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INFLUENCE OF SHEAR WALL ON SEISMIC RESPONSE OF RC FRAME BUILDINGS ON PILE FOUNDATION CONSIDERING SSI

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Abstract

This paper highlights the influence of shear wall on RC building frame supported on pile foundation. The provision of shear walls contributes to the increase in the lateral load capacity and the lateral stiffness of the building which can lead to significant modification is the elastic and inelastic behavior of RC frame. The influence of shear wall on RC frame in the presence and absence of soil structure interaction (SSI) can be different. The present study aims to investigate the change in the seismic behavior, elastic and inelastic, of an RC frame with pile foundation, on the inclusion of an RC wall, considering soil-structure interaction effects. RC shear wall modifies the natural vibrational characteristics which causes the inelastic global and local response of the frame system to be modified. This modification depends on several factors including the presence of SSI effects. The present study provides an insight into the suitability of incorporating shear wall in RC frame supported on pile foundations with and without SSI effects.

Keywords: soil structure interaction; RC frame building; shear wall; seismic behavior; nonlinear analysis

1. Introduction

Most buildings in the urban areas comprise Reinforced Concrete (RC) frame type construction with or without the presence of RC shear walls. In severe seismic zones, provision of these walls contributes to the increase in the lateral load capacity and the lateral stiffness of the building. In past earthquakes, it has been observed that Soil-Structure Interaction (SSI) may play an important role on the seismic behavior of a building, particularly if the building is located on soft soil [1]. Although past studies have highlighted both the beneficial and the detrimental effects of SSI [2], the influence of SSI on seismic behavior of RC wall frame building on pile foundation has not been studied in detail [3]. Consequently, the inclusion of SSI in the seismic design provisions of such buildings has also not been explored in detail.

The present study aims to investigate the change in the seismic behavior of an RC frame with pile foundation, on inclusion of an RC wall, considering soil-structure interaction. A representative frame is first considered from a multistoried RC frame building supported on pile foundation [4-5]. The seismic design of the beams, columns and the piles is carried out as per the guidelines of the relevant Indian Standards. RC walls are placed in the same RC frame building to study the influence of shear wall, and similar seismic design of the shear wall has been carried out. Like the previous model, a representative frame with shear wall is also isolated from the wall frame building. To simulate the realistic soil-structure interaction, finite element modelling of the entire frame-pile-soil domain system (with and without shear wall) is carried out using the computer program OpenSEES [6]. Absorbing boundaries are imposed at the ends of the soil domain to simulate radiation damping during the propagation of seismic waves in the domain. Material nonlinearity is incorporated in the soil and structural members. The nonlinearity in the structural members is simulated by means of plastic hinges using fiber sections, wherein, the realistic stress-strain characteristics of concrete and steel reinforcement are assigned.

The effect of SSI on linear elastic behavior for both the models is evaluated in terms of natural vibrational characteristics. To study the influence of SSI on the nonlinear behavior of the two models, two sets of analyses are carried out. Displacement-controlled nonlinear static analysis is carried out to assess the displacement ductility capacity (global level) of the models. Also, using a selected ground motion, nonlinear time history analysis is carried out to assess the corresponding demands for the two models. To assess the influence of SSI on the response of the RC frame with and without shear wall, the results are compared with that of the fixed base case (i.e., without SSI effects). The study provides an insight on the suitability of incorporating shear wall in RC frame supported on pile foundations with and without SSI effects.

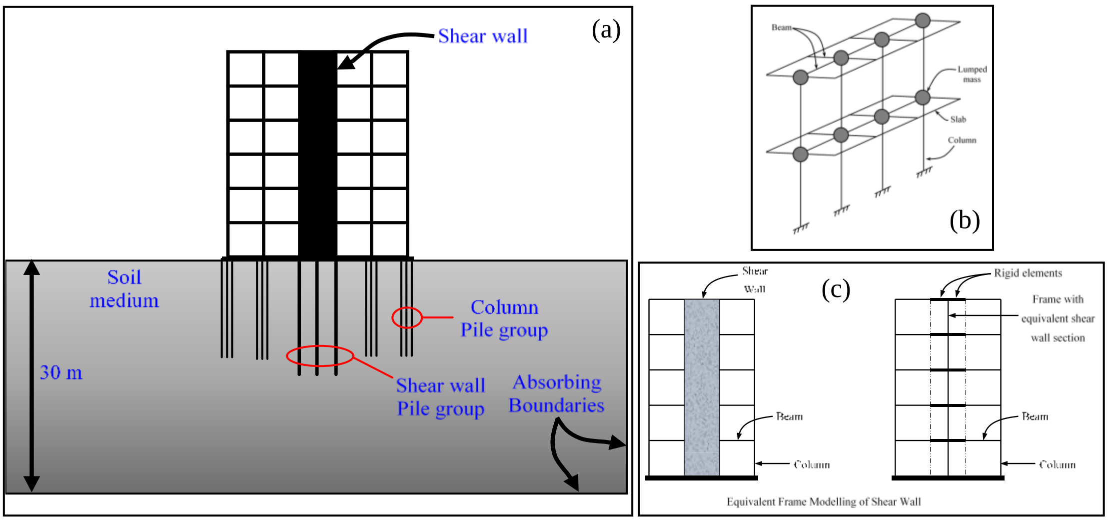


Fig. 1 – Aspects of the finite element numerical model adopted in the present study showing an (a) illustrative representation of the soil-pile structural system, (b) idealization of the inertial mass and (c) Equivalent Frame Model (EFM) idealization of the shear wall

2. Modelling

Two-dimensional modelling of the RC building frame has been carried out using the finite element based software framework, OpenSEES [6]. Fig. 1 shows the various aspects of modelling of the superstructure, substructure and soil system adopted in the present study and are discussed briefly in the following subsections.

