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Effect of soil-flexibility on dynamic behaviour of building frames on raft foundation

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Abstract

The overall lateral stiffness of any building decreases due to the compressibility of soil. This leads to a subsequent increase in the natural periods of the structural system. The seismic lateral response may change due to natural periods while seismic torsional response arising out of mass or stiffness eccentricity depends on the ratio of uncoupled torsional-to-lateral natural period of the building. Hence, the effect of soil–structure interaction on lateral natural period, seismic base shear and fundamental torsional-to-lateral period ratio of building frames resting on raft foundation needs a detailed investigation. Present study is a limited effort to accomplish these objectives. Influence of the variation of a number of parameters such as (a) different soil conditions, (b) number of stories, (c) number of bays, (d) the ratio of flexural stiffness of columns to that of beams and (e) ground excitation frequency is considered in the present study. Buildings are modelled by two parallel approaches, viz., (1) frame with brick in-fill having fixed supports and (2) frame with brick in-fill having supports accounting for soil-flexibility. The soil-flexibilities for various types of soil and foundation based on their properties, e.g., shear modulus, the Poisson ratio of the soil, and shape and size of the rafts are computed following the well-accepted literature. The lateral natural period, torsional-to-lateral natural period ratio and seismic base shear of a variety of building frames at fixed base condition are compared to the same considering soil-flexibility due to variation in different influencing factors. The trends observed are attempted to be interpreted physically. The curves and tables presenting the change in lateral natural period and torsional-to-lateral period ratio due to effect of soil-flexibility of various building frames seem to be useful for calculating base shear of low-rise buildings through a simple methodology. Such simple methodology may be useful in the design offices for its simplicity and accuracy.

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1. Introduction

A large number of spread footings are required for constructing building structures on weak sub-surfaces. The mat or raft foundations may be an adequate solution for construction of low to medium rise buildings in such situations. This type of foundation may also be appropriate in the well-defined bearing stratum for deep foundations if it is not near to the foundation base. In fact, such a foundation is also preferable when spread footings cover more than one-half of the foundation area. Well-defined guidelines are available for analysis and design of such foundation, particularly under gravity loading with incorporation of the effect of soil–structure interaction [1,2] as either rigid or as flexible plates supported by an elastic foundation representing the soil. These design guidelines provide option for approximate analysis as well as more refined analysis with the help of finite difference or finite element method. Details of such more refined analyses are also available in the well-accepted literature [3–6].

The effect of soil flexibility is generally ignored in seismic design of building frames. The design is generally carried out based on the results of dynamic analysis considering fixed-base condition. Flexibility of soil causes lengthening of lateral natural periods due to overall decrease in lateral stiffness. Such lengthening may considerably alter the seismic response of the building frames resting on raft foundation. Various influential parameters have been identified and the effect of the same on change in lateral natural periods of the building frames due to incorporation of soil-flexibility has been studied extensively. The study has been carried out for numerous building frames resting on raft foundations and a comparison between the nature of change in the lateral natural periods due to incorporation of soil-flexibility relative to that at fixed base condition has been presented. Such a study may help to provide guidelines to assess more accurately the seismic vulnerability of the building frames resting on this type of foundation and may be useful for seismic design.

Eccentricity between centre of mass (*CM*) and centre of stiffness (*CS*) in plan of building gives rise to coupled lateral-torsional response under even a purely horizontal seismic excitation. It is already established in the literature [7–9] that the ratio of uncoupled torsional-to-lateral period (τ) of a building structure may greatly influence its seismic torsional response due to coupling between torsional and lateral mode of vibration resulting from eccentricity between *CM* and *CS*. For instance, if torsional-to-lateral period ratio (τ) is close to 1, the torsional effect under translational seismic excitation may be amplified to thrice that of the static effect even due to a small accidental eccentricity (e). The detailed investigations [10–12] on this aspect have revealed that the curves showing variation of displacement of lateral load-resisting elements as a function of torsional-to-lateral period ratio (τ) are found to have two maxima. One of them is found to be in the domain $0.7<\tau<1$, while the other is in the range of $1<\tau<1.25$. Hence, the buildings having τ in the critical range $0.7<\tau<1.25$ can be considered as torsionally vulnerable. Evidence of buildings with small eccentricity exhibiting considerable torsional response during earthquake due to closely spaced torsional and lateral periods has been recorded in the past [13]. In fact, such coupling between torsional and lateral vibration seems to be a potential cause of failure of many building structures. The vulnerability of such coupling effects in asymmetric (plan-eccentric) structures has been repeatedly demonstrated in strong earthquakes. Surveys and analyses conducted following the 1985 Mexico earthquake [14,15] concluded that approximately 50% of the building failures were either directly or indirectly attributable to such effect. It was observed [16] that many buildings located at the intersection of two streets suffered damage to their sides facing the streets during the 1995 Kobe earthquake. Similar failure is also found to be well-demonstrated at least through one reinforced concrete building with mass eccentricity during the damage survey after recent Gujrat earthquake on 26th January, 2001 in India [17]. Hence, it is important to correctly assess the period ratio, τ, of buildings with reasonable accuracy for assessing their torsional vulnerability. This parameter may be changed if the effect of soil–structure interaction is accounted for and this possibility is also highlighted earlier in a limited form [18].

In this context, an attempt has also been taken in the present study to determine the effect of soil–structure interaction on the change in the ratio of uncoupled torsional-to-lateral natural period, τ. Various influential parameters have been identified and the effect of the same on such issues has been studied extensively. Such a study considering integrated effect of three-dimensional building frames, foundations and flexible soil may help to provide guidelines to assess more accurately the seismic vulnerability of the building frames resting on raft foundation and may be useful for seismic design.

For low-rise buildings, generally, the lateral natural period is small and may lie within the sharply increasing acceleration sensitive zone of response spectrum. Hence, an increase in lateral natural period due to the effect of soil–structure interaction may cause an increase in the spectral acceleration ordinate. Moreover, the change of various natural periods due to soil-flexibility may reduce the spacing between them. This, in turn, may increase the contribution of cross-modal coupling terms to the base shear. The study also extends its scope to assess the impact of these effects due to variation of a number of influential parameters on the seismic base shear of the buildings.

2. System idealization

2.1. Structural idealization

To analyze the dynamic behaviour of building frames with the effect of soil–structure interaction, buildings have been idealized as three-dimensional space frames consisting of two-nodded frame elements. Slabs at different storey-level and the slabs of the ribbed-raft foundation are modelled with the help of four-nodded plate elements with consideration of adequate thickness of these slabs. Each node of this element is considered to have six-degrees-of-freedom and it employs a hybrid element formulation. The rib portion of the foundation is modelled with the help of two-nodded frame elements. For the purpose of design, in a numerous occasions, the buildings are analyzed as bare frames with the help of computer software ignoring the presence of in-fill brick walls. The earthquake and wind primarily impart in-plane lateral sway deformation of the frames parallel to the direction of the force. Due to this mode of deformation, elongation of one diagonal and shortening of the other diagonal of each panel of the frames occur. The brick in-fill within the panel resists this deformation by offering resistance against the shortening of the diagonals and thus, effectively behaves like a compressive strut. This attributes significant additional lateral stiffness to the buildings [19] and may alter the shear distribution [20]. Thick brick (250 mm) in-fill walls are considered in peripheral, i.e., outer panel while the same of 125 mm thick brick partition walls are considered in inner panels of the building frames in the present study. To account for this effect of additional stiffening, 'equivalent strut approach' [19] has been used in the present study. The dimensions and properties of these diagonally placed equivalent compressive struts have been chosen from Refs. [19,21]. To study the effect of soil–structure interaction, 2 storeyed building with raft foundation resting on soft soil, 2–6 storeyed buildings for medium soil and 2, 4, 6 and 7 storeyed buildings on stiff soil, each having 2 bays in two mutually perpendicular directions are considered. Along with these frames, 4 bay 4 bay 2 storeyed building on soft, medium and stiff soil, 4 bay 4 bay 6 storeyed building on medium soil and a 4 bay 4 bay 7 storeyed building on stiff soil are also considered. Moreover, to exclusively observe the effect of soil-flexibility on seismic characteristics of building frames due to variation of number of bays, one 6 bay 6 bay 2 storeyed building frame on soft clay, 6 bay 6 bay 3 storeyed and 6 bay 6 bay 4 storeyed building frames on both medium and stiff clay are considered, too. The foundations, which are provided to the frames, are of ribbed-raft type and designed following the Indian Design Code [22]. The storey height as well as length of each bay of all the building frames are chosen as 3 m which may be reasonable for domestic or small office buildings. The ratio of column-to-beam stiffness is usually considered unity for the present study, if not mentioned otherwise. The dimensions of columns, beams and slabs are arrived at on the basis of the design following the respective Indian Design Code [22].

