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EFFECT OF SOIL-FLEXIBILITY ON LATERAL NATURAL PERIOD IN RC FRAMED BUILDINGS WITH SHEAR WALL

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Abstract: Shear walls are the typically used lateral load resisting systems having very high in-plane stiffness and strength which resist large horizontal loads. Flexibility of soil medium underneath the foundation diminishes the overall stiffness of a building resulting in a consequent increase in the natural periods of the system which further leads in the change of seismic lateral response of the structure. The effectiveness of shear walls in resisting lateral forces when placed at different locations in buildings incorporating the flexibility of soil is less discussed in any literature. Hence in the present study, an attempt has been made to find the effectiveness of shear wall locations on RC frame buildings of varying height with raft foundation by noting the effect of soil flexibility on change in lateral natural period. Free vibration analysis of the three dimensional models of these buildings with five different shear wall positions founded on different soils has been carried out using finite element software. And the best location for the least spectral acceleration in the structure is identified.

Keywords: Shear wall, Soil structure interaction, Spectral acceleration coefficient, Natural period.

I. INTRODUCTION

Soil–Structure Interaction is an interdisciplinary field of soil, structural mechanics and structural dynamics. The effect of soil on the response of structures depends on the properties of soil, structure and the nature of the excitation. The process, in which the response of the soil influences the motion of the structure and vice versa, is referred to as Soil-Structure Interaction (SSI). Implementing soil-structure interaction effects enables the designer to assess the inertial forces and real displacements of the soil-foundation structure system precisely under the influence of free field motion.

Fixed-base analyses ignoring the effect of soil-flexibility are generally carried out for the seismic design of buildings which results in either unnecessarily costly or unsafe design. Thus the interaction between the structure and the soil needs to be modelled accurately in order to design earthquake resistant structures correctly. The possible severities of neglecting the effects of the SSI are fore grounded in previous research works [1]–[3].

Flexibility in soil causes an overall decrease in lateral stiffness resulting in the lengthening of lateral natural periods [4]–[6]. Such lengthening considerably change the seismic response of building drawing the effect of soil–structure interaction an important issue from the viewpoint of design considerations.

The lengthening of lateral natural periods especially becomes more important for seismic behaviour of low-rise buildings having fundamental lateral period in the short period region of the design response spectrum. In addition the periods corresponding to higher modes get shorter as compared to the fundamental lateral period. The contribution to seismic base shear by each of these modes enhances as the lengthening of lateral periods due to soil-flexibility lead to an increase in base shear [1], [2], [12].

In the present work, a parametric study is accomplished for the determination of lengthened lateral natural period of RC frame buildings with shear wall by incorporating the effect of soil flexibility for buildings of varying height over raft foundation. A comparative study has also been done on spectral acceleration coefficient (Sa/g) as per IS 1893-2002 for buildings with fixed base and buildings founded over different soil. This study may help to provide guidelines to assess the seismic vulnerability of buildings more accurately.

II. IDEALIZATION OF THE SYSTEM

A. Structural idealization

To examine the dynamic behaviour while considering the effect of soil–structure interaction, building frames of 4, 6, 8, 12 and 16 storey with and without shear wall was idealized as 3D space frames using standard two nodded beam element with three longitudinal degrees of freedom and three rotational degree of freedom at each node. Slabs at different storey level, shear wall and the slabs of raft foundation were modelled with four-nodded plate elements with consideration of adequate thickness. The storey height as well as length of each bay of all the building frames was chosen as 3m and 4m respectively which is reasonable for domestic or small office buildings. The dimensions of components of the buildings were arrived on the basis of the design following the respective Indian code for design of reinforced concrete structures [7], [8]. These dimensions are as given in table below. The thickness of floor slab and roof slab were taken as 0.15m and beam dimensions as 0.23X0.23m. Slab thickness of raft was taken as 0.3m.The materials considered for design of the elements were M20 concrete and Fe 415 steel.

TABLE I:
DIMENSIONS OF COMPONENTS OF BUILDING

Stories	Columns (m)		Shear wall thickness (m)
	Up to 3 story	Above 3 story	
4	0.32 X 0.32	0.32 X 0.32	0.15
6	0.35 X 0.35	0.35 X 0.35	0.15
8	0.40 X 0.40	0.35 X 0.35	0.20
12	0.50 X 0.50	0.40 X 0.40	0.20
16	0.60 X 0.60	0.50 X 0.50	0.25

The idealized form of a typical 3 bay x 3 bay frame with different shear wall locations in the building denoted as SW1 to SW5 are represented schematically in Fig.1.

