is independent of frequency of input motion due to its marginal impact on system response (Makris and Gazatas 1992, Gazatas *et al.* 1993, Novak 1974, NCHPR 461 2001). Pile group interaction factor under dynamic lateral loading is not considered in the present study in order to avoid additional complexity as this only marginally influences the dynamic response of whole system considering kinematic interaction as recommended by Gazetas *et al.* (1991). However, the inertial interaction was found to be sensitive for particular frequency ranges (Dobry and Gazetas 1988) which may be explored in future scope of study.

2.4 Depth-wise variation of soil stiffness

An idealized constant soil profile is assumed in this study to define soil stiffness. Constant soil profile indicates uniform variation of $E_s(z)$ with depth which represents a homogenous medium. Gazetas and Dobry (1984) and Gazetas (1984) stated that consideration of various depth-wise distribution (e.g., constant, linear and parabolic) of soil, $E_s(z)$, covers variation of properties in wide range of soil profiles. However, the effect of these three different idealised soil profiles on seismic response of soil-pile raft-structure system is found to be marginal (Saha *et al.* 2013). Hence, present study considers only constant soil profile for the sake of brevity of the paper. Soil spring stiffness values at all pile nodes (i.e., situated at different soil depth), $k_x(z)$ are obtained from the assumed soil model.

3. Parametric case studies

Behaviour of soil-pile raft-superstructure system is investigated with the following parameters: four natural periods of vibration (T_{fixed}), namely 0.25 sec, 0.5 sec, 1.0 sec, and 2.0 sec are considered. These values broadly reflect the fundamental natural periods of two storey, five storey, ten storey and twenty storey building, respectively. Three different types of homogenous clay namely, very soft, soft and moderately stiff are considered in the present study. Three values of relative stiffness of raft (k_{rs}), values, namely 0.01, 0.1, 1.0 and 10 are chosen to encompass flexible to rigid behaviour of raft. Three relative stiffness values of pile, expressed in terms of E_p/E_s, namely 10000, 5000 and 1500 are selected for piles embedded in very soft, soft and moderately stiff clay, respectively. Young's modulus of pile is taken as E_p=25×10^6 kN/m^2. Note that, Young's modulus of pile and raft are assumed to be same. The Young's modulus of soil are referred from well accepted literature (Bhattacharya *et al*. 2004, Dutta *et al.* 2009, Bowles 1997) and presented in Table 3. Two different pile spacing (s) to diameter (d) ratios namely s/d=3 and 7 for T_{fixed}=0.5 sec and s/d=3 and 5 for T_{fixed}=1.0 sec are considered in the present study. The values of s/d ratios for two different T_{fixed} values are selected on the basis of feasible spacing for the selected area of raft. The effect of flexible and stiff behaviour of pile during lateral load is also investigated considering different slenderness ratios (L/d) of pile. L/d ratios for flexible (for example L/d=100, 75, 60 irrespective of all consistency of soil) and for stiff pile group (L/d=20 in E_p/E_s=10,000, L/d=18 in E_p/E_s=5,000 and L/d=13 in E_p/E_s=5,000) are selected. Three different choices of L/d ratio in case of stiff pile for three different soil consistencies are obtained based on active length consideration under lateral loading as suggested in literature (Gazetas 1984). Active length of pile depends on E_p/E_s ratio, where E_s varies with type of soil.

A piled raft having plan area of 10 m × 10 m is taken into consideration and a plan area of 8.5 m×8.5 m is retained for superstructure floor on the boundary of which peripheral columns are placed. Based on a convergence study, raft is discritized into 1600 elements (40×40) and piles are divided into 20 elements irrespective of L/d ratios. Vertical load is considered to be 8.0 kN/m^2 per superstructure floor area with a realistic consideration of combined live and dead load. Further, an additional dead load depending on design thickness of raft is included with the total superstructure load for design of piled raft foundation. Floating pile group is designed on the basis of imposed superstructure load and subsoil condition. It is assumed that a part of the superstructure weight is taken by the raft based on the allowable bearing capacity of soil it is resting on. The remaining weight is considered to be carried by piles which admitted in current design philosophy of piled raft foundation (Horokoshi and Randolph 1998, Hain and Lee 1978, Clancy and Randolph 1996). Material properties of reinforced concrete are used for the structural elements.

A detailed scheme presenting all case studies are summarised in Table 3. While attempting to arrive at only realistic cases, it has been found that piled raft foundation is a feasible footing system for very soft soil, while such a foundation system may become uneconomic for structures on soft to medium soil if they have less number of storeys having less fundamental natural period. These cases are not included in present study. However, superstructure with fundamental period

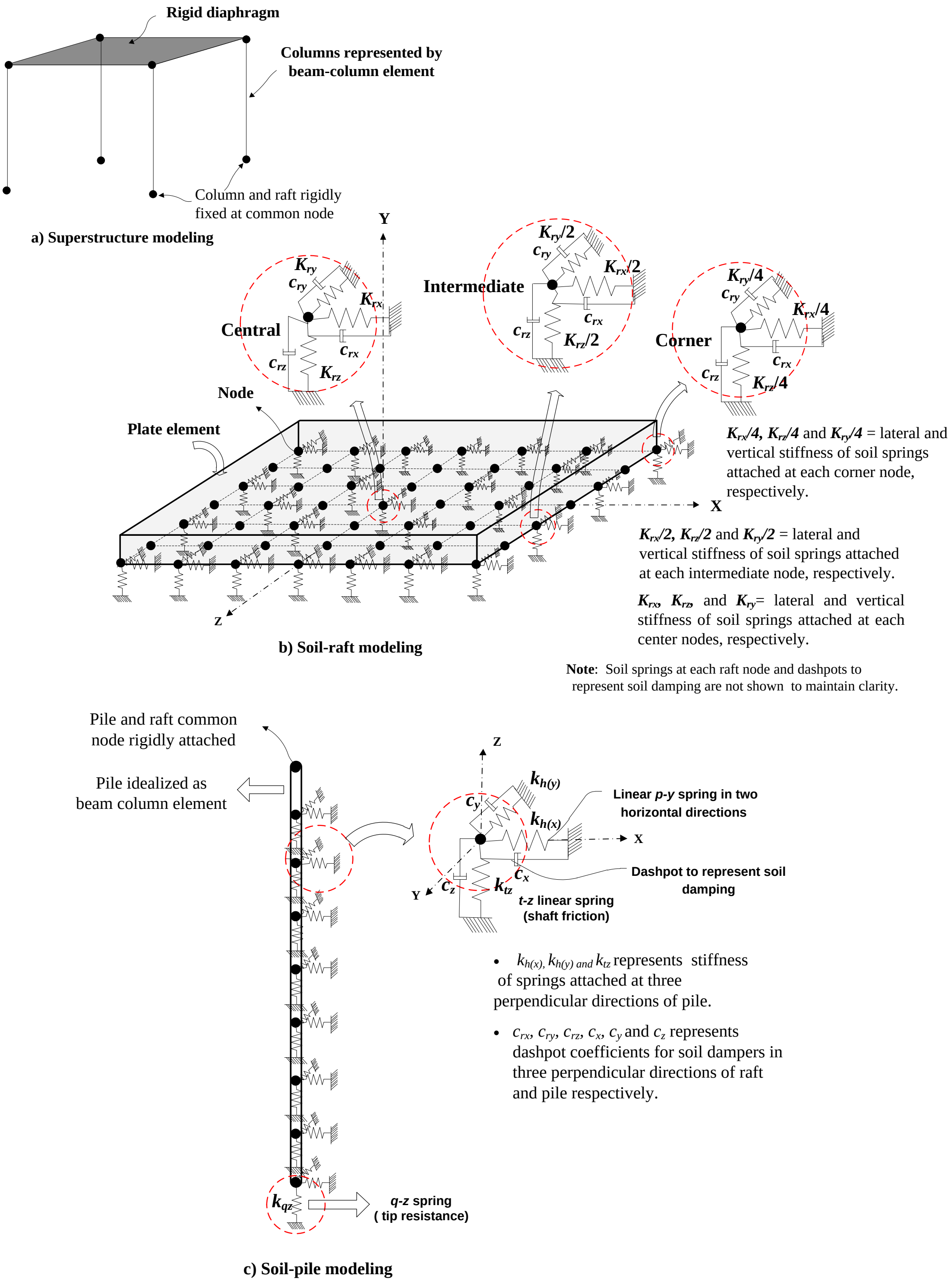

Fig. 2 Representation of finite element model (a) Superstructure, (b) Raft-soil and (c) Pile-soil system

(T_{fixed}) of 0.25 sec constructed on very soft soil is found to be an exceptional case, for which piled raft foundation is a too conservative solution. From this viewpoint, two storey building conforming to an approximate fundamental period of 0.25 sec is excluded from the present scope of analysis.

4. Methodology for analysis

Finite element method of analysis is adopted to obtain the response of soil-pile foundation-superstructure system through solving traditional Eigen solution and subspace iteration method. Fundamental frequency (or fundamental natural period) of system incorporating soil-structure interaction is obtained and compared with fixed base period of superstructure. A schematic diagram of detailed FE model is presented in Fig. 2. Seismic base shear forces are estimated for each case analysed in this study using the following seismic analysis methods:

4.1 Response spectrum analysis

In case of response spectrum based seismic analysis, design response spectrum of Indian earthquake code IS 1893-Part-I (2002) is adopted (see Fig. 3(a)). Dynamic analysis is conducted by combining the contributions of all significant lateral modes using complete quadratic combination (CQC) method, since it incorporates the contribution of various modes for different natural frequencies with reasonable accuracy. Seismic base shear is obtained by selecting seismic zone factor=0.36 for severe seismic intensity, reduction factor=3.0 for ordinary moment resisting frame, importance factor=1.0 for general residential building frames as given in IS 1893-Part-I (2002). Soil site factor is considered as Type II and III to obtain the response of structure founded in very soft, soft clay and moderately stiff clay respectively.