Dual design approach [23] is an accepted philosophy for seismic design of structures. Following this approach, buildings are generally designed to behave elastically only under earthquakes of moderate magnitude while they are supposed to withstand an earthquake of large magnitude through dissipating energy in the post-elastic range vibration. Such a design philosophy not only reduces the strength demand of the structure but also the cost of the structure, which has much relevance in designing most of the low-rise building frames. Hence, for evaluating the effect of soil–structure interaction on seismic behaviour of the low-rise buildings resting on raft foundation under earthquakes of moderate magnitude, throughout the study, the linear elastic behaviour of the structure is considered.

2.2. *Idealization and modelling of soil*

The seismic load acts during a very small interval of time. Hence, during the action of such loads, instead of consolidation settlement, the instantaneous settlement is expected to occur. This behaviour of soil can be conveniently simulated by modelling the same with a set of elastic springs. Perhaps, due to this reason, the formulation for finding out the dynamic impedance functions to account for the effect of soil-flexibility assumes a linear behaviour in almost all Refs. e.g., [6,24,25] on the basis of assuming the soil as a set of linear elastic springs. Hence, the present study also adopts this approach.

To analyze the soil–foundation–structure systems under dynamic loading, the impedance functions associated with a rigid massless foundation are often used. Translations of foundations in two mutually perpendicular principal horizontal directions and vertical direction as well as rotations of the same about these three directions are considered in the present study. For buildings with raft foundation, below the centre of gravity of the foundation, three translational springs along two horizontal and one vertical axes together with three rotational springs about these three mutually perpendicular axes have been attached to simulate the effect of soil-flexibility.

The stiffnesses of this centrally placed spring for raft type of foundation resting on homogeneous elastic half-space have been computed on the basis of the guidelines prescribed in a well-accepted literature [24] formed on the basis of an extensive literature survey and study based on boundary element method. These expressions were developed in such a form that the single spring located at the centroid of the raft, in each of the said six degrees of freedom, can account for the flexible behaviour of soil below the entire raft in the equivalent sense. Expressions for such spring stiffnesses have been extracted from the literature [24] and presented in Table 1 of the present paper for the sake of convenience.

It has also been observed that the stiffnesses of the equivalent springs are dependent on the frequency of the forcing function, i.e., the ground excitation frequency, more strongly if the foundation is long and on saturated clay [24,25]. In fact, 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 [24,25]. Thus, the dependence of the stiffness of equivalent springs representing the deformable behaviour of soil is due to the incorporation of the influence that frequency of ground excitation exerts on inertia, though purely stiffness properties are frequency independent. This frequency dependence is incorporated by multiplying the equivalent spring stiffnesses by a frequency-dependent factor. This factor is plotted as a function of a non-dimensional parameter a_0 where $a_0 = \omega B/V_s$, ω is the frequency of the forcing function, B is the half of the width of the footing and V_s is the shear wave velocity in soil medium [24,25]. In an earthquake motion, pulses with a wide range of frequencies participate together. So it appears very difficult to adopt any frequency-dependent factor in terms of the non-dimensional parameter $a_0 = \omega B/V_s$. In fact, the use of such multiplication factor was not recommended in some other literature [26,27]. Further, many studies [28,29] on the effect of soil–structure interaction on seismic behaviour of structures have not considered such factors perhaps due to the same reason. Hence, the effect of such multiplication factor is not, in general, considered in the present study.

However, a limited study has been carried out to observe the maximum possible extent of the effect of excitation frequency on seismic response of buildings incorporating the soil–structure interaction effect. A typical 2 bay 2 bay 2 storeyed building frame with raft foundation is chosen

Table 1
Stiffnesses of equivalent springs along various degrees of freedom [24]

Degrees of freedom	Stiffness of equivalent soil spring
Vertical	$[2GL/(1-\nu)](0.73+1.54\chi^{0.75})$ with $\chi = A_b/4L^2$
Horizontal (lateral direction)	$[2GL/(2-\nu)](2+2.50\chi^{0.85})$ with $\chi = A_b/4L^2$
Horizontal (longitudinal direction)	$[2GL/(2-\nu)](2+2.50\chi^{0.85}) - [0.2/(0.75-\nu)]GL[1-(B/L)]$
Rocking (about the longitudinal)	$[G/(1-\nu)]I_{bx}^{0.75}(L/B)^{0.25}[2.4+0.5(B/L)]$
Rocking (about the lateral)	$[3G/(1-\nu)]I_{by}^{0.75}(L/B)^{0.15}$
Torsion	$3.5GI_{bz}^{0.75}(B/L)^{0.4}(I_{bz}/B^4)^{0.2}$

A_b –Area of the foundation considered.
B and L—Half-width and half-length of a rectangular foundation, respectively.
I_{bx}, I_{by}, and I_{bz}—Moment of inertia of the foundation area with respect to longitudinal, lateral and vertical axes, respectively.

Table 2
Soil parameters considered

Type of clay	N value	C (kN/m^2)	ϕ (deg)	γ_{sat} (kN/m^3)	C_c	e_0
Soft	3	18.5	0.0	17.0	0.189	0.90
Medium	6	36.8	0.0	18.5	0.135	0.72
Stiff	12	73.5	0.0	19.4	0.12	0.67

N, C, ϕ, γ_{sat}, C_c and e_0 denote N value obtained from SPT test, cohesion value, internal friction angle, density in the saturated condition, compression index and initial void ratio of soil, respectively.

to study the effect of excitation frequency on the base shear of buildings under the seismic response considering the effect of soil-flexibility. In case of raft foundation, the frequency-dependent multipliers for stiffness of the springs along all the directions always decrease with increasing a_0, and attain a maxima and minima at $a_0 = 0.0$ and $a_0 = 1.5$, respectively [6,24]. Hence, these two values have been chosen to arrive at the most critical effect of the frequency-dependent soil-flexibility on the overall behaviour of the interactive system.

Primarily, the study attempts to see the effect of soil–structure interaction on buildings resting on different types of clayey soil, viz., soft, medium, stiff, etc. To obtain the values of the stiffnesses of the springs for these varieties of clayey soil, values of shear modulus (G) of soil have been estimated using the relationship $G = 120N^{0.8}$ t/ft^2 [30], where N is the number of blows to be applied in standard penetration test (SPT) of the soil. The Poisson ratio (v) of soil has been taken to be equal to 0.5 for all types of clay [31]. N is taken as 3, 6 and 12, for soft, medium and stiff clay, respectively. These values have been chosen from the range of 'N' values prescribed in the literature [32] for each category of soil. The various details of different soil parameters have been tabulated in Table 2. Bearing pressures have been determined for foundations placed at a depth of 1.5 m below ground level under full submergence condition to arrive at the most critical value following the recommendations provided by Indian Standard Code [33,34]. Since the stiffnesses of the springs used to represent the soil-flexibility are highly sensitive to the size of the foundation below which they are attached to, dimension of raft has been very rigorously computed separately based on the allowable as well as net safe bearing capacity to have an exhaustive idea. However, finally the building frames are considered to be provided with footings of dimension obtained from the consideration of allowable bearing capacity.

