# changing urban development scenario.

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# CHAPTER 1

# INTRODUCTION

## 1.1. GENERAL

Tall buildings are becoming more and more necessary in the changing urban development scenario. Due to space constraints and expanding populations, cities all across the world are expanding upward. Buildings' structural dynamics become more complicated as they go taller, especially if they are situated on unstable soils. The foundation has historically been viewed by engineers as a solid, immovable base. Although this assumption makes research easier, it can be severely misleading, particularly for buildings built in seismically active areas or on fragile soils.

In practice, there is dynamic interaction between buildings and the earth beneath them. Whether because to seismic activity, wind, or occupation, loads are transferred through the structure to the soil, which deforms in response.

The fields of geotechnical and structural engineering are connected by SSI. SSI must be taken into consideration for tall buildings, especially those with basements or those situated in seismically active areas like Delhi. Ignoring it can result in dangerous or overly cautious designs, understated displacements, and problems with performance under intense events or service. From basic concepts to advanced modeling techniques, this study examines SSI in an organized way, emphasizing its use in high-rise building design and analysis.

## 1.2. BASIC CONCEPTS OF SSI

Structure of Soil The way a building and its foundation affect one another's reaction to loads is reflected in interaction. The reaction of the soil alters the forces that the building transfers to the ground, creating a system that cannot be completely comprehended unless both components are examined simultaneously.

### 1.2.1. Types of Interaction

**1. Kinematic Interaction:** This happens when the stiffness and geometry of the foundation change the incoming ground motion, producing a different motion than the free-field soil.

**2. Inertial Interaction:** This occurs when the mass of the building produces extra forces during seismic motion, which feed back into the soil and change the distribution of stress.

### 1.2.2. Why SSI Matters

SSI is crucial under the following conditions:

- Buildings on **soft or loose soil**, where foundation flexibility is significant.
- Structures with **basement levels**, where lateral earth pressures influence behavior.
- Regions with **seismic risk**, where dynamic loading exaggerates interaction effects.
- Buildings with **longer natural time periods**, potentially aligning with ground motion.

Ignoring SSI could result in designs that are dangerous or not cost-effective. Using it encourages improved decision-making and increases simulation realism.

## 1.3. INFLUENCING PARAMETERS

Several factors govern how much SSI affects a structure:

1. **Soil Stiffness**: More compliant soils amplify interaction effects.

2. **Foundation Type and Depth**: Shallow foundations distribute loads differently than deep piles.

3. **Mass and Geometry of the Building**: Heavier and more flexible buildings tend to exhibit stronger interaction.

4. **Seismic Characteristics**: The amplitude, frequency, and duration of ground shaking influence SSI.

5. **Damping Mechanisms**: Energy is dissipated through material and radiation damping.

These parameters must be carefully assessed in both the structural and geotechnical design phases.

## 1.4. STRUCTURAL IMPLICATIONS OF SSI

1. **Time Period Extension:** With SSI, the foundation adds flexibility to the system, effectively lengthening the structure's time period. This shift can either increase or decrease seismic demands, depending on how the building's new frequency matches the seismic spectrum.

2. **Altered Base Shear and Moments:** The interaction may lead to lower base shears due

to period elongation, but this is not always beneficial. Increased flexibility might result in larger displacements and overturning moments.

Increased Drift and Deformation: SSI can cause more pronounced lateral displacements and story drifts. These affect not just structural safety but also the performance of non-structural elements and serviceability.

## 1.5. MODELING TECHNIQUES

1. **Winkler Approach:** This simplified model uses discrete springs to simulate soil reactions. Each spring's stiffness represents the subgrade modulus. Although useful for initial design, it neglects soil continuity and shear interaction.

2. **Finite Element Method (FEM):** FEM divides both soil and structure into small elements, allowing accurate representation of stresses, nonlinearities, and deformations. Programs like PLAXIS and ABAQUS are widely used for such analyses.

3. **Substructure vs. Direct Method:**

- **Substructure Method**: Soil response is modeled separately and integrated via stiffness matrices into structural software like ETABS.
- **Direct Method**: Combines soil and structure in a single model for holistic analysis. While more precise, it's computationally intensive.

## 1.6. APPLICATION IN TALL BUILDINGS WITH BASEMENT

Basement walls restrain soil movement and provide additional stiffness, altering the building's dynamic response. Their interaction with surrounding backfill introduces complexities such as passive and active pressures, friction, and possible water table effects.

Design considerations include:

- Assigning lateral and vertical springs along basement walls
- Modeling earth pressure distributions
- Considering confinement and soil arching

ETABS allows these effects to be approximated via spring supports.