2.2 Soil Domain Modelling

A rectangular sandy soil domain of 30 m depth, as shown in Fig. 1(a), is considered where the bedrock is assumed to be located. The basic properties of the soil considered is shown in Table 1. It is essential to consider a sufficient size of the soil domain in SSI studies for proper modelling of radiation damping and to ensure that the response in the region of interest is not influenced by the boundaries. Simultaneously, it is to be ensured that the SSI model does not become computationally expensive. Moreover, the lateral extent of the soil depends on the structural width, soil property, and the potential amount of nonlinearity that can develop. To account for the aforementioned aspects in the modelling of the soil, simplified relationships proposed by Sharma et al. [7] have been utilized for fixing the horizontal extent of the soil domain. The soil domain is discretized using four noded plane strain quadrilateral elements, with bilinear isoparametric formulation. A non-uniform meshing is adopted to appropriately capture the soil behavior in the region of interest. In total, 3406 nodes and 3250 elements have been used for the representation of the soil. Fine meshing is adopted near the structure and mesh is coarsened away from the structure with the maximum size of the soil element restricted to 1.5 m. PressureDependMultiYield [8] material has been used to simulate the nonlinear behavior of the soil. The plastic behavior in this material model follows the Drucker-Prager yield surface (nested yield surface) criteria. Bulk density is used for mobilization of the inertial mass of the soil.

Table 1 – Basic properties of the soil considered

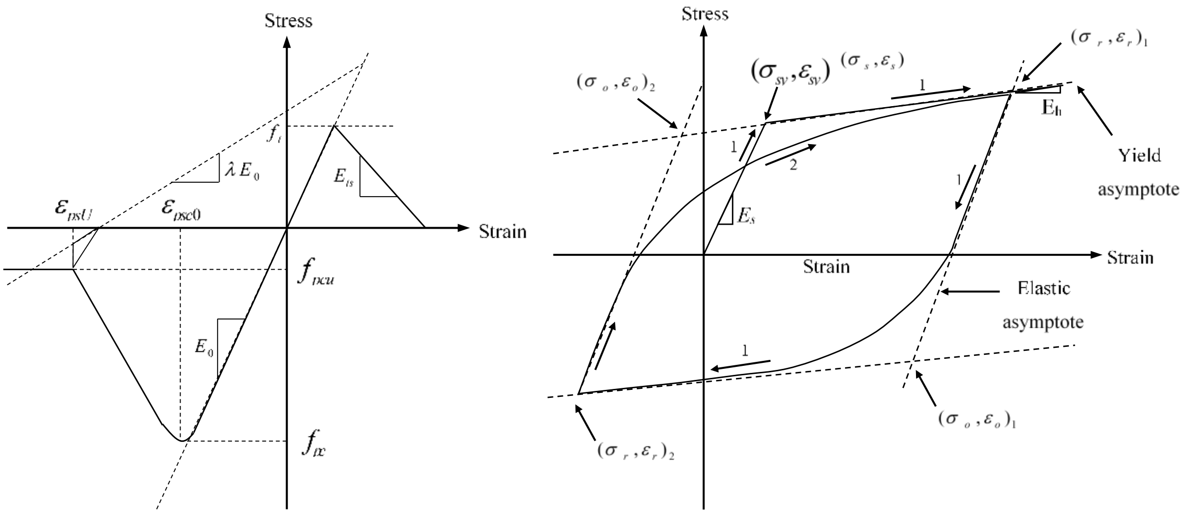
Density ρ (kg/m^3)	Friction angle φ	Poisson's ratio υ	Ref. shear Modulus G_r (MPa)
1900	33	0.33	750

In the absence of SSI effects, it is appropriate to consider the frame to be fixed at the base. However, for SSI studies, modelling of the boundaries is very important to simulate the effect of radiation damping and the application of excitation input. Also, proper modelling of the boundary allows truncation of the soil domain to a finite extent. In the present study, the vertical and horizontal boundaries have been modelled using Lysmer-Kuhlemeyer viscous dashpots [9] to arrest the waves at the boundary in the transverse and longitudinal directions and to prevent the same from reflecting back into the soil medium after being incident at the far-off boundaries. Fixed base condition is adopted for the model wherein SSI effects are considered to be absent.

2.1 Superstructure-Substructure system

Fig. 1(a) shows a representative illustration of a wall-frame system supported on soil-pile foundation system. The superstructure consists of beams, columns and shear wall. The shear wall is located in the central bay. The width of a single bay is 3 m and the frame consist of 5 bays. Two different heights of 18m and 36m of the superstructure are considered. The frame is supported on pile groups. The super-structure and pile foundation elements have been designed and detailed using IS 456 [10], IS 13920 [11] and IS 2911: Part I/Sec I [12] considering the imposed and lateral loads using IS 875: Part 2 [13] and IS 1893: Part I [14]. The masses of the structural elements are lumped at their respective discretized nodes as shown in Fig. 1(b). Equivalent frame method of idealization for the shear wall has been adopted in the present study, as shown in

Fig. 1(c); and the modelling of the structural members (superstructure and foundation) is carried out with the help of two noded force-based beam column elements. M30 grade of concrete and Fe500 grade of reinforcement are used for the super-structural and pile-foundation elements. The nonlinearity in the structural elements is considered in the form of plastic hinges. For superstructure, plastic hinge region is mobilized over a finite length known as plastic hinge length located at the end regions of the members [15-16] while for the piles the nonlinearity is distributed over the entire length. The incorporation of nonlinearity in the plastic hinge regions has been made with the help of fiber sections which are assigned with nonlinear stress strain properties of concrete and rebar, as shown in Figs. 2(a) and 2(b), using the material models Concrete02 and Steel02 in OpenSEES. The piles are connected to the soil elements using zero length rigid link member and interface nonlinearity has not been considered. Rigid pile caps are modelled to connect the piles in a group and the pile groups are interconnected by means of grade beams. For the column members, a pile group of three is selected whereas, for the shear wall, a pile group of six is considered.



