

Soil–Structure Interaction Effect on Seismic Force Evaluation of RC Framed Buildings with Various Shapes of Shear Wall: As Per IS 1893 and IBC

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Abstract Behaviour of a structure is altered by the interaction amid the structure, foundation and the soil medium below the foundation. This mutual dependent behaviour of structure and soil is called as soil–structure interaction (SSI). Hence, it is not realistic to analyse a structure as per conventional structural design practice which considers the base to be fixed. Comparative study on seismic provisions of Indian seismic code, IS 1893:2002 (IS) and International building code IBC:2006 (IBC) is carried out in present study to look into the effect of soil flexibility on variation in natural period, spectral acceleration coefficient, base shear and storey shear. Multi-storey reinforced concrete framed buildings of varying height with various shapes of shear walls over raft foundation were considered. Analysis of 3D SSI models with three different shear wall shapes founded on four different soil types which are classified based on shear wave velocity has been carried out using finite element software LS DYNA. Study shows the significant effects of SSI in altering the seismic response of structure. It also shows that the base shear obtained as per IBC are higher than the IS values and the corrugated shape of shear wall experience the lowest base shear compared to cylindrical and rectangular shape shear walls for buildings with aspect ratio below 3.

Keywords Soil–structure interaction · Soil flexibility · Shear wall · Base shear · Seismic codes · Design response spectrum

Introduction

Analysis of structures requires the structural and geotechnical engineering to be closely connected as the two fields are interdependent of each other. Analysis of neither the super structure nor the subgrade (soil) can be performed independently with accurate results. To get the real behaviour of superstructure, the subgrade must be considered in the analysis. However, conventional structural design practice assumes the base of building to be fixed by neglecting the influence of soil. This is unrealistic as the supporting soil influences the structural response by permitting movement to some extent due to its natural ability to deform. The lessons learnt from previous earthquakes of neglecting the effect of soil are emphasizing on the importance of considering soil–structure interaction in the seismic analysis of structures. Employing soil–structure interaction effects enables the designer to evaluate the real displacements of the system precisely under seismic motion.

The effects of soil flexibility are generally ignored considering it to be beneficial in seismic response of a structure. However, the consequences and severities of neglecting the effect of SSI were reported in the studies of [1–4]. Similar studies on conventional elastic and inelastic design procedure of moment-resisting building frames by Tabatabaiefar et al. [5] showed the implications of neglecting the SSI in ensuring the structural safety. Bielak [6] and Stewart et al. [7, 8] reported the effects of lengthening of lateral natural period on seismic responses of the buildings due to the effect of soil flexibility and also showed the importance of considering SSI in design consideration. A similar study on lengthening of fundamental lateral natural period in low-rise buildings was carried out by Bhattacharya and Dutta [9] showing the significance of

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fundamental lateral period in short period region of the design response spectrum. Saad et al. [10] showed the impact of soil–structure interaction on base shear, moments and inter-storey shears of reinforced concrete buildings with underground stories. Influence of soil–structure interaction on reinforced concrete moment resisting frames was carried out by Tabatabaiefar and Maussumi [11] by using 3D finite element model to simulate the effects of interaction. The implication of considering SSI in seismic design of RC-MRF buildings higher than three and seven stories on soft soils were discussed in the study. The virtues of considering nonlinear soil–structure interaction analysis over conventional fixed-base and elastic-base models showing the substantial reduction in force and displacement demands was studied by Raychowdhury [12]. The effect of soil–structure interaction on stress resultants experienced by the raft and the interface between the rock and raft of massive concrete structures supported over raft foundation was carried out by Rajasankar et al. [13]. ANSYS and LS DYNA finite element software were used in the study to understand and assess the significances of the simplified modelling strategy to ensure stability in the performance of the model.

In design and construction of structures with adequate resistance to seismic forces, guidelines from seismic codes are followed. Codes vary from region to region to handle the differing levels of seismic risk. These codes are the most reliable guidance available in design and construction of structures to ascertain adequate resistance to seismic forces.

Determining the natural period of vibration of a reinforced concrete structure is a necessity in earthquake design and assessment. Realization of global demands of structure under seismic action can be better determined from sole characteristic, the natural period. Goel and Chopra [14] showed that the measured periods of frame buildings are generally longer than the period provided by seismic code formulas. Hence authors developed improved formula by regression analysis to provide better correlation with frame buildings.

Seismic provisions of various international building codes were compared by Pong et al. [15] and Dogangun [16] to study the differences in base shear and storey drift. Comparative design study showing the variations in base shear and quantity of steel in shear wall as per IBC 2000 and UBC 1997 seismic design provisions was reported by S.K Gosh et al. [17]. Comparative study of four major codes, viz. ASCE7 (United States), EN1998-1 (Europe), NZS 1170.5 (New Zealand) and IS 1893 (India) showing various ductility classes, representing response reduction factors and reinforcement detailing provisions of a ductile RC frame building were reported by Singh et al. [18]. Similarly the significant differences existing in basic

provisions of four major national seismic building codes ASCE 7, Eurocode 8, NZS 1170.5, and IS 1893 was studied by Khose et al. [19]. Imashi and Massumi [20] compared the seismic provisions of Iranian seismic code (standard no. 2800) and IBC 2003 to determine the seismic forces by static analysis method. The need of review of Iranian seismic code to develop more appropriate relations in achieving economic and functional objectives was stated in study. Similar comparative studies on different seismic codes were carried out by [21–24].

Parametric study for determining the variation in lateral natural period, spectral acceleration coefficient (S_a/g), base shear and storey shear using Indian seismic code IS 1893 (part 1):2002 (IS) [25] and International building code (IBC) [26] design spectrum for buildings assumed to be constructed over different soil sites and founded over different soil types is attempted in present study. The seismic response variation is also assessed by considering shear walls of various shapes placed at the exterior frames of buildings. Results of the study are expressed in terms of parameters such as aspect ratio which is the height-to-base ratio of building (h/d), relative stiffness of superstructure (K_{sb}) and raft (K_{rs}), which are the ratios of the absolute stiffness of the super structure K_b , the raft K_r and the soil K_s .

Soil–Structure Interaction Analysis

Structural response under any type of loading is varied by the interaction among the structure, its foundation and the soil medium below the foundation. The motion of supporting soil alters the response of the structure and the response of structure alters the motion of the soil. This mutual dependency in the structure and soil response is called as soil–structure interaction (SSI). The most widely used SSI approach in three dimensional soil–structure systems is based on the “added motion” formulation [11] which is mathematically simple, theoretically correct, and is easy to automate and can be used within a general linear structural analysis program. Looking into the modeling method of soil region, SSI problems are classified into two main categories, namely direct method and substructure method [1]. In direct method, response of the entire structure foundation–soil system is modelled and analysed in a single step. However, in substructure method, analysis of parts of whole structural system is performed in several steps and the final response is based on the principle of superposition.

In SSI problems, the soil medium is most commonly modelled using Winkler spring model and elastic continuum model. In Winkler spring method, soil medium is presumed to be consisting of a series of closely spaced

springs on which the foundation slab lies. The springs considered are assumed to be linear in nature and their stiffness are dependent on the subgrade modulus [27, 28]. Elastic continuum model is a deterministic approach of physical illustration of the infinite soil media [13]. Here soil medium is divided into elements interconnected only at a finite number of nodes.

