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Effect of Soil-Structure Interaction on A Building Frame with Shear Walls

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Abstract

The soil conditions highly influence the damage to structures throughout earthquakes. Hence the research on the energy transfer mechanism from soils to buildings during earthquakes is demanding area of study for the high-rise buildings. For the current study, reinforced concrete frames of G+15 stories with shear walls in the buildings were modeled using ANSYS software. The effect of soil-structure interactions was considered as well. Transient analysis was performed on the three-dimensional frames with shear walls subjected to seismic loading were gauged for the contrast in natural frequency, base shear, roof deflection and Storey drifts. The analysis of results indicates that the behaviour of the structure is very much dependent on the natural frequency of the structure.

Keywords: *Soil-Structure Interaction; Shear Walls; Base Shear; Finite Element Modelling; Time History Analysis; Natural Frequency.*

1. Introduction

Over the past 40 years, considerable progress has been made in understanding the nature of earthquakes and how they could cause structure damages, and in improving the seismic performance of the built environment. However, much remains unknown regarding the prevention or mitigation of earthquake damage in worldwide, leaving room for further studies [6]. During the past and recent earthquakes, it is realized that the soil–structure interaction (SSI) effects play an important role in determining the behaviour of building structures [5]. Given the fact that soil can have a significant impact on the seismic response of structures, it is important to consider the effect of soil-structure interactions [2]. The seismic excitation experienced can be considered a function of the fault rupture mechanism, travel path effects, local site effects, and SSI effects. Irrespective of the structure, the local soil conditions can dramatically influence the earthquake motion from the bedrock level to the ground surface, through their dynamic filtering effects [1]. The seismic SSI of multi-story buildings becomes very important after the destruction of recent major earthquakes. For the structure founded on the soil, the motion of the base of the structure will be different from the case of fixed base, because of the coupling of the Structure–Soil system. It is true that taking the soil into account when calculating the seismic response of the structure does complicate the analysis considerably [2]. SSI is an interdisciplinary field of strive. It combines structural mechanics, soil dynamics, structural dynamics, earthquake engineering, geophysics and geomechanics, material science, computational and numerical methods and other various technical disciplines. Its lineage draws back to the late nineteenth century, evolving and maturing in a gradual manner in the ensuing decades and during the first half of the twentieth century. SSI advanced rapidly during the second half, accelerated mainly by the needs of the nuclear power and offshore industries, by the introduction of powerful computers and simulation tools such as finite elements and by the desire for improvements in seismic safety [7].

1.1. Effect of Soil-Structure Interaction

During the seismic activity, the seismic waves are transmitted through the soil from the fault rupture to the structure of interest. The response of structural system depending on the material properties of the soil medium, the source of excitation and the type of foundation can deviate significantly due to SSI from the structure on rigid supporting system. In a specific frequency range of ground motion, the ductility demand increases with increasing the structure's natural period, causing detrimental effects of SSI [1].

The effect of interaction is generally considered favorable in the seismic design because the supporting soil medium provides means for energy absorption (damping), consequently reducing the response. It has become a common practice to avoid the complication of accounting for SSI by 2 simply ignoring its effects. This avoidance is thought to lead to improved safety margins while simplifying the analysis [3]. Structure–foundation–soil system modelled using direct method consists of super structure, foundation, unbounded soil, interface between foundation and soil and earthquake induced acceleration at the level of the bed rock, is as shown in figure 1[7].