4.2 Equivalent static approach

In the case of equivalent static approach, base shear is obtained using specified response spectrum (see Fig. 3(b)) presented in Uniform Building Code (UBC 1997). The following parameters are considered: seismic zone factor=0.40 for severe seismic intensity, importance factor=1.0 for standard occupancy, soft and stiff soil profile types having shear wave velocity less than 180 m/sec. and 320 m/sec., seismic source factor=1.0 with the consideration of closest distance to known seismic source being greater than 10 km to 15 km. Two different soil profiles are considered in order to rationally predict the response in very soft to soft and moderately stiff soil respectively as considered in parametric cases of present study.

4.3 Time history analysis

Time history analysis is also performed to obtain the base shear forces. Present study considers a ground motion having peak ground acceleration of 0.1 g observed at JMA Kobe observatory station during 1995 Kobe earthquake (Fig. 3(c)). North-south component of the motion is applied at the base of the structure during analysis.

Three different analysis techniques attributing two different codal spectrums and one typical recorded earthquake motion are attempted with an aim to recognize the effect of SSI in broad

Table 3 Summary of case studies

Soil stiffness	Time period of structure T_{fixed} (sec.)	Relative stiffness of pile ($k_p=E_p/E_s$)	Relative stiffness of raft (k_{rs})	Raft thickness (m.)	*L/d*	Pile behaviour	Soil profile	Design Pile group
Very Soft (E_s=2500 kN/m^2)	0.5, 1.0, 2.0	10^4	1.0	0.9	100	Flexible	Const.	4×4, 6×6, 8×8
			1.0	0.9	75	Flexible	Const.	4×5, 6×7, 9×9
			0.01	0.2	60	Flexible	Const.	3×3, 6×6, 9×9
			0.1	0.4		Flexible	Const.	4×4, 6×7, 10×9
			1.0	0.9		Flexible	Const.	5×5*, 7×7**, 10×10
			10.0	1.5		Flexible	Const.	5×5, 7×7, 10×10
			0.01	0.2	20	Stiff	Const.	5×5, 10×10, NF
			0.1	0.4		Stiff	Const.	7×7, NF, NF
			1.0	0.9		Stiff	Const.	8×9, NF, NF
			10.0	1.5		Stiff	Const.	NF, NF, NF
Soft (E_s=5000 kN/m^2)	0.5, 1.0, 2.0	5×10^3	1.0	1.1	100	Flexible	Const.	NR, 3×3, 6×5
			1.0	1.1	75	Flexible	Const.	NR, 4×4, 6×6
			0.01	0.3	60	Flexible	Const.	NR, 3-1-3, 6×6
			0.1	0.5		Flexible	Const.	NR, 4×3, 8×5
			1.0	1.1		Flexible	Const.	NR, 4×5, 7×7
			10.0	1.85		Flexible	Const.	4×4, 4×5, 7×7
			0.01	0.3	18	Stiff	Const.	NR, 5×6, NF;
			0.1	0.5		Stiff	Const.	NR, 6×6, NF;
			1.0	1.1		Stiff	Const.	NR, 8×8, NF;
			10.0	1.85		Stiff	Const.	7×7, 9×9, NF
Moderately stiff (E_s = 15000 kN/m^2)	0.5, 1.0, 2.0	1500	1.0	1.6	100	Flexible	Const.	NR, NR, 4×3
			1.0	1.6	75	Flexible	Const.	NR, NR, 4×4
			0.01	0.4	60	Flexible	Const.	NR, NR, 3×3
			0.1	0.8		Flexible	Const.	NR, NR, 4×3
			1.0	1.6		Flexible	Const.	NR, NR, 4×5
			10.0	3.25		Flexible	Const.	4×4, 4×4, 5×6
			0.01	0.4	13	Stiff	Const.	NR, NR, 6×6
			0.1	0.8		Stiff	Const.	NR, NR, 6×6
			1.0	1.6		Stiff	Const.	NR,NR, 8×9
			10.0	3.25		Stiff	Const.	8×8, 7×9, NF

Note: 4×4 pile group indicates 4 nos. of pile in row and 4 nos. in column; Const. indicates constant; NF indicates pile group of selected *L/d* ratio is not feasible to place under particular raft size; NR indicates pile not required, 5×5* indicates two different pile group configurations are incorporated, i.e., (*s/d*=3 & 5) and similarly 7×7** indicates two different configurations, i.e., (*s/d*=3 & 7). Remaining all other cases of pile group are designed at *s/d*=3 if otherwise mentioned.

sense independent of methodology adopted.

The seismic base shear is obtained corresponding to 5% of critical damping considering fixed base condition as well as incorporating interaction among soil, pile, raft and structure. Roy and Dutta (2010) has conducted a study in order to observe the effect of foundation damping

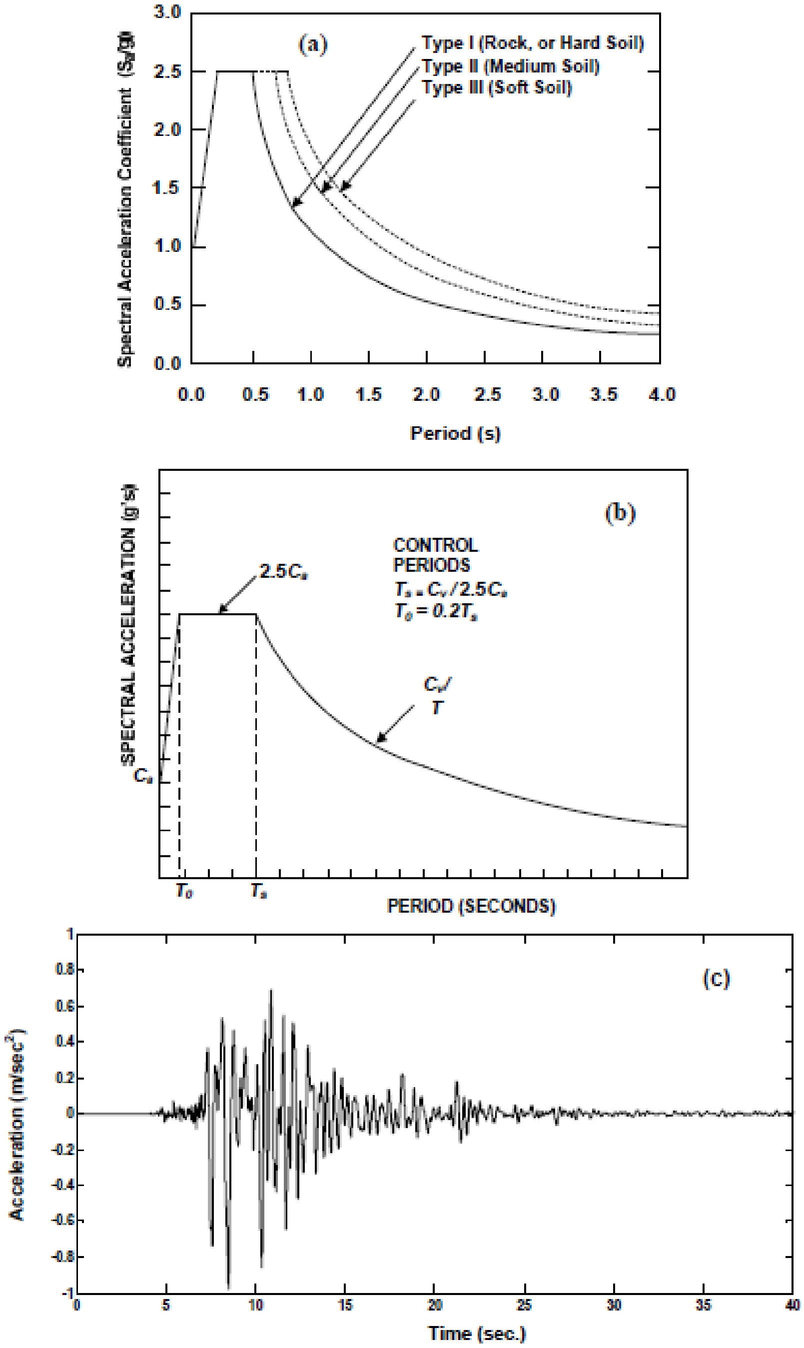

Fig. 3 Details of design spectrum and ground motion used in the present analysis: (a) IS:1893 Part-I (2002), (b) UBC (1997), (c) Time history recorded during 1995 Kobe earthquake (Scaled)

(incorporating material and radiation damping of soil) with feasible ranges of soil damping (2% to 30%), on overall response of the system. They reported that consideration of 5% of critical damping in each mode of combined structure, foundation and soil system overestimates the response of system marginally. Therefore, to strike a balance between rigour and accuracy, 5% of critical damping in each mode of vibration of soil, raft, pile and superstructure system is considered.

5. Results and discussion

The results are expressed in the form of ratio of response quantity obtained considering the effect of soil-flexibility with that of the fixed base condition as a function of various influential parameters. Lengthening of period of such structure supported by piled raft foundation and its effect in developing shear force at column as well as pile head under seismic loading is primarily investigated. The results aim to study mainly the effect of relative stiffness of raft and pile along with other associated parameters on the response quantities.