The effect of depth of foundation has been ignored in the determination of the spring stiffness to represent soil-flexibility below foundation, though the effect of the same has been incorporated to compute the bearing capacity. In fact, the effect of depth has little bearing on the stiffness of the spring elements. It may be considerable only under a controlled construction condition [6].

A typical 4 storeyed building frame with brick in-fill resting on raft and the corresponding idealized soil–foundation–structure system for the same is shown in Fig. 1a and b, respectively. However, in Fig. 1b, the lateral soil spring stiffness along Z-direction and rocking stiffness about Z-direction are not shown for the limited space of the figure.

With this idealization of structure and soil as briefly depicted above, the change in lateral natural period, torsional-to-lateral period ratio and base shear of the low-rise building frames with raft foundation due to consideration of the effect of soil–structure interaction are investigated and discussed in the following sections.

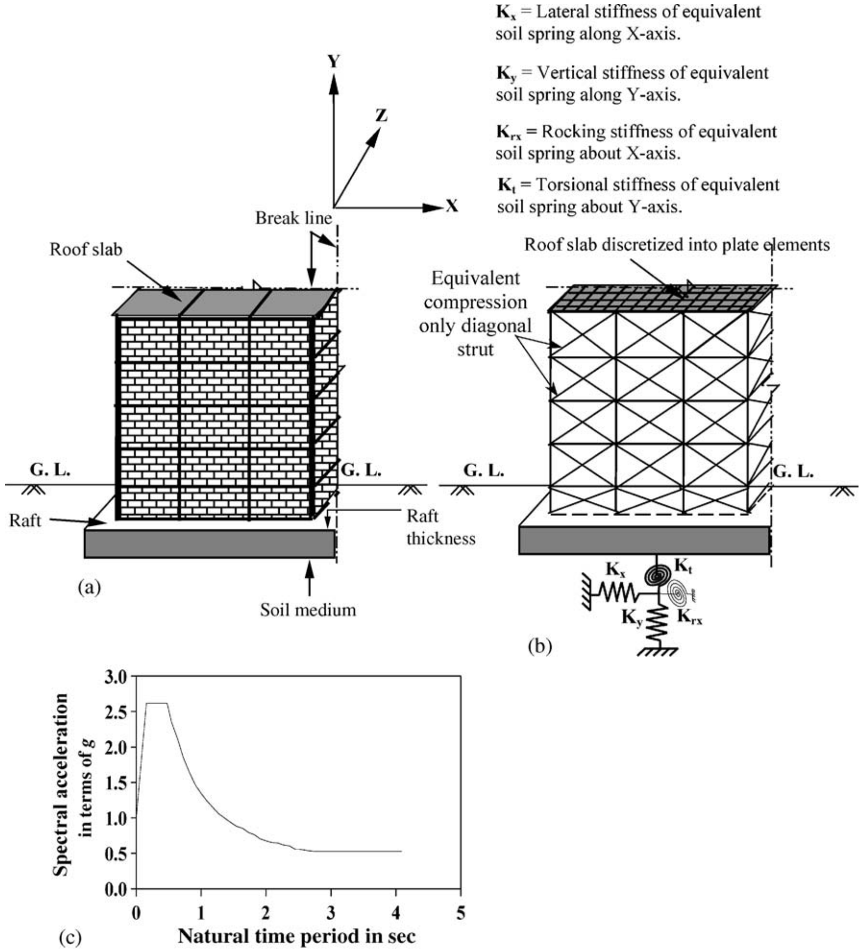


Fig. 1. System idealization and ground excitation input. (a) Typical 4 storeyed frame with brick in-fill resting on raft foundation. (b) Idealized 4 storeyed building frame with equivalent compressive strut resting on raft foundation with equivalent soil springs accounting for soil-flexibility effect. (c) Design spectrum (IS: 1893–2000) for 5% critical damping.

3. Analysis methodology

Finite element method is adopted to formulate the mass and stiffness matrices for the building frames. Consistent mass matrix approach is used to make the formulation as accurate as possible. The eigenvalue problem corresponding to the free vibration condition is solved by subspace iteration method to obtain the natural periods of the building frames under consideration. Seismic analysis of building frames accounting for the effect of soil–structure interaction is carried out with the help of the design spectrum provided in IS: 1893–2000 and shown in Fig. 1. The seismic base shear of these buildings are obtained due to the design spectrum (Fig. 1) corresponding to 5% of critical damping [35] considering fixed base condition as well as considering flexible-base condition resulting from soil-flexibility.

Five percent of critical damping is reasonable for concrete structures. Soil damping was calculated following the guidelines as outlined in Refs. [6,24] accounting for both radiation and material damping. It was found that for an isolated raft and equivalent soil-spring system, the damping is not considerably larger than 5% for a wide range of shallow foundations with embedment less than half of the lateral dimension. This observation is in line with the findings of an experiment as well as computation based study [36]. Moreover, this damping will be further reduced if the effect is considered with respect to the entire structure-foundation-equivalent soil spring system, instead of isolated raft-equivalent soil-spring system. Thus, 5% of critical damping in each mode was considered irrespective of the fixed base condition or support flexibility.

Finally, due to incorporation of the effect of soil-flexibility, the variations in lateral natural period and fundamental torsional-to-lateral period ratio are obtained. Similarly, the change in the base shear which has been computed by combining the contributions of all the possible lateral modes by complete quadratic combination (CQC) method, with respect to the same for similar building frames with fixed base condition (i.e., without considering the effect of soil-flexibility), are obtained. The CQC method is used to obtain the contribution of the modes with close-spaced natural frequencies with reasonable accuracy. If the combined modal response be denoted by r_0, then according to CQC rule,

$$r_0 \cong \left(\sum_{i=1}^{N} \sum_{n=1}^{N} \rho_{in} r_{io} r_{no} \right)^{1/2}, \tag{1}$$

where r_{io} and r_{no} are the peak responses corresponding to ith and nth mode respectively. The correlation coefficient between these two modes is denoted by ρ_{in}. The range of ρ_{in} is bounded in between 0 and 1. For $i = n$, ρ_{in} becomes unity. Hence, Eq. (1) can be rewritten in simple form as

$$r_0 \cong \left(\sum_{n=1}^{N} r_{no}^2 + \sum_{i=1}^{N} \sum_{n=1}^{N} \rho_{in} r_{io} r_{no} \right)^{1/2}. \tag{2}$$

This modal combination method is applicable for wide variety of structures. The expressions for combined modal response depicted in Eqs. (1) and (2) are available in standard literature, e.g., [37].

In the present study, the seismic base shear of the building frames for both the fixed base and flexible soil condition is arrived at following the provisions of Indian Earthquake Code [35] and a recent literature [38] by applying seismic zone factor 0.36 for very severe seismic intensity, reduction factor 3.0 for ordinary moment-resisting frame and importance factor 1.0 for general residential building frames.

4. Results and discussions

This section presents the change in lateral natural period, fundamental torsional-to fundamental lateral period ratio and base shear as a function of various influential parameters, namely, N values of clay, number of stories, column-to-beam stiffness ratio and frequency of ground excitation for brick in-filled building frames with raft foundation. The figures containing separate curves corresponding to the building frames supported by different types of soil are marked by the corresponding soil types, namely, 'soft', 'medium' and 'stiff', respectively.