(a) (b)

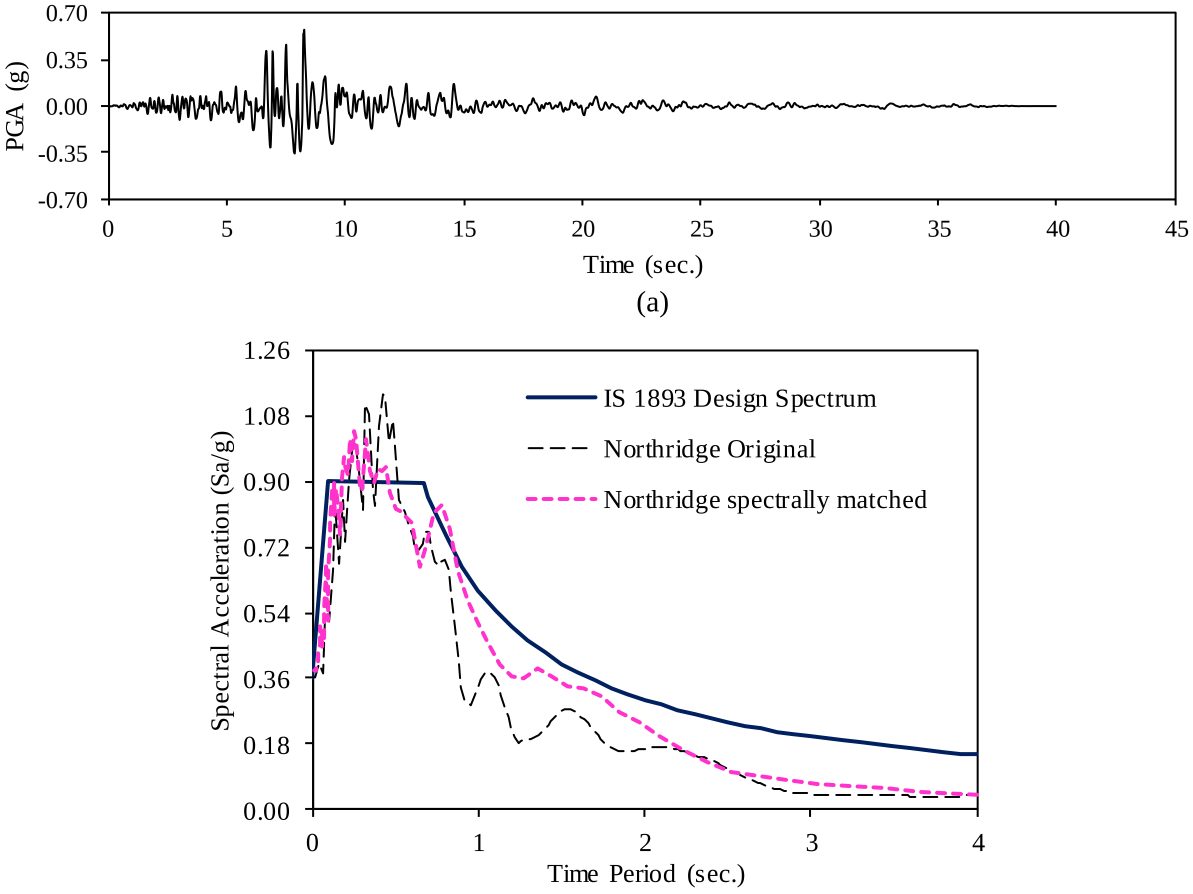
Fig. 2 – Stress-strain properties of (a) concrete using Concrete02 and (b) reinforcement using Steel02 in OpenSEES program

3. Ground Motion Input

The simulation of the dynamic earthquake loading is done be means of applying a ground motion time history corresponding to the 1994 Northridge earthquake as shown in Fig. 3(a). As shown in Fig. 3(b), the motion is spectrally matched with the design spectrum given in IS 1893 Part 1 and the peak acceleration intensity is considered as per the Maximum Considered Earthquake (MCE) level. The ground motion input, for SSI cases, is applied in the form of equivalent nodal forces using the procedure outlined in [17] after conducting staged gravity analysis to ensure proper simulation of static state of stress within the soil [18].

4. Results and Discussion

The following subsections discuss the influence of shear wall on the various seismic response characteristics of RC frame supported on pile foundation. The effect of shear wall on the linear elastic behavior is investigated by means of natural vibrational analysis, and that on the inelastic response is determined by performing nonlinear static and nonlinear time history analyses. The effect of shear wall on the response of the frame is expected to get modified under the influence of SSI and hence the behavior is investigated separately, considering and ignoring the effects of SSI.