5.1 Validation of proposed numerical model

To validate the proposed numerical model, an attempt has been made by comparing fundamental lateral natural period of the present model incorporating SSI effect with different well accepted empirical or semi-analytical solutions available in literature (e.g., Rovithis *et al.* 2009). These classical expressions used for calculating fundamental natural period of structure incorporating SSI are suggested by different investigators (Veletsos and Meek 1974, Gazetas 1996, Maravas *et al.* 2007). The lateral natural period considering SSI from these classical formulations are computed and compared with the values obtained by present method of analysis using a simplistic soil-pile-raft-structure model for a few benchmark cases as presented in Table 4. It has been found that the present model predicts the fundamental natural period of soil-pile raft-structure system with reasonable accuracy and may be used further for obtaining valuable insight into the seismic behaviour of such structural systems. It is to be noted that in empirical or semi-analytical formulations, frequency dependent pile group stiffness which is a function of group interaction factor are used to calculate the lateral period of the system incorporating SSI. While on the other hand, proposed numerical model calculates the SSI period without any consideration of frequency dependent group interaction factor. Interestingly, it has been observed that influence of such group interaction factor on fundamental period of SSI systems is seem to be marginal for the benchmark cases considered in the present study. Further, it is also observed that the influence of cross sway-rocking stiffness of pile group as used in semi-analytical expression proposed by Gazetas *et al.* (1996), in obtaining fundamental period of whole SSI system is negligible for the considered cases herein. These issues may be investigated in detail considering a wide variation of system parameters to arrive at more definite conclusions.

Present analysis considers linear behaviour of soil. The acceptability of linear soil behaviour is studied by Saha *et al.* (2012). In this literature, it was identified that linear model of soil overestimates the column and pile shear forces in the range of 0-20% as compared to what is exhibited by an advanced nonlinear soil model (which uses dynamic *p-y* curve with gap element) proposed by Boulanger *et al.* (2009) for the same earthquake time history considered herein. Moreover, fundamental lateral period of different structures obtained from both the models are found to exhibit insignificant difference.

Table 4 Comparison of lateral natural period considering SSI computed by analytical expression with present analysis

Subsoil Stiffness (in terms of relative stiffness of pile)	Fundamental natural period under fixed base condition (T_{fixed}), sec.	L/d (dia = 0.3 m)	Raft thickness (m.) assuming k_{rs} = 1.0	Pile group used	Fundamental lateral natural period incorporating soil structure interaction (T_{ssi}), sec. — Analytical/Empirical approach — Veletsos and Meek (1974)				Gazetas (1996)				Maravas *et al.* (2007)				Present model with F.E. analysis
					a_0= 0.05	a_0= 0.3	a_0= 1.0	WGI	a_0= 0.05	a_0= 0.3	a_0= 1.0	WGI	a_0= 0.05	a_0= 0.3	a_0= 1.0	WGI	
Very soft (E_p/E_s= 10000)	0.50	20	0.9	8×9	0.59	0.56	0.56	0.56	0.62	0.59	0.56	0.59	0.59	0.56	0.56	0.56	0.52
	1.00	60		7×7	1.12	1.08	1.08	1.08	1.15	1.12	1.12	1.11	1.12	1.08	1.08	1.08	1.07
	2.00	60		10×10	2.07	2.04	2.04	2.04	2.09	2.06	2.06	2.06	2.07	2.04	2.04	2.04	2.09
Soft (E_p/E_s= 5000)	1.00	18	1.1	8×8	1.07	1.05	1.05	1.05	1.21	1.19	1.20	1.19	1.07	1.05	1.05	1.05	1.07
	2.00	60		7×7	2.10	2.07	2.08	2.07	2.12	2.10	2.10	2.1	2.10	2.07	2.08	2.07	2.09
Moderately stiff (E_p/E_s= 1500)	2.00	13	1.6	4×5	2.11	2.10	2.10	2.1	2.14	2.13	2.13	2.13	2.11	2.10	2.10	2.10	2.09
		60		3×4	2.17	2.17	2.16	2.16	2.22	2.22	2.21	2.21	2.17	2.17	2.16	2.16	2.15

WGI: Without group interaction.

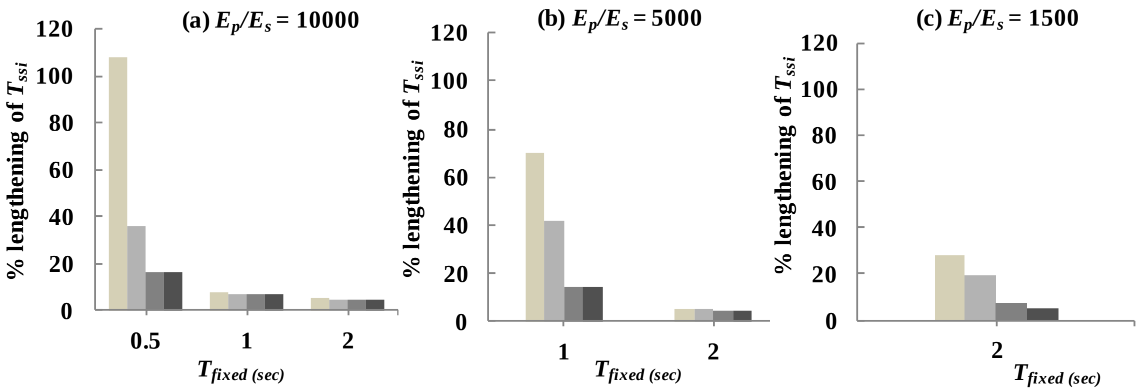

Fig. 4 Variation in percentage lengthening of T_{ssi} incorporating different k_{rs} values for flexible pile group (L/d=60). (a) E_p/E_s=10000 (b) E_p/E_s=5000 and (c) E_p/E_s=1500

5.2 Influence of SSI on natural period of the system

The fundamental lateral periods of vibration of pile supported raft-structure system accounting SSI (T_{ssi}) are obtained and compared with the natural periods of the structures defined under fixed

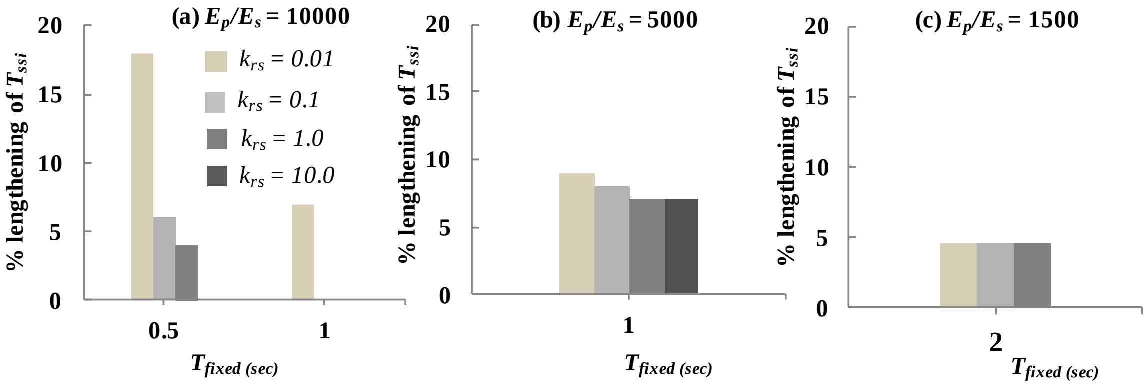

Fig. 5 Variation in percentage lengthening of T_{ssi} incorporating different k_{rs} values for stiff pile group: (a) E_p/E_s=10000 for L/d=20 (b) E_p/E_s=5000 for L/d=18 and (c) E_p/E_s=1500 for L/d=13

base conditions (T_{fixed}) in the form of percentage lengthening due to SSI. Further, the influence of various parameters associated with the design of piled raft foundation on percentage lengthening of period is explicitly investigated. These parameters are recognized as (a) relative stiffness of raft (k_{rs}) and pile (k_p), (b) flexible and stiff behaviour of piles (recognized by L/d ratios) and (c) spacing of pile by s/d ratios. Figs. 4(a) to (c) present percentage lengthening of T_{ssi} as a function of selected values of T_{fixed} for three different E_p/E_s ratios (10000, 5000 and 1500) and k_{rs} values in case of flexible pile group (L/d=60). Similar plots are presented in Figs. 5(a)-(c) for the case of rigid pile group.

It is observed that the effect of relative stiffness of raft on percentage lengthening of period for different fixed base systems irrespective of E_p/E_s and L/d ratios is significant. In general, such percentage lengthening due to different k_{rs} value is observed to be very high in flexible pile supported structures as compared to structures supported by stiffer pile group. For instance, in Fig. 4(a), percentage lengthening of fundamental lateral period for structure with T_{fixed}=0.5 sec may go up to 100% if L/d=60 and k_{rs}=0.01. However, percentage lengthening of T_{fixed}=0.5 sec structure increases by 15% for L/d=20 and k_{rs}=0.01 (Fig. 5(a)). This is due to the fact that stiffer pile group involves more number of piles in a group as compared to flexible one which leads to increase in lateral stiffness of the structure, and as a result percentage lengthening results to a relatively lesser value.