## 1.7. CONCLUSION

As cities reach higher, the foundations of tall buildings must go deeper, not just physically, but also in design precision. Soil-Structure Interaction is a fundamental concept that must be incorporated into the engineering workflow for skyscrapers, particularly those with basements or located in seismic zones. By accounting for the ground’s response, engineers can design more resilient, efficient, and reliable structures. Whether through simplified methods or detailed finite element simulations, the future of high-rise engineering lies in understanding and embracing SSI.

## 1.8. STRUCTURE OF THIS DISSERTATION WORK

- Introduction
- Objectives
- Literature review
- Research Gap
- Methodology
- Results and Discussion
- Conclusion
- Future scope of the work
- References

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. PAST STUDY

**Requena-Garcia-Cruz et-al (2022):** This study addresses the often-overlooked impact of soil-structure interaction (SSI) on the seismic vulnerability of mid-rise reinforced concrete (RC) buildings, particularly in Lisbon. Previous seismic vulnerability assessments frequently assumed fixed-base conditions, neglecting the influence of soil flexibility. However, recent research indicates that SSI can significantly affect the seismic performance of structures, especially mid- to high-rise buildings founded on soft soils.

The authors highlight that traditional assessments may overestimate building capacity by not accounting for SSI, leading to unreliable results. They reference Eurocode 8, which stipulates the consideration of SSI effects in structures with significant second-order effects, slenderness, or medium to high-rise configurations.

The study uses two modeling techniques—3D continuum modeling and the Nonlinear Beam on Winkler Foundation (NBWF) method—to examine SSI effects.

Although NBWF simulates soil behavior using inelastic springs, it might not account for all pertinent factors, including bulk moduli and shear, which have a big impact on seismic response.In order to accurately characterize the nonlinear behavior of both soil and structure, the authors thus support 3D continuum modeling.

**Pinto et-al. (2022):** New issues in earthquake engineering and design are brought about by the growing demand for tall buildings worldwide. The fixed-base assumption, which is frequently used in traditional seismic analysis techniques, might not adequately capture the boundary conditions and behavior of tall buildings with basement levels. This fixed-base concept has been shown to be inadequate for assessing the seismic response of such structures in previous research and current seismic design recommendations. The conditions under which soil-basement-structure interaction (SBSI) should be taken into account in the design of the superstructure, foundation, and basement levels are unclear, though, because studies concentrating on soil-structure interaction (SSI) for tall buildings have generally been inconclusive. Given the rising demand for tall buildings, it is essential to evaluate the relationship between global system variables—such as basement depth, structure height, and soil characteristics—and the building's seismic response through numerical and experimental modeling.

**Mercado et-al (2021):** The intricate relationship between soil-structure interaction (SSI) and the nonlinear-inelastic seismic response of tall buildings—especially those with weak foundations is the subject of this study. Conventional seismic assessments frequently overlook the dynamic interplay between the structure and the supporting soil by assuming fixed-base conditions. However, during intense seismic occurrences, both the soil and the structure may experience inelastic deformations, requiring a more comprehensive modeling strategy.

The authors employ a direct, fully-coupled modeling approach to evaluate the nonlinear behavior of soil-structure systems. They simulate a 30-story archetype building supported on a mat foundation, incorporating nonlinear link elements to accurately represent geometry, stiffness, and strength. The structural stiffness and mass profiles are algorithmically generated to match prescribed modal characteristics, ensuring a realistic dynamic response.ASCE Library.

**ATC Guide (2020):** The Applied Technology Council (ATC) created the FEMA P-2091 report, which provides practicing engineers with a thorough manual for comprehending and incorporating soil-structure interaction (SSI) impacts into seismic design. The guide attempts to close the gap between intricate SSI theories and real-world engineering applications, acknowledging that SSI can have a substantial impact on how buildings react during earthquake shaking.

The guide emphasizes that SSI can either amplify or reduce seismic demands on structures, depending on various factors such as soil properties, foundation characteristics, and building configurations. To assist engineers in determining when SSI effects are significant, the report introduces a "rule of thumb" test based on readily available parameters: building height, fundamental period, and shear wave velocity of the supporting soil.

**Givens J. Michael (2013):** *Dynamic Soil-Structure Interaction of Instrumented Buildings and Test Structures*, submitted to the University of California, Los Angeles, presents a comprehensive and data-driven investigation into the dynamic soil-structure interaction (SSI) of real-world buildings and experimental test structures. The literature review component of his work critiques prevailing modeling practices in earthquake engineering and synthesizes past experimental, analytical, and theoretical efforts that have aimed to characterize how soil and structural systems interact during dynamic loading events such as earthquakes.

Traditionally, SSI effects have been either simplified or neglected in seismic design on the assumption that excluding these effects leads to conservative (i.e., safe) estimations of structural demand. Givens challenges this prevailing assumption, citing previous research and observed performance data to argue that the influence of SSI is more nuanced. He emphasizes that in many situations, neglecting SSI may not be conservative at all—particularly in structures with soft soils, tall profiles, or deep foundations—where it can actually lead to underestimated structural displacements and accelerations.