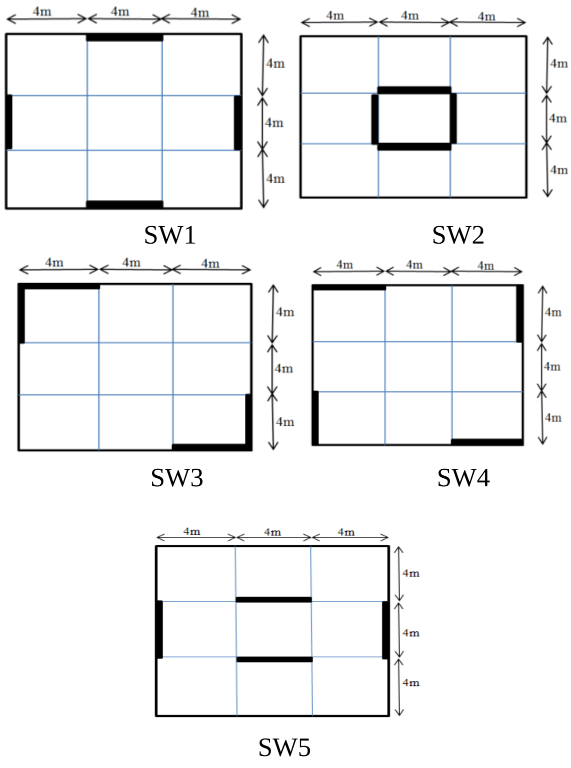


Fig. 1 Various locations of shear wall.

Present study considers RC framed buildings with shear wall to see how accurately the position of shear walls and the effect of soil–structure interaction influences the spectral acceleration on the building. This affords an idea about the error, which one should apt to commit if this popular but grossly inaccurate approach of ignoring the effect of soil flexibility is conceived.

B. Idealization of soil

To analyse the soil-foundation and structure, soil is treated as an isotropic, homogenous and elastic half space medium. For linear analysis, the density of soil, Young's modulus (Es) and Poisson's ratio (μ) are the inputs. The soil medium below the raft was modelled using the eight-node brick element having three degrees of freedom of translation in the x, y and z directions at each node. The width and the thickness of the soil medium were taken as 2.5 times the least width of the raft foundation which shows a negligible influence on the settlement and the contact pressure. The depth of the bed rock was considered to be at 30m from the surface. All translations were restricted at the bottom boundary while the lateral translation is arrested at the vertical boundary of soil. Fine meshes with aspect ratio 1.0 were generated close to the raft while meshes generated away from the raft area were made coarser gradually [9].

The study primarily attempts to see the effect of soil–structure interaction on buildings resting on different types of non-cohesive soil, viz., soft, stiff, dense and rock. The details of different soil parameters are as tabulated in Table II

TABLE III:
DETAILS OF SOIL PARAMETERS CONSIDERED [10], [11]

Soil profile type	Description	Shear wave velocity (Vs) (m/sec)	Poission's ratio	Unit weight (ρ) (kN/m^3)
Sb	Rock	1200	0.3	22
Sc	Dense soil	600	0.3	20
Sd	Stiff soil	300	0.35	18
Se	Soft soil	150	0.4	16

A typical 4 storeyed frame-shear wall building on raft and the corresponding idealized soil–foundation–structure system for the same is shown in Fig. 2a and 2b, respectively.