4.1. *Change in lateral natural period*

4.1.1. *Effect of clay variation*

The change in fundamental lateral natural period due to the effect of soil–structure interaction is studied on 2 storeyed building with raft foundation resting on soft soil, 2–6 storeyed buildings for medium soil and 2, 4, 6 and 7 storeyed building for stiff soil, each having 2 bays in two mutually perpendicular directions. In addition to these building frames, 4 bay 4 bay 2 storeyed building on soft, medium and stiff clay, a 4 bay 4 bay 6 storeyed building on medium clay and a 4 bay 4 bay 7 storeyed building on stiff clay are also considered. Along with these, one 6 bay 6 bay 2 storeyed building frame on soft clay, 6 bay 6 bay 3 and 6 bay 6 bay 4 storeyed building frames on both medium and stiff clay are considered, too. Results for 2 bay 2 bay 2 storeyed building frames have been plotted as percentage change in lateral natural period versus *N* value for different types of clay in Fig. 2. The results corresponding to the other building frames are presented in Table 3. Though, the variation of change in lateral natural period for 2 bay 2 bay 2 storeyed building supported on soft, medium and stiff clay is presented in Fig. 2, but, these results are also included in Table 3, for the sake of completeness. A maximum increase of more than 55% is observed for 4 bay 4 bay 2 storeyed building frame resting on soft clay (Table 3). From Fig. 2 and Table 3, it is observed that this increase in general gradually decreases with the increasing hardness of soil. However, Fig. 2 shows that the increase in the lateral natural period minimizes for medium soil (i.e., at *N* value of 6). In fact, shear modulus decreases with softness of clay and size of foundation increases with the same. The stiffnesses of equivalent soil spring decrease with decrease in shear modulus and increase with sizes of foundation. As a result of these two contradictory effects, perhaps, the spring stiffness maximizes in case of medium clay.

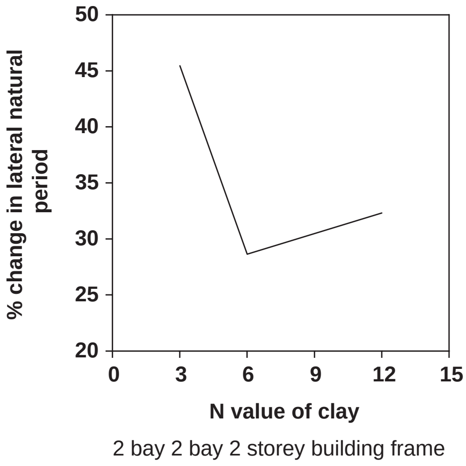


Fig. 2. Variation of change in lateral natural period due to change in *N* value of clay.

Table 3
Variation of change in lateral natural period for building frames resting on raft foundation

Soil type	Frame type	Lateral natural period at fixed base condition (s)	Lateral natural period considering soil-flexibility (s)	% Deviation
Soft	2 bay 2 bay 2 storey	0.08301	0.12075	45.46
	4 bay 4 bay 2 storey	0.08039	0.12495	55.43
	6 bay 6 bay 2 storey	0.09411	0.14191	50.80
Medium	2 bay 2 bay 2 storey	0.08342	0.10731	28.64
	2 bay 2 bay 3 storey	0.12748	0.15207	19.29
	2 bay 2 bay 4 storey	0.16694	0.19288	15.54
	2 bay 2 bay 5 storey	0.27409	0.28513	4.03
	2 bay 2 bay 6 storey	0.39411	0.40400	2.51
	4 bay 4 bay 2 storey	0.08039	0.11672	45.19
	4 bay 4 bay 6 storey	0.32019	0.32829	2.53
	6 bay 6 bay 3 storey	0.14550	0.19382	33.21
	6 bay 6 bay 4 storey	0.19436	0.22712	16.85
Stiff	2 bay 2 bay 2 storey	0.08110	0.10731	32.32
	2 bay 2 bay 4 storey	0.16694	0.18250	9.32
	2 bay 2 bay 6 storey	0.39411	0.42906	8.87
	2 bay 2 bay 7 storey	0.50626	0.54347	7.35
	4 bay 4 bay 2 storey	0.08039	0.09556	18.87
	4 bay 4 bay 7 storey	0.39962	0.40182	0.55
	6 bay 6 bay 3 storey	0.14550	0.19370	33.13
	6 bay 6 bay 4 storey	0.19436	0.22586	16.21

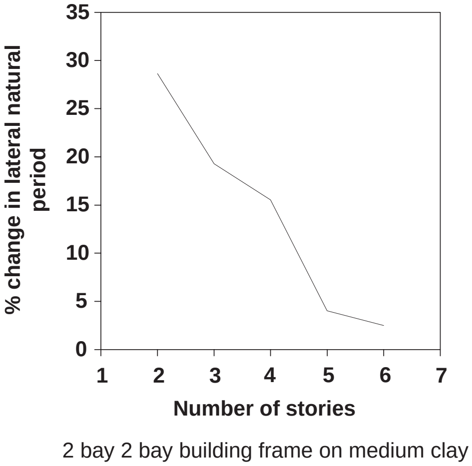


Fig. 3. Variation of change in lateral natural period due to change in number of stories.

4.1.2. Effect of number of stories variation

Among a large number of cases studied, the results corresponding to 2 bay 2 bay building frames on medium soil are presented in graphical form in Fig. 3 to show the trend of variation in changes in lateral natural period with the changes in the number of stories. For this soil type, the number of storey is varied from 2 to 6. The effect corresponding to the stiff clay can be obtained from Table 3 itself, where, the numbers of storey considered are 2, 4, 6 and 7, respectively. The number of storey is not varied for buildings supported on soft clay. It is due to this reason that increased number of storey for buildings supported on soft clay requires practically infeasible size of raft foundation. It is observed that the percentage change in lateral natural period may differ by 26% due to the variation of number of stories from 2 to 6 in case of buildings with raft foundation for medium clay (Fig. 3). The same variation is found to be in the order of 25% due to change in number of stories from 2 to 7 for stiff clay (Table 3). Both Fig. 3 and Table 3 clearly indicate that the effect of soil–structure interaction on the change in lateral natural period gradually decreases with increase in number of stories in the building frame. From Fig. 3 and Table 3, it is also observed that for buildings having higher than 3 storey, the maximum percentage change in lateral natural period due to incorporation of the effect of soil–structure interaction is not more than about 15%, irrespective of the soil type. Hence, the base shear of these buildings with higher storey is not expected to exhibit considerable increase due to incorporation of soil-flexibility effect. However, this issue is investigated in details in the later part of the study. With the increase in number of stories, the building frame itself becomes relatively flexible compared to a similar building frame with lesser number of stories. This results in a lesser stiffness compared to that of similar buildings with lesser number of stories. Hence, if the equivalent soil springs of comparatively lesser stiffness acts in series with lesser stiffness of building with large number of stories, the resulting fractional decrease in overall stiffness is less. Further, the buildings with larger number of stories have a greater foundation size leading to a larger stiffness of the equivalent springs representing the soil behaviour. Thus, this factor additionally makes the effect of soil–structure on overall stiffness lesser. Hence, change in lateral natural period due to the effect of soil–structure interaction is relatively less for buildings with large number of stories.

4.1.3. Effect of number of bays variation

A large number of cases were studied to observe the variation in the change in lateral natural period with variation of number of bays. Since, the change in period due to the effect of soil–structure interaction is found to be very strong for buildings with lesser number of stories, results corresponding to the 2 storeyed building frame has been chosen to exhibit this effect of variation in number of bays and is presented in Fig. 4. Results corresponding to all other cases, though studied, are not presented for the sake of brevity. The figure shows that maximum change in lateral natural period may differ due to variation of number of bays in the order of about 15%. For 2 storeyed building frames resting on soft clay, it is observed from Table 3, that for 2 bay 2 bay (i.e., $6\,\text{m} \times 6\,\text{m}$) building frame, the increase in lateral natural period due to effect of soil-flexibility is 45.46%, while the same is 55.43% for 4 bay 4 bay (i.e., $12\,\text{m} \times 12\,\text{m}$) and 50.80% for 6 bay 6 bay (i.e., $18\,\text{m} \times 18\,\text{m}$) building frame, respectively. Hence, it is observed that no definite generalized trend in the change in lateral natural period due to variation in number of bays can be obtained for building frames with raft foundation resting on soft clay.