From an extensive literature review it is noticed that the effect of shapes of shear walls in structural seismic resistance is less studied. Comparative study on seismic provisions of Indian seismic code, IS1893:2002 (IS) and International building code IBC: 2006 (IBC) incorporating SSI are also seldom considered. Advantages of various geometric shapes of shear walls as compared to regular rectangular shear walls in attracting the least earthquake forces are explored in the present study by including the effect of soil–structure interaction. Present soil–structure interaction analysis considers multi-storey reinforced concrete framed buildings of aspect ratio in the range 1:4 with shear wall of varying shapes resting over raft foundation. Four types of soil classified based on shear wave velocity are considered in the study.

Characteristics of Structural and Geotechnical Model

Structural Characteristics

Present analysis considers multi-storey reinforced concrete framed buildings of aspect ratio 1, 1.5, 2, 3 and 4 with and without shear wall resting on raft foundation. Buildings comprises of ordinary moment resisting frames having three bays equal in length in each direction with effect of infill being neglected. Buildings are symmetric in plan. Shear walls of varying shapes were symmetrically placed in both directions of exterior frames of the building to study the effect of varying shapes of shear wall. Regarding the building to be for domestic or small office building, the storey height was chosen as 3 m and length of each bay of building frames as 4 m. The thickness of rectangular shape shear wall is varied from 150 to 250 mm depending on the building height. Thickness of other shear wall shapes is varied accordingly such that the total mass of the structure is same as that of the rectangular shear wall building. The percentage variation in mass of these buildings is less than 2 %. Dimension of building elements were arrived on the basis of structural design following the respective Indian standard codes for design of reinforced concrete structures IS 456:2000 [29] and IS13920:1993 [30]. Details of different geometric parameters of building components are as given in Table 1. Thickness of raft foundation slab was taken as 0.3 m, thickness of floor slab at various storey levels and roof slab were taken as 0.15 m and web

dimensions of beams were taken as 0.23×0.23 m which are sufficient to satisfy the requirement of residential class buildings under gravity loads with a live load of 2.75 kN/m^2 . M20 grade concrete and Fe 415 grade steel were selected as the materials for design of structural elements. The Poisson's ratio and density of concrete were taken as 0.15 and 25 kN/m^3 respectively.

Idealized forms of a distinctive 3×3 bay frame having plan dimensions of 12×12 m with various shapes of shear walls with good aesthetic appeal are presented schematically in Fig. 1. Moment resisting frames without shear wall is denoted as 'bare frame' (BF) and frames with shear wall of different cross sections are listed as rectangular, cylindrical and corrugated. Openings in shear walls were neglected assuming that additional strengthening and stiffening were provided around the openings.

Geotechnical Characteristics

Soil is a semi-infinite medium, an unbounded domain. Present study treats soil as a homogenous, isotropic and elastic half space medium. Soil types with different elastic properties were considered. The properties of soils were chosen in accordance with FEMA 273 [31] and FEMA 356 [32] on the basis of shear wave velocity of soil. Sb, Sc, Sd and Se are the soil types considered which represent non-cohesive soil types rock, dense, stiff and soft. The properties of soil are as given in Table 2. Different seismic codes classify the soil sites based on shear wave velocity or standard penetration test (SPT) values. Hence, for a uniform approach they are mapped according to FEMA 356 as shown in Table 3. Soil is represented as an elastic continuum in the present finite element analysis.

Generally the boundary of the soil should be placed at a sufficient distance away from the structure such that the static response dies out [1]. For this study, the lateral boundary of soil is placed at a distance of 1.5 times the least width of the raft foundation beyond which there is a negligible influence on the settlement and the contact pressure as reported by Maharaj et al. [33] and Thangaraj and Ilamparuthi [34]. The bedrock was assumed to be at a depth of 30 m. This confines a finite domain for the soil. The bottom boundaries were restricted from translations while the lateral vertical soil boundaries were modelled with non-reflecting boundaries.

Finite Element Modeling

In present study, the finite element modeling and analysis were carried out using the commercial finite element software LS DYNA. In finite element modeling, building frames were idealised using 3D space frames with Belytschko-

Table 1 Dimensions of components of building

h/d	Columns (m)		Shear wall thickness (m)		
	Up to 3 storey	Above 3 storey	Rectangular	Cylindrical	Corrugated
1	0.32 × 0.32	0.32 × 0.32	0.15	0.11	0.09
1.5	0.35 × 0.35	0.35 × 0.35	0.15	0.11	0.09
2	0.40 × 0.40	0.35 × 0.35	0.20	0.15	0.13
3	0.50 × 0.50	0.40 × 0.40	0.20	0.15	0.13
4	0.60 × 0.60	0.50 × 0.50	0.25	0.19	0.16

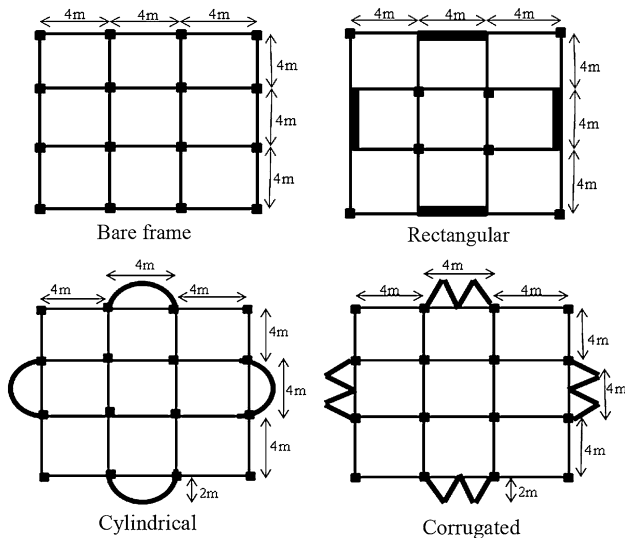


Fig. 1 Plan of bare frame and frame with various shapes of shear wall

Table 2 Details of soil parameters [FEMA 273(1997) and FEMA 356 (2000)]

Soil profile type	Description	Shear wave velocity (Vs) (m/sec)	Poisson's ratio μ	Unit weight (ρ) (kN/m ³)	Young's modulus (Es) (kN/m ²)
Sb	Rock	1,200	0.3	22	8.40E + 6
Sc	Dense soil	600	0.3	20	1.91E + 6
Sd	Stiff soil	300	0.35	18	4.46E + 5
Se	Soft soil	150	0.4	16	1.03E + 5

Schwer resultant beam element having three translational and three rotational degrees of freedom at each node. Roof slab, floor slabs at various storey levels, shear wall and raft foundation slab were modelled with four-node shell element Belytschko-Tsay which has both bending and membrane capabilities. This element has six degrees of freedom at each node. The three dimensional soil stratum is modelled with fully integrated S/R solid having three translational degrees of freedom at each node. To overcome the node incompatibility problem occurring between soil and structure, a tied surface to surface contact between the soil surface and base of the structure is employed such that the translational

Table 3 Mapping of soil sites of IS and IBC

Soil profile type	Description	Equivalent site class	
		IS	IBC
Sb	Rock	Type I	B
Sc	Dense soil	Type I	C
Sd	Stiff soil	Type II	D
Se	Soft soil	Type III	E