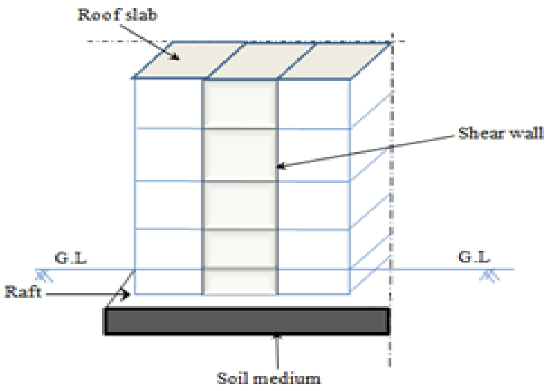


Fig 2 (a): Isometric view

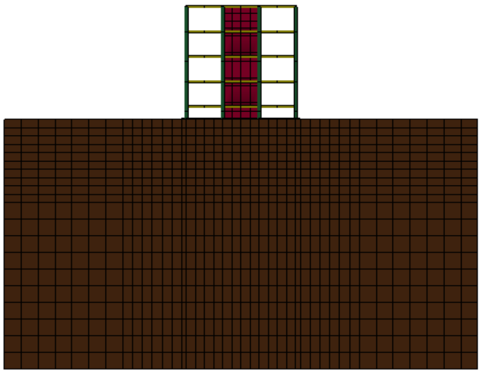


Fig. 2 (b). Idealized soil-foundation-structure model.

III. METHODOLOGY

One of the main parameters in the calculation of earthquake forces acting on a structure is fundamental period. The fundamental period of a building is used to estimate the design base shear and lateral forces based on the design response spectrum shown in fig. 3. Therefore, correct assessment of fundamental periods of buildings is very essential to compute earthquake forces.

The total design lateral force or design seismic base shear (V_B) along any principal direction is determined by the expression:

$$V_B = A_h W$$

Where,

Ah = Design horizontal acceleration spectrum value obtained using the fundamental natural period T

W= Seismic weight of the building

$$A_h = \frac{ZIS_a}{2Rg}$$

Where,

Z=Zone factor

I=Importance factor,

R= Response reduction factor

Sa/g= Average response acceleration coefficient

The spectral acceleration coefficient (Sa/g) for various soil types is as shown in Fig.3 and corresponding expressions are given below

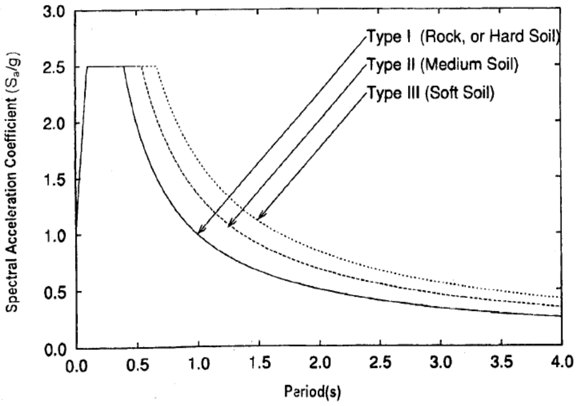


Fig.3 Design response spectra for 5% damping (IS 1893(part1):2002).

For rocky, or hard soil site

$$\frac{S_a}{g} = \begin{cases} 1+15T; 0.00 \le T \le 0.10 \\ 2.50; 0.10 \le T \le 0.40 \\ 1.00/T; 0.40 \le T \le 4.00 \end{cases}$$

For medium soil site

$$\frac{S_a}{g} = \begin{cases} 1+15T; 0.00 \le T \le 0.10 \\ 2.50; 0.10 \le T \le 0.55 \\ 1.36/T; 0.55 \le T \le 4.00 \end{cases}$$

For soft soil site

$$\frac{S_a}{g} = \begin{cases} 1+15T; 0.00 \le T \le 0.10 \\ 2.50; 0.10 \le T \le 0.67 \\ 1.67/T; 0.67 \le T \le 4.00 \end{cases}$$

The spectral acceleration coefficient (Sa/g) found using fundamental natural period T of the structure determines the earthquake force on the structure. Hence in the present study the effect of soil-structure interaction and the stiffness of shear walls in modifying the estimated earthquake forces were evaluated. For this the modification in the average response acceleration coefficient (Sa/g) of RC buildings with various locations of shear walls were obtained from free vibration analysis of the integrated soil-structure system.

Eigen value analysis of three dimensional finite element model of soil-foundation-structure idealized as explained in section II was carried out for buildings with and without shear wall including soil flexibility. Shear wall configurations at five different locations as shown in fig. 1 were considered. Four different types of supporting soil as tabulated in table II were considered.

LS DYNA explicit dynamic analysis finite element software was used for the Eigen value analysis. Knowing the fundamental lateral periods of the building frames and shear wall buildings, with and without considering the effect of soil–structure interaction, the change in fundamental lateral natural period was computed.