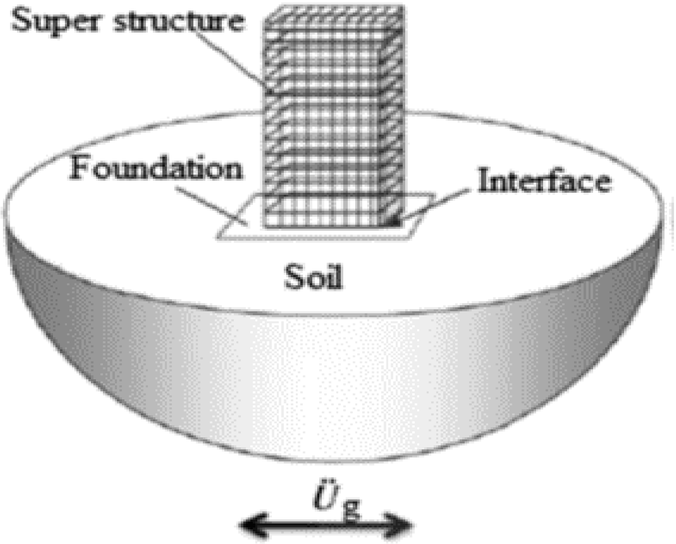

Figure 1 Soil-Structure System

2. Methodology

The buildings considered for the study of irregularities were three-dimensional (3D) idealized frames of 16 storey buildings (aspect ratio 3.75). The storey height and bay length of all the building frames were chosen as 3 m and 3 m respectively. The floor slab and the raft slab thicknesses were taken as 0.15 m and 0.5 m respectively. The beam dimensions of 0.3 × 0.4 m and column dimensions of 0.4 m × 0.4 m. The dimensions of building components were selected and the structural design was carried out as per Indian standard codes IS 456:2000 [8] and IS 13920:2016 [9]. Concrete of M30 grade and steel of Fe 500 grade were considered as the material for the structural elements. Reinforced concrete buildings with shear wall location (middle bay of exterior frame) while maintaining the mass added due to these shear walls to be the same, were considered. The thickness of shear wall was 0.15 m. The materials considered for the design of structural elements were concrete of grade M30 and Fe500 grade steel (Table 1). Concrete is assumed to be homogenous, isotropic and elastic material. The elastic properties of materials are taken as per IS 456 :2000. The modulus of elasticity of concrete as per clause 6.3.2.1 of IS 456: 2000 is [8]:

$$E = 5000\sqrt{f_{ck}}$$

Table 1 Building Description

PARTICULAR	RCC STRUCTURE
Plan and Dimension	12 m x 12 m
Height of Each Floor	3 m
Number of Stories	G+15
Type of Building	RCC Building
Grade of Concrete	M30
Grade of Reinforcing Steel	Fe 500
Column Dimension	400 x 400 mm
Beam Dimension	300 x 400 mm
Slab Thickness	150 mm
Raft Thickness	500 mm
Type of Soil	Soft Soil

2.1.Idealization of Soil

For the SSI building model, the soil medium at the lateral boundary at a distance of four-times the width of the raft at each side (i.e., 48 m) is considered [4]. The thickness of the soil medium is considered as 20 m. Viscous boundaries are provided to the lateral soil boundaries by using the spring-damper element in order to prevent the reflection of input earthquake wave. The bottom soil is restrained in all the six degrees of freedom.

Modulus of elasticity: 2000 k N/m^2
Poisson's ratio: 0.3
Shear modulus: 7692 kN/m^2
Density of soil:1800 Kg/m^3

$$G = \frac{E}{2 * (1 + \nu)}$$

$$K = \frac{E}{3 * (1 - 2\nu)}$$

$$V_p = \sqrt{\frac{K + \frac{4G}{3}}{\rho}}$$

$$V_S = \sqrt{\frac{G}{\rho}}$$

- G =Shear modulus
- E =Modulus of Elasticity
- K =Bulk modulus
- ν =Poisson's ratio
- ρ =Density of soil

- $C_n = A_n * \rho * \nu_p$
- $C_{t1} = A_{t1} * \rho * \nu_s$
- $C_{t2} = A_{t2} * \rho * \nu_s$

- ν_p = Dilatational velocity
- ν_s = Shear wave velocity
- A_n, A_t = Area controlling viscous dampers

The subscripts n and t are the normal and tangential directions in the boundary.

