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Assessing lateral period of building frames incorporating soil-flexibility

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Abstract

Flexibility of soil medium below foundation decreases the overall stiffness of the building frames resulting in a subsequent increase in the natural periods of the system. It is well established that the seismic lateral response may considerably alter due to the change in lateral natural periods. Hence in the present study, an attempt has been made to observe the effect of soil–structure interaction on the change in lateral natural periods of building frames resting on isolated and grid foundations. Variation of a number of factors 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) frequency of the ground excitation is considered. For such analysis, buildings are modelled by four alternate approaches, namely, (1) bare frame with fixed supports, (2) bare frame with supports accounting for soil-flexibility, (3) frame with brick in-fill having fixed supports and (4) frame with brick in-fill having supports accounting for soil-flexibility. For each category, two cases, viz., one without tie beams, and the other with tie beams at plinth level are considered. The soil-flexibility 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 footings are computed by methodology prescribed in well-accepted literature. Modelling the system so rigorously, a comparative study of variations of lateral natural periods of various building frames due to variation in different influencing factors are made and interpreted physically. The study shows that the presented variation curves for dynamic characteristics may be used for reasonably accurate assessment of the effect of soil–structure interaction on any building frame with the help of simple linear interpolation. These curves are also useful for incorporating the effect of soil-flexibility in calculating base shear through a simple methodology and may prove useful in the design offices for its simplicity and accuracy.

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1. Introduction

Seismic design of building frames is generally carried out on the basis of the results of fixed-base dynamic analysis ignoring the effect of soil-flexibility. Flexibility of soil causes an overall decrease in lateral stiffness resulting in the lengthening of lateral natural periods [1–3]. Such lengthening may considerably change the seismic response of building frames. The effect of soil-flexibility is suggested to be accounted through consideration of springs of specified stiffness as prescribed in well-accepted literature [4] and the possible severity of without taking the effect of the same is highlighted in only a few earlier research works [5–7]. Moreover, considerable change in fundamental natural period may also significantly influence the behaviour of the building frames under wind loading, which predominantly excites the fundamental lateral mode. Thus, the change in lateral natural periods due to the effect of soil–structure interaction may be an important issue from the viewpoint of design considerations. This issue may particularly become more important for seismic behaviour of low-rise buildings having fundamental lateral period in the short period region of the response spectrum. In these cases, the periods corresponding to other higher modes will be even still shorter as compared to the fundamental lateral period. The contribution to the seismic base shear by each of these modes may increase due to lengthening of lateral periods for soil-flexibility, as indicated by the increasing nature of the seismic response spectrum ordinate with increasing period, particularly, in the short period region. Furthermore, due to various degrees of lengthening effect in periods of various lateral modes, the coupling between them may increase. All these may cause an increase in base shear [6,7].

Present study attempts to provide systematic guidelines for determining the lengthened lateral natural periods of building frames due to incorporation of the effect of soil–structure interaction. Various influential parameters have been identified and the effect of the same on change in lateral natural periods of the building frames has been studied extensively. The study has been carried out for buildings with both isolated and grid foundations and a comparison between the nature of change in the lateral natural periods has been presented. Such a study may help to provide guidelines to assess more accurately the seismic vulnerability of the building frames and may be useful for seismic design. The utility of the curves, exhibiting the variation of the change in lateral natural period due to inclusion of the effect of soil-flexibility, is demonstrated through prediction of changed lateral natural period of a few example building frames. Based on these variation curves, a simplified analysis procedure is suggested for finding out the seismic base shear considering the effect of soil–structure interaction. The procedure is justified through a few example cases.

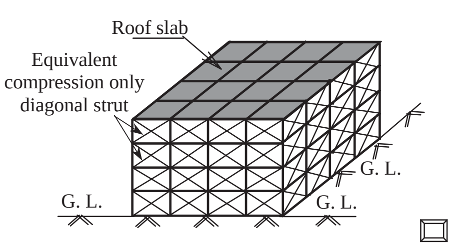
2. Idealization of the system

2.1. Structural idealization

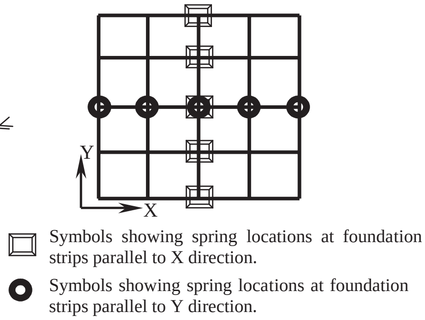
To analyze the dynamic behaviour while considering the effect of soil–structure interaction, building frames have been idealized as 3D space frames using two nodded frame elements. Plate elements are used considering the proper thickness for modelling the roof and floor slabs. In the conventional design technique, the buildings are analyzed as bare frames with the help of computer software. The earthquake and wind primarily exert lateral loading at floor levels and cause in-plane lateral sway deformation of the frames parallel to the direction of the force. This type of sway deformation causes elongation of one diagonal and shortening of the other diagonal of each vertical panel of the frames. The brick in-fill within the panel tends to resist this deformation by offering resistance against compression by means of the shortening tendency of the diagonals and thus, effectively behaves like a compressive strut. This attributes significant additional lateral stiffness to the buildings [8,9] and may considerably change the lateral period as well as base shear [10]. To account for this additional stiffening effect, ‘equivalent strut approach’ [8,9] has been used in the present study. The dimensions and properties of these diagonally placed equivalent compressive struts have been chosen from the literature [8,9,11] to simulate the effect of the brick walls. Subsequently, the bare frames with equivalent diagonal struts are studied to obtain the results realistically applicable for building frames with brick wall. The effect of 250 mm thick brick in-fill walls is considered in peripheral outer panel while the same of 125 mm thick brick partition walls is considered in inner panels. The idealized form of a typical 4 bay 4 bay 4 storey building frame (upto ground level (GL)) with equivalent compression only diagonal struts is presented schematically in Fig. 1a to demonstrate how the effect of brick in-fill is considered in the present study. The present study also considers bare frame to see how correctly the influence of soil–structure interaction on dynamic behaviour can be predicted. This may give an idea about the error, which one should liable to commit if this popular but grossly inaccurate approach is invoked. The influence of tie beam on the dynamic behaviour of various categories of these building frames, namely, the frames with isolated footings and those with grid foundations with and without considering the effect of soil–structure interaction has also been studied. To look into such effect, 2 bay 2 bay 1 storey, 2 bay 2 bay 2 storey and 2 bay 2 bay 4 storey building frames resting on isolated footing; and 4 bay 4 bay 3 storey, 4 bay 4 bay 4 storey and 4 bay 4 bay 6 storey building frames with grid foundation have been considered. Buildings with such configuration have been considered to include the possible representative cases of typical low-rise buildings. A 4 bay 4 bay 4 storey building frame with isolated footing has also been analyzed to point out the characteristic differences in the behaviour of the building frame with isolated and grid foundation. The storey height as well as length of each bay of all the building frames was chosen as 3 m which may be reasonable for domestic or small office buildings. For all the cases, the dimensions of reinforced-concrete columns, beams and tie beams were taken as 250 × 250 mm, irrespective of the building or foundation type. Similarly, the thickness of the roof and floor slabs was taken as 125 mm for all types of building frames considered, here. These dimensions were arrived on the basis of the design following the respective Indian code for design of reinforced-concrete structures [12]. However, these design data are believed to be practicable and hence, do not affect the generality of the conclusions.

2.2. *Idealization of soil*

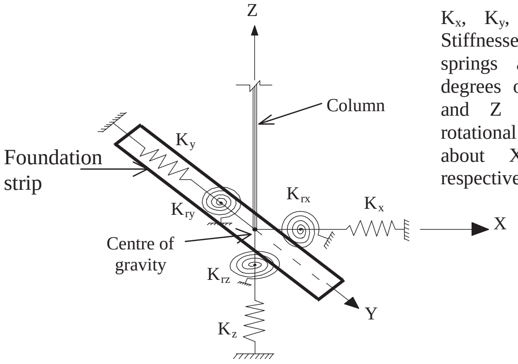
To analyze the entire structural system consisting of soil-foundation and structure under dynamic loading, the impedance functions associated with a rigid massless foundation may be used. To make the analysis most general, translations of foundations in two mutually perpendicular principal horizontal directions and vertical direction as well as rotations of the same about these three directions are considered in the present study. For buildings with isolated



(a) Idealized superstructure (upto G. L.) of 4 bay 4 bay 4-storey building frame with equivalent compressive strut to simulate the effect of brick in-fill.