The spectral acceleration coefficient (Sa/g) corresponding to the natural period of the system can be obtained from design response spectrum provided in IS 1893(part1): 2002(fig. 3). As in practice, the Sa/g values corresponding to the natural period of fixed base structure to be built on different types of soil were computed from fig. 3 and are referred as Sb(f), Sc(f), Sd(f) and Se(f) in the study.

To incorporate the effect of soil-structure interaction, the lateral natural period obtained from the eigen value analysis of the three dimensional finite element soil-raft foundation-building system was used to obtain the corresponding Sa/g values from Type I curve of IS 1893(part1):2002 which is referred as Sb (SSI), Sc (SSI), Sd (SSI) and Se(SSI).

IV. RESULTS AND DISCUSSIONS

Frequency response analysis for computing natural period of buildings accounting for the effect of soil–structure interaction was carried out on the three dimensional finite element model of integrated soil-raft foundation-RC shear wall building.

The results are shown in the form of percentage changes in lateral natural period, regarding the effect of soil-flexibility with that of the fixed base condition. The results of the building with different shear wall locations and the trends observed are presented in the following sub-sections.

A. Change in lateral natural period

1) *Effect of soil flexibility:*

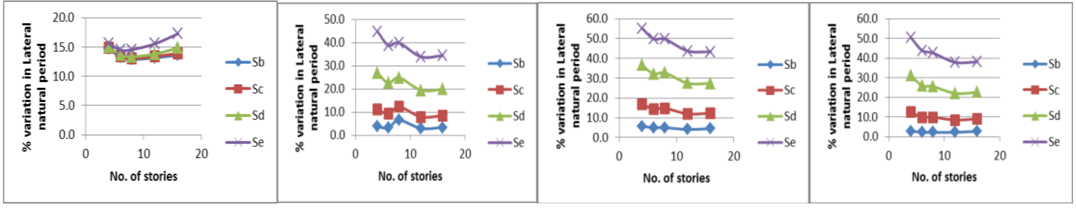
The modification in fundamental lateral natural period due to the effect of soil–structure interaction was studied on buildings of varying height over raft foundation resting on various soil types viz. Sb, Sc, Sd and Se.

The percentage variation in lateral natural period for all the building frames with and without shear walls incorporating soil stiffness is tabulated in table III as compared to that of its fixed base condition.

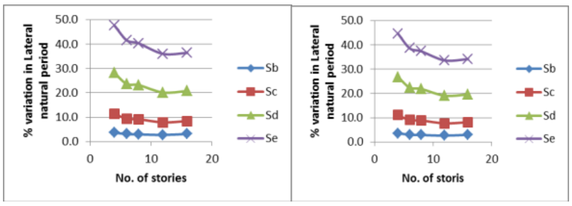
TABLE III:
PERCENTAGE VARIATION IN LATERAL NATURAL PERIOD OF BUILDING

Storeys	Base Condition	Variation in natural period (%)					
		Bare Frame	Frame-shear wall building				
			SW1	SW2	SW3	SW4	SW5
4	Sb	14.75	3.66	5.70	2.9	3.7	3.6
	Sc	14.83	11.18	16.89	12.5	11.5	11.1
	Sd	15.00	26.97	36.59	31.1	28.1	26.8
	Se	15.60	44.87	55.17	50.4	47.6	44.6
6	Sb	13.29	3.09	5.03	2.2	3.1	3.0
	Sc	13.40	9.10	14.40	9.9	9.4	9.0
	Sd	13.64	22.52	32.14	25.9	23.6	22.4
	Se	14.47	38.81	49.77	43.8	41.5	38.6
8	Sb	12.89	6.45	5.03	2.2	3.0	2.9
	Sc	13.04	12.25	14.85	9.9	9.2	8.9
	Sd	13.34	24.85	32.69	25.5	23.2	21.8
	Se	14.54	39.84	49.72	42.5	40.3	37.3
12	Sb	13.13	2.88	4.12	2.2	2.8	2.6
	Sc	13.35	7.88	11.97	8.5	7.9	7.7
	Sd	13.79	19.38	27.45	22.0	20.2	19.1
	Se	15.54	33.87	43.68	37.8	36.0	33.6
16	Sb	13.64	3.33	4.55	2.8	3.2	3.0
	Sc	13.94	8.40	12.40	9.1	8.5	8.1
	Sd	14.85	19.81	27.37	22.6	20.8	19.6
	Se	17.27	34.39	43.33	38.1	36.4	34.1

Though, the variation of change in lateral natural period for buildings supported on various soil are included in table III, these results are also plotted in fig. 4, for the sake of wholeness. A maximum increase of more than 55% is observed for buildings with shear wall of type SW2 resting in Se type of soil and minimum of 2.2% is observed for buildings with shear wall of type SW3 resting in Sb type of soil.