5.2.1 Effect of relative stiffness of raft (k_{rs})

The effect of k_{rs} on fundamental lateral period of structure is also evident from the same figures. Results show that lengthening of period due to different k_{rs} values is a function of relative stiffness of pile (E_p/E_s) irrespective of T_{fixed}. Fig. 4(a) shows that lengthening of fundamental lateral period of T_{fixed}=0.5 sec structure varies from 12%-110% if k_{rs} values varies from 10 to 0.01 (i.e., raft becomes rigid to flexible) for structure supported on flexible pile group (i.e., L/d=60) which is embedded in very soft soil (i.e., E_p/E_s=10000). However, in this case effect of k_{rs} on T_{ssi} is marginal for structures with T_{fixed}=1.0 sec and 2.0 sec. Interestingly, effect of k_{rs} on T_{ssi} is observed to be pronounced (see Fig. 4(b)) in case of structures with T_{fixed}=1.0 sec supported on flexible pile group which is embedded in soft soil (i.e., E_p/E_s=5000). But this similar effect of k_{rs} on T_{ssi} is marginal for structures having T_{fixed}=2.0 sec structure. Fig. 4(b) shows that variation in period lengthening is

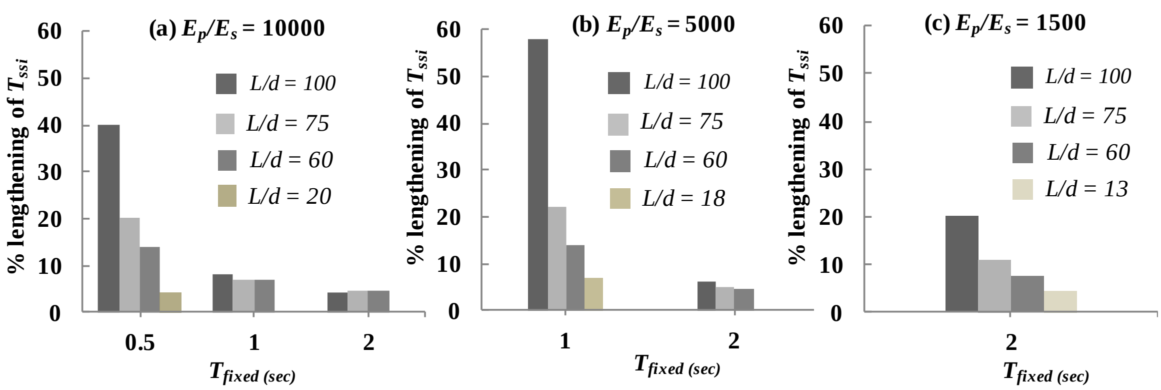

Fig. 6 Variation in percentage lengthening of T_{ssi} for different L/d ratios: (a) E_p/E_s=10000 (b) E_p/E_s=5000 and (c) E_p/E_s=1500, when k_{rs}=1.0

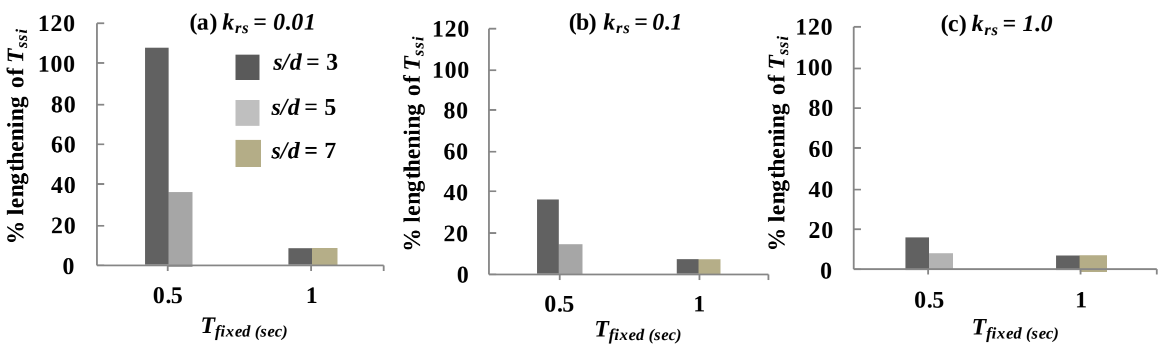

Fig. 7 Variation in percentage lengthening of T_{ssi} for different s/d ratios: (a) E_p/E_s=10000 (b) E_p/E_s=5000 and (c) E_p/E_s=1500

observed to be in the order of 10% to 70% if k_{rs} varies from 10 to 0.01 for T_{fixed}=1.0 sec structure.

5.2.2 Effect of relative stiffness of pile (E_p/E_s)

Similarly, when E_p/E_s value changes from 5000 to 1500 (i.e., soil consistency becomes moderately stiff from soft), lengthening of period varies from 5%-30% for T_{fixed}=2.0 sec structure (Fig. 4(c)). Effect of k_{rs} on period lengthening is significant in case of short period structure (T_{fixed}=0.5 sec) supported on rigid pile group which is embedded in very soft soil (see Fig. 5(a)). This change is subdued in case of structure supported on rigid pile group as compared to the same observed for structure supported on flexible pile group and for long period structures (i.e., T_{fixed}=1.0 sec and 2.0 sec).

5.2.3 Effect of L/d ratio

Effects of different slenderness ratios (L/d) of pile on lengthening of fundamental period of structure are presented in Fig. 6. It is observed that flexible pile in general exhibits relatively higher percentage of lengthening in period as compared to what is observed for rigid pile. For example, lengthening of period is observed to be about 40% for L/d=100, whereas lengthening of period is about 5% for *L/d*=20 when T_{fixed}=0.5 sec and E_p/E_s=10000 (see Fig. 6(a)). Figs. 6(b) and 6(c) indicate that period lengthening effect is observed to be same for structures having T_{fixed}=1.0 sec and 2.0 sec due to E_p/E_s ratios ranging from 5000 to 1500. In fact, the pile group lateral stiffness depends on relative stiffness of pile with respect to soil (i.e., E_p/E_s ratio), number of piles in a group, pile configuration (i.e., *S/d* ratio) and frequency dependent interaction factor (Makris and Gazetas 1992). As per gravity design, variation of *L/d* ratio causes variation in number of piles for a particular height of structure and the pile group stiffness accordingly gets modified. Further, the stiffness modifies with change in E_p/E_s ratio and interaction factor. Hence, the lateral period of the whole structural system which is a function of lateral stiffness of pile group increases with the increase in *L/d* ratio as observed in Fig. 6. While on the other hand, choice of a stiff/rigid pile group (i.e., *L/d*=20 in E_p/E_s=10000) involves maximum number of piles in a group leading to a marginal increase in lengthening of period.

5.2.4 Effect of s/d ratio

Figs. 7(a)-(c) present the effect of different *s/d* ratios on lengthening of natural period of structure for different fixed base systems incorporating selected k_{rs} value. A feasible combinations of *s/d* ratios of 3 and 7 (for T_{fixed}=0.5 sec) and 3 and 5 (for T_{fixed}=1.0 sec) are considered. The choice of maximum *s/d* ratio in each case is arrived on the basis of maximum feasible spacing arrangement for pile groups to be provided beneath the available raft area. The effect of *s/d* ratios is reflected only for relatively stiff period of structure (i.e., T_{fixed}=0.5 sec) irrespective of k_{rs} values. For instance, structure having T_{fixed}=0.5 sec, exhibits percentage lengthening of period in order of 100% and 40% for *s/d* ratios 3 and 7, respectively considering k_{rs}=0.01 (which designates highly flexible raft). Fig. 7 explains that the effect of *s/d* ratios on period lengthening is marginal for T_{fixed}=1.0 sec. Therefore, this implies that the lengthening of period of structures with stiffer natural period supported by piled raft system is significantly influenced by *s/d* ratios. Note that, such influence is noticed to be significant for flexible piled raft.

5.3 Study on seismic base shear

This section presents the variations of base shear for structures supported on piled raft foundation incorporating the effect of soil-structure interaction for the representative class of single degree of freedom structural systems with low to high fundamental natural period in fixed base condition. Such change in response due to the effect of soil- flexibility compared to the response under fixed-base condition is expressed as a ratio of shear forces obtained due to SSI to that at fixed base condition. The value greater than one of such quantity indicates increased response due to SSI and vice versa indicates decreased response. Since total shear transmitted to the soil is distributed through the total length of pile, the maximum shear (V_{Bpile}) in pile occurs at pile head level. These base shear forces are normalised with respect to the base shear (V_{Bfixed}) obtained under fixed base condition. Normalised base shear forces at ground storey columns (V_{Bcol}/V_{Bfixed}) and that at pile head (V_{Bpile}/V_{Bfixed}), respectively are plotted as a function of period of structures at fixed base condition.