(a)

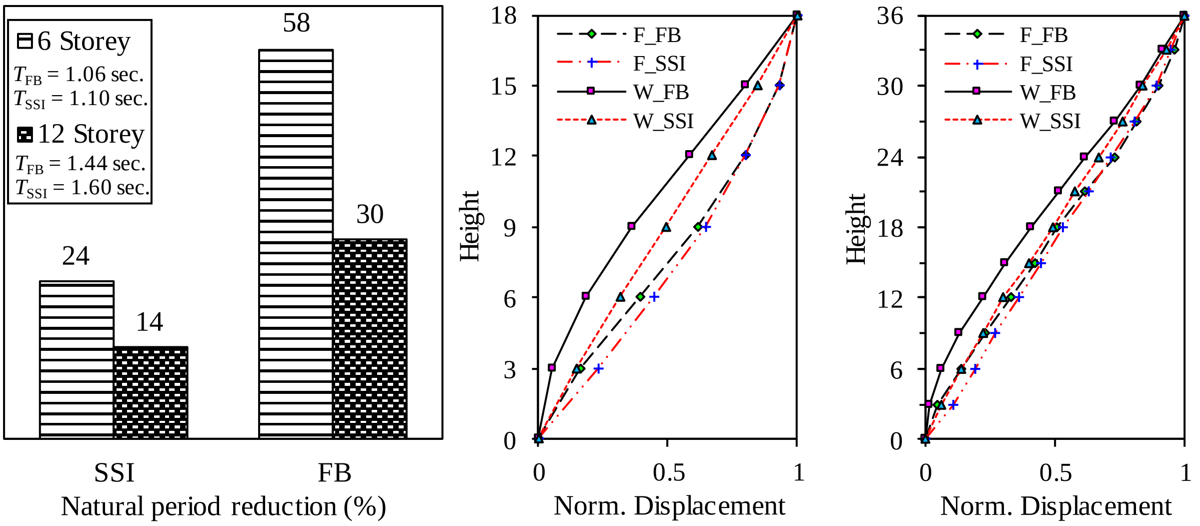
(b)

Fig. 3 – Details of the seismic input considered in the study (a) accelerogram corresponding to Northridge earthquake, and the (b) original and the spectrally matched response spectra

4.1 Influence on Natural Vibrational Characteristics

Fundamental natural period is an important parameter as it gives the information about the natural vibrational characteristics of the structural system. In seismic design the amount of lateral force is estimated based on the natural period of the structural system. Incorporating shear wall causes two levels of modifications in the linear elastic behavior, i.e., (a) change in the fundamental natural period of the frame which governs the total magnitude of forces that can develop within the system and (b) change in the mode shape which governs the distribution of the developed forces at various storey levels within the frame system. The presence of shear wall in an RC frame system increases the lateral stiffness of the overall frame system thereby reducing the natural period. This reduction may vary as per the prevalence of SSI effects. Fig. 4(a) shows the reduction of natural period due to the presence of shear wall in a 6 storeyed and 12 storeyed RC frame with and without SSI effects. The natural period of the 6 storeyed and 12 storeyed frames without the shear wall in the absence SSI effects (T_{FB}) are 1.06 and 1.44 seconds respectively. Similarly, the natural period of the frames without the shear wall and with SSI effects (T_{SSI}) is 1.10 and 1.60 seconds respectively. For a particular height of the frame, incorporating SSI effects makes the system flexible. It can be noted that the increase in the natural period of the frame due to presence of SSI effects is about 4% and 11% for 6 storeyed and 12 storeyed frame respectively. Moreover, on increasing the height, the frame system becomes relatively more flexible with and without SSI effects. The reductions in the natural period, due to shear wall, of the 6 storeyed frame are 24% and 58% with and without SSI effects respectively. Similarly, the corresponding reductions for the 12 storeyed frame are 14% and 30% respectively with and without the SSI effects. It can be observed that the reduction in the natural period of 6 storeyed frame is greater than that of the 12 storeyed frame. This indicates that the RC frame would attract greater seismic forces due to the presence of shear wall when SSI effects are absent and the effect is greater for stiffer frame system.

Along with the natural period, presence of shear wall also modifies the natural mode of vibration of the RC frame. Figs. 4(b) and 4(c) show the influence of the presence of shear wall with and without SSI on the normalized mode shapes of the 6 storeyed and 12 storeyed RC frames respectively. F_FB indicates the mode shape profile of frame without shear wall and without SSI effects. The addition of shear wall to the frame significantly modifies the mode shape as shown by W_FB. The model shape profile of the frame without shear wall and with SSI effects is indicated by F_SSI. The incorporation of shear wall into the frame under SSI effects also modifies the mode shape profile but to a relatively lesser degree as indicated by W_SSI. The modification in the mode shape profile on incorporation of shear wall, with and without SSI effects, is greater for 6 storeyed frame compared to 12 storeyed frame. The alteration in the mode shape profile provides an estimate of the variation in the distribution of forces that would arise at various storey levels in the frame due to the presence of shear wall.



(a) (b) (c)

Fig. 4 – Details of natural vibration analysis of RC frame depicting the influence of shear wall (a) on fundamental natural period (b) natural vibrational mode of the 6 storeyed frame (c) natural vibrational mode of the 12 storeyed frame