Bare Frame SW1 SW2 SW3



SW4 SW5

Fig. 4 Percentage variation in lateral natural period for various building configurations

The study shows that incorporation of soil flexibility tends to increase the fundamental lateral natural period of frame shear wall buildings by various per cent depending on the soil type. From table III and fig.4, it is observed that percentage variation in general, gradually decreases with the increasing hardness of soil.

2) *Effect of location of shear wall:*

The inclusion of shear wall in building at various location heads to variance in natural period by diverse amount. Such variations in lateral natural period by inclusion of shear wall at various locations as shown in the fig. 1 are tabulated in table IV.

TABLE IV

EFFECT OF SHEAR WALL LOCATIONS ON VARIATION IN LATERAL NATURAL PERIOD OF BUILDING

Storeys	Base Condition	Variation in natural period (%)				
		Frame-shear wall building				
		SW1	SW2	SW3	SW4	SW5
4	Fixed	70.59	78.66	68.60	70.07	70.76
	Sb	73.98	80.70	72.41	73.48	74.13
	Sc	71.80	78.12	69.43	71.19	71.98
	Sd	65.77	71.39	61.25	64.58	66.03
	Se	54.98	59.80	46.57	51.80	55.44
6	Fixed	63.28	72.93	60.40	62.26	63.55
	Sb	67.15	75.29	64.89	66.22	67.41
	Sc	65.02	72.63	61.96	63.95	65.32
	Sd	59.08	65.57	53.85	57.34	59.48
	Se	48.68	53.93	39.72	44.79	49.26
8	Fixed	60.16	69.78	55.38	57.29	59.20
	Sb	62.90	72.28	60.26	61.65	63.41
	Sc	60.52	69.14	56.94	59.09	61.07
	Sd	54.05	61.10	48.11	51.83	54.77
	Se	43.40	48.63	33.63	38.89	44.38
12	Fixed	51.33	61.70	46.98	49.10	51.89
	Sb	56.47	65.30	52.91	54.53	57.08
	Sc	54.22	62.30	49.80	52.11	54.84
	Sd	47.95	54.49	41.37	45.05	48.76
	Se	37.84	42.57	27.99	32.88	38.83
16	Fixed	47.70	57.79	43.10	45.18	48.35
	Sb	53.28	61.81	49.47	51.12	54.04
	Sc	50.87	58.53	46.11	48.46	51.62
	Sd	44.47	50.52	37.42	41.09	45.34
	Se	34.06	38.38	23.96	28.72	35.15

From table IV it is observed that percentage variation is maximum in shear wall of type SW2 in buildings of all heights. This could be due to increase in stiffness at the inner core of the building when compared to the other types of building where the shear wall is distributed at the outer periphery of the building.

A maximum increase of more than about 78% is noted for 4 storey building frame with shear wall of type SW2 for fixed base. This increase gradually reduces with the increase in number of stories of the building frame.

3) Effect of location of shear wall and soil flexibility

The change in fundamental lateral natural period due to the compounded effect of soil flexibility and shear wall at different locations are studied on buildings with raft foundation resting on various soils. Results of shear wall building of varying height resting over various soil types have been tabulated in table V. It shows the cumulative effect of shear wall and soil on the fundamental lateral natural period of the shear wall building as compared with the bare frame building with fixed base.