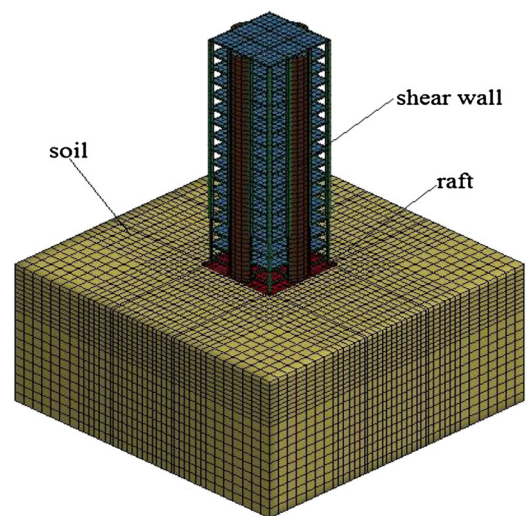


Fig. 2 Idealized soil–foundation–structure model

motion of soil due to bending of raft is imposed and the raft and soil are coupled effectively for the modal analysis of the entire soil-structure system. A very fine finite element mesh was generated close to the raft, which was gradually made coarser away from the raft area. Three dimensional finite element model of the idealized soil–foundation–structure system is as shown in Fig. 2.

Methodology

Fundamental natural periods are the main parameter used in finding the anticipated seismic loads coming to structures in earthquake resistant design. Hence the value of the fundamental period needs to be as accurate as possible.

Table 4 Ordinates of elastic spectra, base shear and storey shear as per IS 1893

Seismic quantities	Type of soil constituting the foundation		
	For rocky, or hard soil site	For medium soil site	For soft soil site
Spectral acceleration coefficient ($\frac{S_a}{g}$)	$\frac{S_a}{g} = \begin{cases} 1 + 15T; 0.00 \leq T \leq 0.10 \\ 2.50; 0.10 \leq T \leq 0.40 \\ 1.00/T; 0.40 \leq T \leq 4.00 \end{cases}$	$\frac{S_a}{g} = \begin{cases} 1 + 15T; 0.00 \leq T \leq 0.10 \\ 2.50; 0.10 \leq T \leq 0.55 \\ 1.36/T; 0.55 \leq T \leq 4.00 \end{cases}$	$\frac{S_a}{g} = \begin{cases} 1 + 15T; 0.00 \leq T \leq 0.10 \\ 2.50; 0.10 \leq T \leq 0.67 \\ 1.67/T; 0.67 \leq T \leq 4.00 \end{cases}$
Design base shear (V_B)	$V_B = A_h W$, Where $A_h = \frac{ZIS_a}{2Rg}$		
Storey shear (Q_i)	$Q_i = V_B \frac{w_i h_i^2}{\sum_{j=1}^n w_j h_j^2}$		

T = fundamental natural period; A_h = design horizontal seismic coefficient; W = seismic weight of the building; Z = zone factor; I = importance factor; R = response reduction factor; w_i = seismic weight of floor i ; h_i = height of floor i measured from base; n = number of storeys in the building

Table 5 Ordinates of elastic spectra, base shear and storey shear as per IBC

Seismic quantities	$0 \leq T \leq T_0$	$T_0 \leq T \leq T_s$	$T_s \leq T \leq T_L$	$T_L \leq T$
Spectral acceleration coefficient (S_a)	$S_a = 0.6 \frac{S_{DS}}{T_0} T + 0.4 S_{DS}$	$S_a = S_{DS}$	$S_a = \frac{S_{D1}}{T}$	$S_a = \frac{S_{D1} T_L}{T^2}$
Design base shear (V)	$V = C_s W$, where $C_s = \frac{S_{DS}}{(\frac{T}{T_0})}$ need not exceed $C_s = \frac{S_{D1}}{T(\frac{T}{T_s})}$ for $T \leq T_L$, need not exceed $C_s = \frac{S_{D1} T_L}{T^2(\frac{T}{T_L})}$ for $T > T_L$ and shall not be less than 0.01			
Storey shear (F_x)	$F_x = C_{vx} V$, where $C_{vx} = \frac{w_i h_i^k}{\sum_{i=1}^n w_i h_i^k}$			

S_{DS} = design spectral response acceleration parameter at short periods; S_{D1} = design spectral response acceleration parameter at 1 s period; T = fundamental period of the structure $T_0 = 0.2 S_{D1} / S_{DS}$; $T_s = S_{D1} / S_{DS}$; T_L = Long-period transition period; C_s = seismic response coefficient; W = effective seismic weight; I = occupancy importance factor; R = response modification factor; C_{vx} = Vertical distribution factor; w_i and w_x = portion of the total effective seismic weight of the structure located or assigned to level i or x ; h_i and h_x = height from the base to level i or x ; n = total number of storeys; k = an exponent related to the structure period

Table 6 Variation in natural period

Building type/shape of shear wall	h/d	% variation due to soil				% variation due to shear wall			
		K_{rs}				K_{rs}			
		1e-5	8e-5	1e-4	1e-3	1e-5	8e-5	1e-4	1e-3
Bare frame	1	17.65	17.65	17.65	18.82	-	-	-	-
	1.5	15.13	15.13	15.13	16.81	-	-	-	-
	2	14.67	14.67	15.33	16.67	-	-	-	-
	3	15.07	15.53	15.98	18.26	-	-	-	-
	4	15.84	16.17	17.49	20.79	-	-	-	-
Rectangle	1	4.00	12.00	36.00	80.00	-74.00	-72.00	-66.00	-55.45
	1.5	2.27	9.09	27.27	61.36	-67.15	-64.96	-59.12	-48.92
	2	6.67	13.33	31.67	65.00	-62.79	-60.47	-54.34	-43.43
	3	3.77	9.43	24.53	51.89	-56.35	-54.15	-48.03	-37.84
	4	3.80	9.49	25.32	53.16	-53.28	-50.85	-44.38	-33.88
Corrugated	1	4.95	11.89	30.88	65.68	-72.09	-70.25	-65.20	-56.38
	1.5	3.74	9.40	24.94	52.98	-65.89	-64.03	-58.92	-50.43
	2	3.95	9.99	26.14	54.12	-62.30	-60.11	-54.52	-45.07
	3	2.84	7.86	21.41	45.20	-56.63	-54.69	-49.20	-40.42
	4	2.71	7.81	21.32	44.82	-54.30	-52.17	-46.78	-38.21
Cylinder	1	6.50	13.47	33.35	70.49	-72.44	-70.64	-65.50	-56.32
	1.5	4.81	10.52	26.73	56.39	-66.27	-64.43	-59.22	-50.39
	2	4.51	10.41	26.76	55.44	-62.45	-60.33	-54.72	-45.11
	3	3.25	8.30	22.12	46.41	-56.87	-54.94	-49.39	-40.50
	4	3.06	8.30	22.22	46.23	-54.52	-52.35	-46.82	-38.12