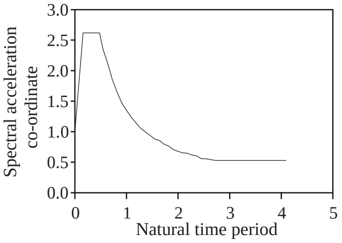


(b) Typical layout of idealized grid foundation system in plan showing equivalent soil spring locations.



K_x, K_y, K_z, K_{rx}, K_{ry}, K_{rz} = Stiffnesses of equivalent soil springs along the translational degrees of freedom along X, Y and Z axes, and along the rotational degrees of freedom about X, Y and Z axes, respectively.

(c) Idealized arrangement at a typical column-rectangular foundation strip and equivalent soil spring junction.



(d) Design spectrum (IS: 1893-2000) corresponding to 5% critical damping.

Fig. 1. System idealization and ground motion characteristics.

footing, below each column, three translational springs along two horizontal and one vertical axes, respectively, together with three rotational springs about those mutually perpendicular axes, respectively, have been attached to simulate the effect of soil-flexibility, as suggested in well-accepted literature [4].

Similarly, the entire grid foundation system is idealized as a combination of a series of parallel foundation strips oriented in two principal directions resting in the same horizontal plane. Hence, below the centre of gravity of each strip, springs are attached in the above-mentioned six degrees of freedom (as shown in Fig. 1). The locations of the springs attached to the centre of gravity of each strip are shown in a typical grid foundation layout in Fig. 1b. The spring locations for foundation strips parallel to two principal horizontal directions are denoted by two different symbols. The details of a typical column-grid foundation-equivalent soil spring junction are shown in Fig. 1c. The stiffnesses of these springs for footings resting on homogeneous elastic half-space have been computed as explained in the literature [4]. The expressions for these spring stiffnesses have been suggested on the basis of an extensive literature survey, study based on boundary element method and experimental verification as per the literature [4]. These expressions for stiffnesses were developed in such a form that one single spring located at the centre of gravity of the foundation strip, in each of the said six degrees of freedom, can account for the flexible behaviour of soil below the entire length of the same strip in the equivalent sense. These expressions have also been presented in Table 1 of the present paper for the sake of convenience. In fact, these were also experimentally verified elsewhere [13].

It has been observed that the stiffnesses of the springs are dependent on the frequency of the forcing function, i.e., the frequency of the ground excitation more strongly if the foundation is long and on saturated clay [14]. In fact, the inertia force exerted by a time varying force imparts a frequency-dependent behaviour of soil medium that seems to be more conveniently incorporated in stiffness in the equivalent sense [4]. Thus the frequency dependence of the stiffness of equivalent springs representing the deformable behaviour of soil is due to incorporation of the influence that frequency 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 $a_0 = \omega B/V_s$ [4]. Here, 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. However, during a real earthquake, pulses with a wide range of frequencies participate together. So it is very difficult to adopt any particular frequency-dependent factor in terms of the non-dimensional parameter $a_0 = \omega B/V_s$. From this viewpoint some other literature [15,16] have not recommended the use of such multiplication factors. Further, many studies [17,18] 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.

Table 1
Expressions for stiffnesses of equivalent springs along various degrees of freedom

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

Note: A_b–Area of the foundation considered; B and L—halfwidth 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.

Besides this, a limited study has been carried out to observe the maximum possible extent of the effect of excitation frequency on dynamic behaviour of building frames with consideration of soil–structure interaction effect. For this purpose, 2 bay 2 bay 2 storey building frame with isolated footing is analyzed. In case of isolated footing, such multipliers for stiffness of the springs in all the directions always decreases with increasing a_0, and attains a maxima and minima at $a_0 = 0.0$ and $a_0 = 1.5$, respectively [4,19]. 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 structural system. Literature [19] may be consulted for a more comprehensive idea on the same.

Likewise, 4 bay 4 bay 3 storey building frame with grid foundation is used for this purpose, as this frame may be considered as a typical case of a low-rise building frame. It is observed from the literature [4,19] that for footing with very high aspect ratio (e.g., strip footing), frequency-dependent multiplier for the equivalent spring with stiffness, K_{vert} in vertical direction attains a maximum value at $a_0 = 0.3$. This increase is in the order of 30% (compared to $a_0 = 0.0$ case), which is associated with about 20% increase (compared to $a_0 = 0.0$ case) in $K_{lateral}$. On the other hand, maximum increase in equivalent spring stiffness in lateral direction $K_{lateral}$ is about 50% (compared to the same at $a_0 = 0.0$) at $a_0 = 1.5$ corresponds to a sharp decrease in K_{vert} of about 92% (compared to the same at $a_0 = 0.0$). Again, $K_{lateral}$ always increases with the increase in a_0 and its maximum value is equal to unity for $a_0 = 0.0$, when all other multipliers become simultaneously unity. Studying this wide nature of variations of different frequency-dependent multipliers, critical cases corresponding to $a_0 = 0.0, 0.3$ and 1.5 are analyzed to obtain the upper-bound and lower-bound values considering the effect of soil–structure interaction. Corresponding changes in rotational stiffnesses are relatively small, yet, such changes have been suitably incorporated in the analysis. However, the stiffness in the direction parallel to the direction of the length of the footing is assumed to remain constant, since it is almost independent of the frequency [4,19]. A better understanding in this regard may be achieved from the graphical representation of these multipliers available elsewhere [4,14,19]. Further, the effect of such frequency dependence can be accurately and conveniently incorporated, interpreted and understood by a frequency domain analysis, which is presently not employed in the limited scope of this study.

In case of closely spaced footings, group effects may develop. This may have some influence on foundation stiffness. However, a limited experimental study [20] verifying a computational scheme, which neglects this effect, shows well agreement with the computational results, for a few model frames with isolated footings under static loading. Though such a limited study is not confirmatory, this effect could not be accounted in the limited scope of the present paper. However, this aspect needs attention in future.

The effect of soil–structure interaction on buildings resting on different types of clayey soil, viz., very soft, soft, medium, stiff, very stiff and hard is also attempted to be studied in the present work. The sandy soil is excluded from the scope of the present study. However, it is seen from the well-accepted literature [19] that the shear modulus for sandy soil varies in a range of about 4000–29 000 kN/m^2 and the corresponding range of variation for clayey soil is 2800–33500 kN/m^2. The clayey soil having a relatively wider range of variation of shear modulus G is expected to exhibit a range of variation of the soil–structure interaction effect well inclusive of the corresponding range of variation of the interactive effect for sand. Nevertheless, a study focusing on the sandy soil can be a further scope of extension of the present work.

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 following the empirical relationship $G = 120\,N^{0.8}$ t/ft^2 [21], where N is the number of blows to be applied in Standard Penetration Test (SPT) of the soil; and the Poisson ratio (v) of soil has been taken to be equal to 0.5 for all types of clay [22]. N is taken as 1, 3, 6, 12, 22 and 30 for very soft, soft, medium, stiff, very stiff and hard soil, respectively. These values have been chosen following the range of 'N' values for different types of clayey soil as prescribed in the literature [23]. The various details of different soil parameters considered have been tabulated in Table 2. Bearing pressures have been determined for footings placed at a depth of 1.5 m below GL under full submergence condition to arrive at the most critical value following the Indian Standard Code [24,25] recommendations. Since, the stiffnesses of the springs used to represent the soil-flexibility are highly sensitive to the size of the footings below which they are attached to, dimensions of various footings have been very rigorously computed separately based on the allowable as well as net safe bearing capacity to have an exhaustive idea. The load carried by the individual column was obtained from the conventional static analysis of the building frames. All isolated footings are assumed to be square in shape.