TABLE V:
CUMULATIVE EFFECT OF SHEAR WALL AND SOIL ON THE FUNDAMENTAL LATERAL NATURAL PERIOD

Storeys	Base Condition	Variation in natural period (%)				
		Frame-shear wall building				
		SW1	SW2	SW3	SW4	SW5
4	Sb	69.48	77.37	67.66	68.91	69.67
	Sc	66.89	74.33	64.13	66.19	67.12
	Sd	59.73	66.35	54.44	58.35	60.06
	Se	46.66	52.40	36.73	42.92	47.24
6	Sb	62.11	71.50	59.50	61.04	62.41
	Sc	59.61	68.38	56.06	58.36	59.94
	Sd	52.61	60.12	46.53	50.58	53.05
	Se	40.00	46.12	29.50	35.44	40.66
8	Sb	57.41	68.18	54.37	55.97	57.99
	Sc	54.59	64.51	50.47	52.95	55.23
	Sd	46.98	55.10	40.12	44.41	47.80
	Se	33.76	39.89	22.34	28.50	34.92
12	Sb	49.89	60.05	45.78	47.65	50.59
	Sc	47.17	56.49	42.07	44.74	47.89
	Sd	39.63	47.21	31.99	36.26	40.57
	Se	26.41	31.99	14.73	20.52	27.57
16	Sb	45.90	55.78	41.48	43.39	46.77
	Sc	42.91	51.82	37.38	40.10	43.78
	Sd	34.78	41.88	26.50	30.81	35.79
	Se	20.29	25.51	8.07	13.83	21.61

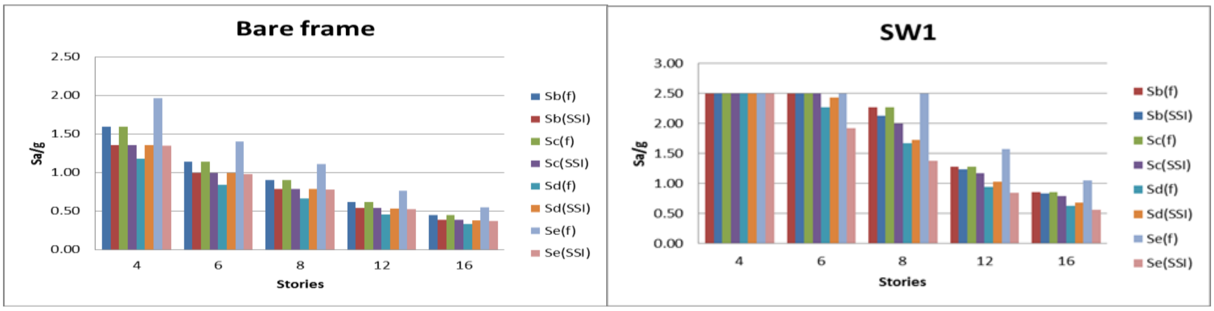
Inference from the above table shows that by considering the effect of supporting soil in the analysis for shear wall building the variation in natural period is reduced in all the buildings resting over soil.

The percentage variation in lateral natural period of building by inclusion of soil flexibility to the shear wall gradually decreases with increase in hardness of the soil.

B. *Change in spectral acceleration coefficient (Sa/g)*

1) *Effect of soil flexibility:*

Spectral acceleration coefficient Sa/g is the potent component in the estimation of design base shear and lateral forces of the building based on the design spectrum and are dependent on the primary parameter fundamental period T of the building. As the period alters by considering the effect of soil the value of spectral acceleration coefficient Sa/g is liable to shift to high or low values which in turn effect the value of design base shear calculated. The change in spectral acceleration coefficient (Sa/g) due to the effect of soil–structure interaction were studied on buildings resting on various soil types viz. Sb, Sc, Sd and Se. Variation in spectral acceleration coefficient for various building configurations are represented in fig 5.