5.3.1 Response for various code provisions implicating different analysis techniques

A comparison of shear force obtained from different analysis methods at column and pile head of pile-raft-structure systems pertaining to different natural period is discussed in this section. Fig. 8(a) to (d) present the normalized shear forces in column and pile head analyzed considering

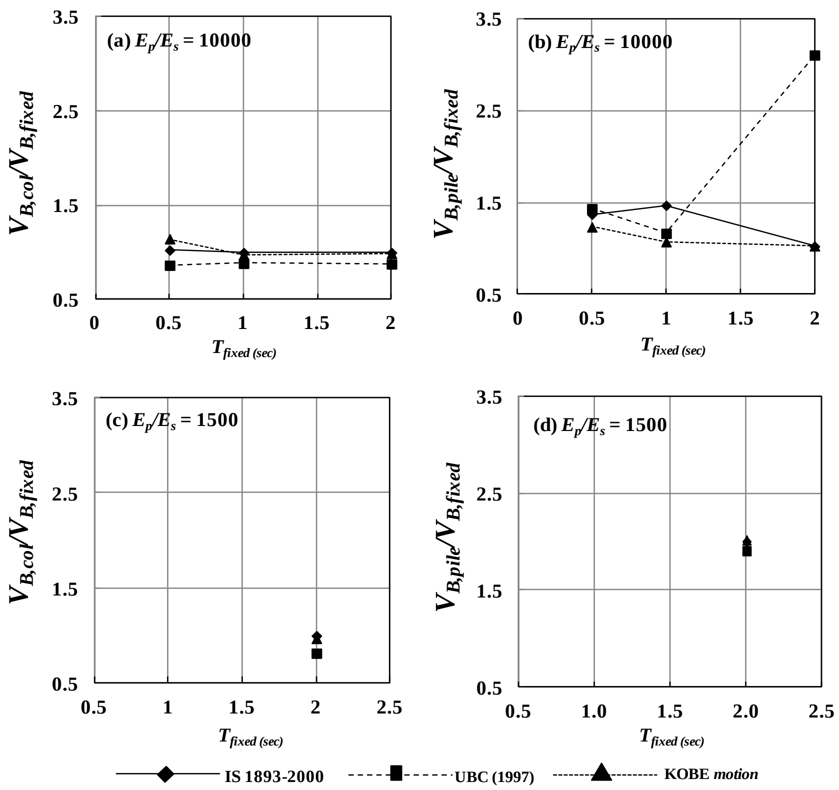

Fig. 8 Variation of normalised base shear for constant E_s distribution with depth, k_{rs}=1.0, s/d=3.0 and L/d=60 incorporating different analysis techniques: (a) and (b) represents $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ in E_p/E_s=10000; (c) and (d) $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ in E_p/E_s=1500

response spectrum analysis (IS 1893-Part-I (2002)), equivalent static approach (UBC (1997)) and time history analysis (acceleration history for 1995 Kobe earthquake) for E_p/E_s=10000 and 1500. Results indicate that a marginal difference is observed in prediction of the response quantities (i.e., normalized shear values) due to difference in methodologies. However, Fig. 8(b) shows that an exceptionally high response (approximately 3 times the shear obtained in fixed base condition) is observed in case of equivalent static method (UBC 1997) for T_{fixed}=2 sec and E_p/E_s=1500. This seems to be a conservative prediction as compared to other methods of analysis. Overall, comparative results in a limited form clearly indicate that SSI is an important factor to be considered in seismic design of piled raft supported structure irrespective of method of analysis.

5.3.2 Effect of relative stiffness of raft (k_{rs})

Effect of selected four different relative stiffness of raft (k_{rs}), on V_{Bcol} and V_{Bpile} is examined by all three analyses techniques considering L/d=60 and s/d=3. Figs. 9(a), (c) and (e) show variation of V_{Bcol}/V_{Bfixed} versus T_{fixed} values for selected k_{rs} values considering three analysis methods when E_p/E_s=10000. Similarly, variation of V_{Bpile}/V_{Bfixed} are obtained and presented in Figs. 9(b), (d) and (f). Similar types of results are presented in Figs. 10(a) to 10(f) considering soft soil (i.e.,

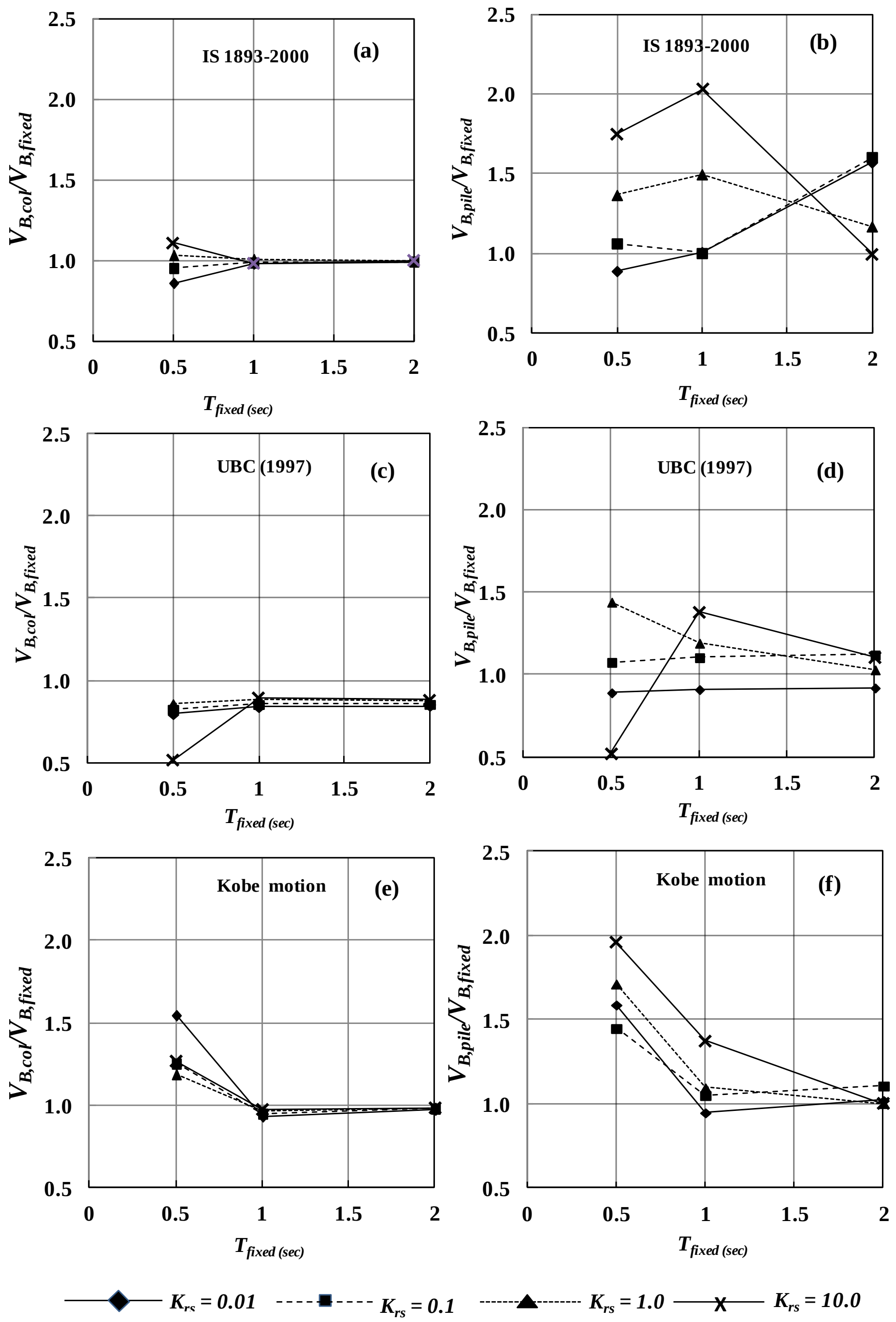

Fig. 9 Variation of normalised base shear in column and pile head for different k_{rs} value in very soft soil (E_p/E_s=10000) under constant E_s distribution with depth for s/d=3.0 and L/d=60 respectively: (a) and (b) represents response computed by response spectrum analysis following IS1893- Part I (2000); (c) and (d) by UBC (1997) , and (e) and (f) by Time history analysis followed by 1995 Kobe motion

E_p/E_s=5000). It is observed that the normalized shear at column generally exhibits a value very close to 1.0 irrespective of different values of k_{rs}. However, in few cases V_{Bcol}/V_{Bfixed} are observed to be significantly more than 1.0 (see Fig. 9(e) and Fig. 10(c)). This implies that though the column shear does not appreciably alter due to soil structure interaction even with a feasible variation of different relative stiffness of raft, as compared to fixed base counterparts, except a few cases. But at least this effect is needed to be incorporated at least to see whether any sporadic increase in column shear is taking place or not.

Figs. 9(b), (d), (f) and Figs. 10(b), (d), (f) represent normalized base shear at pile head level. These results show that the shear forces in the pile in E_p/E_s=10000 may be as high as 2.5 times the shear obtained at fixed base condition in case of rigid raft (i.e., k_{rs}=10). In fact, results show that shear experienced at pile head increases with the increase in relative stiffness of raft. For instance, in Figs. 9(b), (d) and (f), the ratio of V_{Bpile}/V_{Bfixed} becomes less than 1.0 for k_{rs}=0.01 in case of T_{fixed}=0.5 sec, 0.5 to 2.0 sec and 1.0 sec, while for k_{rs}=10.0 such response may go up to 2.0 times the shear under fixed base condition corresponding to T_{fixed}=1.0 sec as is evident from Fig. 9(b) and T_{fixed}=0.5 sec in Fig. 9(f). Similar responses are also observed in case of E_p/E_s=5000 (Fig. 10). This is possibly due to the involvement of additional inertia force attracted by foundation mass since thickness of raft increases to achieve higher relative stiffness. In fact, it appears that effect of inertia force attracted by higher mass rules over the effect of period lengthening due to SSI.