For design of grid foundation, the column load obtained from the static analysis of the bare building frames at fixed support condition has been distributed in the ratio of the flexural stiffness of the strips meeting at the junction below them, as per the guideline given in the literature [26,27].

However, 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, which may be considerable only under a controlled construction condition [19].

The foundation mass has been considered to be lumped at the foundation level to arrive at a more realistic picture in case of isolated footing. However, for a grid foundation mass of the same is considered to be distributed similar to the other members to account for both the translational as well as rotary inertia component during analysis with the consideration of consistent mass matrix. So, with this idealization of structure and soil as briefly depicted above, the change in lateral natural periods of building frames is investigated.

When a shallow foundation undergoes lateral movement, a very small amount of mass moves with the foundation. On the contrary, for foundations with sufficient embedment or group of

Table 2
Details of soil parameters considered

Type of clay	N value	C (kN/m^2)	ϕ (deg)	γ_{sat} (kN/m^3)	C_c	e_0
Very soft	1	9.8	0.0	13.5	0.279	1.2
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
Very stiff	22	147.0	0.0	19.8	0.099	0.60
Hard	30	220.0	0.0	21.0	0.093	0.58

Note: 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.

piles, considerable amount of soil mass may be forced to move with the foundation itself. Hence, the studies conceptualizing the effect of soil-flexibility [4,13–15,19] for shallow foundations did not account for any such effect and subsequently, many other studies (e.g. [18]) have followed the same assumption. However, a limited study based on a few sample building frames resting on isolated and grid foundations are carried out to verify whether the soil mass has any appreciable effect on the lengthened lateral natural period incorporating soil-flexibility for the building frames resting on these two types of surface/ shallow foundations. To find out the effective soil mass moving with the foundations, the formulations suggested in a well-accepted literature [28] is followed. This literature [28] suggests to increase the mass of the foundation by an amount such that its effect will be approximately same as that of the real soil mass participating in the vibration. This mass m' is called the apparent mass of the soil and is given by

$$m' = \frac{\rho b^3}{g\alpha} C_m, \tag{1}$$

where ρ is the unit weight of soil, b the width of the foundation, g the acceleration due to gravity and C_m the apparent soil mass factor, presented in graphical form in the same literature [28]. The graphical forms are not reproduced here for the sake of brevity. The vertical component of the pressure from the footing is considered to decrease with depth and to be uniformly distributed over rectangular areas bounded by planes sloping outward from the footing at an angle with the vertical, the tangent of which is $\alpha/2$. The results, presented in the paper, show that the lateral period incorporating soil-flexibility is not altered appreciably due to consideration of soil mass. Hence, the effect of the soil mass moving with the foundation is neglected in the rest of the study as its scope is restricted to isolated and grid foundations which essentially belong to the category of shallow/surface foundations.

3. Method of analysis

Finite element method is adopted to formulate the mass and stiffness matrices for the building frames considering the effect of soil–structure interaction, and also for those at fixed base condition. Consistent mass matrix is used to make the formulation as accurate as possible. Natural periods are determined from traditional eigenvalue problem using the mass and stiffness matrices. Knowing the fundamental lateral periods of the building frames with and without accounting the effect of soil–structure interaction, the change in fundamental lateral natural period compared to the same at fixed support condition of the corresponding cases has been plotted against different influential parameters to understand the trends.

Utility of knowing lengthened lateral periods due to the effect of soil-flexibility in predicting base shear is discussed in Section 5.2. Seismic analysis for computing base shear 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. 1d. The seismic base shear of these buildings are obtained due to the design spectrum (Fig. 1d) corresponding to 5% of critical damping provided in ‘Indian standard criteria for earthquake resistant design of structures’ [29] considering fixed base condition and also considering the effect of soil-flexibility as depicted earlier.

The value of damping considered in the computation of response is arrived at from the following considerations. It is reasonable to consider 5% of the critical damping for concrete structures at fixed base condition. The concept for deriving soil damping was proposed by Veletsos and co-workers [30–33]. Numerous other studies on this aspect were made later on [1–3]. Based on such 15 studies as listed in Gazetas [4] the guidelines are prescribed in the Literature [4,19] for calculation of soil damping considering the contribution of radiation and material damping. Following such guidelines, damping was calculated for an isolated raft footing-soil spring vibrating system due to a large variation in the range of foundation sizes. The calculations show that such an isolated raft (without pile)-soil spring system, the overall soil damping is not more than about 5% of the critical damping for such system, if the frequency of exciting pulses is not very small. This is in line with the experimental damping ratio observed for coupled sway-rocking of such isolated shallow/surface foundation (with embedment about half of its least lateral dimension) and equivalent soil spring system, as reported in the literature [34]. This literature [34] also provides the damping ratio computed through the procedure outlined by Gazetas [4], for the cases studied experimentally. These numerically calculated values also do not appreciably exceed about 5%. However, it may substantially increase due to foundation embedment or due to the vertical vibration [4]. However, such foundation and type of vibration are beyond the scope of the present study. Again, the effect of soil damping will be further reduced if the equivalent effect is considered with respect to the entire structure foundation-equivalent soil spring system instead of an isolated foundation-equivalent soil spring system as considered in the previous literature [4,14,19]. Hence, 5% of critical damping in each mode of vibration is considered for all the cases in the present study.

The Complete Quadratic Combination (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,

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

where, r_{io} and r_{no} are the peak responses corresponding to ith and nth mode, respectively, and ρ_{in} is the correlation coefficient between these two modes. ρ_{in} varies between 0 and 1 and $\rho_{in} = 1$ for $i = n$; thus Eq. (1) can be further simplified as

$$r_0 \cong \left(\sum_{n=1}^{N} r_{no}^2 + \sum_{i=1}^{N} \sum_{n=1}^{N} \rho_{in} r_{io} r_{no} \right)^{1/2}. \tag{3}$$

This modal combination method is applicable for wide variety of structures and the expressions for combined modal response depicted in Eqs. (2) and (3) are available in standard literature (e.g. [35])

4. Results and discussions

The results are presented in the form of percentage changes in lateral natural period, considering the effect of soil-flexibility with that of the fixed base condition as a function of various influential parameters. The results for three different types of building frame, namely, brick in-filled building frames, bare frames and brick in-filled frames with diagonal braces at peripheral panels are presented in three sub-sections, respectively. The trends observed in the results are also discussed in these sub-sections. Throughout the results and discussions part, the change in fundamental lateral natural period is considered, if not mentioned otherwise. The change in the other higher lateral natural periods due to incorporation of the effect of soil-flexibility is not only lesser in general, but also their changes have lesser effect on overall seismic response. So, a limited study has been carried out on this aspect.

4.1. Frames with brick in-fill

Building frames with brick in-fill may exhibit considerable increase in lateral natural period due to the effect of soil–structure interaction. The stiffness of the structure considerably increases due to the stiffening effect of brick in-fill. Therefore, the incorporation of the soil-flexibility should lessen the stiffnesses of the system quite considerably due to combination of a lesser stiffness of soil with a very high stiffness of the structure in series. Hence, the behaviour of the building frames under such condition has been analyzed in details. The major trend has been studied considering two different types of foundation of the building frames from the consideration of allowable and net safe bearing pressure. Since a similar trend in behaviour is observed in both the cases, results corresponding to the foundation size designed on the basis of allowable bearing pressure (which is more appropriate as it satisfies both shear failure and permissible settlement criteria) are presented, for the sake of brevity. The curves plotted in the same figure for the frames whose foundations are designed on the basis of allowable and net safe bearing pressure are marked by '$q_{allowable}$' and '$q_{net\ safe}$', respectively, to differentiate them from each other. The figures in which all the curves are for frames with foundations designed on the basis of allowable bearing pressure, no such mark is used. Again, the curves corresponding to the frames with tie beams at plinth level are marked by the word 'tie' while those corresponding to the frames without tie beams, no such mark is used. Similarly, in the figures containing separate curves corresponding to building frames resting different soil types are marked by the corresponding soil types, namely, very soft, soft, medium, stiff and very stiff, etc.