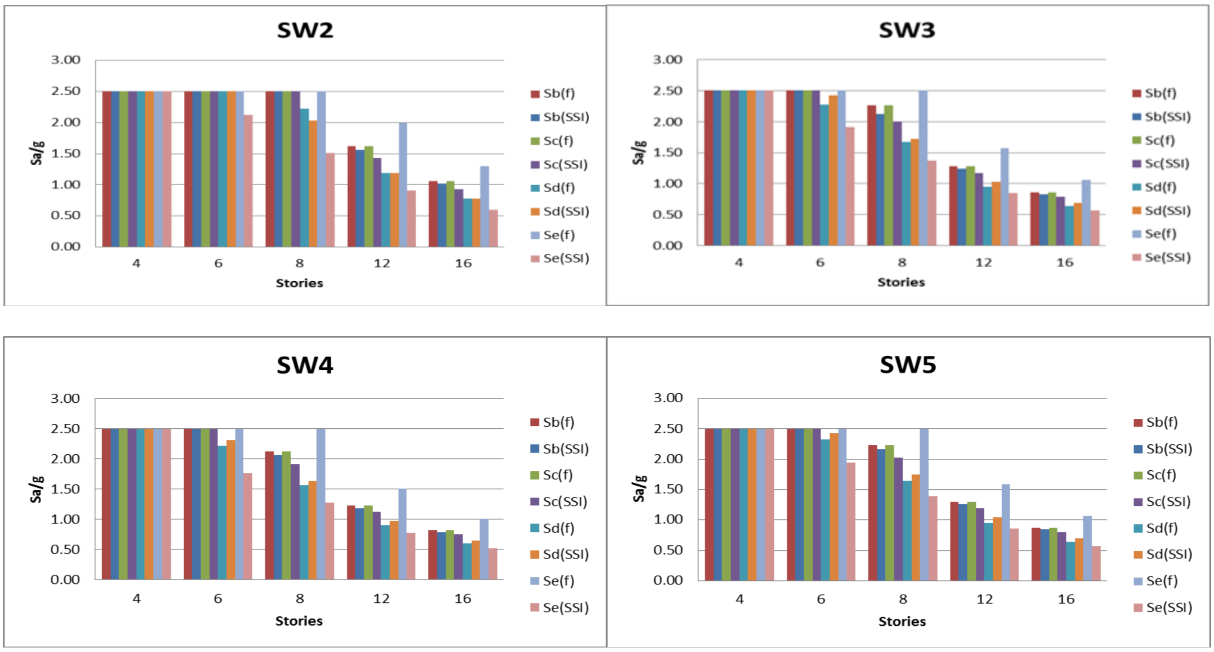
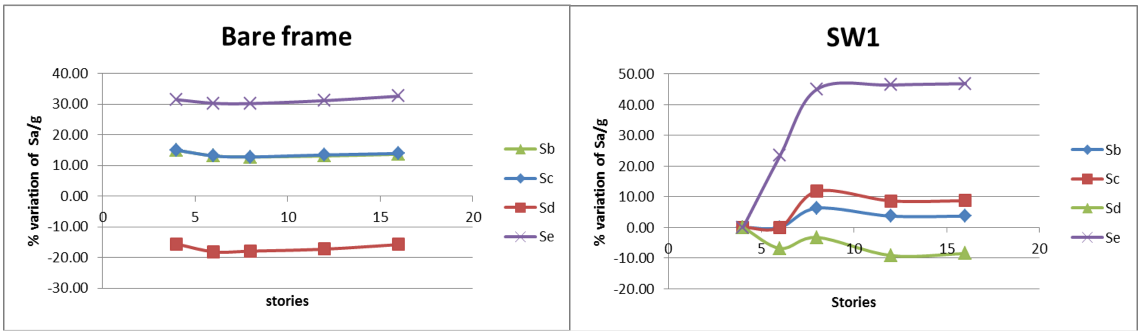


Fig. 5 Variation in spectral acceleration coefficient

The results of spectral acceleration coefficient Sa/g for buildings with various soil base conditions and heights,are as presented in the Fig 5. The addition of shear walls increases the structural stiffness which in turn increases the Sa/g value in all buildings. In the case of 4 and 6 story buildings the inclusion of shear wall in any location has an adverse effect on the Sa/g and could be avoided by the proper design of bare frame for earthquake loads. The Spectral acceleration coefficient Sa/g corresponding to the natural period of a fixed base structure to be built on Sd type soil obtained from Type II curve of IS 1893(part1):2002 is less than the value obtained by considering the SSI effect in the three dimensional model. Hence it is important to consider the SSI effect for similar buildings to be built on medium soil. For buildings of all heights with fixed base condition the spectral acceleration as per IS 1893(part1):2002 is higher than considering SSI effect except for the Sd type soil.

The values of spectral acceleration coefficient Sa/g with soil-structure system are lesser than the corresponding values of the same building founded on fixed-base. Hence if a structural design is executed with reference to design acceleration response spectra, the effect of an increase in fundamental period due to soil flexibility leads invariably to a reduction of the design base shear except in Sd type of soil.

Percentage variation in spectral acceleration coefficient (Sa/g) as per IS 1893-2002 for buildings with SSI effect when compared with fixed base condition is plotted in Fig 6.