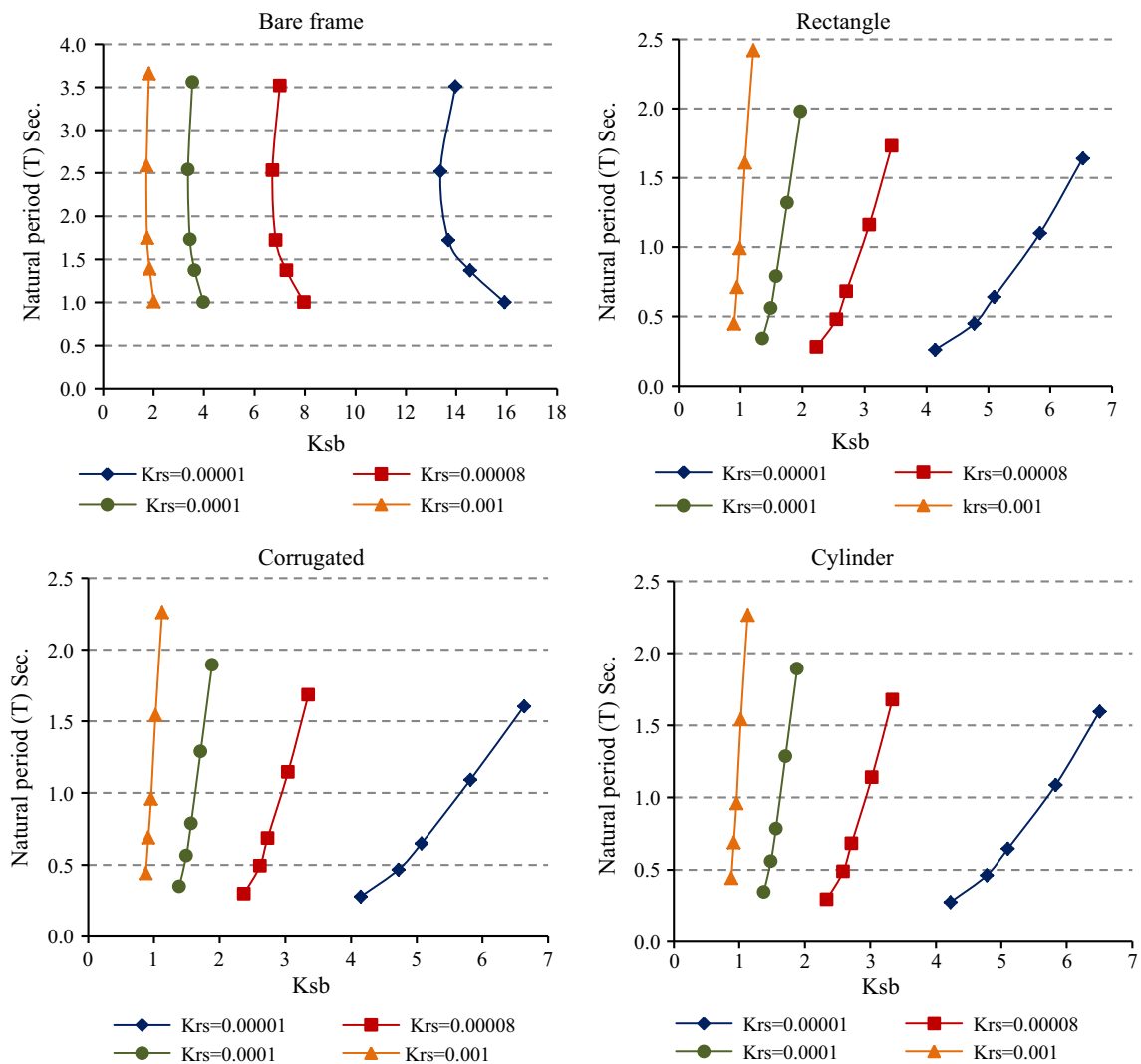


Fig. 3 Lateral natural period of buildings over various soil types

Lateral forces and design base shear are determined by using the fundamental natural period and matching design response spectrum of code of practice. Design response spectrum symbolizes the average smoothed plot of maximum acceleration as a function of time period of vibration for a specified damping ratio for earthquake excitations at the base of a single degree of freedom system equivalent to the structure. Expressions for design spectrum presented in IS and IBC for varying soil sites are as expressed in Tables 4 and 5.

Design Response Spectra and Design Base Shear as per IS1893 (part1):2002

The average spectral acceleration coefficients (S_a/g) corresponding to natural period T (sec) of structures represented as design response spectra in IS 1893 for various soil sites are as expressed in Table 4.

Design Response Spectra and Design Base Shear as per IBC:2006

The design response spectrum represented in IBC is as expressed in Table 5.

Simplified modal response spectrum analysis considering chiefly the fundamental mode of vibration in both main directions of the building is carried out on 3D space frames. Reckoning the corresponding fundamental period and relevant design spectra which give a static consideration of the seismic excitation, the seismic effects in the building were found from the total inertia forces. This method is often mentioned as equivalent linear static analysis where in a totally dynamic phenomenon is dealt with.

The earthquake forces on structures are found employing the spectral acceleration corresponding to fundamental natural period T . The effect of soil–structure interaction and varying shapes of shear walls in buildings constructed

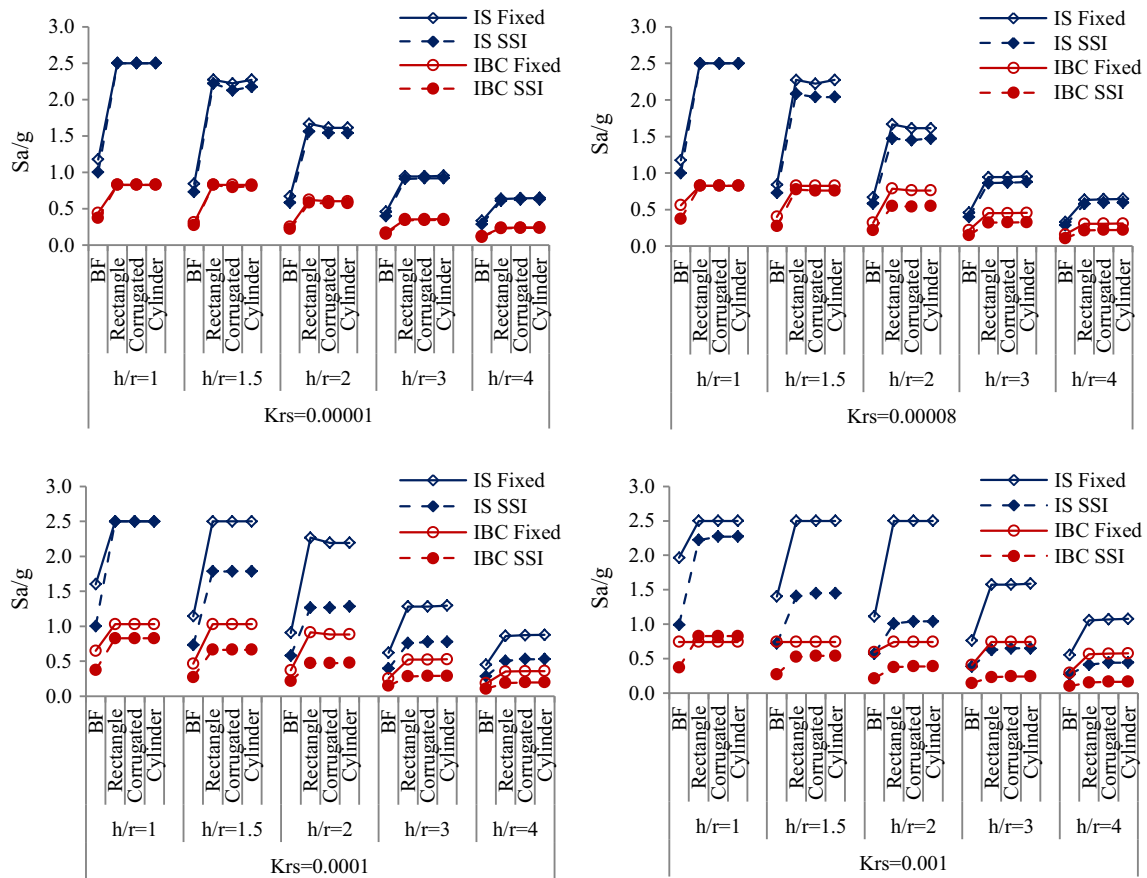


Fig. 4 Value of spectral acceleration coefficient as per IS and IBC for various site classes