Fig. 4. Variation of change in lateral natural period due to change in number of bays.

This is, perhaps, due to the reason that increase in number of bays results in an increase in stiffness of the structure against lateral mode of vibration. But, consequently, the size of the raft also increases. For this reason, the impedance functions against the lateral mode of vibration, which are directly proportional to the size of the foundation, also increase. Therefore, due to increase in number of bays, whether the effect of soil–structure interaction on lateral natural period of building frames with raft foundation is increasing or decreasing in trend, cannot be generalized. In fact, it is also expected that due to a similar reason, the trend in the soil-flexibility effect on the seismic base shear of building frames for variation in number of bays cannot be predicted.

4.1.4. Effect of column to beam stiffness ratio

The ratio of column to beam stiffness is varied as 0.25, 0.50, 1.0, 2.0 and 4.0 with the same beam stiffness in two mutually perpendicular directions to observe the influence of this parameter on lateral natural period due to the consideration of soil flexibility. The ratios are so chosen to cover all practical cases. Out of extensive case studies, results for 2 bay 2 bay 2 storeyed building frames have been presented to show the trend in behaviour in Fig. 5, as the effect of soil–structure interaction is found to be maximum for this type of low-rise building frame. It is observed that the change in lateral natural period due to the effect of soil–structure interaction alters appreciably especially for the stiff clay with the change in the ratio of column to beam stiffness. Such change may be as high as, about, 45%.

4.1.5. Effect of excitation frequency

It is already established that the dynamic stiffness of the soil medium is dependent on the frequency of the forcing function, i.e., ground excitation frequency. To study this effect on the overall behaviour of the soil–structure–foundation system, the present study incorporates the frequency-dependent multiplier for the two critical cases, i.e., $a_0 = 0.0$ and 1.5 for 2 bay 2 bay 2

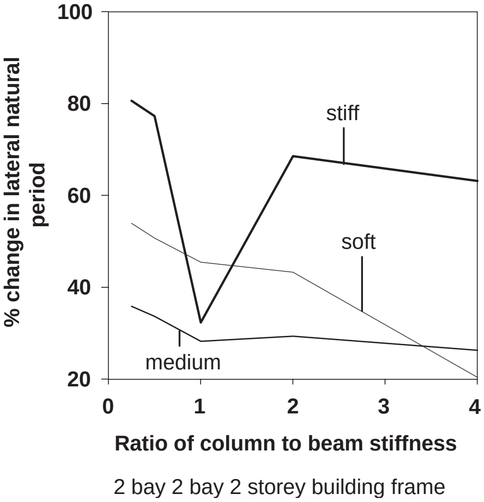


Fig. 5. Variation of change in lateral natural period due to change in ratio of column to beam stiffness.

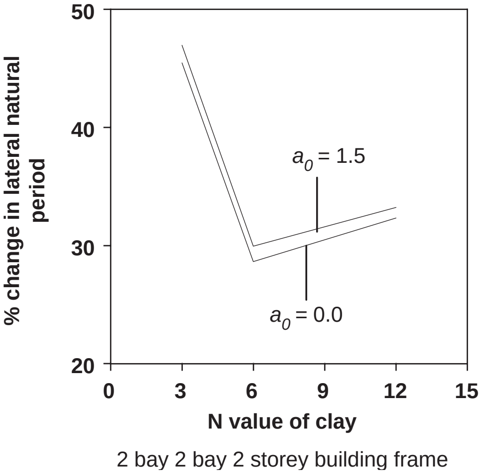


Fig. 6. Variation of change in lateral natural period due to change in ground excitation frequency.

storeyed buildings. The results of such investigation have been presented in Fig. 6. Maximum change in lateral natural period is found to be in the order of about 17% for both $a_0 = 1.5$ as well as $a_0 = 0.0$.

Fig. 6 itself shows that the effect of frequency of the forcing function may influence the dynamic behaviour of the system only to a limited extent. However, such effect of frequency may be considered for the purpose of analysis of the important structures for choosing a maximum possible conservative estimate. On the other hand, for most of the common building frames, it seems reasonable to assume the equivalent springs representing soil deformability to be frequency independent while assessing the overall seismic behaviour of the structures.

4.2. Change in fundamental torsional-to-lateral period ratio

4.2.1. Effect of clay variation

The change in the ratio of fundamental torsional-to-lateral natural period due to the effect of soil–structure interaction is studied on all the building frames mentioned earlier since such ratio has been proved to be a very crucial input to assess seismic vulnerability of any structure [7–9,12,13]. The percentage change in fundamental torsional-to-lateral period ratio is plotted in Fig. 7 as a function of N values of soil for a 2 bay 2 bay 2 storeyed building frame. The results of all the building frames considered in this study are presented in Table 4 similarly as in the cases corresponding to the change in lateral natural period. It is found that a maximum increase of about 44% is observed for 4 bay 4 bay 6 storeyed building with raft foundation, supported by medium soil (Table 4). Fig. 7 shows that the change in torsional-to-lateral period ratio maximizes for medium soil (with $N = 6$). The possible reason is, perhaps, the same as that presented to interpret the minimum change in lateral natural period for medium soil in Section 4.1.1.

4.2.2. Effect of number of stories variation

2 bay 2 bay 2 storeyed building frame with raft type of foundation supported by medium soil is chosen for presenting the trend-indicating behaviour in Fig. 8. Number of storey is varied as in the cases corresponding to the change in lateral natural period. In addition to this, the results corresponding to the effect of variation of storey for stiff clay can be obtained from Table 4 itself. It is observed that the maximum percentage change in torsional-to-lateral natural period ratio may differ by about 38% due to the variation of number of stories from 2 to 6 in case of buildings with raft foundation on medium clay (Fig. 8). Fig. 8 and Table 4 indicate that the effect of soil–structure interaction on the change in fundamental torsional-to-lateral natural period ratio generally diminishes with increasing number of stories in the building frame.

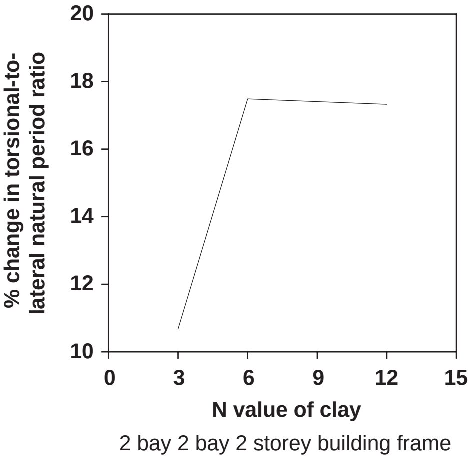


Fig. 7. Variation of change in torsional-to-lateral natural period ratio due to change in N value of clay.