5.3.3 Effect of s/d ratio

Figs. 11 (a)-(f) illustrate the normalized shear at column and pile head (V_{Bcol}/ V_{Bfixed} and V_{Bpile}/V_{Bfixed}), respectively for *s/d*=3, 7 (for T_{fixed}=0.5 sec) and 3, 5 (for T_{fixed}=1.0 sec) considering three different values of k_{rs} (0.01, 0.1 and 1.0). Soil consistency is considered as very soft (i.e., E_p/E_s=10000) and *L/d*=60. It is observed that variation in *s/d* ratios have a marginal effect in the column and pile responses for both T_{fixed}=0.5 sec and 1.0 sec.

5.3.4 Effect of L/d ratio

Figs. 12(a), (c) and (e) present variation of $V_{B(col)}/V_{B(fixed)}$ incorporating different *L/d* ratios of pile for E_p/E_s=10000, 5000 and 1500 while Figs. 12(b), (d) and (f) show results of V_{Bpile}/V_{Bfixed} for the same E_p/E_s ratios. A value of k_{rs}=1.0 representing moderately rigid raft is considered to examine the effect of *L/d* ratio. It is observed that *L/d* ratios have marginal effect on transmitted shear at column. However, in an exceptional case, a high value of normalized shear in column is observed. For instance, in Fig. 12(e) V_{Bcol}/V_{Bfixed} is observed in order of 1.7 for T_{fixed}=2.0 sec supported by stiffer pile group having slenderness ratio (*L/d*) of 13.

Hence, such increase in column shear may be accounted for system with stiffer pile having lower relative stiffness of raft compared to flexible counterparts. On the other hand, the trend for distribution of normalized shear at pile head is quite different from column shear. Results show that the shear forces in pile may be as high as 1.6, 1.7 and 2.0 times that obtained from fixed base consideration in E_p/E_s=10000, 5000 and 1500, respectively. However, it is observed that structure supported on stiff pile group contributes a relatively higher response. This may happen due to relatively lesser percentage of lengthening of period in comparison to flexible pile group. In fact, such lesser percentage in lengthening is anticipated due to increase of lateral stiffness of foundation which is caused due to involvement of more number of piles. Further, the effect of SSI in the form of a high inertia force due to heavy mass of raft may be the reason behind the higher response in stiff pile group supported structures. The results highlighting the effect of *L/d* ratio, mainly reflected by choosing stiff and flexible piles, encompassing different k_{rs} value (other than

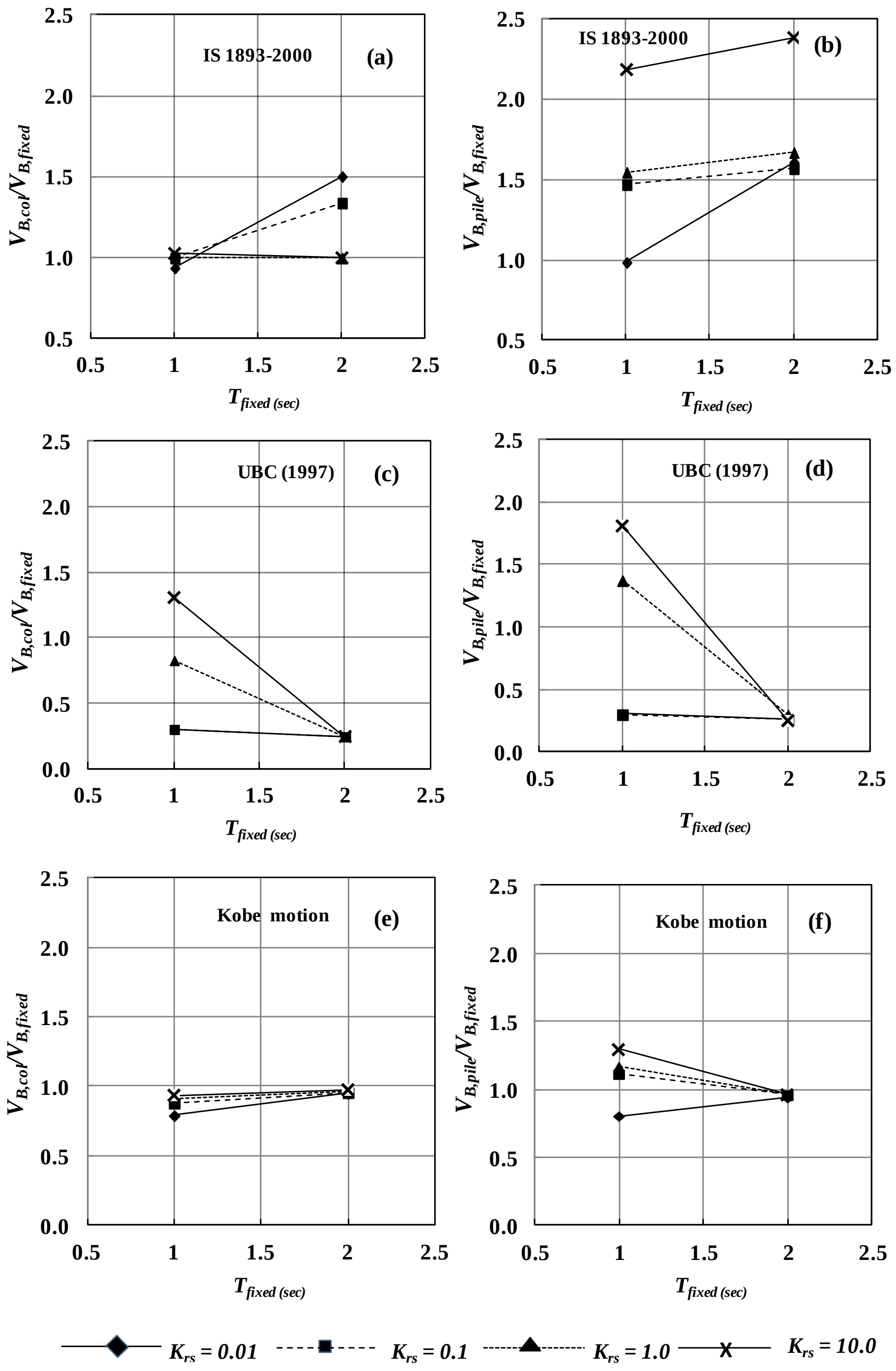

Fig. 10 Variation of normalised base shear in column and pile head for different k_{rs} value in soft soil (E_p/E_s=5000) under constant E_s distribution with depth for *s/d*=3.0 and *L/d*=60 respectively: (a) and (b) represents response computed by response spectrum analysis following IS1893- Part I (2000); (c) and (d) by UBC (1997) and (e) and (f) by Time history analysis followed by 1995 Kobe motion

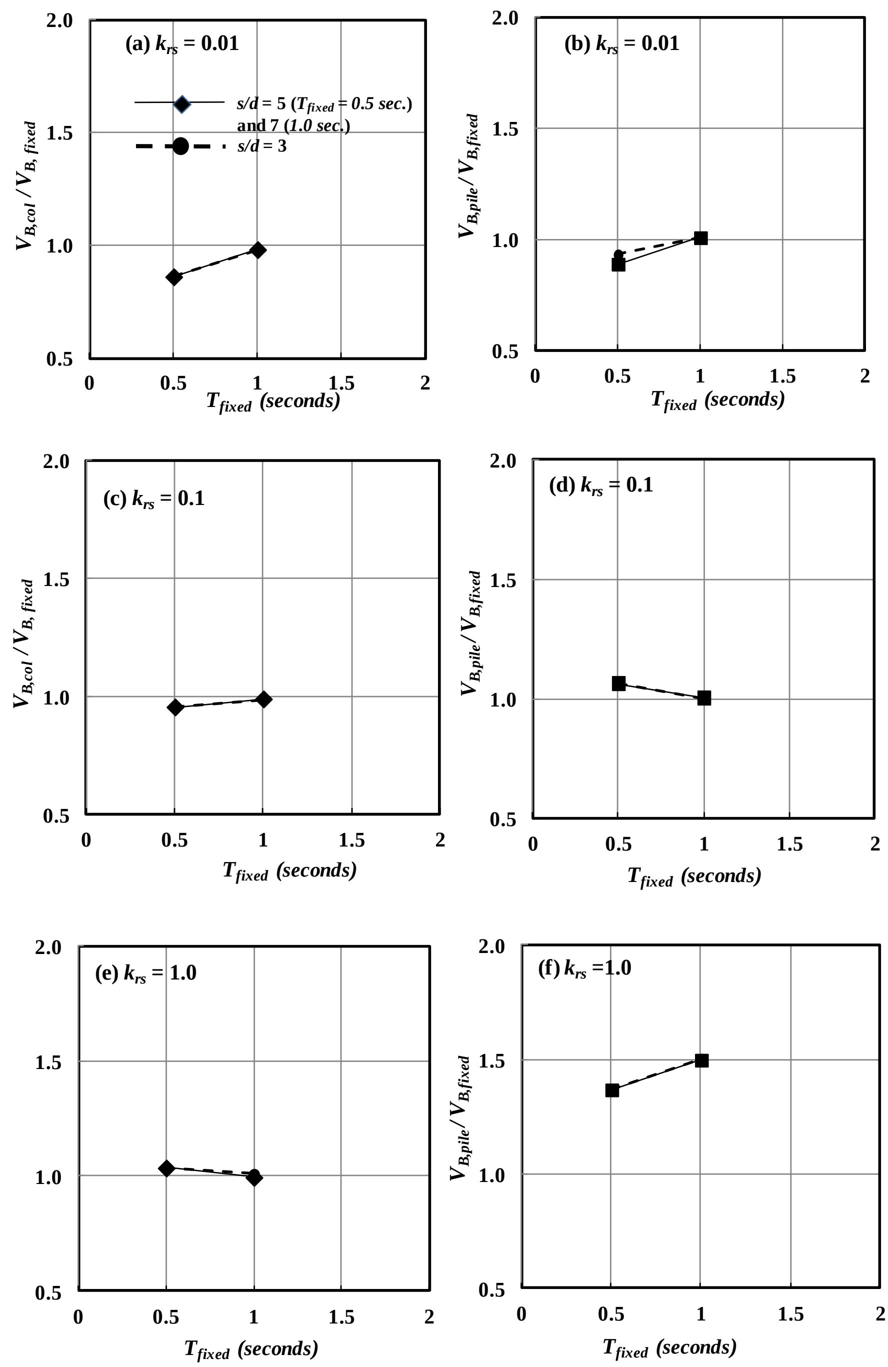

Fig. 11 Variation of normalised base shear in column and pile head in very soft soil (E_p/E_s=10000) incorporating different *s/d* ratios for constant E_s distribution with depth under IS1893-2000 response spectrum analysis : (a) and (b) represents response computed for k_{rs}=0.01 ; (c) and (d) for k_{rs}=0.1, and (e) and (f) for k_{rs}=1.0