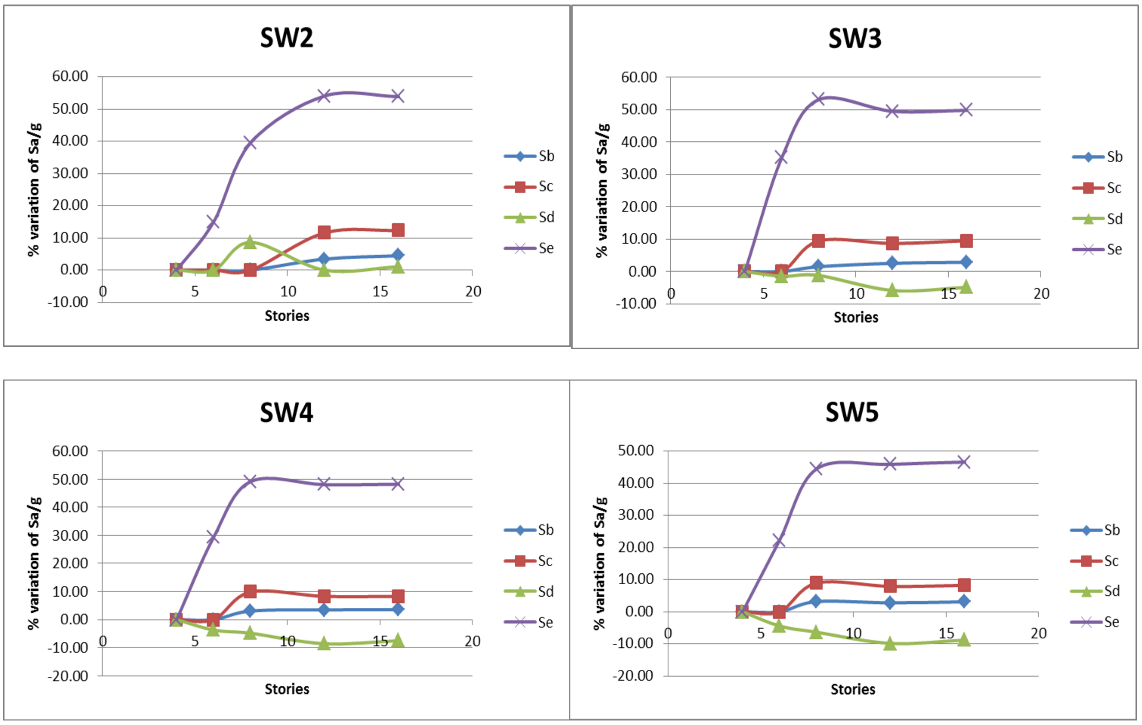


Fig. 6 Percentage variation in spectral acceleration coefficient (Sa/g)

Figure 6 describes that except for the buildings founded on Sd type soil, the spectral acceleration coefficient as per IS 1893 is higher than the values obtained by considering SSI effect which implicates that building as per IS code leads to higher values of the design base shear.

V. CONCLUSION

The present study makes an effort to evaluate the effect of soil-structure interaction on primary dynamic characteristic of bare frame buildings and frame-shear wall buildings of varying heights over raft foundation founded on different soil types.
The following conclusions were drawn from the present study

- The fundamental periods of the soil-structure system are more than the corresponding values of the same building founded on fixed-base. If a structural design is executed with reference to design acceleration response spectra of fixed base, the effect of an increase in fundamental period leads to increase/decrease of the spectral acceleration coefficient which causes the increase/decrease of design base shear.
- The percentage variation in fundamental lateral natural period due to incorporation of soil increases with the reduction in stiffness of soil. It is minimum in case of hard soil (Sb) and maximum in soft soil (Se).
- The value of Sa/gas per IS 1893 for all buildings with fixed base condition to be built on different soil types is higher than those with SSI effect except for the Sd soil type.
- It is observed that variation in natural period by inclusion of shear wall is reduced with increase in height of the building as well as increase in flexibility of soil.
- The building configuration SW3 causes the least average response acceleration coefficient and results in least design base shear
- The building configuration SW2 causes the maximum average response acceleration coefficient resulting in higher values of design base shear.
- The addition of shear walls for lateral strength increases the structural stiffness which in turn increases the Sa/g value in all buildings. In the case of buildings upto six stories the inclusion of shear wall in any location has an adverse effect on the spectral acceleration and could be avoided by the proper design of bare frame for earthquake loads.

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