Soil-structure interaction analysis of RC frame shear wall buildings over raft foundations under seismic loading

H.K Chinmayi, B.R Jayalekshmi.

Abstract— Structural failures during earthquakes in the past demonstrated the importance of soil-structure interaction (SSI) effects and its consideration to avoid failure and ensure safety. The present study focuses on SSI analysis of RC frame shear wall building over raft foundation subjected to seismic loading. Multi story buildings symmetric in plan of height below 45m, located in seismic zone V according to IS1893:2002 are considered. The stress resultants in the structure and raft foundation considering SSI are compared with stress resultants obtained by the conventional method of analysis assuming rigidity at the base of the structure. The results show the significance of SSI effect

Index Terms — Base shear, Equivalent soil spring system, Natural period, Raft foundation, RC frame-shear wall building, Seismic loading, Soil structure interaction.

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1 INTRODUCTION

Response of structure 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 real displacements of the soil-foundation structure system precisely under the influence of seismic motion. Present design practice for dynamic loading assumes the building to be fixed at their bases. Whereas, in reality supporting soil medium allows movement to some extent due to their natural ability to deform which decrease the overall lateral stiffness of the structural system resulting in the lengthening of lateral natural periods[1],[2],[3]. Such lengthening of lateral natural periods does 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 neglecting the effect of the same is fore grounded in few of the research works [5],[6].

The present study has been carried out for buildings with the same geometry found on varying soil types over raft foundations in Zone V [7]. An attempt has been made to find the stress resultants under seismic loading in the structure and raft foundation by incorporating the effect of soil-structure interaction which was further compared with those of fixed base condition.

Influence of variation of the parameters such as, different soil conditions and number of stories were also considered in the present study for which the buildings were modelled by four alternate approaches, namely, (1) bare frame with fixed supports, (2) bare frame with supports accounting for soil-flexibility, (3) frame-shear wall with fixed supports and (4) frame-shear wall with supports accounting for soil-flexibility.

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2 IDEALIZATION OF THE SYSTEM

2.1 Structural idealization

To analyse the dynamic behaviour while considering the effect of soil-structure interaction, building frames of 2, 3, 6 and 12 storey with and without shear wall have been idealized as 3D space frames using two nodded frame elements. Slabs at different storey level, shear wall and the slabs of raft foundation was 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 3.5m and 4m respectively which is reasonable for domestic or small office buildings. For all the cases, the dimensions of reinforced concrete columns were taken as 320X320mm and beams as 230X300 mm. Similarly, the thickness of the roof slab, floor slabs and shear wall was taken as 150mm for the building considered. These dimensions were arrived on the basis of the design following the respective Indian code for design of reinforced concrete structures [8], [9].

2.2 Soil Idealization

To incorporate the effect of soil-structure interaction in the analysis impedance functions associated with rigid mass less foundations was utilized. The present study considers translations of foundations in two mutually perpendicular principal horizontal directions and vertical direction as well as rotations of the same about these three directions. For buildings with raft foundation, three translational springs along two horizontal and one vertical axes together with three rotational springs about these three mutually perpendicular axes have been attached below the centre of gravity of the foundation to simulate the effect of soil-flexibility. The stiffness's of this centrally placed spring for raft type of foundation resting on homogeneous elastic half space have been computed on the basis of the guidelines prescribed in a well-accepted literature [4] formed on the basis of an extensive literature survey and study based on boundary element method. These expressions were developed in such a form that the single spring located at the centroid of the raft, in each of the said six degrees of freedom, can account for the flexible behaviour of soil below the entire raft in the equivalent sense.

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Expressions for such spring stiffness have been extracted from the literature [4], [10] and are presented in Table1. 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. To obtain the values of the stiffness of the springs for these varieties of soil, values of shear modulus (G) of soil have been estimated using the shear wave velocity [11]. The other details of different soil parameters are tabulated in Table 2.

Table 1: Expressions for stiffness's of equivalent springs along various degrees of freedom

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

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

Table 2: Details of soil parameters considered [12], [13]

Soil profile type	Description	Shear wave velocity (Vs) (m/sec)	SPT value	Mass density (ρ) (kN/m^3)	Shear modulus G (kN/m^2)
S_B	Rock	1200		22	$3.23x10^6$
S_C	Dense soil	600	>50	20	$7.34x10^5$
S_D	Stiff soil	300	15-50	18	$1.65x10^5$
S_E	Soft soil	150	<15	16	$3.67x10^4$

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. 1a and 1b, respectively. Seismic analysis for computing base shear of building frames accounting for the effect of soil-structure interaction was carried out with the help of the design spectrum provided in IS: 1893-2002 as shown in Fig. 1c for a critical damping of 5% [7] considering fixed base condition and also the effect of soil-flexibility.