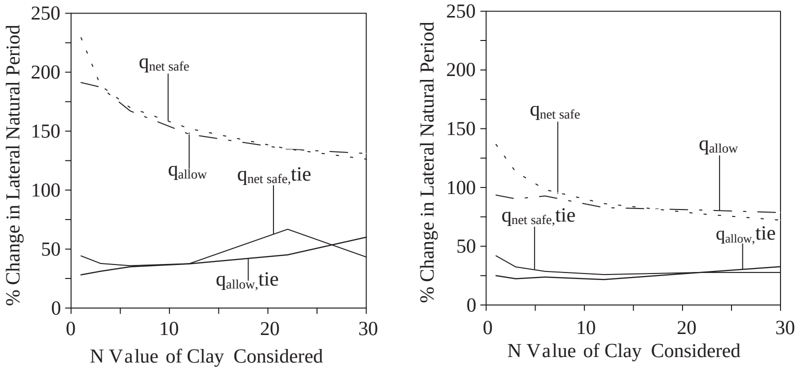
The effect of soil mass on natural period of vibration is demonstrated for a 2 bay 2 bay 1storey and a 4 bay 4 bay 4 storey building frame with isolated footings, and a 4 bay 4 bay 4 storey building frame with grid foundation. The frames with and without tie beams are considered in each case. Soft, medium and stiff soil are considered as the three typical supporting soil mediums. The results are presented in Table 3. The table shows that the change in fundamental lateral period incorporating soil-flexibility is marginal due to inclusion of the soil mass participating in the vibration. The apparent soil mass comes to be very low as compared to the total mass of the systems primarily contributed by the masses at various storey levels. This perhaps explains the marginal effect of inclusion of apparent soil mass. The effect is further minimized as the apparent soil mass attached at the foundation level is less effective to influence the earthquake induced lateral vibration as compared to the storey mass attached at much larger heights. Hence, the effect of the soil mass is not considered in rest of the study presented in the paper.

Table 3
Effect of 'apparent soil mass' on fundamental lateral natural period considering soil-flexibility

Frame type	Foundation type	Soil type	Period considering 'apparent soil mass' (s)	Period without considering 'apparent soil mass' (s)	% deviation
2 bay 2 bay 1 storey without plinth	Isolated	Soft	0.08119	0.07987	1.65
		Medium	0.07494	0.07414	1.08
		Stiff	0.06931	0.06887	0.64
2 bay 2 bay 1 storey with plinth	Isolated	Soft	0.10817	0.10770	0.44
		Medium	0.10698	0.10677	0.20
		Stiff	0.10678	0.10669	0.08
4 bay 4 bay 4 storey without plinth	Isolated	Soft	0.19973	0.19842	0.66
		Medium	0.18781	0.18725	0.30
		Stiff	0.16031	0.15949	0.51
4 bay 4 bay 4 storey with plinth	Isolated	Soft	0.24598	0.24552	0.19
		Medium	0.24113	0.24094	0.08
		Stiff	0.23186	0.23117	0.30
4 bay 4 bay 4 storey without plinth	Grid	Soft	0.24154	0.24138	0.07
		Medium	0.23360	0.23348	0.05
		Stiff	0.22232	0.22219	0.06
4 bay 4 bay 4 storey with plinth	Grid	Soft	0.29989	0.29980	0.03
		Medium	0.29596	0.29590	0.02
		Stiff	0.28769	0.28763	0.02

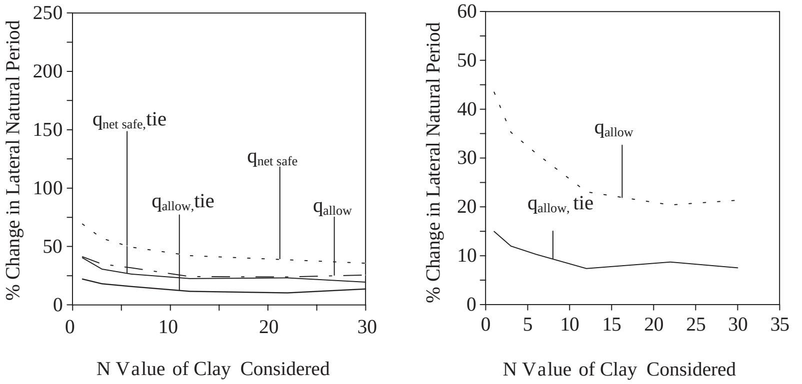
4.1.1. *Effect of variation of clay*

The change in lateral natural period due to the effect of soil–structure interaction is studied on 1, 2 and 4 storied building frames each having 2 bays in two mutually perpendicular directions. Another 4 storied frame with 4 bays in two mutually perpendicular directions is also considered for the sake of comparison of behaviour of same frame with grid foundation. These building frames are resting on isolated footings and have been analyzed both with and without considering the effect of tie beam. Results of such analysis have been plotted as percentage change in lateral natural period versus 'N' value of different types of clay in Fig. 2. A maximum increase of more than about 200% is observed for 2 bay 2 bay 1 storey building frame. This increase gradually reduces with the increase in number of stories of the building frame. On the other hand, when tie beam is added to these buildings such changes sharply decrease. Under such circumstances, only an increase of about 70% in the lateral natural period is observed in the same building frame. A more or less similar trend in behaviour is recognized irrespective of the fact whether the foundation is designed from the consideration of net safe or allowable bearing pressure. Hence, the results corresponding to the foundation design based on allowable bearing pressure is only presented in rest of the study. Further, the curve of 2 bay 2 bay 1 storey frame (whose foundations



2 bay 2 bay 1 storey

2 bay 2 bay 2 storey



2 bay 2 bay 4 storey

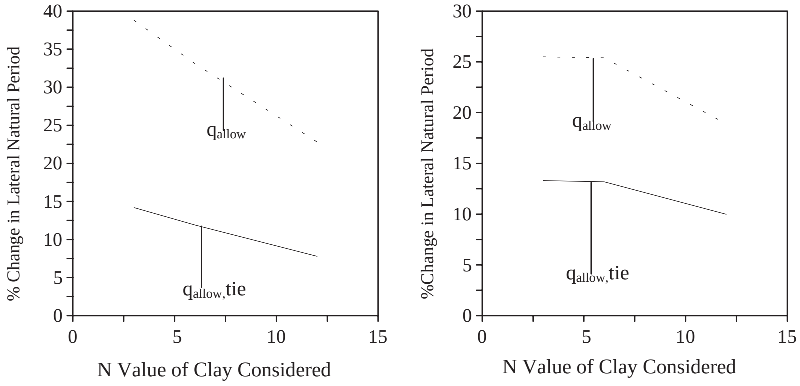
4 bay 4 bay 4 storey

Fig. 2. Variation of percentage change in fundamental natural period for building frames with isolated footing.

are designed on the basis of net safe bearing pressure) exhibits a peak at $N = 22$ in Fig. 2. The increase in N values may cause an increase in shear modulus while tends to decrease the dimensions of foundations. The former effect increases while the later one decreases the stiffnesses of equivalent soil springs. As a result of these two counterbalancing effects, perhaps the maximum value is reached at $N = 22$ for this curve.

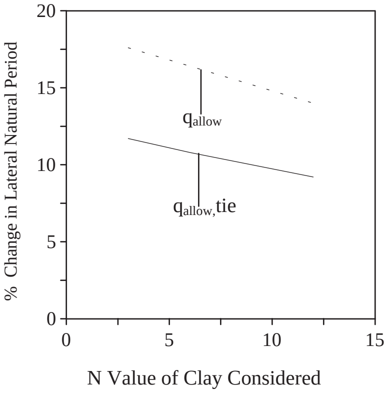
For buildings with grid foundation, 3 storey, 4 storey and 6 storey building frames each having four bays in two mutually perpendicular directions have been considered. These building frames are considered to be resting on soft, medium and stiff clay to perceive the trend in behaviour. Detailed results of such analysis have been plotted in Fig. 3. It is found that a maximum increase of about 40% in lateral natural period occurred for 4 bay 4 bay 3 storey building frame without tie beam. Due to the addition of tie beam, a maximum increase not more than 15% is observed. This amount of change in lateral natural period again is found to be decreasing with increase in number of stories likewise building frames with isolated footings.