Givens delves into the theoretical development of foundation damping, an essential component of SSI, and critiques the simplistic use of idealized models that assume rigid circular foundations on elastic half-spaces. These models, while mathematically tractable, fall short in capturing the complexity of real foundations with varied shapes and soil properties. To address this gap, he revisits the derivation of damping expressions from first principles, incorporating both radiation damping (energy dissipation through wave propagation in the soil) and material damping (hysteretic losses within the soil medium). He acknowledges the limitations of assuming constant damping ratios across frequencies and geometries and seeks to generalize damping expressions for broader application in design and analysis.

**Turan et-al (2013):** The effects of seismic soil–structure interaction (SSI) on buildings with embedded basements built on stiff clay soils are thoroughly examined in the 2013 study by Turan, Hinchberger, and El Naggar titled "Seismic Soil–Structure Interaction in Buildings on Stiff Clay with Embedded Basement Stories" that was published in the Canadian Geotechnical Journal. Because it discusses the intricate interactions between soil and structural systems during seismic events—particularly for constructions with underground components—this research is highly important.

The authors looked into how embedded basement stories affect a building's seismic response using a combination of parametric analysis and numerical modeling. In order to evaluate the dynamic behavior under seismic loads, they simulated several building layouts with varying numbers of basement floors. According to the study's findings, embedded basements can drastically change a structure's seismic response, mostly by changing the soil-structure system's stiffness and damping properties.

One of the research's main conclusions is that because embedded basements contribute mass and stiffness below ground level, they may result in higher base shear and overturning moments. On the other hand, they also help to lessen interstory drifts and lateral displacements, which can improve the overall structural performance during earthquakes. The study highlights that the characteristics of the surrounding stiff clay soil and the basement's depth have a significant impact on these impacts.

The study also emphasizes how crucial it is to include SSI impacts in seismic design procedures, particularly for structures with sizable underground components. Ignoring these relationships may result in erroneous structural behavior predictions, which could jeopardize performance and safety. Beyond the conventional fixed-base assumptions frequently employed in engineering practice, the authors support more sophisticated modeling approaches that take into consideration the intricate relationships between soil and structure.

**Stewart P. Jonathan (2012):** For the National Institute of Standards and Technology (NIST), the NEHRP Consultants Joint Venture prepared the 2012 report "Soil-Structure Interaction for Building Structures" (NIST GCR 12-917-21), which provides detailed instructions on how to apply soil-structure interaction (SSI) in seismic response history analyses of building structures. Farzad Naeim, Bret Lizundia, Tara C. Hutchinson, Jonathan P. Stewart, C.B. Crouse, and Farhang Ostadan wrote the study, which combines decades of SSI research into a useful framework for engineering applications.

The primary objective of the report is to develop consensus guidance for incorporating SSI effects into seismic analysis and design. It addresses the collective response of three interconnected systems: the structure, the foundation, and the underlying soil. Recognizing that SSI is often overlooked in practice due to complexities in understanding and modeling, the report aims to bridge this gap by providing clear methodologies and recommendations.

## 2.2. RESEARCH GAPS

- Most existing studies on soil-structure interaction (SSI) have primarily focused on low to mid-rise buildings, creating a significant opportunity to explore the effects of SSI on tall buildings, particularly those with multiple basement levels.

- Much of the existing literature emphasizes modeling soil flexibility using springs and dashpots; however, there is a lack of guidelines regarding the acceptable margins of error in determining spring stiffness and the implications of substituting soil flexibility with these simplified models.
- In the analysis of soil-basement-tower interactions, the prevailing approach involves decomposing the problem into several components and subsequently integrating the results to assess the interactions. However, there is a notable scarcity of studies that employ coupled analysis through continuum modeling of the soil medium.
- There has been limited attention given to the specification of interface elements to ensure adequate contact at the junction between the soil medium and the structural components, such as the foundation or basement walls.
- There are currently no standardized code provisions for determining lateral design forces or base shear for structures located below ground level, specifically for all basement levels.
- Currently, there are no adequate design methodologies available for structural designs considering the force redistribution resulting from soil-structure interaction (SSI) effects.

## CHAPTER 3

# METHODOLOGY

In this research work prepare four different cases in ETABS. Base isolation devices are typically installed between a building's foundation and superstructure. They serve as a flexible interface, depending, in the case of a seismic event, on the structure's ability to move regardless of its position on the ground.