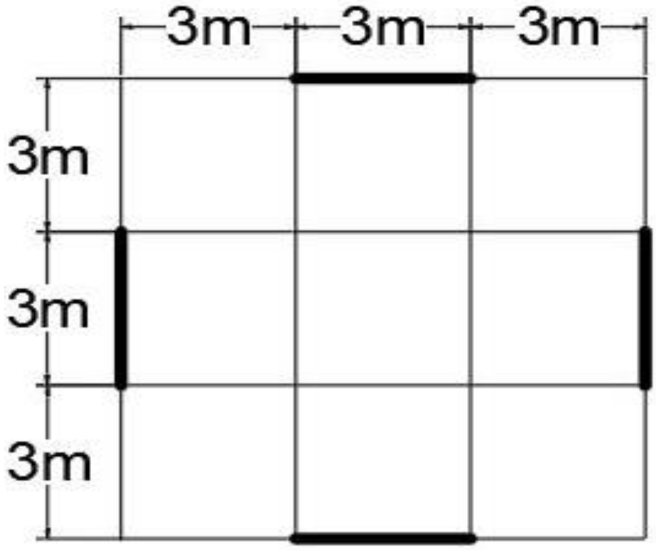

Figure 2 Position of Shear Walls in the Building Frame

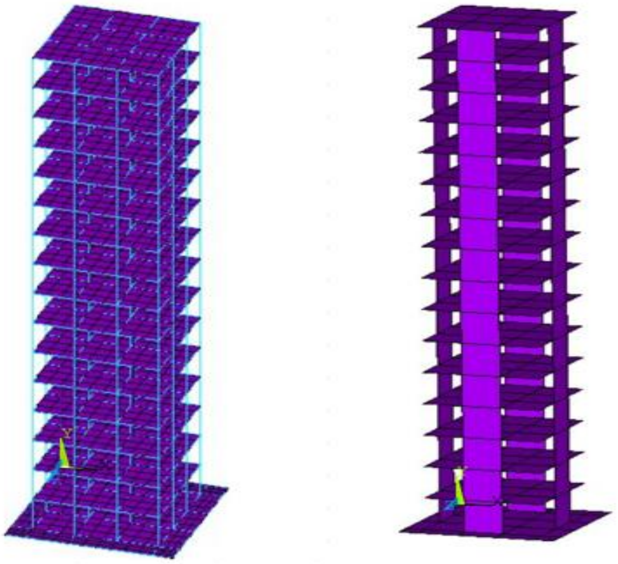

Figure 3 3D View of G+15 Building Without and with Shear Walls Respectively

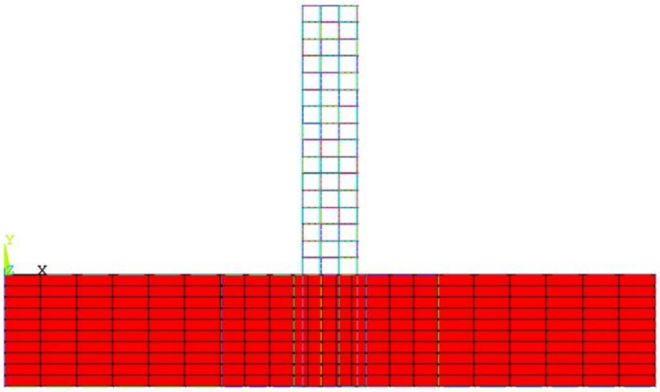

Figure 4 Elevation of G+15 Building without Shear Walls

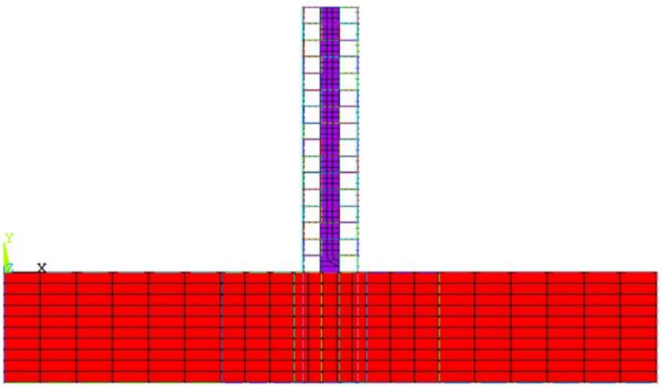

Figure 5 Elevation of G+15 Building with Shear Walls

Figure 2 represent the building frame with shear walls at the outer frame on the centre bays. Figure 3 shows the bare building frame and building frame with shear walls in the periphery frame on the centre bays. Figure 4 represents the elevation of the bare frame with the soil medium and Figure 5 depicts the frame with shear walls resting on the soil medium.