A 4 bay 4 bay 4 storey building with isolated footing resting on different types of soils mentioned earlier has also been analyzed corresponding to the footing dimension based on



4 bay 4 bay 3 storey

4 bay 4 bay 4 storey



4 bay 4 bay 6 storey

Fig. 3. Variation of percentage change in fundamental natural period for building frames with grid foundation.

allowable bearing capacity. Results of such analysis have been presented in Fig. 2, to facilitate a direct comparison with the behaviour of the same frame resting on grid foundation. Such a comparison will help to distinguish the effect of change of foundation from isolated footings to grid. The comparison of these results with those of the 4 bay 4 bay 4 storey frame with grid foundation shows that order of change in lateral natural period are almost same in both the cases. Thus, the lesser order of change observed for buildings with grid foundation may be due to the consideration of increased number of stories and bays (for which grid foundation is adopted, generally), probably not due to the provision of grid foundation instead of isolated footing. Both isolated and grid foundations perhaps undergo the same mechanism during lateral vibration as both of them are shallow/surface foundations. Probably due to this reason, the effect of soil-flexibility does not appreciably change due to provision of grid foundation instead of isolated footing.

Introduction of tie beam may be a very viable measure to reduce the effect of soil–structure interaction. Tie beams make higher contribution to the mass at GL than what it makes to the overall stiffness. Thus, it results in a comparatively flexible structural system, with lesser effect of soil–structure interaction. For the buildings resting on isolated footing, the introduction of tie beam effectively transfers the wall load of ground storey level resting on it onto the foundation leading to an increase in foundation size. Hence, this enhances the stiffness of the equivalent springs representing the soil behaviour leading to the lesser change in soil-flexibility. Increase in the size of the footing and subsequently the change in stiffness of the equivalent springs representing soil behaviour is relatively higher for the tie beam addition to the building frames having lesser number of stories. Moreover, reducing the unsupported length of the column, tie beams reduce the rotational flexibility of the column of the building frames with isolated footing at the GL. Combined effect of these two factors reduces the effect of soil–structure interaction due to the addition of tie beams. Hence, reducing effect due to addition of tie beam is very strong for buildings having lesser number of stories and gradually diminishes with increasing number of storey in the building frame. Further, the results, as a whole, reveals that the effect of soil–structure interaction on the increase in lateral natural period gradually decreases as the hardness of the soil increases.

4.1.2. Effect of variation of number of stories

2 bay 2 bay building frame with isolated footings and 4 bay 4 bay building frame with grid foundation have been considered for this purpose. Frames with and without tie beams are considered in each case. Number of stories is varied as 1, 2 and 4 for buildings with isolated footings and 3, 4 and 6 for buildings with grid foundations. Corresponding to each combination of all these parameters, frames on different types of soil are considered. Thus, a large number of case studies are needed to be conducted. However, in the limited scope of the present paper, limited trend-indicating results of a few sample cases are only included. Figs. 4a and 4b exhibit variation of percentage change in lateral natural period as a function of number of stories for buildings with isolated footings and those with grid foundations, respectively. It is observed that the percentage change in lateral natural period may differ by 150% due to the variation of number of stories from one to four in case of buildings with isolated footings, while the same is found to be only in the order of 25% for buildings with grid foundations. Both of the figures clearly

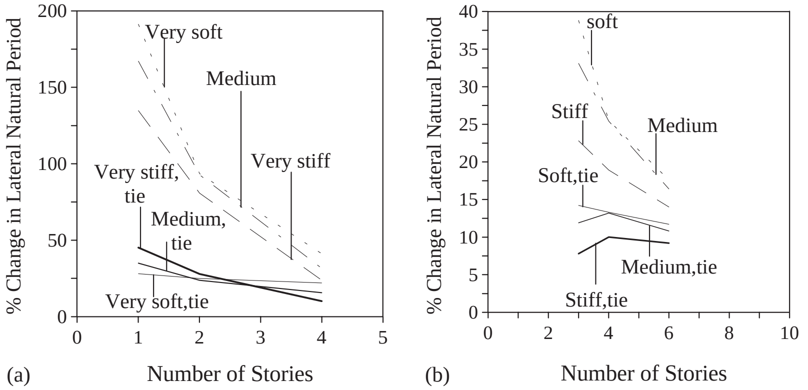


Fig. 4. Variation of percentage changes in fundamental natural period for (a) isolated footing with 2 bay 2 bay and (b) grid foundation with 4 bay 4 bay building frames.

indicate that the effect of soil–structure interaction on the change in lateral natural period generally decreases with increase in number of stories in the building frame. With the increase in number of storey, 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. On the other hand, the fractional decrease in overall stiffness will be high when the effect of lesser stiffness of equivalent springs representing soil behaviour acts in series with relatively very stiff behaviour of low-rise buildings with lesser number of stories. 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 in overall stiffness lesser. Hence, change in lateral natural period due to the effect of soil–structure interaction, is relatively lesser for buildings with larger number of stories.

4.1.3. *Effect of variation of number of bays*

A large number of case studies on the change in lateral natural period with the variation of number of bays have been studied in details. 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 single storey building frame with isolated footing and three storey frame with grid foundation have been considered to exhibit the maximum possible effect of bay variation on change in lateral natural period due to incorporation of the effect of soil–structure interaction. Results corresponding to all other cases, though studied, are not presented for the sake of brevity. For buildings with isolated footings, number of bays has been shown to be varied as 1, 2 and 4; while for buildings with grid foundation, cases corresponding to 4 and 6 bays are presented. The percentage change in lateral natural period has been presented in Figs. 5a and 5b as a function of number of bays, for buildings with isolated and grid foundation, respectively. The figures show that maximum change in lateral natural period may only be about 30% due to change in number of bays. However, no clear trend in the results is obtained.

4.1.4. *Effect of ratio of column to beam stiffness*

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 lateral natural period due to the effect of soil–structure interaction. The ratios are so chosen as to cover all practical cases. Out of the extensive case studies, results for 2 bay 2 bay 2 storey building frames resting on isolated footing and that for 4 bay 4 bay 4 storey building frames with grid foundation have been presented to show the trend in behaviour in Figs. 6a and 6b, respectively. It is observed that the change in lateral natural period due to the effect of soil–structure interaction does not alter appreciably with the change in the ratio of column to beam stiffness in the feasible range.

4.1.5. *Effect of frequency on soil-flexibility*

It is well accepted that the dynamic stiffness of the soil medium is dependent on the frequency of the forcing function, i.e., frequency of ground excitation to account for the effect of the same

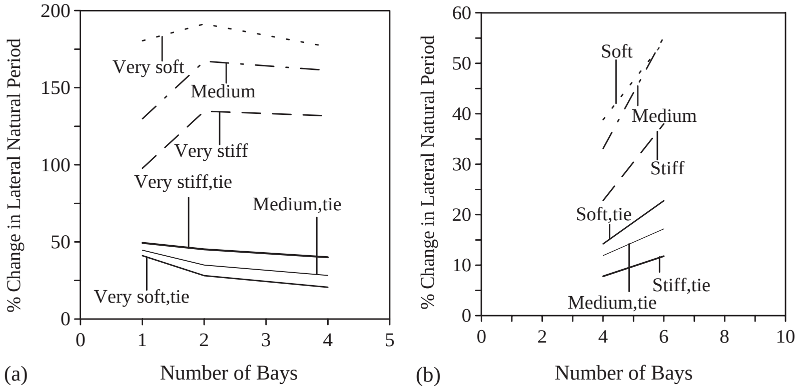


Fig. 5. Variation of percentage changes in fundamental natural period for (a) isolated footing with 1 storey and (b) grid foundation with 3 storey building frames.