Table 4
Variation of change in ratio of torsional-to-lateral natural period for building frames resting on raft type of foundation

Soil type	Frame type	Torsional-to-lateral natural period ratio at fixed base condition	Torsional-to-lateral natural period ratio considering soil-flexibility	% Deviation
Soft	2 bay 2 bay 2 storey	0.74184	0.82112	10.69
	4 bay 4 bay 2 storey	0.78094	0.92010	17.82
	6 bay 6 bay 2 storey	0.83211	1.05348	26.60
Medium	2 bay 2 bay 2 storey	0.74646	0.87699	17.49
	2 bay 2 bay 3 storey	0.67501	0.82469	22.17
	2 bay 2 bay 4 storey	0.62663	0.74907	19.54
	2 bay 2 bay 5 storey	0.52800	0.52853	00.10
	2 bay 2 bay 6 storey	0.46939	0.39429	−16.00
	4 bay 4 bay 2 storey	0.78094	1.00218	28.33
	4 bay 4 bay 6 storey	0.80651	1.16081	43.93
	6 bay 6 bay 3 storey	0.81656	1.00753	23.39
	6 bay 6 bay 4 storey	0.79795	0.96790	21.30
Stiff	2 bay 2 bay 2 storey	0.74747	0.87699	17.33
	2 bay 2 bay 4 storey	0.62663	0.70427	12.39
	2 bay 2 bay 6 storey	0.85017	0.72290	−14.98
	2 bay 2 bay 7 storey	0.86198	0.74300	−13.80
	4 bay 4 bay 2 storey	0.78094	1.01720	30.25
	4 bay 4 bay 7 storey	0.80651	1.12790	12.79
	6 bay 6 bay 3 storey	0.81656	1.00279	22.81
	6 bay 6 bay 4 storey	0.79795	0.96821	21.34

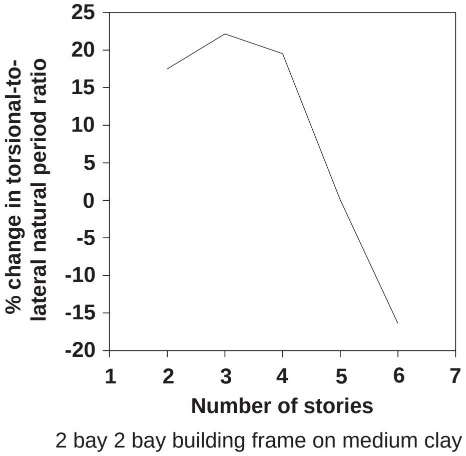


Fig. 8. Variation of change in torsional-to-lateral natural period ratio due to change in number of stories.

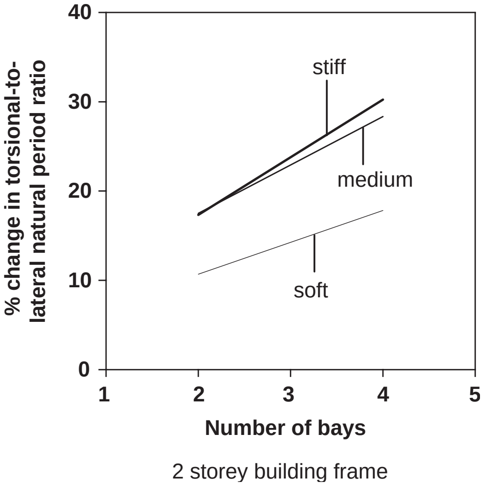


Fig. 9. Variation of change in torsional-to-lateral natural period ratio due to change in number of bays.

4.2.3. Effect of number of bays variation

A large number of cases is also studied in detail to observe the effect of variation of number of bays on the change in fundamental torsional-to-lateral natural period ratio. Since the change in period ratio due to the effect of soil–structure interaction becomes maximum for buildings having lesser number of stories, results corresponding to 2 storeyed building frame with raft foundation have been presented in Fig. 9, however for change in number of bays from 2 to 4; while Table 4, presents the same for the increase in number of bays from 2 to 6 (corresponding to 2, 3 and 4 storeyed building frames on soft, medium and stiff clay, respectively). The maximum change in period ratio for frames may be as high as about 16% due to variation in number of bays from 2 to 6 (Table 4). Fig. 9 and Table 4 clearly demonstrate that the effect of soil–structure interaction on fundamental torsional-to-lateral period ratio depends on the number of bays of the building frame. The increase in number of bays causes an increase in number of columns. This leads to a larger increase in torsional stiffness as compared to that in lateral stiffness, since the outer columns increase the torsional stiffness largely due to a larger distance from centre of stiffness. Hence, the soil–structure interaction causes a larger proportional decrease in torsional stiffness being connected in series with very stiff torsional springs of buildings at fixed base condition as compared to the same for lateral stiffness. This results in increasing torsional-to-lateral period ratio due to increase in number of bays.

4.2.4. Effect of column to beam stiffness ratio

The ratio of column to beam stiffness is varied as 0.25, 0.50, 1.0, 2.0 and 4.0 maintaining the same beam stiffness in two mutually perpendicular directions to observe the influence of this parameter on fundamental torsional-to-lateral natural period ratio likewise the cases corresponding to the change in lateral natural period. It is observed that in general, the change in fundamental torsional-to-lateral natural period ratio does not vary appreciably with the change in ratio of column to beam stiffness, except for the stiff soil (Fig. 10). The maximum variation in

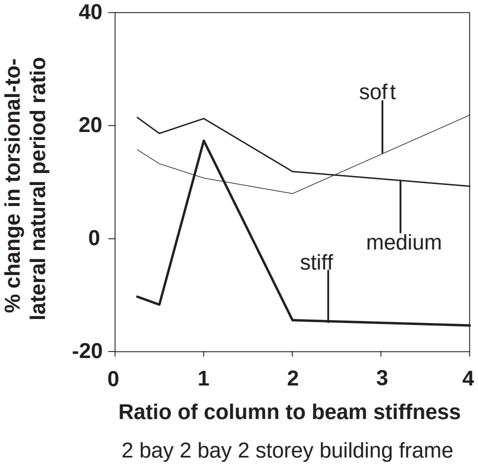


Fig. 10. Variation of change in torsional-to-lateral natural period ratio due to change in ratio of column to beam stiffness.

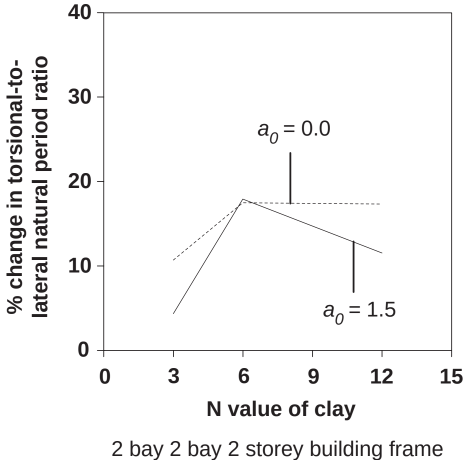


Fig. 11. Variation of percentage change in torsional-to-lateral natural period due to change in ground excitation frequency.

period ratio due to the change in the ratio of column to beam stiffness is in the order of 30% for the building resting on stiff clay (Fig. 10).

4.2.5. *Effect of excitation frequency*

It is well-accepted that the dynamic stiffness of the soil medium is dependent on the frequency of the forcing function, i.e., ground excitation frequency to account for the effect of the same on the inertia force. To study this effect on the overall behaviour of the soil–structure–foundation system, the present study incorporates the frequency-dependent multiplier for a critical case, i.e., $a_0 = 1.5$ for the building frames resting on raft foundation as mentioned earlier. Curves corresponding to $a_0 = 0.0$ are also included for the sake of comparison. The results of such study for 2 bay 2 bay 2 storeyed building frame with frequency-dependent multiplier have been presented in Fig. 11. From Fig. 11, it is observed that while for $a_0 = 0.0$, the maximum percentage change in period ratio is around 18%, and for $a_0 = 1.5$, this is around 20%. Hence, it is observed that the change in torsional-to-lateral period ratio does not vary appreciably due to frequency of the ground excitation. However, since, the torsional vulnerability of buildings is extremely sensitive to the torsional-to-lateral period ratio if this ratio is close to unity, consequence of the possible adverse effect of the change in period ratio should be accounted in the seismic design.

4.3. *Change in base shear*

4.3.1. *Effect of clay variation*

The change in base shear due to the effect of soil–structure interaction is studied on the same building frames which are considered to study the change in lateral natural period and the change in the period ratio. The outcomes of these analyses for 2 bay 2 bay 2 storeyed building frame have been plotted as percentage change in base shear versus N value corresponding to different types of clay in Fig. 12. The results for all the building frames are presented in Table 5. Fig. 12 and Table 5 show that the maximum increase in base shear may be as high as more than about 50% for 2 storeyed building frames resting on soft clay. The results presented in the form of percentage change in base shear due to consideration of soil-flexibility show the significance of considering this effect. However, Fig. 12 and Table 5 clearly exhibit the gradually diminishing effect of soil–structure interaction with increasing hardness of soil, in most of the cases.