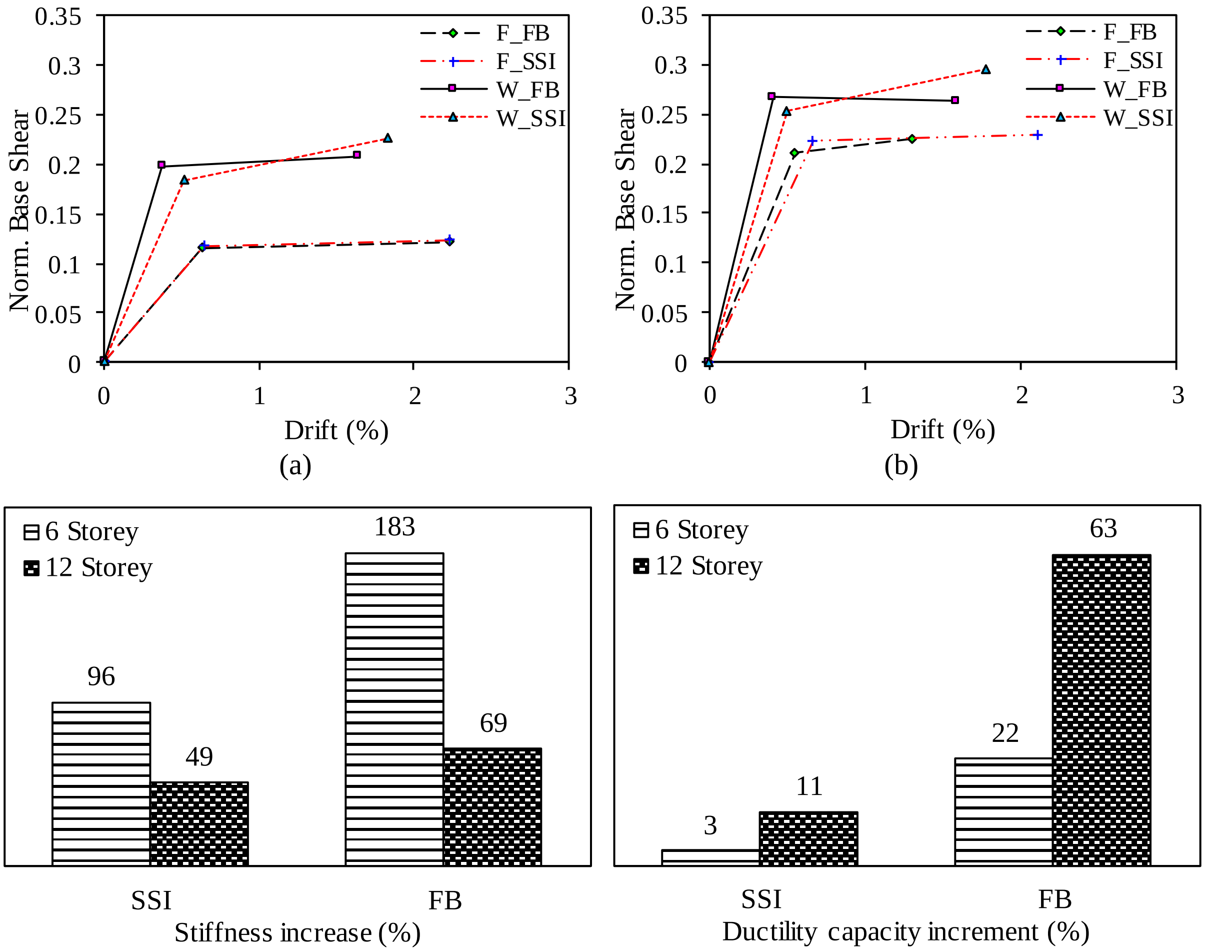
4.2 Influence on Inelastic Behavior

As observed in the previous section, presence of shear wall modifies the natural vibrational characteristics of the RC frame and results in the modification of magnitude and distribution of forces and deformations. In the event of a severe earthquake, any RC structure is expected to undergo significant inelastic behavior. In the present study, the inelastic response is studied at the global (or structural) level and at the local (or member) level. The following subsections discuss the influence of shear wall on the modification of the global and local response.

4.2.1 Global Response

To assess the influence of the presence of shear wall on the global response, performance evaluation of the RC frame with and without shear wall in the presence and absence of SSI effects has been carried out by means of nonlinear static analysis, also known as pushover analysis. The interstorey lateral drift limits (4%

for concrete frame and 2% for concrete shear wall) corresponding to collapse prevention state as prescribed in FEMA 356 [19], are utilized to obtain the ultimate drift of the frames. The yield drifts have been obtained by carrying out bilinear idealization of the actual pushover curves based on equality of areas under the actual and idealized curves [19]. Figs. 5(a) and 5(b) show the influence of shear wall with and without SSI effects on the 6 storeyed and the 12 storeyed RC frames respectively. It can be observed that the presence of shear wall modifies (a) yield and ultimate base shear, (b) the effective lateral stiffness, and (c) yield and ultimate drifts. The observation holds valid for both the heights of the frame. For the 6 storeyed frame, the increase in yield base shear is 57% and 70% with and without SSI effects respectively. Similarly, for the 12 storeyed frame, the increase in yield base shear is 12% and 25% with and without SSI effects respectively. The increase in the ultimate base shear for the 6 storeyed frame is 82% and 70% with and without the SSI effects respectively. Similarly, for the 12 storeyed frame, the increase in the ultimate base shear is 28% and 17% with and without the SSI effects respectively.



(a) (b)

(c) (d)

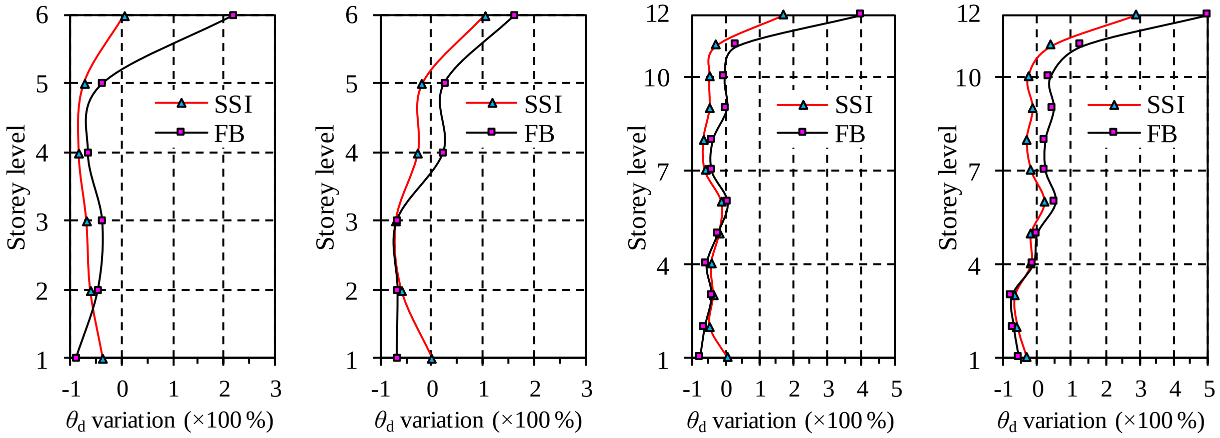
Fig. 5– Influence of shear wall on RC frame with and without soil-pile foundation interaction on (a) nonlinear static response of 6 storeyed frame and (b) 12 storeyed frame; influence of shear wall on (c) lateral stiffness and (d) ductility capacity