3. Results and Discussion

3.1.Results

3.1.1. Roof Displacement

Roof displacement refers to the lateral movement of the roof of a building during seismic events. It is the total horizontal displacement experienced by the roof level relative to its position at rest.

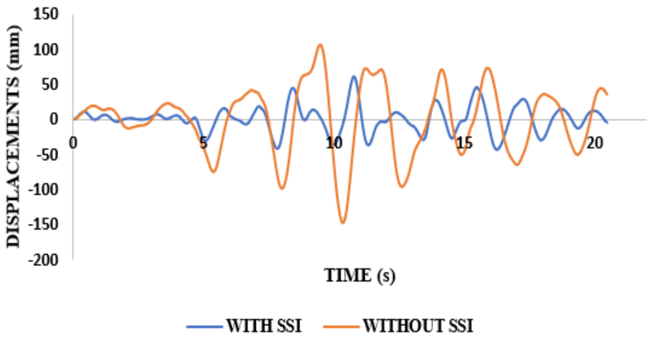

Figure 6 **Roof Displacement Plots without Shear Walls**

In figure 6, the graph shows that the frame without SSI has higher displacement of 143.32 mm, while frame with SSI exhibit moderate displacement.

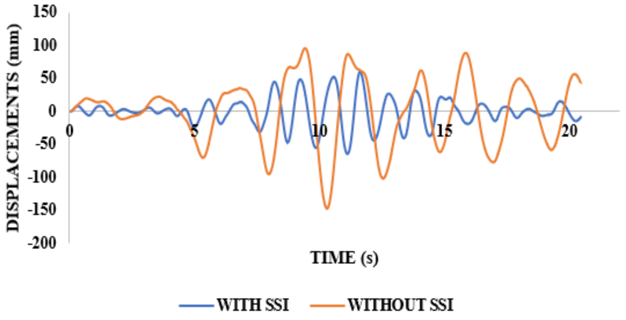

Figure 7 **Roof Displacement Plots with Shear Walls**

In figure 7, the graph shows that the frame without SSI has higher displacement of 147.42 mm, while frame with SSI exhibit moderate displacement.

3.1.2. Inter Story Drift

Inter story drift is defined as the relative lateral displacement between the floors of a building due to seismic forces. It is typically expressed as the difference in horizontal displacement between two successive floors of a multi-story building, often measured at the center of mass of each floor.

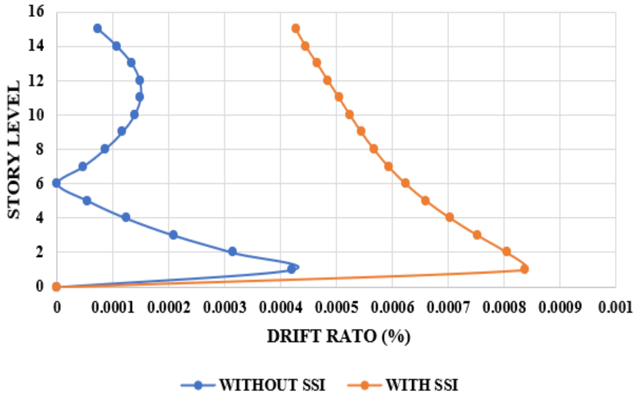

Figure 8 **Inter Story Drift Ratio without Shear Walls**

In figure 8, the graph shows that the frame with SSI has highest drift ratio of 0.00084% measured at the instance of occurrence of PGA, while frame without SSI exhibit slightly lower drift ratio. All the inter drift ratios are within the limit of IS 1893 (2016) of 0.004 times the height of the story [7]