over different soil types are assessed as variation in the estimated spectral acceleration and are compared as per seismic provisions of IS and IBC seismic codes in the present study. For this, multi-storey reinforced concrete framed buildings of aspect ratio 1, 1.5, 2, 3 and 4 without and with shear walls of various shapes resting over raft foundation with 12 × 12 m plan dimensions were considered. Aspect ratio (h/d) is the ratio of height of building (h) to lateral dimension (d). Structures are regular in plan and elevation and were assumed to be constructed in zone IV with an importance factor of 1. Response reduction factor R of 3 and 4.5 were considered for moment resistant frames and ductile shear wall buildings respectively as per IS provisions and equivalent parameters were considered from IBC.

Analysis of 3D finite element model of soil–foundation–structure were carried out using explicit dynamic analysis finite element software LS DYNA to determine the fundamental natural period ‘T’ of buildings by Eigen value analysis. Once the fundamental natural period of the building frames and shear wall buildings with and without considering the effect of soil flexibility were determined, the change in spectral acceleration coefficients (Sa/g)

corresponding to the natural period of structure were calculated from design response spectra of IS and IBC. Further, design base shear and lateral forces of the building were determined from the equations specified in Tables 4 and 5. The results found were analysed and compared to assess the effect of shape of shear wall, effect of soil flexibility and the seismic provisions of codes.

For a better representation of the interaction among superstructure, foundation and soil of varying stiffness the results are expressed in terms relative stiffness of superstructure (K_{sb}) and raft (K_{rs}). The relative stiffness K_{sb} and K_{rs} were determined based on the recommendation of Wu [35] and Hemsely [36] which are as follows.

$$K_{sb} = \frac{V_s}{h\omega_u}; \tag{1}$$

$$K_{rs} = \frac{E_r(1 - \nu_s^2)}{E_s(1 - \nu_r^2)} \left(\frac{t_r}{B}\right)^3, \tag{2}$$

where, E_s = Elastic modulus of soil; E_r = Elastic modulus of raft; ν_s = Poisson’s ratio of soil; t_r = thickness of raft; B = width of the raft; ν_r = Poisson’s ratio of foundation material; V_s = shear wave velocity; h = Height of the building; ω_u = cyclic frequency of the structure.

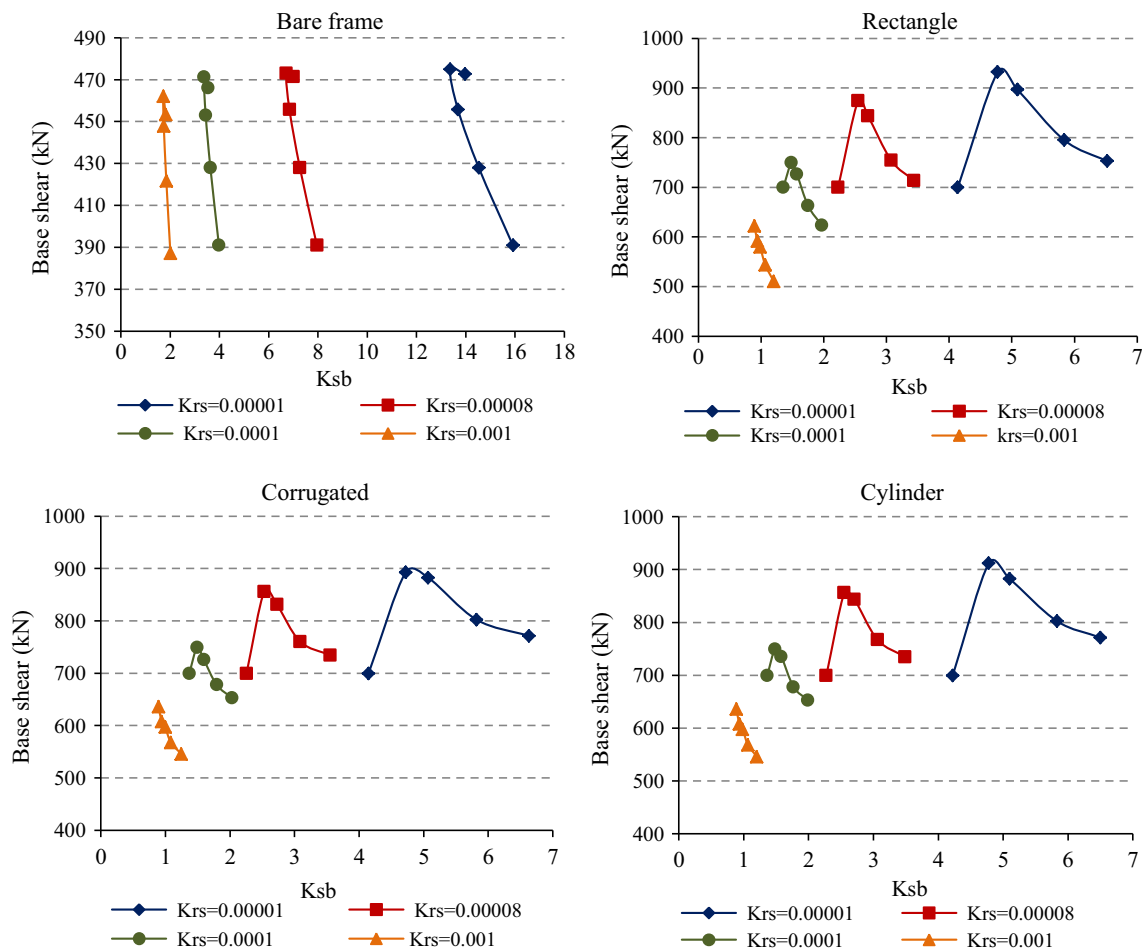


Fig. 5 Variation in value of base shear for various K_{rs} as per IS

The influence of parameters K_{sb} and K_{rs} on natural period, spectral acceleration and base shear were studied. Analyses were carried out for SSI systems having the values of K_{sb} ranging from 1 to 17 and K_{rs} ranging from 0.00001 to 0.001. The lower limit of K_{sb} corresponds to building with high aspect ratio over soft soil (Se) and higher limit corresponds to building with lower aspect ratio over hard soil (Sb). In case of parameter K_{rs} , lower limit corresponds to a foundation over hard soil and higher limit corresponds to foundation over soft soil.

Results and Discussions

Free vibration analysis was carried out on 3D integrated soil–foundation–structure finite element models to compute the natural period of buildings by accounting the effect of soil–structure interaction. Lateral natural periods thus obtained were employed in determining the corresponding values of Sa/g as per the seismic code provisions of IS and IBC. Further, from the corresponding equations specified in

building codes, design base shear and lateral force distribution in the building were computed. The effect of soil flexibility and various shapes of shear walls in altering the base shear and storey shear were analysed.