Table 5 Normalised base shear obtained at column and pile head from IS1893-2002 response spectrum analysis for different *L/d* ratios considering different k_{rs} and E_p/E_s values

Cases	E_p/E_s	k_{rs}	L/d	$V_{B, column} / V_{B, fixed}$			$V_{B, pile} / V_{B, fixed}$		
				T_{fixed} = 0.5 sec.	1.0 sec.	2.0 sec.	0.5 sec.	1.0 sec.	2.0 sec.
I	10000	0.01	60	0.861	0.98	0.994	0.90	1.009	1.571
			20	1.110	1.025	×	1.662	1.101	×
		0.10	60	0.953	0.988	0.994	1.064	1.003	1.605
			20	0.988	×	×	1.10	×	×
II	5000	0.01	60	×	0.936	1.502	×	0.985	1.608
			18	×	0.982	×	×	1.067	×
		0.10	60	×	0.996	1.337	×	1.469	1.568
			18	×	0.988	×	×	1.147	×
		10.0	60	×	1.025	0.997	×	2.184	2.383
			18	×	1.006	×	×	2.387	×
III	1500	0.01	60	×	×	0.979	×	×	0.979
			13	×	×	1.678	×	×	1.696
		0.10	60	×	×	0.985	×	×	0.985
			13	×	×	1.678	×	×	1.696

N.B. Cases denoting×symbol represents not feasible for pile group of a particular *s/d* and *L/d* ratio as number of calculated piles exceed the raft area.

k_{rs}=1.0) is presented in Table 5 with an objective to develop a better insight into the problem.

5.3.5 Effect of relative stiffness of pile (E_p/E_s)

The effect of E_p/E_s ratios on V_{Bcol}/V_{Bfixed} and V_{Bpile}/V_{Bfixed} is presented in Fig. 13. Fig. 13(a), (c), (e) and (g) present variation of V_{Bcol}/V_{Bfixed} for three different E_p/E_s ratios (10000, 5000 and 1500) and three different T_{fixed} (0.5 sec, 1 sec and 2.0 sec) and incorporating four different k_{rs} values. Figs. 13(b), (d), (f) and (h) show the results of V_{Bpile}/V_{Bfixed} for same parameters. *s/d*=3.0 and *L/d*=60 are considered to obtain the responses. Results show that change in E_p/E_s has a less influence on normalized shear at column for different period of structures. However, in few cases, column shear increases to 1.3-1.5 times the shear obtained for fixed base conditions (see Figs. 13(a) and (c)). It is interesting to observe that normalized shear in pile significantly influenced by the change of E_p/E_s values. For instance, Figs. 13(b) and (d) show that normalized pile head shear for T_{fixed}=2.0 sec increases with the increase in E_p/E_s values. Such increase may go up to even 60% with a change in E_p/E_s value from 1500 to 5000 and remain almost constant with further change in E_p/E_s value from 5000 to 10000. It is also observed that in case of flexible raft (i.e., k_{rs}=0.01 and 0.1 in Fig. 13(b) and (d)), pile head shear gradually increases with increase in E_p/E_s values. However, in case of k_{rs}=1.0 and 10.0 (moderately stiff and stiff raft) as observed in Figs. 13(f) and (h), the change in pile head shear is observed to be opposite from what is obtained in flexible raft cases. For instance, a maximum decrease of normalized pile head shear in order of 250% with respect to variation of E_p/E_s value from 1500 to 10000 is observed in case of k_{rs}=10.0 (Fig. 13(h)). It indicates that pile head shear sharply decreases with the increase in E_p/E_s of pile.

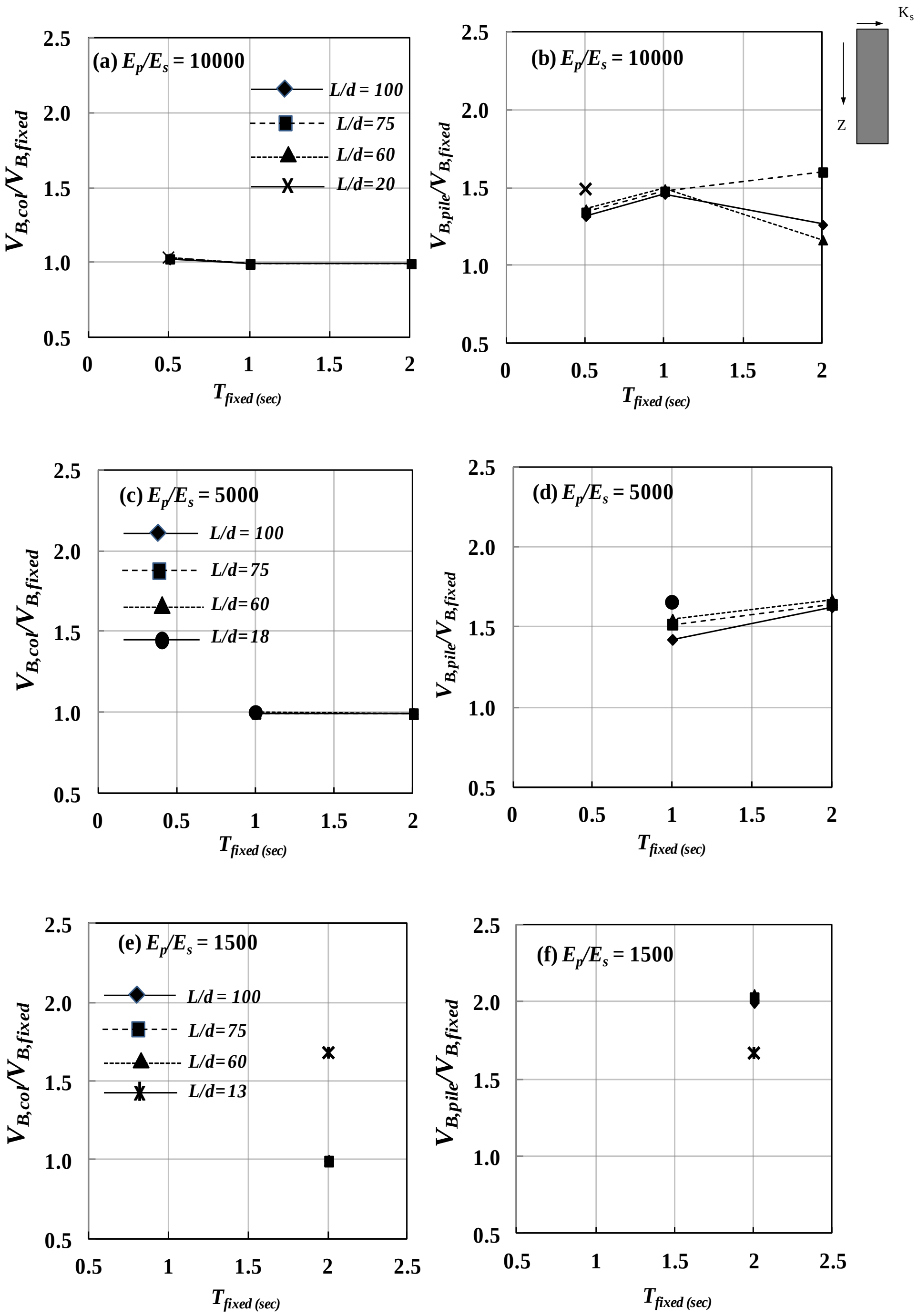

Fig. 12 Variation of normalised base shear incorporating constant E_s distribution with depth, k_{rs}=1.0, s/d=3.0 and different L/d ratio under IS1893-2000 response spectrum analysis: (a) and (b) represents $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ in E_p/E_s=10000; (c) and (d) $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ in E_p/E_s=5000 , and (e) and (f) $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ in E_p/E_s=1500