The increase in the yield base shear and ultimate base shear is relatively greater for the 6 storeyed frame as compared to the 12 storeyed frame. Moreover, it can be observed that the increase in yield base shear is relatively lesser with SSI effects, however, the increase in ultimate base shear is relatively greater with SSI effects. The observation holds equally good for the 6 storeyed and the 12 storeyed frames. The influence of shear wall on the increase in effective lateral stiffness of the frame is evaluated and is shown in Fig. 5(c). For the 6 storeyed frame, the increase in effective lateral stiffness is 96% and 183% with and without SSI effects. Similarly, the increase in effective lateral stiffness of the 12 storeyed frame is 49% and 69% with and without SSI effects. The increase in the effective lateral stiffness is greater for 6 storeyed frame compared to the 12 storeyed frame. It can be observed that the influence of shear wall on the effective lateral stiffness is relatively lesser considering SSI effects. On incorporating shear wall, frames exhibit greater change in the natural period and effective lateral stiffness thereby exhibiting an increase in yield and ultimate base shear. The magnitude of increase is influenced by presence of SSI effects. The increase in the yield base shear is relatively lesser with SSI effects, however, the increase in ultimate base shear is relatively greater. This is due to two primary reasons: (a) frame without SSI effects attract greater forces and undergo higher damage as compared to the frame with SSI effects causing a greater increase in yield base shear but lesser increase in ultimate base shear, and (b) the foundation of the frame with SSI effects also participates in the inelastic behavior which causes less damage in the frame thereby increasing its ability to exhibit greater load resisting ability at higher inelastic deformation.

As already observed, on addition of the shear wall the lateral load resistance and effective lateral stiffness are modified both in the presence and absence of SSI effects. Shear wall also modifies the lateral displacement response of the frame, as observed in Figs. 5(a) and 5(b), in terms of yield and ultimate drifts. This ultimately influences the ductility capacity of the frame. The presence of shear wall increases the ductility capacity of the frame as shown in Fig. 5(d). For the 6 storeyed frame, the increase in the docility capacity is 3% and 22% with and without SSI effects respectively. Similarly, for the 12 storeyed frame, the increase is about 11% and 63% with and without SSI effects. The increase in ductility is greater for the relatively flexible frame of 12 storey compared to the relatively stiffer frame with 6 storey. Moreover, it can be observed that the increase in the ductility capacity is lesser with SSI effects. For stiffer frame, it is possible for the inelasticity to develop at relatively lesser drifts thereby allowing greater mobilization of the ductility contribution due to shear wall and exhibiting larger ductile behavior before collapse. For frames with SSI, due to the inelasticity developing at relatively higher drifts, the opportunity available for the shear wall to mobilize its ductile behavior is reduced thereby exhibiting relatively lesser increase in the ductility capacity.

4.2.2 Local response

Shear wall modifies the natural vibrational characteristics and also the mode shape profile of an RC frame building. This causes a modification in the member or local level response for the different frame members. To assess the influence of shear wall on the local level response of the frame, nonlinear time history analysis has been performed using the selected ground motion. The local level response is assessed in terms of the rotational demand (θ_d) developed in the inelastic region (plastic hinge) of the column and beam members. Average value of the demand is obtained for a particular storey level and its profile at various storey levels is obtained. Figs. 6(a) and 6(c) show the variation of average rotational demand (θ_d) in the columns at various storey level in the 6 storeyed and the 12 storeyed frames respectively. Similarly, Figs. 6(b) and 6(d) show the variation of the average rotational demand (θ_d) in the beams at the various storey levels in the 6 storeyed and the 12 storeyed frames respectively. It can be observed that the presence of shear wall influences the rotational demands (θ_d) in the frame members and the extent of change depends on the frame height, member type (columns or beams), storey level and the SSI effects.



(a) (b) (c) (d)

Fig. 6 – Influence of shear wall on RC frame with and without soil-pile foundation interaction on the variation of average plastic hinge rational demands at various storey levels in (a) columns of the 6 storeyed frame (b) beams of the 6 storeyed frame (c) columns of the 12 storeyed frame (d) beams of the 12 storeyed frame

For the 6 storeyed frame, shear wall reduces θ_d in columns at SL1 (storey level 1 is abbreviated as SL1 and similar abbreviation is adopted for other storey levels) and the reduction is about 37% and 91% with and without SSI effects, respectively. At SL6, the shear wall increases θ_d in the columns by about 4% and 220% with and without SSI effects respectively. Presence of the shear wall causes a reduction in θ_d in columns at SL1 and the reduction is relatively less for frame with SSI effects. At SL6, shear wall significantly increases θ_d in columns for frame without SSI effects, however, for frame with SSI effects the increase is very minute. At other intermediate storey levels (L2-L5), shear wall causes similar reduction of θ_d in the columns with maximum reductions of about 85% and 67% with and without SSI effects respectively. In the beams shear wall reduces θ_d at SL1 by 0.5% and 68% with and without SSI effects respectively, however at SL6, it increases θ_d by about 102% and 160%. At other intermediate storey levels, shear wall reduces θ_d in beams with a maximum reduction of 72% in the frame with SSI effects. For the frame without SSI effects, presence of shear wall reduces θ_d at SL2-SL3 (with maximum reduction of about 68%), however at SL4 and SL5, presence of shear wall increases θ_d by about 23%.