Lateral Natural Period

Fundamental natural period plays a significant role in the seismic response of a structure. The values of natural period obtained from the 1st mode of free vibration analysis of 3D finite element models are shown in Fig. 3. Percentage variation in natural period of buildings with varying aspect ratio over raft foundation due to effect of soil and varying shapes of shear walls are as tabulated in Table 6.

From Fig. 3 it is observed that value of natural period of building increases with increase in K_{rs} and decreases with increase in K_{sb} , i.e., value of natural period increases with increase in height of building and flexibility of soil. From Fig. 3 it is evident that the value of natural period in buildings with shear wall are very much lower than bare

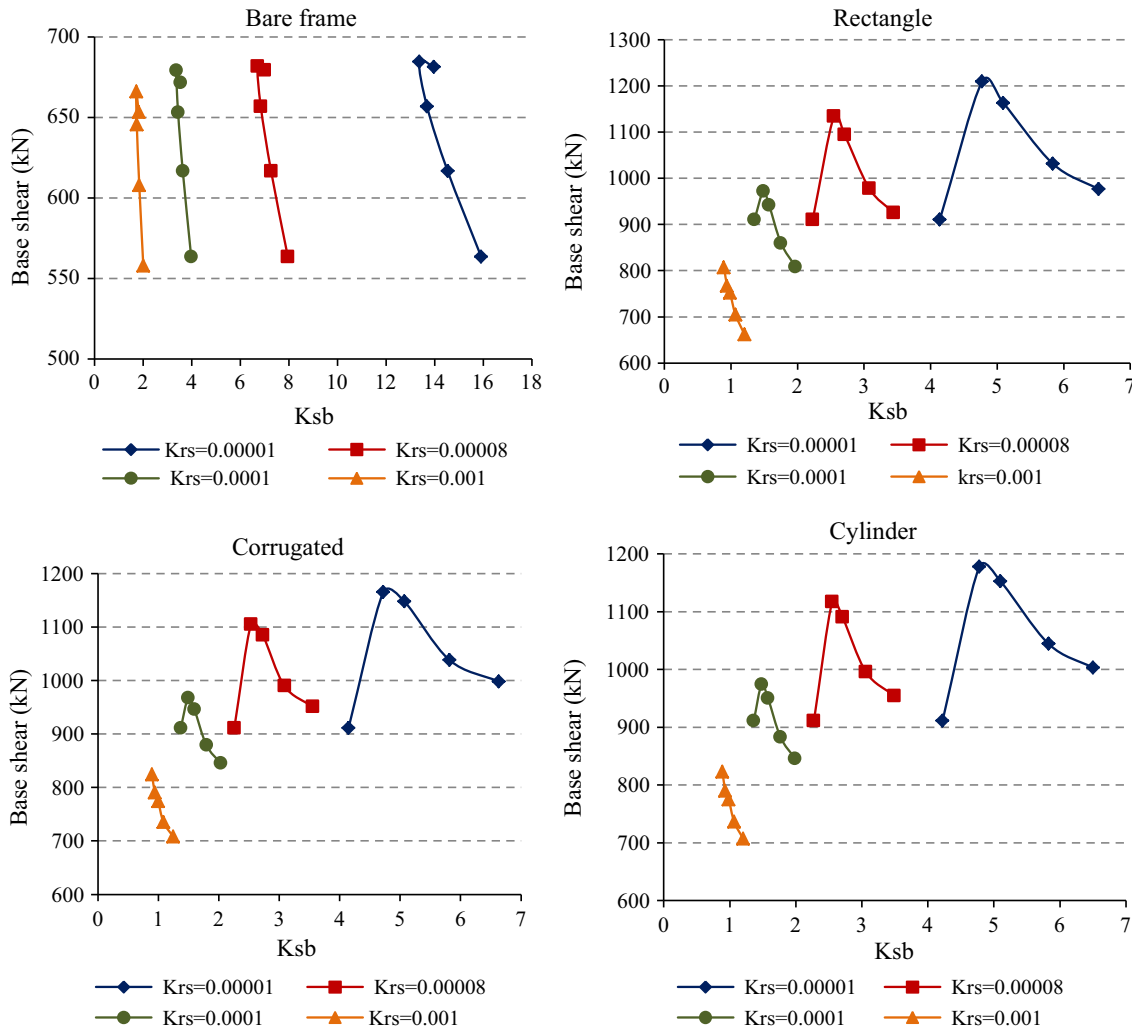


Fig. 6 Variation in value of base shear for various K_{rs} as per IBC

frame building as the value of absolute stiffness of the super structure K_b is very much higher due to inclusion of shear wall. Highest value of natural period is observed in corrugated shape shear wall building with aspect ratio 1, 1.5 and 2 for all the values of K_{rs} except for 0.01. For buildings with higher aspect ratio the rectangular shape shear wall possess the highest value of natural period.

It is noted from Table 6 that the inclusion of supporting soil flexibility in buildings increases the value of natural period. Percentage variation in natural period increases with increases in the value of K_{rs} . It is noted that highest percentage variation is observed in cylindrical shape shear wall building with aspect ratio 1 and $K_{rs} = 0.001$ and lowest in rectangular shape shear wall building with aspect ratio 1.5 and $K_{rs} = 0.00001$. However when percentage variation in natural period due to inclusion of shear walls only are considered, the value decreases with increase in

aspect ratio and increase in K_{rs} value. Highest and lowest percentage reduction of 74 and 33.8 % are observed in rectangular shape shear wall building with aspect ratio 1 and 4 and K_{rs} values 0.00001 and 0.001 respectively.

Present study considers only the first mode of vibration of buildings, as the contribution of first mode is highest among all possible modes in regular buildings. In addition, the basic assumption of simplified modal response spectrum method is that only the first mode of vibration of buildings governs the dynamics.

Spectral Acceleration Coefficient

The critical element in determination of design base shear for a building by design response spectrum is the spectral acceleration coefficient. It is dependent on the principal parameter, the fundamental period T of the building.