4.3.2. *Effect of number of stories variation*

Among a large number of cases studied, the results for only the 2 bay 2 bay building frames with raft foundation resting on medium clay is presented here to show the trend of variation in base shear changes with the changes in the number of stories. For this particular soil and building type, the number of storey is varied from 2 to 6, likewise the other two dynamic characteristics.

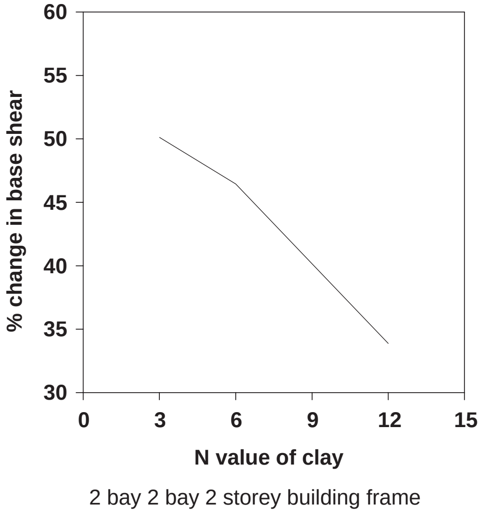
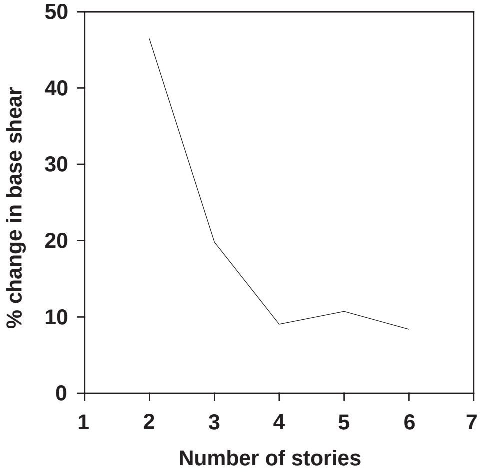


Fig. 12. Variation of change in base shear due to change in N value of clay.

Table 5
Variation of change in base shear for building frames resting on raft type of foundation

Soil type	Frame type	Base shear at fixed base condition (kN)	Base shear considering soil-flexibility (kN)	% Deviation
Soft	2 bay 2 bay 2 storey	129.99	195.15	50.13
	4 bay 4 bay 2 storey	436.35	680.46	55.94
	6 bay 6 bay2 storey	1050.76	1641.25	56.20
Medium	2 bay 2 bay 2 storey	125.86	184.34	46.46
	2 bay 2 bay 3 storey	221.44	265.31	19.81
	2 bay 2 bay 4 storey	333.16	363.28	9.04
	2 bay 2 bay 5 storey	458.33	507.44	10.72
	2 bay 2 bay 6 storey	545.74	591.51	8.39
	4 bay 4 bay 2 storey	436.35	580.96	33.14
	4 bay 4 bay 6 storey	1896.54	1950.55	2.85
	6 bay 6 bay 3 storey	2360.97	2771.10	17.37
	6 bay 6 bay 4 storey	3120.27	3499.71	12.16
Stiff	2 bay 2 bay 2 storey	121.46	162.63	33.89
	2 bay 2 bay 4 storey	333.16	358.65	8.67
	2 bay 2 bay 6 storey	545.74	586.28	7.43
	2 bay 2 bay 7 storey	613.57	615.72	0.35
	4 bay 4 bay 2 storey	436.35	505.55	15.86
	4 bay 4 bay 7 storey	2174.59	2237.59	2.90
	6 bay 6 bay 3 storey	2360.97	2725.58	15.44
	6 bay 6 bay 4 storey	3120.27	3428.79	9.89



2 bay 2 bay building frame on medium clay

Fig. 13. Variation of change in base shear due to change in number of stories.

Fig. 13 exhibits the variation of percentage change in base shear as a function of number of stories for a 2 bay 2 bay building frame resting on medium clay, while the change in base shear due to change in number of stories corresponding to the stiff clay can be obtained directly from Table 5. Fig. 13 shows that the change in base shear may vary from 46% to 8% for buildings resting on medium clay. On the other hand, the corresponding changes in base shear for buildings on stiff clay (Table 5) are found to vary from a value as high as about 34% to a value as low as less than 1% due to a change in number of stories from 2 to 7. Both the figure and table clearly indicate that the effect of soil–structure interaction on the change in base shear generally decreases with increase in number of stories in the building frame. The possible reason behind such an observation is the same as explained earlier in Section 4.1.2. Again, it is also observed that the change in base shear due to the effect of soil–structure interaction is not more than 10% for the buildings having more than 3 stories, irrespective of the soil type. Hence, it can be concluded that for the buildings resting on raft foundation having more than 3 stories, a multiplication factor of 1.1 to the seismic base shear in fixed base condition can suffice the purpose of accounting for the effect of soil–structure interaction on base shear of the similar building frames.

4.3.3. *Effect of number of bays variation*

A large number of building frames is studied to observe the effect of variation in number of bays. However, the results of a few limited trend-indicating cases are presented in graphical forms. Since, the change in period due to the effect of soil–structure interaction is found to be most amplified for buildings with lesser number of stories, results corresponding to the 2 storeyed building frame with raft type of foundation have been presented to exhibit the maximum possible effect of soil–structure interaction. For this type of buildings, number of bays has been shown to be varied as 2–4. The percentage change in base shear has been presented in Fig. 14 as a function of number of bays. The figure shows that the variation in number of bays may cause a maximum variation of about 18% in the percentage change in base shear in case of building frames resting on very stiff clay.

Furthermore, from Table 5, it is observed that for 2 storeyed building frames resting on soft clay, the changes in seismic base shear due to incorporation of the effect of soil-flexibility are

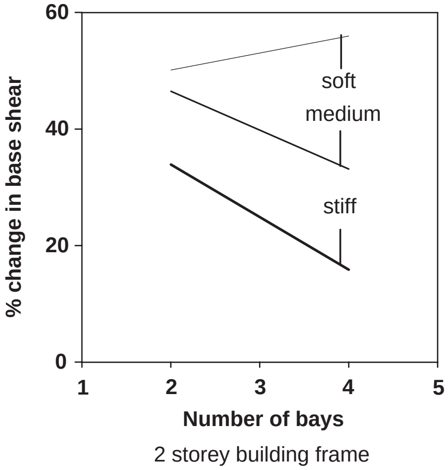


Fig. 14. Variation of change in base shear due to change in number of bays.

50.13%, 55.94% and 56.20% for 2 bay 2 bay, 4 bay 4 bay and 6 bay 6 bay building frames, respectively. On the other hand, for 3 storeyed building frame supported by medium clay, the corresponding changes are 19.81% and 17.37%, while for 4 storeyed building frame resting on stiff clay, the same are 8.67% and 9.89%, for 2 bay 2 bay and 6 bay 6 bay building frame, respectively. Hence, for building frames supported by soft clay, the change in seismic base shear due to incorporation of the effect of soil-flexibility gradually increases with increase in number of bays. On the contrary, the same effect is observed to be decreasing in nature for building frames resting on medium and stiff clay. So, no general trend is observed for these cases. The reason, perhaps, is the same as that explained under Section 4.1.3 of the present paper.