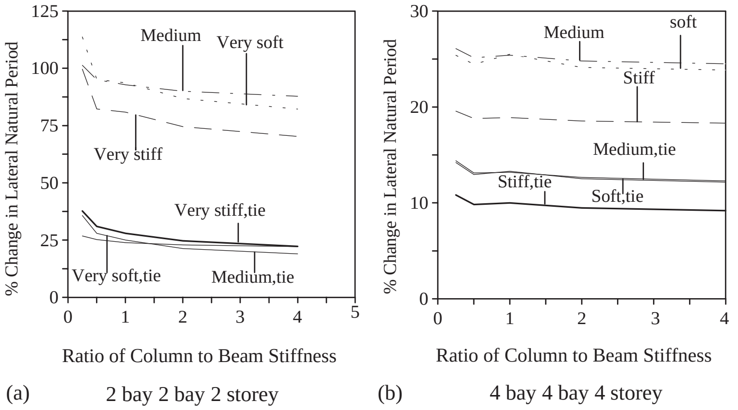


Fig. 6. Variation of percentage changes in fundamental natural period with variation of column to beam stiffness for building frames with (a) isolated footing and (b) grid foundation.

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 the two critical cases, i.e., $a_0 = 0.0$ and 1.5 for buildings with isolated footing and three critical cases, i.e., $a_0 = 0.0$, 0.3 and 1.5 for buildings with grid foundation as mentioned earlier. The results of such study have been presented in Figs. 7a and 7b for building frames with isolated footings and grid foundations, respectively. The results corresponding to the frequency independent behaviour of soil, i.e., $a_0 = 0.0$ has also been included for the sake of comparison.

Maximum changes in lateral natural period is found to be in the order of about 115% and 45% for $a_0 = 1.5$, while the same is observed to be around 95% and 30% for $a_0 = 0$, for buildings with isolated footings without and with tie beam, respectively. An undulation is exhibited in range of $N = 1-12$ for the curve corresponding to $a_0 = 1.5$ for the 2 bay 2 bay 2 storey frame in Fig. 7a. This also perhaps due to the same two counter balancing effect of increase in shear modulus and decrease in foundation dimensions with increasing N as mentioned in Section 4.1.1.

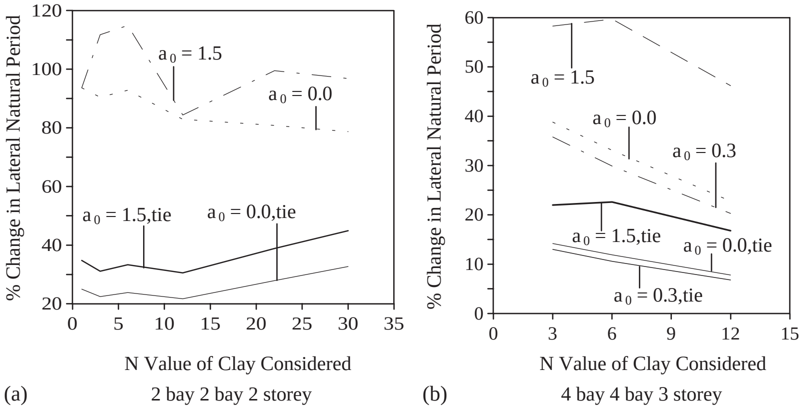


Fig. 7. Variation of percentage changes in fundamental natural period with variation of excitation frequency for building frames with (a) isolated footing and (b) grid foundation.

For buildings with grid foundations without tie beam, the results presented in Fig. 7b show a maximum increase in fundamental lateral period at $a_0 = 0.3$ as 36%. At $a_0 = 1.5$, this increase may go up to 60% as against a peak increase of about 40% corresponding to $a_0 = 0.0$ under this consideration. Likewise, for such buildings with tie beam a maximum increase in fundamental lateral period is observed in the order of about 13% corresponding to $a_0 = 0.3$, and about 22% for $a_0 = 1.5$; while such increase is found to be in the order of 15% at $a_0 = 0.0$. This shows that the effect of frequency of the forcing function may influence the dynamic behaviour of the system. However, the effect of such frequency-dependent factors becomes subdued if tie beam is introduced in the building frame. Nevertheless, such effect of frequency may be considered for the purpose of analysis of the important structures to have a 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. Bare frames

Bare frame idealization is not realistic, but such idealization is used many a time in the design offices. Hence, from the viewpoint of academic interest, a limited case study has also been made on such frames. The change in fundamental lateral natural period obtained from such analysis for 2 bay 2 bay building frames with isolated footing having 2 and 4 stories are presented in Table 4. The results for 4 bay 4 bay frames with grid foundation having 3 and 4 stories are presented in Table 5. The percentage changes in lateral natural period due to incorporation of the effect of soil–structure interaction compared to the same in fixed base condition are also presented in the same tables. The results for all other cases are not presented for the sake of brevity as they also exhibit similar trends. It is seen that, the bare frames exhibit a very insignificant change in their fundamental lateral natural periods, irrespective of the buildings or foundations type. Again, this observation is found to be true for both types of the bare frames, namely, the ones without tie beams as well as the ones with tie beams.

Table 4
Percentage change in fundamental lateral natural periods of bare frames with isolated footing

Details of building		Type of soil	Fundamental lateral natural period (s)		% change in lateral period
No. of bay	No. of storey		Without SSI	With SSI	
(a) *Bare frames without tie beams*					
2 in both principal directions	2	Soft	0.431	0.441	2.32
		Medium		0.449	4.18
		Stiff		0.458	6.26
	4	Soft	0.915	0.923	0.87
		Medium		0.923	0.87
		Stiff		0.915	0.00
(b)*Bare frames with tie beams*					
2 in both principal directions	2	Soft	0.498	0.504	1.20
		Medium		0.506	1.61
		Stiff		0.506	1.61
	4	Soft	1.028	1.037	0.87
		Medium		1.036	0.78
		Stiff		1.034	0.58

Note: ‘without SSI’ denotes the results without considering the effect of soil–structure interaction; ‘with SSI’ denotes the results with considering the effect of soil–structure interaction.

Since, the bare frames exhibit a very small change in natural period due to the effect of soil–structure interaction as expected, no significant change is supposed to be found in their seismic response due to the effect of soil–structure interaction. Hence, the actual seismic responses of the building frames will not be reflected through the analysis of these bare frames. This observation has concurrence with the observation for buildings on isolated footings modelled as bare frames elsewhere [36].

4.3. Building frames with diagonal braces in peripheral panels

It has been found in the literature [6] that the change in force quantities in the column members of the building frames with isolated footing due to the effect of soil–structure-interaction under static gravity loading may be considerably minimized by the addition of diagonal braces in all the peripheral panels of the building frames. Hence, it is needed to be seen whether such addition is having any additional effect on this important dynamic characteristic, namely the lateral natural period of the system. In fact, such an addition to minimize the severe effect of soil–structure interaction on building frames with isolated footings arising due to differential settlement may not be feasible if this alters the dynamic characteristics of buildings, adversely. This section investigates this issue in a limited form. The steel diagonal braces were provided and the diameter of these steel braces was adjusted in such a way that the axial rigidity, i.e., cross-sectional area × modulus of elasticity is same as that of the reinforced-concrete columns. In fact, the previous study [6] used the diagonal braces of this same axial rigidity to study its influence on the

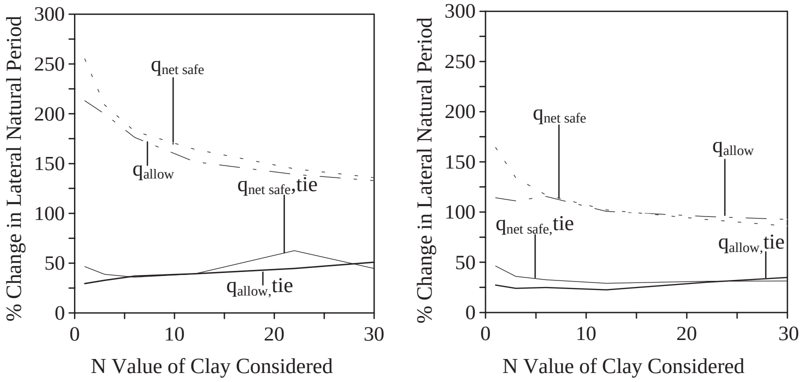
Table 5
Percentage change in fundamental lateral natural periods of bare frames with grid foundation

Details of building		Type of soil	Fundamental lateral natural period (s)		% change in lateral period
No. of bay	No. of storey		Without SSI	With SSI	
(a) *Bare frames without tie beams*					
4 in both principal directions	3	Soft	0.720	0.730	1.39
		Medium		0.729	1.25
		Stiff		0.728	1.11
	4	Soft	0.970	0.980	1.03
		Medium		0.980	1.03
		Stiff		0.979	0.93
(b) *Bare frames with tie beams*					
4 in both principal directions	3	Soft	0.797	0.807	1.25
		Medium		0.807	1.25
		Stiff		0.806	1.13
	4	Soft	1.050	1.055	0.48
		Medium		1.055	0.48
		Stiff		1.054	0.38

Note: 'without SSI' denotes the results without considering the effect of soil–structure interaction; 'with SSI' denotes the results with considering the effect of soil–structure interaction.