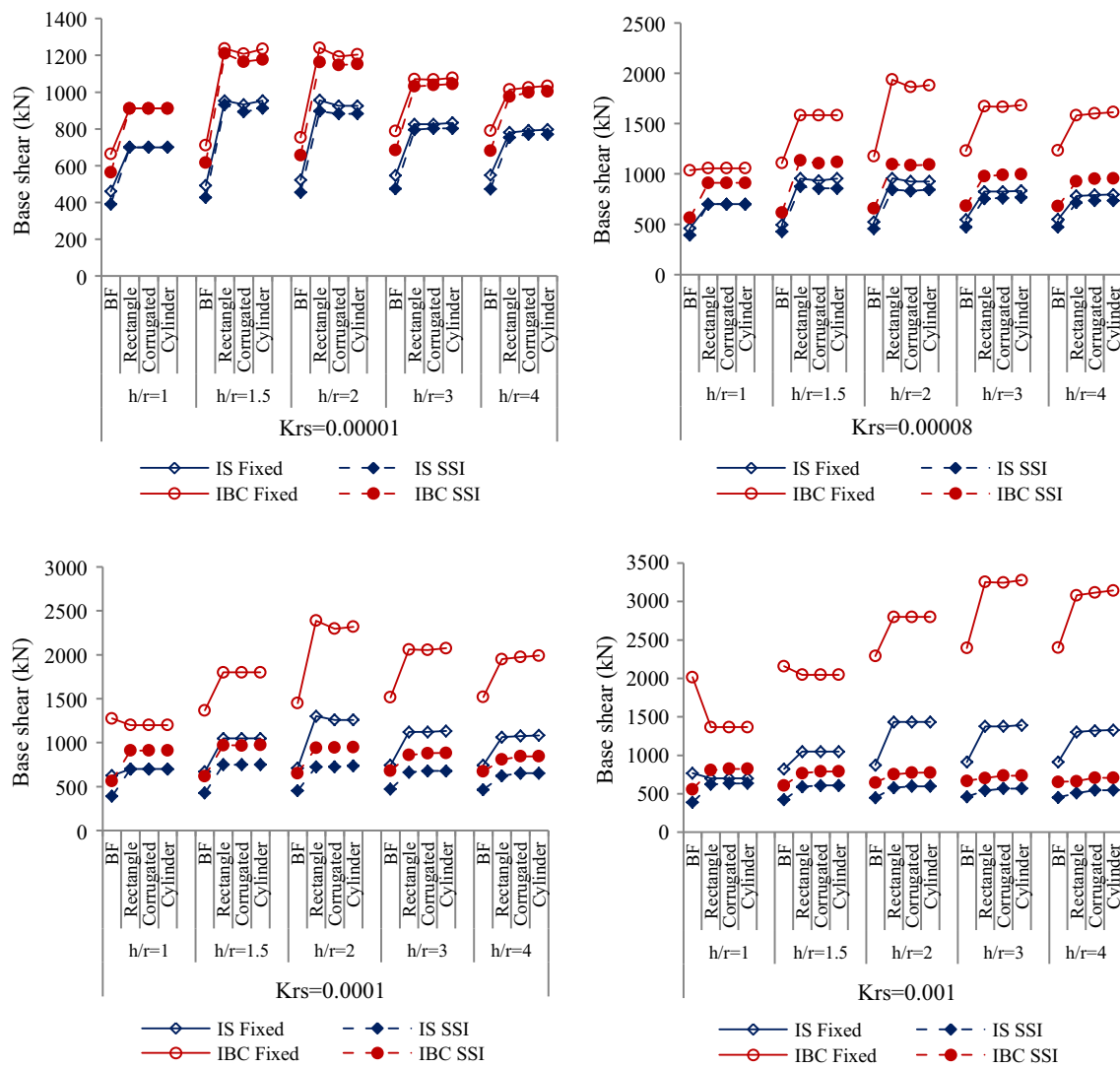


Fig. 7 Value of base shear as per IS and IBC with various K_{rs} values

Spectral acceleration coefficient is the maximum acceleration in an equivalent single degree of freedom structure with same natural period when subjected to design basis earthquake excitations for the region. When the period ‘T’ changes on account of building interaction with supporting soil spectral acceleration coefficient shifts to higher or lower values which in turn affect the value of design base shear estimated.

As per the design response spectrum proposed in IS and IBC, spectral acceleration coefficient value of structures were found for various soil types. The values of spectral acceleration coefficient obtained by considering the SSI were observed to be much lesser than those obtained by the standard conventional design practice. This variation in values of spectral acceleration is observed to increase with increase in the value of K_{rs} . The highest percentage

variation of 60.33 % as per IS and 72.73 % as per IBC were observed in rectangular shape shear wall building with aspect ratio 4 and $K_{rs} = 0.001$.

Viewing into the effect of aspect ratio on spectral acceleration coefficient, the value reduces with increase in aspect ratio due to the increase in fundamental natural period of building that corresponds to the descending curve of design response spectrum. The value of design spectral acceleration obtained as per design response spectrum of IS are very much higher than IBC.

Spectral acceleration values of buildings for various site classes are plotted in Fig. 4. S_a/g values corresponding to the natural period of fixed base structure to be built on different site classes were computed conventionally and designated as ‘Fixed’. Spectral acceleration values corresponding to the natural period of building founded on

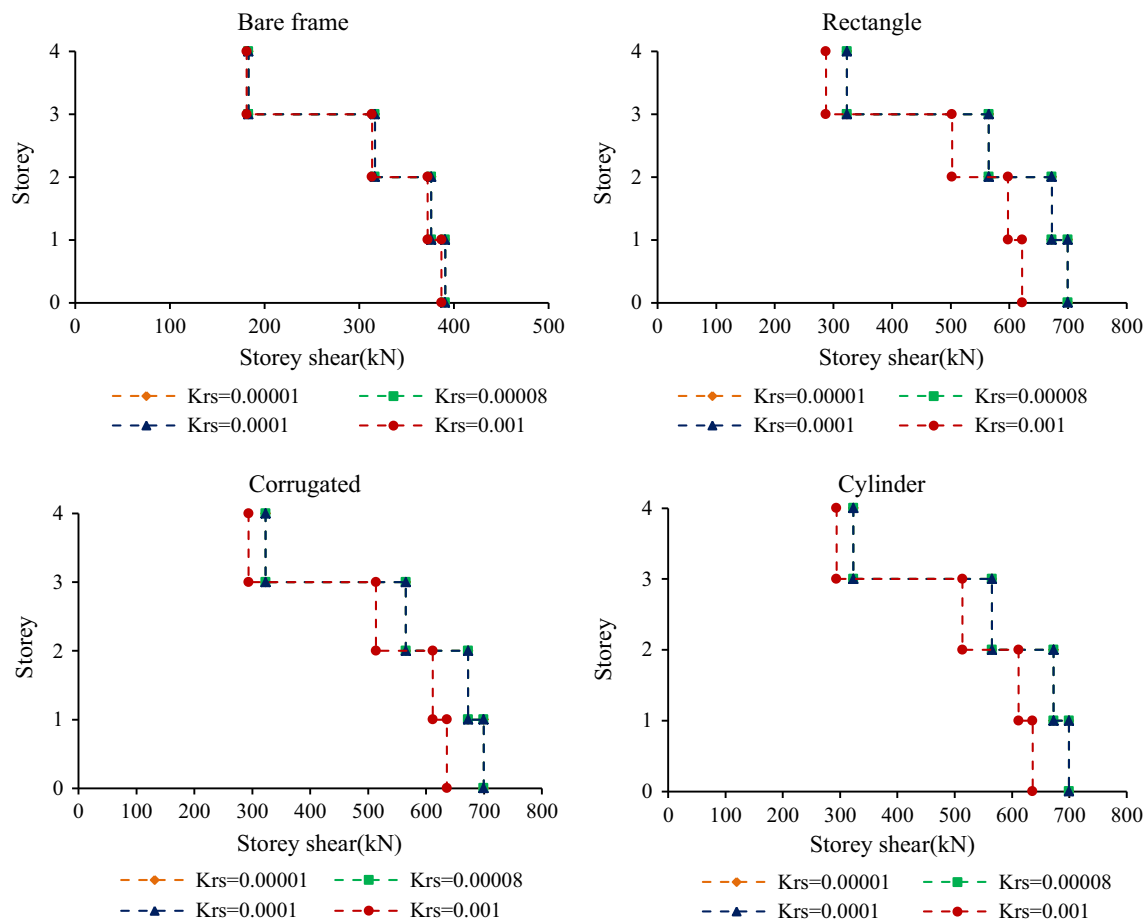


Fig. 8 Variation of storey shear in building with varying K_{rs} values as per IS

different soil types computed from the base line for rocky strata of design response spectrum given in codes are computed as ‘SSI’.