4.3.4. Effect of column to beam stiffness ratio

The effect of variation of the ratio of flexural stiffness of column to that of beam is studied with same variation of this parameter as mentioned earlier. Out of the extensive case studies, results for 2 bay 2 bay 2 storeyed building frames resting on all the soil types are presented in this study. Fig. 15 shows that the variation in percentage change in base shear in general may be in the order of about 20% due to the variation in the ratio of flexural stiffness of the columns to that of beams.

4.3.5. Effect of excitation frequency

The effect of excitation frequency on base shear is also studied corresponding to the critical values of a_0, namely, 0.0 and 1.5, as mentioned earlier. The results of such study have been presented in Fig. 16. Maximum change in base shear is found to be in the order of about 49% for $a_0 = 1.5$, while the same is observed to be around 50% for $a_0 = 0.0$, for buildings with raft foundation.

This shows that the effect of frequency of the forcing function does not seem to influence the seismic behaviour of the system, significantly. However, such effect of frequency may be considered for the purpose of analysis of only the important structures to have a conservative estimate of design base shear.

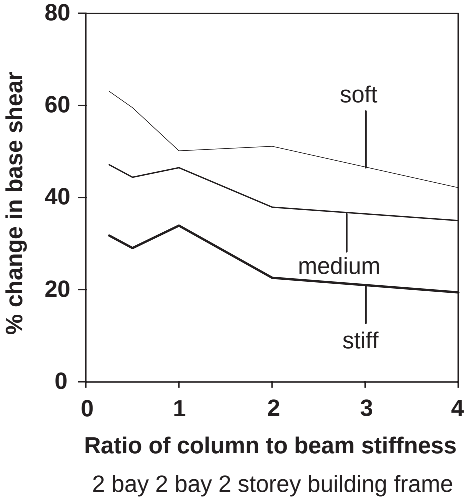


Fig. 15. Variation of change in base shear due to change in ratio of column to beam stiffness.

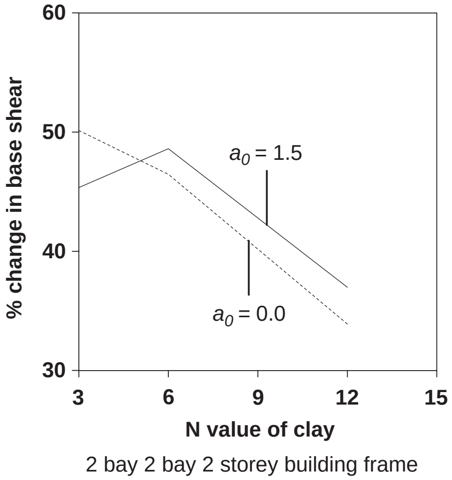


Fig. 16. Variation of change in base shear due to change in ground excitation frequency.

5. Seismic base shear prediction incorporating the effect of soil-flexibility

The effect of soil–structure interaction on lateral natural periods as presented in Fig. 3 and Table 3 for various buildings resting on soft, medium and stiff clay can be used for better seismic design of the low-rise buildings. Firstly, the building frames can be analyzed with fixed base condition to obtain the fundamental natural period at fixed base. The fundamental lateral natural periods at flexible soil condition can be obtained from the percentage change in period presented in the study through figures and tables for various building frames and soil types. Knowing the lateral natural periods of the frames with and without soil–structure interaction, the ratio of the lateral stiffnesses with and without considering the effect of soil-flexibility can be obtained as $(T_{fixed}/T_{ssi})^2$, where, T_{ssi} and T_{fixed} correspond to the fundamental lateral natural period of the building frames with and without considering the effect of soil–structure interaction, respectively. Now, a similar building frame at fixed base condition, the lateral stiffness of which is reduced to a proportion of $(T_{fixed}/T_{ssi})^2$ by reducing the modulus of elasticity in the same ratio, can be considered. Hence, these frames can be considered as frames similar to the actual ones with same fundamental lateral natural period that could be obtained due to incorporation of the effect of soil-flexibility. These building frames at fixed base condition are expected to yield the same base shear as obtained from the frames considering the effect of flexible soil. The base shears obtained in such a way are compared with the base shears obtained from the rigorously modelled similar frames including the effect of soil-flexibility and are found to show very close agreement. The comparison of the base shears for some sample cases is presented in a tabular form through Table 6. The table exhibits that a close resemblance is there between the outcomes of these two procedures. The inherent facility of consideration of such an equivalent fixed base model lies in its simplicity for use in the design offices. However, for building frames with more than three stories, application of a multiplication factor of 1.1 to the base shear may suffice to account for the increase due to soil–structure interaction.

Table 6
Prediction of seismic base shear of building frames with raft foundation through proposed approximation

Soil type	Frame type	Base shear actual (kN)	Base shear approximated (kN)	% Deviation
Soft	2 bay 2 bay 2 storey	195.15	185.98	−4.70
Medium	2 bay 2 bay 2 storey	184.34	181.06	−1.78
Stiff	2 bay 2 bay 2 storey	162.63	158.42	−2.59

6. Conclusions

The present paper attempts to study the effect of soil–structure interaction on two primary dynamic characteristics of low-rise buildings resting on raft type of foundation, namely, the lateral natural period and fundamental torsional-to-lateral period ratio. Consequently, the study also extends to find out the effect of soil-flexibility on one of the important seismic characteristics, the seismic base shear of the similar buildings. The study leads to the following broad conclusions:

1. The effect of soil-flexibility may appreciably change the lateral natural periods of any building. This parameter primarily regulates the seismic lateral response of the building frames. In fact, as a result of such lengthening of lateral period, the seismic base shear is also found to increase considerably for such low-rise buildings having their lateral natural period in the sharply rising zone of response spectrum. Hence, the buildings may be seismically vulnerable if the effect of soil–structure interaction is not considered in the process of design.
2. The study also shows that the effect of soil–structure interaction may appreciably alter the fundamental torsional-to-lateral natural period ratio, which regulates the seismic torsional response arising out of lateral-torsional coupling. Thus, evaluation of this parameter without considering soil–structure interaction may cause serious error in seismic design, as the seismic torsional response is found to be sensitive, particularly, if this ratio is close to 1 [7–9].
3. The effect of soil-flexibility on lateral natural period, torsional-to-lateral natural period ratio and seismic base shear of buildings is pronounced with decreasing hardness of soil and number of stories, in general. Hence, this effect needs to be considered very seriously at least for buildings of this category.
4. The effect of soil–structure interaction on lateral natural period, torsional-to-lateral natural period ratio and seismic base shear alters due to the change in number of bays and column to beam stiffness ratio.
5. Excitation frequency of the ground motion may influence the effect of soil–structure interaction on lateral natural period as well as base shear marginally. Hence, this effect should be considered for very important structures only. However, the consequence of the effect of excitation frequency on fundamental torsional-to-lateral period ratio needs to be considered if the period ratio is nearly in the range of 0.7–1.25, as the seismic torsional vulnerability is extremely sensitive in this range of period ratio [7–9].
6. The study shows that the effect of soil–structure interaction on low-rise buildings on raft foundation can be accounted for applying a multiplication factor of 1.1, if the building frame is of more than 3 stories. For buildings having lesser than 3 stories, the lengthened period of the

buildings may be obtained through the linear interpolation from the results presented. This lengthened period then may further be used to derive an equivalent fixed-base model for obtaining the seismic base shear incorporating the effect of soil–structure interaction, as prescribed in this paper.

The study, as a whole, shows the significance of the effect of soil–structure interaction on seismic behaviour of low-rise buildings on raft foundation. The study also identifies the influential parameters, which can regulate the effect of soil–structure interaction on the change in lateral natural period, fundamental torsional-to-lateral period ratio and seismic base shear of building frames resting on raft foundation. The graphs and tables are presented in easily understandable manner to show the trend in the effect of variation of these characteristics due to incorporation of the effect of soil–structure interaction. These results may also be of help to the designers to assess the significance of considering this effect for the low-rise building frames resting on this particular type of foundation, through a simplified procedure prescribed in the paper.

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