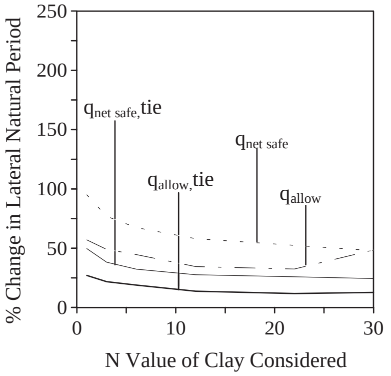
effect of soil–structure interaction under static loading. The following limited trend-indicating results presented from a fairly large sample case study may be helpful to resolve this issue.

Change in lateral natural period due to the addition of diagonal braces in the outer peripheral panels with variation of N values has been studied for 2 bay 2 bay building frames with 1, 2 and 4 stories, both with and without tie beam resting on isolated footing and has been presented in Fig. 8. A comparison of Fig. 8 with Fig. 2 clearly reveals that no appreciable change in the effect of soil–structure interaction on lateral natural period occurs due to such addition. This is possibly because the addition of such braces can alter the lateral stiffness of the building frame, to a very small extent, compared to the stiffening effect imparted to the frame by the in-fill. The peak observed at $N = 22$ for 2 bay 2 bay 1 storey frame with tie beams and isolated footings designed by net safe bearing pressure is perhaps due to the same reason as explained for similar peak of the curve corresponding to the similar frame without diagonal braces in Fig. 2. The effect of soil–structure interaction on such building frames with diagonal braces has also been studied with the change in number of stories and bays. These have been presented in Figs. 9a and 9b, respectively. No significant change compared to the same without such braces in behaviour is noticed for these cases perhaps due to the same reason. Similar effect has been studied with the variation of column to beam stiffness and frequency dependence of soil-flexibility. The results are not presented in the limited scope of the study. A more or less similar trend in behaviour is observed for building frames with and without such diagonal braces. Thus, this addition of diagonal braces may be effectively used to reduce the differential settlement without having any adverse effect on the dynamic characteristic considered in this study.



2 bay 2 bay 1 storey

2 bay 2 bay 2 storey



2 bay 2 bay 4 storey

Fig. 8. Variation of percentage change in fundamental natural period for buildings *with braces* resting on isolated footing.

4.4. Change in higher lateral periods

The effect of soil–structure interaction on higher lateral periods is also studied. For one or two storied building frames with isolated footing, the percentage changes in second, third and higher lateral periods are much lesser than that in fundamental lateral period. Moreover, due to larger lengthening of fundamental lateral period, it becomes more spaced apart from the higher periods leading to the reduced participation of higher modes in seismic response. However, the percentage changes of second lateral periods are found to be considerable relative to the percentage changes of fundamental lateral period for four storied building frames with isolated footings and for all frames under consideration with grid foundation. The changes of third and higher lateral periods become too small in all the cases. The sample results for the change in second lateral period with consideration of four bays in both the principal directions of frames are presented in Fig. 10 (for building frames with isolated footing) and Fig. 11 (for building frames with grid foundation), respectively. The ratio of the percentage change in second lateral period and that in fundamental lateral period is plotted as function of '*N*' value of soil, in these figures. The curves presented in these figures may act as a guideline to estimate the percentage change in second lateral period.

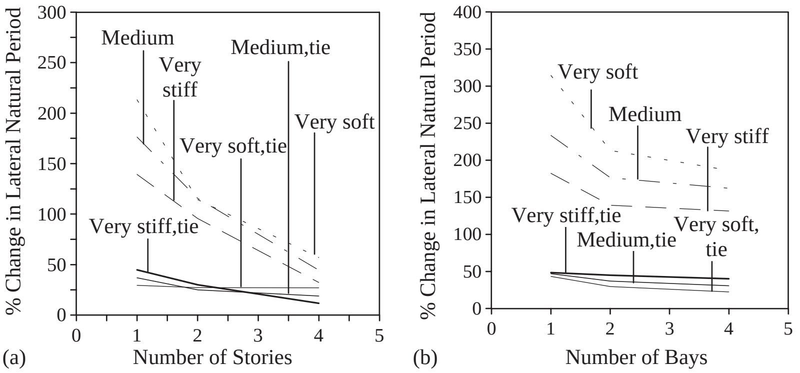


Fig. 9. Variation of percentage changes in fundamental natural period for (a) 2 bay 2 bay and (b) 1 storey buildings *with braces* resting on isolated footing.

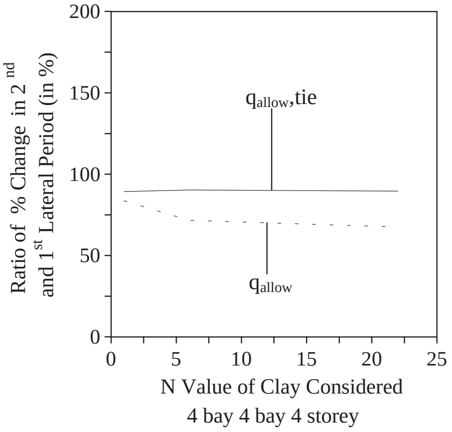


Fig. 10. Ratio of changes of lateral periods in second and first modes for buildings resting on isolated footing.

Such estimation may particularly be reliable for frames with tie beams for which the plotted ratio becomes almost constant being very less dependent on soil type.

5. Utility of variation curves

5.1. Utility of variation curves for predicting lateral natural period

The curves in Figs. 2–7, showing the variation of primary dynamic characteristic, namely, lateral period, can be used for better seismic design of buildings. These curves can be used to estimate the effect of soil–structure interaction on this primary dynamic characteristic of any general low-rise building frames with both the types of foundation, i.e., isolated and grid foundation by using simple linear interpolation. A large number of building frames is analyzed in

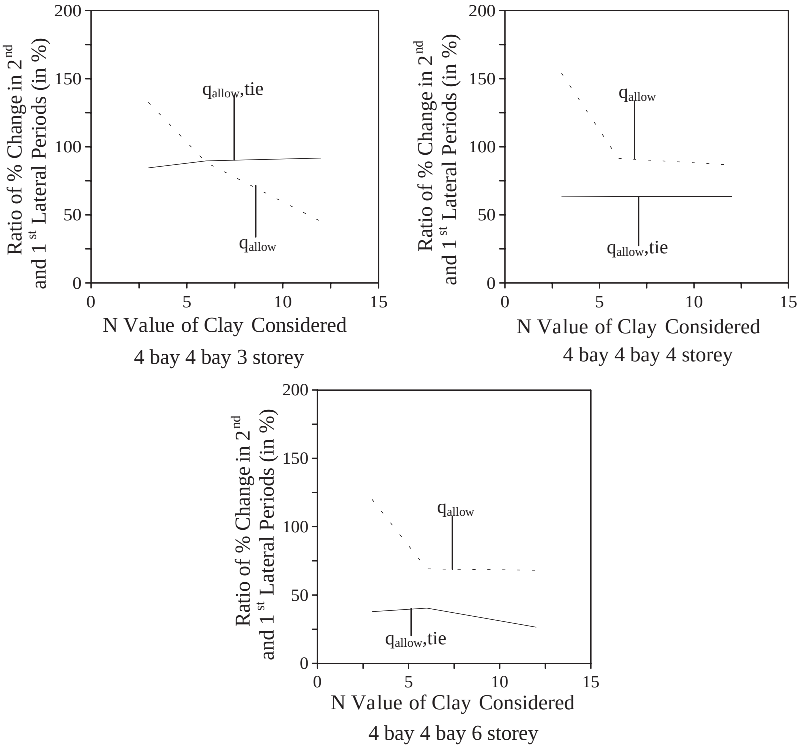


Fig. 11. Ratio of changes of lateral periods in second and first modes for buildings resting on grid foundation.