With idealization of structure and soil as mentioned above, the change in lateral natural period, base shear and stress resultants in the structure and raft foundation due to consideration of the effect of soil-structure interaction are investigated and discussed in the following sections.

2.3 Methodology

Seismic analysis of frame-shear wall building accounting for the effect of soil–structure interaction is carried out based on the design spectrum provided in IS: 1893-2002 .The seismic base shear of these buildings are obtained due to the design spectrum corresponding to 5% of critical damping [7] considering fixed base condition as well as considering flexible-base condition resulting from soil-flexibility. 5% of critical damping which is reasonable for concrete structures is considered.

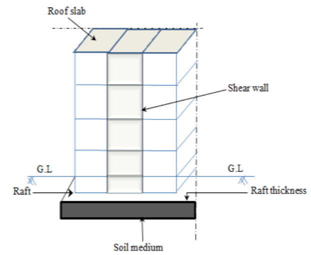

Fig.1 (a)

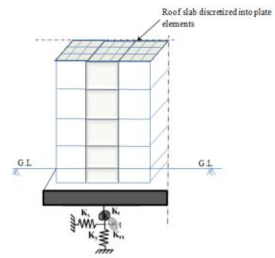

Fig.1 (b)

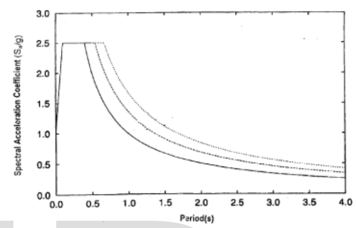

Fig.1(c)

Fig 1: System idealization and ground motion characteristics
Fig 1(a): Typical 4 storeyed frame-shear wall building on raft
Fig 1(b): Idealized soil–foundation structure system
Fig 1(c): Design spectrum (IS: 1893-2002).

From observation in the findings of an experiment as well as computation based study [14] it was found that for an isolated raft and equivalent soil spring system, the damping is not considerably larger than 5%. Further, damping will be still reduced if the effect is considered with respect to the entire structure foundation-equivalent soil spring system, instead of the isolated raft and equivalent soil-spring system [15].

The effect of soil-flexibility contributes to the variations in lateral natural period, base shear and stress resultants in the structure and raft foundation. The change in the base shear has been computed by combining the contributions of all the possible lateral modes by square root of the sum of the squares (SRSS) method for building with fixed base condition and by incorporating the effect of soil-flexibility. When the modes are close-spaced the CQC method is used to obtain the contribution of the modes. This modal combination method is applicable for wide variety of structures. The expressions for combined modal response are available in standard literature, [16].

In the present study, base shear of frame-shear wall building for fixed base and also for flexible base condition was arrived as per the provisions of Indian Earthquake Code [7] by applying seismic zone factor 0.36 for very severe seismic intensity, reduction factor 3.0 for ordinary moment-resisting frame and importance factor 1.0 for general residential building frames.

3 RESULTS AND DISCUSSIONS

This section presents the change in lateral natural period, base shear

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and stress resultants in the structure and raft foundation as a function of influential parameters namely, number of stories and types of soil.

3.1 Effect of soil-flexibility and number of stories

a) On lateral natural period

Idealisation of building as a bare frame is unrealistic, but such idealization is used many a time in the design offices. Hence, a parametric study has been made for such frames and frame shear wall building and the percentage changes in lateral natural period due to incorporation of the effect of soil–structure interaction and the comparison of results are presented in the fig.2, fig 3 and fig 4.