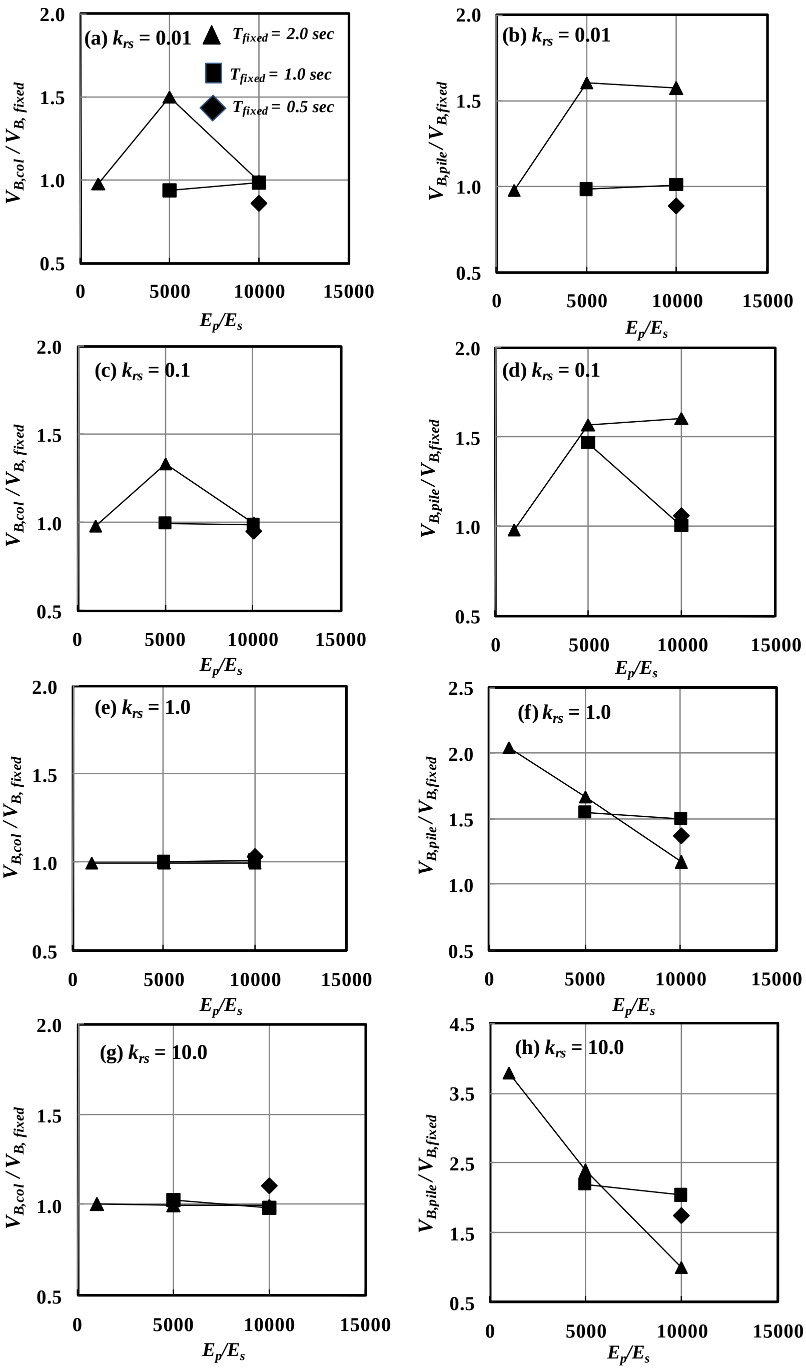

Fig. 13 Variation of normalised base shear under different E_p/E_s ratio different T_{fixed} and various k_{rs} incorporating s/d=3.0, L/d=60 and constant E_s distribution with depth obtained from IS1893-2000 response spectrum analysis: (a) and (b) represents $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ in k_{rs}=0.01; (c) and (d) $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ k_{rs}=0.1 , and (e) and (f) $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ k_{rs}=1.0 and (g) and (h) $V_{B,col}/V_{B,fixed}$ and $V_{B,pile}/V_{B,fixed}$ in k_{rs}=10

6. Conclusions

Present study attempts to highlight the influence of different parameters regulating seismic behaviour of soil-pile raft-superstructure system on seismic design of different elements of such structures. A proposed SSI model taken from a previous study (Saha *et al.* 2013) is used to predict the dynamic characteristics of soil-pile raft-structure system with reasonable accuracy for the cases considered in the present study. This model when compared with various well accepted analytical expressions exhibits satisfactory performance. This study leads to the following broad conclusions.

(i) Relative stiffness of raft has a significant influence on lengthening of period for piled raft supported structure. Such effect is reasonably high in case of flexible pile group supported structure as compared to the ones supported by stiff piles. However, it is observed that lengthening of period is a function of relative stiffness of raft which depends on relative stiffness of pile as well as fundamental period of the superstructure in fixed base condition. Structure supported on piled raft with flexible piles exhibit higher lengthening in comparison to stiff pile group irrespective of relative stiffness of raft and pile. Further, the effect of *L/d* on lengthening of period is also dependent on relative stiffness of pile and fundamental period of superstructure in fixed base condition.

(ii) The effect of spacing to diameter (*s/d*) ratio is negligible for long period structures irrespective of relative stiffness of raft. However, such effect seems to be significant in case of a relatively shorter period of structures with relatively flexible raft. Further, this effect is negligible for rigid raft irrespective of fixed base period of superstructure.

(iii) Effect of relative stiffness of raft on seismic response of column seems to be marginal, whereas, it has significant effect on seismic response of pile foundation. It is interesting to observe that consideration of flexible raft exhibits a subdued response in pile irrespective of fixed base period of superstructure and soil consistency. Hence, it indicates raft flexibility plays a significant role in piled-raft design.

(iv) It is observed that pile head shear considerably increases in case of stiff pile group as compared to flexible one. While, in few cases, column shear increases significantly as compared to fixed base shear which may have a serious implication in column design. Such behavior is observed mostly in case of structure supported on stiff piles. Response obtained through different methods of analysis confirms the general trend of exhibited by soil-pile raft-structure system with marginal difference in results, in most of the cases.

(v) Effect of relative stiffness of pile has negligible influence on column shear, while significant effect is observed in pile head shear. It is observe that in case of flexible rafts, pile head shear increases with increase in relative stiffness of pile. But in case of piles connected with rigid raft, an opposite behaviour in pile response is observed which seems to be an important input in seismic design of pile.

The present study shows that the rigid raft and stiff piles may lead to a considerable increase in soil-structure interaction effect. For instance, a higher choice of rigidity in raft may cause a maximum increase of 150% in pile head shear for the cases considered herein. Similarly, a maximum increase in shear in column as well as in pile head may go up to around 70% and 100%, respectively, due to choice of stiffer or short pile group. While, the increase in pile head shear becomes subdued if the raft on pile becomes flexible. In fact, the effect minimizes for a combination of flexible raft as well as flexible pile system. Further, from the viewpoint of seismic design of flexible piled raft foundation, rigid raft may be preferred in case of pile embedded in very soft soil representing a higher value of relative stiffness of pile. On the other hand, a flexible raft may be preferred in moderately stiff soil representing a lower relative stiffness of pile. It is found that a rigid and flexible raft supported by flexible piles may experience a maximum decrease upto 250% as well as increase upto 60% respectively, in pile head shear with increase in E_p/E_s in order of 1500 to 10000. However, a detailed future study encompassing a good number of cases of superstructure and piled raft system in this regard may be conducted to achieve an optimum design choice for piled raft foundation. Thus, as a design implication, it may be concluded that the structural system with rigid raft on pile should have pile design made on the basis of shear computed considering SSI. Otherwise, such system may be vulnerable under seismic shaking. This may be possible reason of failure of many pile supported structures (for e.g., 1985 Mexico city earthquake, 1989 Loma Prieta earthquake, 1995 Kobe earthquake etc.).

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Appendix A.

The stiffness values of each lateral as well as longitudinal spring at each node are calculated using Eq. (4) based on the end area method proposed by Bowles (1978). Similar method is applied to define the vertical shaft springs and tip spring for each pile which attributes shaft frictional resistance of soil and pile and end bearing capacity of a pile at tip, respectively. The detailed procedure is given below:

Stiffness of horizontal soil spring

The stiffness values of spring connected to pile in two mutually perpendicular lateral directions are calculated on the basis of Eq. (5b) which may be rewritten in the following form as

$$k_x = K_s d = 1.2E_s \tag{A1}$$

where K_s is initial lateral subgrade modulus in kN/m^3 and K_{sd} is degraded modulus in kN/m^3. If the pile is divided into a number of elements, stiffness per unit length for i^{th} node can be given by

$$K_i = \frac{d \times \Delta z}{6}\left[(2K_{s,i} + K_{s,i-1}) + (2K_{s,i} + K_{s,i+1})\right] \tag{A2}$$

where d is width of projected section of pile, or diameter of pile and Δz is the length of each pile element. Considering constant variation of E_s with depth, values of lateral subgrade modulus values can be simplified in Eq. (2) as

Let

$$K_{s,i} = K_{s,i-1} = K_{s,i+1} = K_s \tag{A3}$$

Hence, the stiffness of the spring connected to i^{th} node of pile can be obtained as

$$K_i = d \times \Delta z \times K_s \tag{A4}$$

$$K_i = d \times \Delta z \times 1.2 \times \frac{E_s}{d} = 1.2 \times E_s \times \Delta z \tag{A5}$$

Vertical spring

The stiffness of vertical spring is calculated using the standard formula of shaft friction for pile embedded in clay (Bowles 1978)

$$K_{vertical} = \alpha C_u d \tag{A6}$$

where α is the adhesion factor of soil (IS 2911-part II 1980). Applying similar end area method, stiffness of vertical discrete springs are calculated and assigned. Stiffness of vertical spring connected to the nodes at pile tip which takes care of the end bearing action of the pile

$$K_{endbearing} = N_c C_b d \tag{A7}$$

where N_c=bearing capacity factor (assumed as 9), C_b=cohesion at base of pile.