As observed for the 6 storeyed frame, in the 12 storeyed frame also, shear wall reduces θ_d in columns at SL1 and the reductions are about 7% and 77% with and without SSI effects respectively. At SL12, presence of shear wall increases θ_d in the columns by about 171% and 400% with and without SSI effects respectively. Presence of shear wall causes a reduction in θ_d in columns at SL1 and the reduction is relatively less for frames without SSI effects. At SL12, shear wall significantly increases θ_d in columns and the percentage increase for frame without SSI effects is almost twice that of the frame with SSI effects. At other intermediate storey levels (L2-L11), shear wall causes a reduction of θ_d at most storey levels exhibiting a maximum reduction of about 64% and 57% for frames with and without SSI effects respectively. In the beams shear wall reduces θ_d at SL1 by 30% and 57% with and without SSI effects respectively, however at SL12, it increases θ_d by about 291% and 500%. At other intermediate storey levels in the frame with SSI effects, shear wall reduces θ_d in beams (except at SL6 and SL11 where it increases by 21% and 40% respectively) with a maximum reduction of 65%. For the frame without SSI effects shear wall reduces θ_d at SL2-SL5 (with maximum reduction of about 77%), however at SL6-SL11, shear wall increases θ_d with maximum of about 128%.

Shear wall is equally effective in the reduction of θ_d in beams and columns at the bottom storey of 6 storey as well as 12 storey frame without SSI effects. For frames with SSI effects, the reduction in θ_d of columns is greater for stiffer frame (6 storey) compared to the flexible frame (12 storey) as for stiffer frames, the shear wall causes a greater reduction in the rotational demands and is more effective in arresting the rotational demands. For the frames with SSI, the reduction of θ_d in the beams at bottom storey due to shear wall is greater for the flexible frame (12 storey) compared to the stiffer frame (6 storey). This is because flexible frames cause greater rotation of the columns forcing the beams to comply to the assumed deformed profile thereby increasing the demands in the beams. On incorporation of shear wall, this imposed demand due to the inherent flexibility of the frame is reduced.

On incorporating shear wall, at top storey level, the RC frame experiences increased θ_d in the frame members. In the absence of shear wall, the RC frame members at the top storey level exhibit lower θ_d. This can also be understood from the mode shape profile (Figs. 4(b) and 4(c)) where it can be seen that the normalized interstorey displacements at the top level is much less. The presence of shear wall rigidity modifies the mode shape of the RC frame which causes greater magnitudes of normalized interstorey displacements at the top storey levels thereby causing an increase in θ_d for beams and columns. The increase is greater for frames without SSI effects and can be related with its mode shape profile which shows lesser normalized interstorey displacements as compared to that of the frame without SSI effects. The increase in the rotational demands in the frame members of relatively flexible frame is greater than that of the stiffer frame. This is because flexible frames tend to possess lesser normalized interstorey displacements at the top storey which on incorporation of the shear wall is increased by a greater magnitude as compared to that of a stiffer frame. Moreover, for frames without SSI, the increase in θ_d for columns is greater for stiffer frame (6 storey) while the increase in θ_d for beams is much greater for the flexible frame (12 storey). Owing to the inherent deformation compliance of the frame, the demands in the beams are increased to a greater degree in flexible systems. On incorporating SSI in these frames, the magnitude of increase in θ_d, for the beams and columns, is relatively reduced. At intermediate storey levels, θ_d in columns and beams generally reduces towards the lower storey levels and may increase towards the top storey level and it depends on the continuity of the θ_d variation profile (which is again in coherence with the mode shape profile) of the respective member for both with and without SSI effects.

5. Summary and Conclusions

The present study investigates the influence of shear wall on the seismic response of RC frame buildings on pile foundation. The seismic response of the frame with and without shear wall is investigated for two different heights with and without the influence of soil structure interaction (SSI). The influence of shear wall on the linear elastic behavior is studied in terms of natural vibrational characteristics and that on the inelastic behavior is studied in terms of global and local seismic demands. The main conclusions of the study are as follows:

- Shear wall influences the natural vibration characteristics by reducing the natural period and modifying the mode shape profile of the RC frame. The modification is relatively higher for a stiffer frame as compared to a flexible one. Moreover, the modification is relatively lesser for frames with SSI effects.
- The modification in the natural vibrational characteristics alters the inelastic behavior of the frame. Shear wall increases the effective lateral stiffness which causes an increase in the yield and ultimate base shear in the RC frame and the increase is observed to be higher for stiffer frame.
- The increase in the yield base shear is relatively lesser with SSI effects, however, the increase in ultimate base shear is relatively greater. This is because frames without SSI effects attract greater forces and undergo higher damage as compared to the frame with SSI effects causing a greater increase in yield base shear but lesser increase in ultimate base shear. Moreover, the foundation of the frame with SSI effects

also participates in the inelastic behavior which causes less damage in the frame thereby increasing its ability to exhibit greater load resisting ability at ultimate drifts.

