Seismic soil structure interaction of reinforced concrete frame building supported on foundations

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Abstract. Soil Structure Interaction (SSI) determines the response of structures during seismic activity. An engineering review committee deals only with the study of soil structure interaction as compared to free motion, gives an appreciable impact on the basement motion. This article investigates the influence of soil structure interaction on RC frame building with seismic excitations. By taking different cases like 5, 10, 15, 20 storey of varying soil types are type I, type II and type III, different foundation types are isolated, combined, mat, pile. The entire foundation-soil-structure system is modelled and analyzed in a finite element based SAP2000 Software, to study the stress on soil and framed structure in the presence of SSI. Finally, a comparative study between with and without SSI to reinforced concrete framed structure is done. The study shows that SSI effects are higher than regular approach if we include the SSI effects in our analysis and design of structure to get a safety design.

Keywords: Dynamic analysis, fixed base, soil structure interaction, SAP 2000

1. Introduction

Soil Structure Interaction (SSI) determines the response of structures during seismic activity, which is the mechanism in which the response of soil particles to earthquake ground movement affects the movement of the structure and the structure response affects the movement of soil mass [1]. The collective response of the structure, the base, is evaluated by a seismic soil-structure interaction analysis. Interactions between three related structures influence the response of a building to earthquake shaking: the structure, the base of structure (foundation), and the soil underneath and surroundings of the foundation [2, 3]. For the theoretical state of a rigid base sustained on rigid soil, soil structure interaction impacts are absence. The discrepancy between the structure's real reaction and the response of the imaginary, static base case is then accounted for by SSI [4].

The foundation forms the supportive basis of the whole structure, which transmits the superstructure's load to the ground. It is therefore necessary to build the foundation in such a way that, apart from being economical, it is both secure and efficient [5]. The results of SSI are influenced not only by the structural configuration, but also with the properties of the foundation and soil [6]. The foundation has been built in recent years to bear additional loads from superstructures such as high-rise towers, bridges, power stations or other civil structures and to avoid excessive settlement. Both structural and geotechnical
engineers consider the economic design and reliability of the structure [7]. Because of the lack of properly laid requirements in building codes around the world, SSI consideration in routine design practice is currently uncommon. Now various research is going on seismic soil interaction to get the conservative design interaction of structures [8]. In comparison to the conventional assumption in which interaction is ignored, SSI has a major impact on the building’s base forces and roof displacement [9].

![1(a)](image1.png) ![1(b)](image2.png)

**Figure 1.** Illustrative representation of the model of structure (a) with soil structure interaction (b) structure having fixed base at the foundation in sap 2000.

The IS:1893 (Part1) Indian seismic modeling code suggests avoiding soil-structure Interaction studies for seismic analysis and design of rock-or rock-like material structures [10]. Unfortunately, a lack of SSI results occurring [11].

2. **Modelling and Parametric Studies**

The current study includes structure 3D modeling, performing a parametric study in SAP2000 V22, using finite element analysis [12]. Variations between various parameters of different base types and different soil type models are explored by plotting graphs in this report.

2.1. **Structural system:**

In present study the structural system considered as five stories, ten stories, fifteen stories, twenty stories RC frame with uniform storey height is taken as 3.5m and bay length is 3m. Four different storey heights and bay lengths are respectively 5 stories with 3 bay (17.5 m & 9 m), 10 stories with 5 bay (35 m & 15 m), 15 stories with 7 bay (52.5 m & 21 m) and 20 stories with 9 bays (70 m & 27 m) shown in figure 2.

For analysis of superstructure, which is used for residential purpose in this considering assumed dead load, live load and lateral loads (wind load & earthquake load) are considered as per IS codes. Seismic zone IV is assumed for the soil site using figure 1. seismic zones of India map in IS 1893 (part 1):2016. Structure analysis purpose relevant data referred in Indian standards (Note: seismic zone factor Z = 0.24, importance factor I = 1, Response reduction factor R = 5).
2.2. Structural member dimensions and materials:
Dimensions of structural members are considered as per IS 456:2000 [13] and IS 13829 for ductile detailing of members as whole. Concrete M25, steel Fe 415 and mild steel 250 grades considered.

| Structure storey level | Beam Width (m) | Beam Depth (m) | Column Width (m) | Column Depth (m) | Slab Thickness (m) |
|------------------------|----------------|----------------|------------------|------------------|-------------------|
| 5                      | 0.23           | 0.3            | 0.3              | 0.3              | 0.13              |
| 10                     | 0.23           | 0.4            | 0.3              | 0.4              | 0.13              |
| 15                     | 0.5            | 0.5            | 0.5              | 0.5              | 0.15              |
| 20                     | 0.6            | 0.6            | 0.6              | 0.6              | 0.18              |

2.3. Soil domain:
In present study three types of soil classifications are considered IS code: 1893 for site condition i.e., type I – rock or hard soils, type II – medium or stiff soils, type III – soft soils. Some soil depth is considered a soil structure interaction for simulation of constitute behavior of the material. For analysis table 2 values are taken.