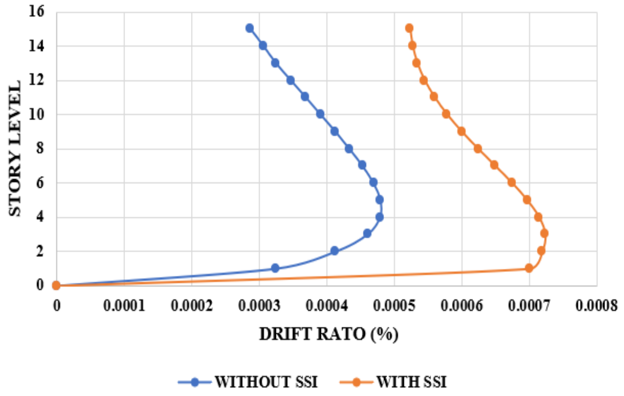

Figure 9 **Inter Story Drift Ratio with Shear Walls**

In figure 9, the graph shows that the frame with SSI has highest drift ratio of 0.00072% measured at the instance of occurrence of PGA, while frame without SSI exhibit slightly lower drift ratio.

3.1.3. Acceleration Time-History

Peak ground acceleration (PGA) is defined as the maximum ground acceleration experienced during an earthquake, measured at the ground surface. It is an important parameter used in seismic design and is expressed in terms of gravity (g), typically in units of m/s² or as a fraction of gravitational acceleration

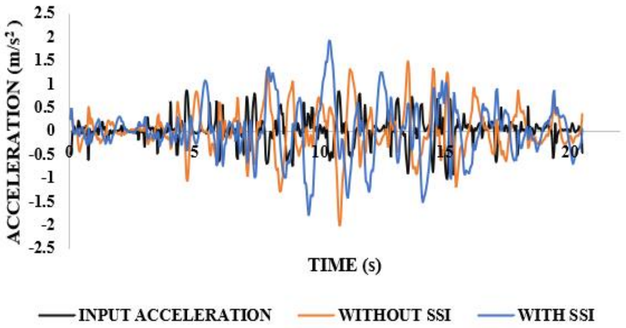

Figure 10 **Acceleration Time-History Plot Without Shear Walls**

In figure 10, the graph shows that the frame with SSI has highest PGA of 1.91 m/s^2, while Bhuj input acceleration and frame without SSI exhibit moderate PGA.

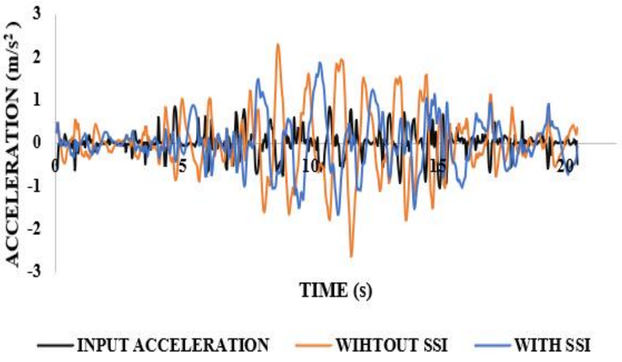

Figure 11 **Acceleration Time-History Plot with Shear Walls**

In figure 11, the graph shows that the frame without SSI has highest PGA of 2.62 m/s^2, while Bhuj input acceleration and frame with SSI exhibit moderate PGA.

3.1.4. Base Shear

Base shear is the maximum anticipated lateral force likely to occur at the base of a structure due to seismic ground motion.

Table 2 **Base Shear (kN) for all Combinations**

BASE SHEAR (kN)		
	Without SSI	With SSI
Without Shear Walls	28.073	3.5631
With Shear Walls	10.584	3.3879

In Table 2, the frame with Shear Walls Excluding SSI has the highest Base shear of 28.073 kN, while the frame with Shear Walls Including SSI has the lowest Base shear of 3.3879 kN.

3.1.5. Natural Frequency

Natural frequency of a structure refers to the frequency at which it tends to oscillate in the absence of any external forces.