- The presence of shear wall tends to increase the ductility capacity of RC frames and it is greater for the relatively flexible frame as compared to the relatively stiffer one. In the frame without SSI effects, inelasticity develops at relatively lesser drifts thereby allowing greater mobilization of the ductility contribution due to shear wall and exhibiting larger ductile behavior before collapse. For frames with SSI, due to the inelasticity developing at relatively higher drifts, the possibility of mobilization of ductile behavior in shear wall is reduced, thereby exhibiting relatively lesser increase in the ductility capacity.
- Shear wall modifies the mode shape of the RC frame causing a variation of the local demands (plastic hinge rotation) in the frame members at various storey levels which are prominently visible at the bottom and top storey levels.
- At bottom storey level: Shear wall reduces the rotation demand in columns and beams and the reduction is greater for frames without SSI effects. Moreover, in the presence of SSI effects, shear wall causes greater reduction of rotational demands in columns of stiffer frames, whereas, the reduction in beams is greater for flexible frames.
- At top storey level: Shear wall rigidity modifies the mode shape to develop greater magnitudes of normalized interstorey displacements leading to an increase in the rotational demands of the beams and columns. The increase in the rotational demands is greater for the members of relatively flexible frame than that of the stiffer frame. Moreover, in the absence of SSI effects shear wall causes greater increase in the rotational demands in the columns of stiffer frames, whereas for beams it is greater for flexible frames. SSI effects reduces the extent of variation in the rotational demands in the beams and columns.
- At intermediate storey level: The variation of the rotational demands in columns and beams, due to shear wall, generally reduce towards the bottom storey level and may increase towards the top storey level; and the variation can be related to the normalized interstorey displacements of the respective mode shape profiles.
- Shear wall can significantly modify the behavior of RC frames and the suitability of incorporating shear wall needs to be assessed judiciously by accounting several factors influencing the decision making such as the properties of the frame, presence of SSI effects and influence on the seismic response parameters.

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7. References

[1] Miranda E, Bertero VV (1989) The Mexico earthquake of September 19, 1985—performance of low-rise buildings in Mexico City. *Earthquake Spectra*, **5** (1), 121-43.

[2] Mylonakis G, and Gazetas G (2000) Seismic soil-structure interaction: Beneficial or detrimental? *Journal of Earthquake Engineering*, **4** (3), 277-301.

[3] Sharma N, Dasgupta K and Dey A (2019) Optimum lateral extent of soil domain for dynamic SSI analysis of RC framed buildings on pile foundations. *Frontiers of Structural and Civil Engineering.* https://doi.org/10.1007/s11709-019-0570-2

[4] Sharma N, Dasgupta K and Dey A (2018) Natural period of RC buildings considering seismic soil structure interaction effects. In: *16th Symposium on Earthquake Engineering*, Paper No. 275, IIT Roorkee, India, 20–22 December 2018.

[5] Sharma N, Dasgupta K and Dey A (2018) Seismic SSI effects on fundamental period of reinforced concrete frame with shear wall. In: *Proceedings of the 11th Structural Engineering Convention*, Jadavpur University, Kolkata, India, 19–21 December 2018.

[6] Mazzoni S, McKenna F, Scott MH, Fenves GL (2006) OpenSEES command language manual. *Command Manual*, Pacific Earthquake Engineering Research (PEER) Center, USA.

[7] Sharma N, Dasgupta K and Dey A (2018) A state-of-the-art review on seismic SSI studies on building structures. *Innovative Infrastructure Solution*, **3** **(**22). https://doi.org/10.1007

[8] Yang Z, Lu J, and Elgamal A (2008) OpenSEES Soil Models and Solid-Fluid Fully Coupled Elements. *User's Manua*l. Ver, vol. 1, Pacific Earthquake Engineering Research (PEER) Center, USA.

[9] Lysmer J, Kuhlemeyer RL (1969) Finite dynamic model for infinite media. *Journal of Engineering Mechanics Division*. **95** (EM4), 859-877.

[10] IS 456 (2000) Indian standard, Plain and reinforced concrete-code of practice. Bureau of Indian Standards, New Delhi, India.

[11] IS 13920 (2016) *Indian standard, Ductile detailing of reinforced concrete structures subjected to seismic forces-code of practice*. Bureau of Indian Standards, New Delhi, India.

[12] IS 2911: Part I/Sec 1 (1979) *Indian standard, Code of practice for design and construction of pile foundations*. Bureau of Indian Standards, New Delhi, India.

[13] IS 875: Part 2 (1987) *Indian standard, Code of practice for design loads (other than earthquake) for building and structures: Imposed loads*. Bureau of Indian Standards, New Delhi, India.

[14] IS 1893: Part I (2016) *Indian standard, Criteria for earthquake resistant design of structures*. Bureau of Indian Standards, New Delhi, India.

[15] Paulay T, Priestley MJN (1992) *Seismic design of reinforced concrete and masonry buildings*. John Wiley and Sons Inc., USA.

[16] Kazaz İ (2013). Analytical study on plastic hinge length of structural walls. *Journal of Structural Engineering*, **139** (11), 1938-1950.

[17] Joyner WB (1975) Method for calculating nonlinear seismic response in 2-dimensions. *Bulletin of the Seismological Society of America* **65** (5), 1337-1357.

[18] Zhang Y, Yang Z, Bielak J, Conte JP, Elgamal A (2003) Treatment of seismic input and boundary conditions in nonlinear seismic analysis of a bridge ground system. In: *16th ASCE Engineering Mechanics Conference*, University of Washington, Seattle, USA, 16-18 July 2003.

[19] FEMA 356 (2000) *Prestandard and commentary for the seismic rehabilitation of buildings*. Federal Emergency Management Agency, Washington, DC.