| Type of soil   | Weight of unit volume (KN/m³) | Poisson’s ratio | Angle of friction (°) | Shear modulus (MPa) |
|----------------|-------------------------------|-----------------|-----------------------|---------------------|
| Hard soils     | 2000                          | 0.35            | 40                    | 130                 |
| Medium soils   | 1800                          | 0.35            | 35                    | 90                  |
| Soft soils     | 1600                          | 0.33            | 29                    | 55                  |
2.4. Soil foundation system:
Soil is modeled using sap software, in that boundaries in x-direction restrained in one direction(x) and similarly for boundaries in y direction restrained another direction(y) at the centers. All four corners are restrained in both x& y directions and bottom of soil is restrained in all directions(x, y and z). In this study four type of foundations are considered i.e. isolated, combined, mat, pile. These dimensions of the foundations are given in the below table 3. For 5, 10, 15, 20 stories these four type of foundations are provided to structure for analysis.

Table 3. Details of foundations used

| Storey level | Isolated Length*width (m*m) | Combined Length*width (m*m) | Mat Thickness (m) | Pile Length*diameter (m*m) |
|--------------|-----------------------------|-----------------------------|------------------|---------------------------|
| 5            | 2*2                         | 2*5                         | 1                | 6*0.5                     |
| 10           | 2*2                         | 2*5                         | 1                | 6*0.5                     |
| 15           | 3*3                         | 3*7                         | 1                | 10*0.5                    |
| 20           | 3*3                         | 3*7                         | 1                | 10*0.5                    |

3. Method of Analysis
To the soil structure system dynamic analysis is carried out, in this time history method is considered. Methods for time history shall be based on acceptable ground motion (preferably associated with the continuum of design acceleration in the desired context of natural periods) and shall be conducted in accordance with accepted concepts of structural dynamics of earthquakes. In present study EL-Centro seismic inputs are considered for seismic soil structure interaction analysis.

![Figure 3](https://images.app.goo.gl/tS5ZtVKswSj37Hd78)

Figure 3. Seismic motion input characteristics of EL-Centro time history
(Source: https://images.app.goo.gl/tS5ZtVKswSj37Hd78)

4. Results and Discussion
The reinforced concrete frame building with 5, 10, 15, 20 stories was modeled and analyzed with time history analysis using SAP 2000 v22 software. The analysis is conducted for structure with fixed base and also flexible base resting on soil boundary with three soil types i.e. soil type-I, soil type-II and soil type-III. Analytical work was carried out to know the structure stress when it is fixed base condition as
well as flexible base condition. The results obtained from analysis are as follows:

4.1. Seismic soil structure interaction:
After performing dynamic analysis to the structure considered soil structure interaction effects i.e. stress induced from superstructure to substructure. The solid stresses (soil stresses which is present below structure), moments observed in frame with different of foundations and soils were shown in the below graphs.

In figure 4(a) & 4(b) for 5 storey the solid stress in isolated and combined foundations are approximately same. Mat foundation having more stress in soil as compared to other three foundations and pile foundation having less stress in soil. In soil type I to soil type III the stress are increasing irrespective of foundation type. In figure 4(c) & 4(d) the moment forces in RC frame of isolated and combined foundations having approximately same. Pile foundation having less compared to mat, and mat also less compared to isolated foundation.

![Graph](image1.png) ![Graph](image2.png) ![Graph](image3.png) ![Graph](image4.png)

**Figure 4.** Dynamic analysis of 5 stories building with isolated(1), combined(2), mat (3), pile (4) type of foundation (a) minimum & (b) maximum solid stress, (c) minimum & (d) maximum frame moments forces with soil structure interaction.

In figure 5(a) & 5(b) the solid stress in combined and mat foundation having similar stress, having more stress compared to isolated and pile foundation. In figure 5(c) & 5(d) the moment forces in RC frame of isolated foundation having more compared to other foundations. From 5 to 10 storey structure solid stress and moment forces are either less or more than twice in different type’s foundation and soils.
Figure 5. Dynamic analysis of 10 stories building with isolated (1), combined (2), mat (3), pile (4) type of foundation (a) minimum & (b) maximum solid stress, (c) minimum & (d) maximum frame moments with soil structure interaction

In figure 6(a) & 6(b) 15 stories structure solid stress of isolated foundation having more in minimum stress. Isolated and mat foundation having more in maximum stress than other two type of foundations. In figure 6(c) & 6(d) moment forces in frames structure having isolated and combined foundation having more forces compared to mat and pile foundation.
Figure 6. Dynamic analysis of 15 stories building with isolated (1), combined (2), mat (3), pile (4) type of foundation (a) minimum & (b) maximum solid stress, (c) minimum & (d) maximum frame moments forces with soil structure interaction.