Table 3 **Natural Frequency (Hz) For All Combinations**

NATURAL FREQUENCY (Hz)		
	Without SSI	With SSI
Without Shear Walls	0.61297	0.42156
With Shear Walls	0.83045	0.40918

In Table 3, the frame with Shear Walls Excluding SSI has the highest Natural frequency of 0.83045 Hz, while the frame with Shear Walls Including SSI has the lowest Natural frequency of 0.40918 Hz.

3.2.Discussion

From figure 6 and 7, the frame with Shear walls including SSI has the highest roof displacement of 147.42 mm and the frame with Shear walls excluding SSI has a roof displacement of 143.32 mm as SSI tends to increase roof displacement**,** particularly in soft soil conditions where foundation movement is more significant. From figure 8 and 9, the frame without Shear walls excluding SSI has highest drift ratio of 0.00084% and the frame with Shear walls including SSI has highest drift ratio of 0.00072% measured at the instance of occurrence of PGA because SSI increases story drift at lower levels due to foundation flexibility and soil deformation, while it can reduce drift at the upper levels due to the lengthened natural period of the structure. The overall effect depends on the soil type, the stiffness of the building, and its foundation design. Shear walls reduce story drift by increasing the building's lateral stiffness and minimizing horizontal displacements. They help control both translational (linear) and torsional (rotational) drift, ensuring a more uniform response to lateral loads. From figure 10 and 11, the frame without Shear walls excluding SSI has highest PGA of 1.91 m/s^2 and the frame with Shear walls including SSI has highest PGA of 2.62 m/s^2 as Soil beneath the foundation deforms and moves, causing the foundation to sway, rotate, or settle. This flexibility reduces the accelerations transferred to the structure because part of the energy is absorbed by the soil. Because the soil is extremely soft or liquefiable, SSI has amplified the motion or cause excessive foundation displacement, which can lead to higher accelerations. From table 2, the frame with Shear Walls Excluding SSI has the highest Base shear of 28.073 kN, while the frame with Shear Walls Including SSI has the lowest Base shear of 3.3879 kN being SSI generally reduces base shear by lengthening the building’s natural period and introducing additional damping, which decreases the seismic forces transmitted to the structure. Foundation movement and soil deformation change the distribution of lateral forces, altering the base shear and its effects on the structure. From table 3, the frame with Shear Walls Excluding SSI has the highest Natural frequency of 0.83045 Hz, while the frame with Shear Walls Including SSI has the lowest Natural frequency of 0.40918 Hz for the reason that the natural frequency decreases because the overall system (structure + foundation + soil) becomes more flexible. The foundation’s movement and soil deformation reduce the effective stiffness, lengthening the natural period and lowering the natural frequency. SSI lowers the natural frequency of a structure, which can help avoid resonance with earthquake ground motions and reduce the seismic forces acting on the building. However, in certain conditions, especially on soft soils, this interaction can introduce other challenges, such as ground motion amplification, which must be carefully considered in seismic design.

Conclusions

In conclusion, the analysis reveals the significant influence of Soil-Structure Interaction (SSI) on the seismic performance of frames with and without shear walls. The roof displacement increases with SSI, particularly in soft soil conditions, as evidenced by the higher displacement in frames with shear walls including SSI. SSI also increases story drift at lower levels due to foundation flexibility but reduces drift at upper levels because of the lengthened natural period. Shear walls prove effective in mitigating drift by increasing the building's lateral stiffness. Regarding peak ground acceleration (PGA), SSI can amplify accelerations in soft soils, as seen in the higher PGA for frames with shear walls including SSI. Moreover, SSI reduces base shear by lengthening the building's natural period and introducing additional damping, as reflected in the lower base shear in frames including SSI. Lastly, SSI significantly reduces the natural frequency, making the structure more flexible, which can help avoid resonance but may introduce other challenges in soft soils. These findings underscore the importance of considering SSI in seismic design, especially for buildings on soft soils, to ensure structural safety and performance.

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