Design Base Shear

Estimate of maximum expected lateral force that is likely to occur at the base of a structure due to seismic ground motion is stated as base shear. It reflects the seismic vulnerability of the structure and is considered as one of the primary input in seismic designs. Base shear in present study is acquired from the standard expressions given in IS and IBC for design spectra of 5 % critical damping. Value of base shear of moment resisting frame and buildings with various shapes of shear walls over raft foundation with varying K_{sb} and K_{rs} values for IS and IBC are shown in Figs. 5 and 6.

From Figs. 5 and 6 it is observed that value of design base shear of building decreases with increase in K_{rs} and decrease in K_{sb} . i.e., Base shear value decreases with increase in flexibility of soil for the fundamental mode.

Lowest value of base shear is observed in buildings with shear walls of corrugated shape for aspect ratio ranging from 1 to 2 and rectangular shape for aspect ratio 3 and 4 for all the values of K_{rs} and codes considered. Highest value of base shear was observed in buildings of aspect ratio 1.5 irrespective of the shapes of shear walls considered. This value reduces with increase in value of K_{sb} as the corresponding spectral acceleration coefficient lies in descending curve of design response spectrum.

The variation in base shear obtained by considering standard conventional design practice (Fixed) and the three dimensional soil–structure interaction effect (SSI) as per IS and IBC are as shown in Fig. 7. It is observed that regardless of the codes considered, base shear values are higher in conventional design practice rather than in SSI. This variation in value of base shear between conventional design practice and SSI increases with increase in value of K_{rs} . Highest percentage variation was observed in rectangular shape shear wall building with aspect ratio 4 and K_{rs} value 0.001. Base shear values obtained from IBC are higher than the IS, thus conservative.

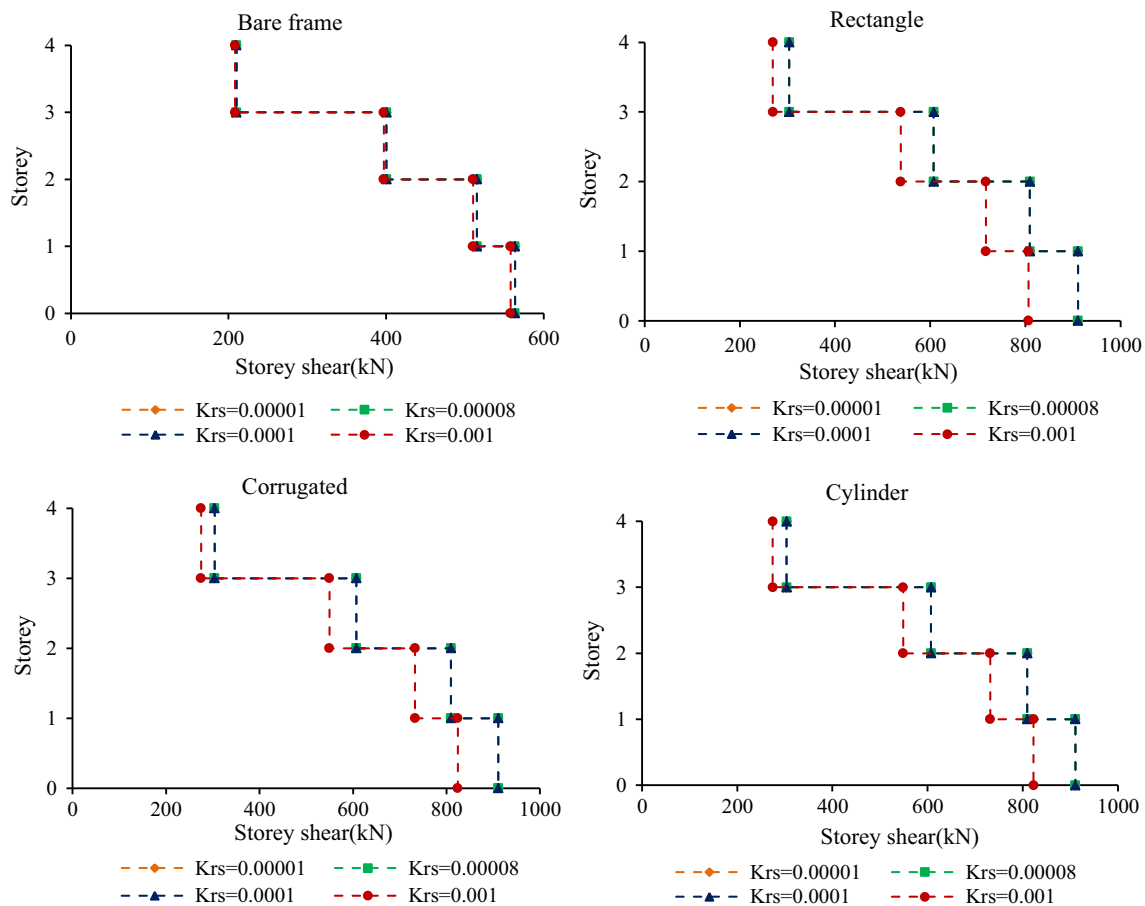


Fig. 9 Variation of storey shear in building with varying K_{rs} values as per IBC

Storey Shear

Summation of all the design lateral forces at every level above the storey under consideration is referred to as storey shear. In shear wall buildings these are mostly carried by horizontal shear in the wall and interface between the wall and beams. Representative values of storey shear as per IS and IBC for a four storey building (aspect ratio 1) with varying K_{rs} values are shown in Figs. 8 and 9.

From Figs. 8 and 9 it is noted that there is significant variation in value of storey shear for varying values of K_{rs} in shear wall buildings. The value is lowest in buildings over raft foundation with highest K_{rs} value. Thus storey shear decreases with increase in relative stiffness of raft.

Conclusions

The effect of SSI was studied for multi-storey reinforced concrete building frames with shear walls of various shapes. Material properties of soil and geometric properties of the super structure were varied to understand the

significance of SSI. Variation in seismic responses of building such as natural period, spectral acceleration coefficient, base shear and storey shear were considered for the study.

The following general conclusions were drawn from the present study.

- Fundamental natural period of buildings increases with increase in K_{rs} and decrease in K_{sb} .
- Spectral acceleration coefficient increase with increase in K_{rs} and decreases with increase in aspect ratio.
- Spectral acceleration coefficients obtained by considering the SSI are lesser than values considered in standard conventional design practice assuming fixed base for the structure.
- Design base shear obtained as per conventional design practice are higher compared to SSI values. Design base shear decreases with increase in K_{rs} and decrease in K_{sb} .
- Corrugated shear wall buildings experience the least base shear in shear wall buildings with aspect ratio up to 2, whereas the least base shear is in rectangular shear wall buildings for aspect ratio above 3.

- Design base shear obtained as per IBC are conservative as compared to IS values.
- No significant variations in storey shear were observed in bare frame buildings with varying K_{rs} values. However, in shear wall buildings storey shear decreases with increase in value of K_{rs} .

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