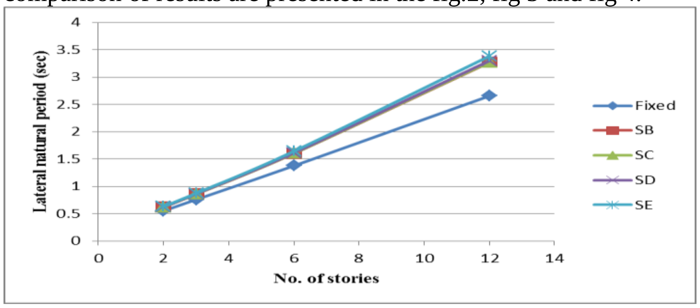

Fig 2 Variation of lateral natural period in bare frame building

Note: SB, SC, SD and SE denotes soil profile type S_B, S_C, S_D and S_E

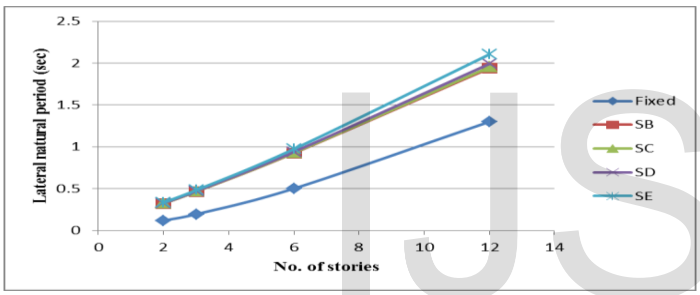

Fig 3 Variation of lateral natural period in shear wall building

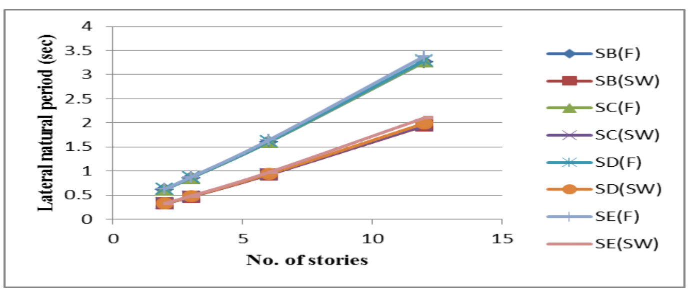

Fig 4 Variation in lateral natural period for building frames with and without shear wall

Note: F and SW denotes frame and shear wall respectively

The study shows that the incorporation of SSI tends to increase the fundamental lateral natural period of buildings by 14%, 15%, 19% and 27% in frame building and 180%, 98%, 94% and 61% in shear wall building for 2, 3, 6 and 12 stories respectively.The comparison of fundamental lateral natural periods of bare frames and building with frame-shear wall as represented in Fig.4 shows a maximum decrease in lateral natural period by 46%,44%,40% and 37% in soft soil for 2, 3, 6 and 12 stories due to the addition of shear wall as an effect of increase in stiffness, which is the primary parameter, which regulates the seismic lateral response of the building.

b) On base shear

Seismic base shear reflects the seismic lateral vulnerability and is considered as one of the primary input for seismic design. Present section presents the variation in base shear due to the effect of soil–structure interaction for building frames with and without shear wall and are presented in fig 5, fig 6 and fig 7.

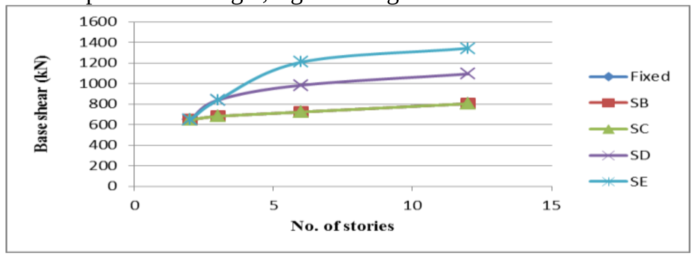

Fig 5 Variation of base shear in bare frame building

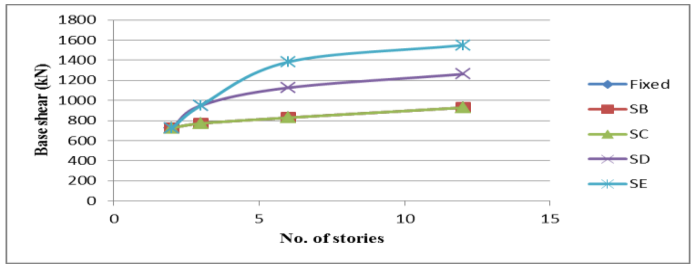

Fig 6 Variation of base shear in shear wall building

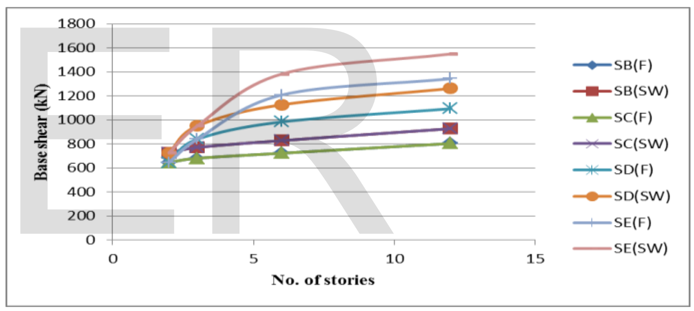

Fig 7 Variation in base shear for building frames with and without shear wall

The study shows that the seismic base shear increases due to soil flexibility which considerably decreases with increase in hardness of soil. The variation is about 1%, 36% and 67% for S_C, S_D and S_E soil profile respectively for a 12 story building and the variation is negligible in two story building and varies considerably with increasing building height.The comparison of base shear in bare frames and building with frame-shear wall as represented in Fig.7 shows significant increase in the value of base shear in frame shear wall building due to the increase in weight of structure by inclusion of shear wall, which is about 12%, 13%, 14% and 15% for 2, 3, 6 and 12 stories respectively on soft soil.

c) On stress resultants in the structure and raft foundation

The incorporation of soil–structure interaction leads to variation in stress resultants, such as bending moment and shear stresses in building as well as in foundation. The outcome of the analysis is given by the changes in stress resultants in structure and raft foundation with and without shear wall and are presented in the fig8 (a), fig8 (b), fig 9(a) and fig 9(b) respectively.