Figure 7. Dynamic analysis of 20 stories building with isolated (1), combined (2), mat (3), pile (4) type of foundation (a) minimum & (b) maximum solid stress, (c) minimum & (d) maximum frame moments forces with soil structure interaction.
In figure 7(a) & 7(b) 20 storey structure having mat foundation more stress than others foundation types, pile having less stress compared to those foundation. When it comes to frame moment forces in figure 7(c) & 7(d) from isolated to pile foundation it is decreasing. From all the above analysis we observed that for different stories structure having foundation type’s behavior is different in each storey. In soil type I to soil type III increasing in solid stress, frame moments are observed in all stories and foundation types. In these analysis pile foundation is getting less solid stress and moment forces in the structure. From the analysis of SSI we will know how the soil behave under the structure, for that we will design the foundation and frame. These results are help full to know which is suitable for our structure to get economic and safety.

4.2. Fixed base without soil structure interaction:
After performing dynamic analysis to the structure considered fixed base condition, maximum moments observed in frame with different of foundations and soils were shown in below graphs. From these analysis there is different between SSI and fixed base moments for structures.

![Graph 8(a)](image1)
![Graph 8(b)](image2)

**Figure 8.** Dynamic analysis of 5 stories building with isolated (1), combined (2), mat (3), pile(4) type of foundation (a) minimum & (b) maximum frame moment forces with fixed base.

![Graph 9(a)](image3)
![Graph 9(b)](image4)

**Figure 9.** Dynamic analysis of 10 stories building with isolated (1), combined (2), mat (3), pile(4) type of foundation (a) minimum & (b) maximum frame moment forces with fixed base.
Figure 10. Dynamic analysis of 15 stories building with isolated (1), combined (2), mat (3), pile(4) type of foundation (a) minimum & (b) maximum frame moment forces with fixed base.

Figure 11. Dynamic analysis of 20 stories building with isolated (1), combined (2), mat (3), pile(4) type of foundation (a) minimum & (b) maximum frame moment forces with fixed base.

5. Conclusions
RC building frame resting on soil which has lower unit weight of volume having highest SSI effects and highest unit weight of volume having lower SSI effects which occurs in the soil domain and also in the framed structure. Moments occurred in the framed structure can vary depending upon the soil foundation system taken for analysis. SSI effects the structure more compared to fixed base at the foundation. From the analysis results for 5, 10, 15, 20 storey it will be minimum range between 2-4 times more SSI than fixed condition. When varying the foundation type to a particular structure the stress are differs from one type to another type of foundation in soil domain and frame of structure having SSI and fixed conditions. For example, take 5 storey structure isolated and combined footings are getting approximately same compared to other two foundation. In 10 storey structure combined and mat footings are getting approximately same compared to other two foundation. Nonlinear modal history (FNA) stresses are also having the effects from SSI are more compared to fixed condition. FNA only depend upon the type of foundation not in soil properties. Higher storey frames having less soil structure interaction effects when compared to short storey frames.
References

[1] Roopa M, Naikar H G and Prakash D D 2015 Soil Structure Interaction Analysis on a RC Building with Raft foundation under Clayey Soil Condition International Journal of Engineering Research & Technology 4(12) 319-323

[2] NEHRP Consultants Joint Venture 2012 Soil structure interaction for building structures National institute of standards and technology U.S. Department of Commerce

[3] Mekki M, Elachachi S M, Breysse D and Zoutat M 2016 Seismic behavior of RC structures including soil-structure interaction and soil variability effects Engineering Structures 126 15-26

[4] Sharma N, Dasgupta K and Dey A 2020 October Natural period of reinforced concrete building frames on pile foundation considering seismic soil-structure interaction effects Structures 27 1594-1612

[5] Hokmabadi A S and Fatahi B 2016 Influence of foundation type on seismic performance of buildings considering soil-structure interaction. International Journal of structural stability and dynamics 16(8) 1550043

[6] Sharma N, Dasgupta K and Dey A 2018 Natural period of rc buildings considering seismic soil structure interaction effects 16th Symposium on Earthquake Engineering December 20-22

[7] Liu S, Li P, Zhang W and Lu Z 2020 Experimental study and numerical simulation on dynamic soil-structure interaction under earthquake excitations Soil Dynamics and Earthquake Engineering 138 106333

[8] Anand V and Kumar S S 2018 Seismic soil-structure interaction: a state-of-the-art review Structures 16 317-326

[9] Raheem S E A, Ahmed M M and Alazrak T M 2015 Evaluation of soil–foundation–structure interaction effects on seismic response demands of multi-story MRF buildings on raft foundations International Journal of Advanced Structural Engineering 7(1) 11-30

[10] Paul D K et al. 2016 IS 1893 (Part 1): Indian Standard Criteria for Earthquake Resistant Design of Structures General Provisions and Buildings Bureau of Indian Standards

[11] Sharma N, Das gupta K and Dey A 2019 Importance of Inclusion of Soil–Structure Interaction Studies in Design Codes Recent Advances in Structural Engineering 2 233-244

[12] Rajeshwari P, Shweta A, Shweta D, Sudha, Gajendra and Mithun K 2017 Analysis and design of residential building by using SAP-2000 International Journal of Engineering Research & Technology 4(5) 2491-2497

[13] Visvesvarya H C et al. 2000 IS 456: Plain and reinforced concrete-code of practice Bureau of Indian Standards