fixed base conditions and the results corresponding to the above-mentioned dynamic characteristic are obtained. After obtaining the percentage change in this dynamic characteristic due to soil–structure interaction by linear interpolation from the present variation curves, the fundamental lateral natural period considering the effect of soil–structure interaction is obtained. These same frames are also analyzed to find out the fundamental lateral natural period considering the effect of soil–structure interaction as discussed in the present study. The characteristic obtained through interpolation from the present curves is found to be sufficiently accurate as compared to their values obtained from actual analysis. Comparisons of results obtained from linear interpolation and those from actual analysis for a few sample buildings with two different types of foundations are presented in Table 6. The tables show that the lateral natural periods obtained through linear interpolation are sufficiently close to the actual values. Hence, the variation curves presented in this paper can be helpful to account for the effect of soil–structure interaction in seismic design even through a conventional fixed-base analysis.

5.2. *Predicting seismic base shear incorporating the effect of soil-flexibility*

A large number of curves demonstrating the variation of the important dynamic characteristic, namely, the lateral natural period from Figs. 2–7 can be used for better seismic design of the low-

Table 6
Performance of the variation curves in predicting lateral period of building frames

Frame type	Foundation type	Soil type	T_x (s) actual	T_x (s) interpolated	% deviation
2 bay 2 bay 3 storey without plinth	Isolated	Medium	0.218	0.219	0.46
3 bay 3 bay 1 storey without plinth	Isolated	Very soft	0.077	0.077	0.00
		Medium	0.070	0.071	1.43
		Very stiff	0.061	0.063	3.28
4 bay 4 bay 5 storey without plinth	Grid	Soft	0.247	0.251	1.62
		Medium	0.246	0.249	1.22
		Stiff	0.238	0.239	0.42
4 bay 4 bay 5 storey with plinth	Grid	Soft	0.309	0.308	−0.32
5 bay 5 bay 3 storey without plinth	Grid	Medium	0.119	0.118	−0.84
		Stiff	0.108	0.106	−1.85

rise buildings. These curves can be utilized to estimate the effect of soil–structure interaction on the significant seismic characteristic, namely the base shear of any general low-rise building frame resting on isolated footing even from a simple fixed base consideration. Firstly, the building frames can be conveniently analyzed with fixed base condition. The fundamental lateral natural periods corresponding to the soil-flexibility condition can be obtained from the variation curves of the above-mentioned figures. Knowing the lateral natural periods of the frames with and without consideration of the soil-flexibility, the ratio of the lateral stiffnesses with and without considering the effect of soil-flexibility can be obtained as $(T_{SSI}/T_{FIXED})^2$, where, T_{SSI} and T_{FIXED} represent 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 can be considered whose lateral stiffness can be reduced to a proportion of $(T_{SSI}/T_{FIXED})^2$ by reducing the modulus of elasticity in the same ratio. Hence, these frames can be considered as frames similar to the actual ones with fundamental lateral natural period same as that incorporating the effect of soil-flexibility. These building frames at fixed base condition may yield the same base shear as obtained from actual frames considering the effect of soil–structure interaction. 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 for some sample cases is presented in a tabular form in Table 7. The results of this table exhibit a close resemblance between the outcomes of these two procedures. The inherent facility of carrying out with this equivalent fixed base model is that no rigorous modelling due to inclusion of the effect of soil–structure interaction is required here. Hence, the variation curves for buildings presented in this study can be helpful to account for the effect of soil–structure interaction in seismic design even through a conventional fixed base analysis.

Table 7
Prediction of seismic base shear of building frames through proposed approximation

Frame type	Foundation type	Soil type	Base shear actual (kN)	Base shear approximated (kN)	% deviation
2 bay 2 bay 1 storey without plinth	Isolated	Very soft	637	619	−2.83
		Medium	579	557	−3.80
		Very stiff	545	524	−3.85
4 bay 4 bay 1 storey with plinth	Isolated	Very soft	5270	5229	−0.78
		Medium	5177	5107	−1.35
		Very stiff	5914	5825	−1.50
2 bay 2 bay 2 storey with plinth	Isolated	Very soft	3399	3474	2.21
		Medium	3388	3408	0.59
		Very stiff	3478	3461	−0.49
2 bay 2 bay 4 storey with plinth	Isolated	Very soft	6172	6350	2.88
		Medium	6239	6346	1.72
		Very stiff	6333	6345	0.19

6. Conclusions

The present study makes an effort to evaluate the effect of soil–structure interaction on primary dynamic characteristic of low-rise buildings with isolated footing and grid foundation and attempts to provide exhaustive guidelines regarding this issue. The results of the study may lead to the following broad conclusions:

1. The study shows that the effect of soil–structure interaction may appreciably alter the lateral natural periods of any building structure. This is the primary parameter, which regulates the seismic lateral response of the building frames. Thus, evaluation of this parameter without considering soil–structure interaction may cause serious error in seismic design.
2. This effect is pronounced if the structure does not have tie beam, irrespective of whether the building frame has isolated or grid foundation. The effect is further aggravated with decreasing hardness of soil. Hence, this effect needs to be considered very seriously at least in these cases.
3. The study shows that the effect of soil–structure interaction on lateral natural period is not appreciably altered even if a grid foundation is provided instead of isolated footings. This is evident from the comparison of the results for two building frames having two types of surface/shallow foundation, namely, isolated footing and grid foundation, respectively; while being exactly similar in other aspects and parameters. The larger change observed for building frames with isolated footings is primarily due to lesser number of stories of these frames, for which this type of foundation is considered to be suitable. In fact, the study shows that building frames with large number of stories are expected to have lesser effect on this important dynamic characteristic parameter because of their increasing flexibility with number of stories.

4. If the effect of the in-fill brick wall is not considered while studying the seismic behaviour of building frames, the effect of soil–structure interaction may not be recognized.
5. The effect of soil–structure interaction on the change in lateral natural period does not appreciably alter due to the change in column to beam stiffness ratio.
6. Excitation frequency of the forcing function may influence the effect of soil–structure interaction on dynamic behaviour of buildings to a limited extent. Hence, such consideration may be incorporated suitably for important structures.
7. Addition of diagonal braces in the outer peripheral panels of the building frames with isolated footing has insignificant effect on the change in lateral natural period. However, it is found elsewhere [6] that such additional braces may significantly reduce the soil–structure interaction effect of building frames with isolated footings arising due to gravity loading. Hence, these braces may be suitably added for reducing the effect of differential settlement without affecting the dynamic behaviour of the building frames resting on isolated footings.
8. The study, as a whole, identifies the influential parameters, which can regulate the effect of soil–structure interaction on lateral natural period of building frames. The variation of this effect due to all these parameters are presented. A large number of curves exhibiting such variation for typical sample cases can help the designer to get a primary idea about the effect of soil–structure interaction on this important dynamic characteristic at least for preliminary seismic design, and to identify the cases expected to have severe effect of the same.

The variation curves are also found to be effective in predicting the dynamic characteristic through linear interpolation after obtaining the dynamic characteristic at conventional fixed-base condition of buildings. Finally, knowing the changed lateral period, the base shear can be calculated through the consideration of a building frame at fixed base condition, but, with lateral period adjusted so as to incorporate the effect of soil-flexibility. Thus, the conventional fixed base analysis may be sufficient to estimate accurately the seismic shear of a building frame considering the effect of soil-flexibility.

The study as a whole may prove useful in formulating design guidelines for seismic design of building frames incorporating the effect of soil-flexibility.

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