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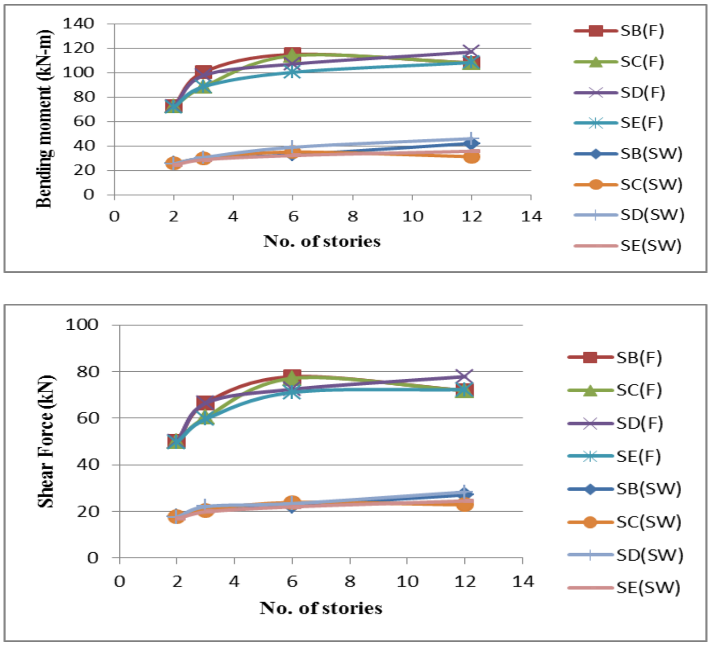

Fig 8(a) and Fig 8(b): Variation of stress resultants in structure for buildings with and without shear wall

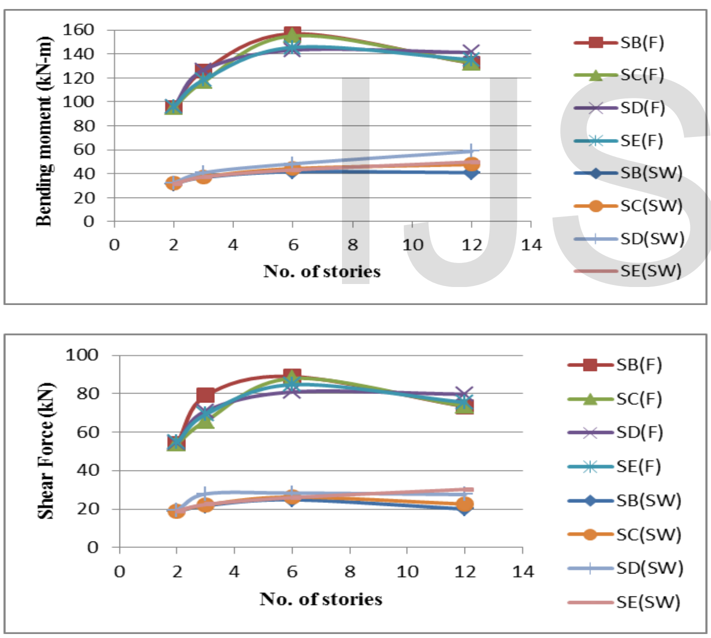

Fig 9(a) and Fig 9(b): Variation of stress resultants in raft for buildings with and without shear wall

The comparison of stress resultants in structure and foundation of bare frames and building with frame-shear wall as did in the above figures clearly reveals the change in the stress resultants due to the inclusion of soil flexibility and addition of shear wall. The bending moments and shear force in the structure and foundation are reduced due to the equal and opposite pull exerted by the vertical components of diagonal tension of shear wall. Thus addition of shear walls to a structure will improve its lateral load capacity.

4 Conclusion

The present study makes an effort to evaluate the effect of soil structure interaction on primary dynamic characteristic of bare frame buildings and building with frame-shear wall of varying heights over varying soil property on raft foundation. For a 12 story building the study shows increase in lateral natural period by 27% and 61% and increase in seismic base shear by 67% and 68%. Reduction in bending moment and shear force by 37% and 20% in structure and 29% and 26% in foundation due to the effect of soil flexibility is seen in bare frames and building with shear wall for a 12 story building on soft soil.

The change in lateral natural period, seismic base shear and stress resultants, due to the varying soil type and height parameters, are presented in the form of graphs to show the trend in the effect of variation of these characteristics. Effect of SSI is neglibile for 2 storey building but it is significant in the case of 12 story building.

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