## 3.1. GEOMETRICAL ANALYSIS OF MODEL


**Fig. 3.1. Top View of G+14 Tower**

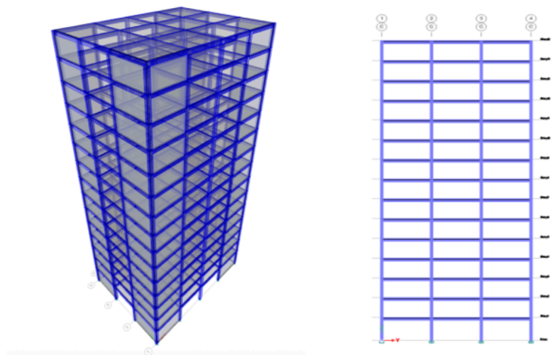


**Fig. 3.2. 3D & Elevation View of G+14 Tower**

**Table 3.1. Model Specifications**

| S. No. | Data | Value |
|---|---|---|
| 1 | Grade of Reinforcement | HYSD 500 |
| 2 | Grade Of Concrete | M25, M30 |
| 3 | No. of stories | G+14 |
| 4 | No. of bay along X-direction | 5 |
| 5 | No. of bay along Y-direction | 4 |
| 6 | Span along X-direction | 6m |
| 7 | Span along Y-direction | 6m |
| 8 | Floor height | 3m |
| 9 | Column Size | 300*600 mm |
| 10 | Beam Size | 230*450 mm |
| 11 | Depth of Slab | 150mm |
| 12 | Wall Load | 13.8 KN/m |
| 13 | Live load | 2.5kn/m2 |
| 14 | Software | CSI ETABS |
| 15 | Earthquake method | Response Spectrum |
| 16 | Seismic Zone | 4 |
| 17 | Soil Type | 2 |
| 18 | Importance factor | 1 |
| 19 | Response Reduction factor | 5 |

## 3.2. MATERIAL PROPERTY

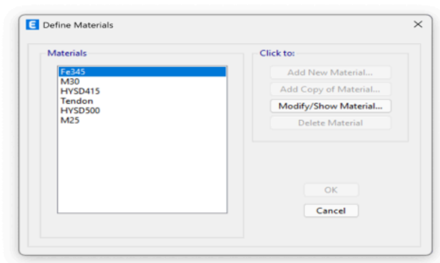



**Fig. 3.3. Define Materials**

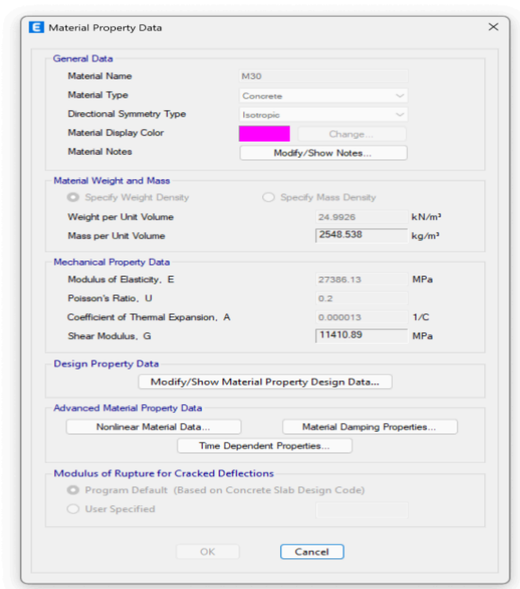



**Fig. 3.4. Property data of Material M30**

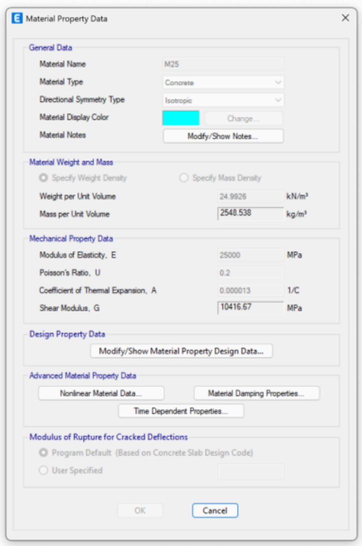



**Fig. 3.5. Property data of Material M25**

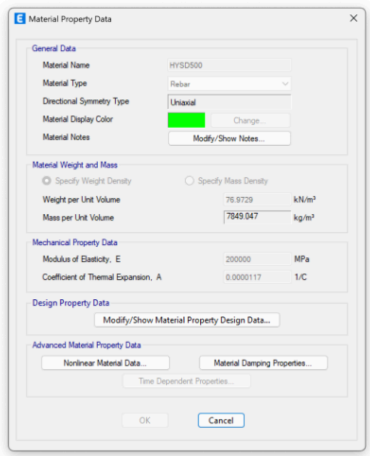



**Fig. 3.6. Property data of Material HYSD500**

## 3.3. SECTION PROPERTY

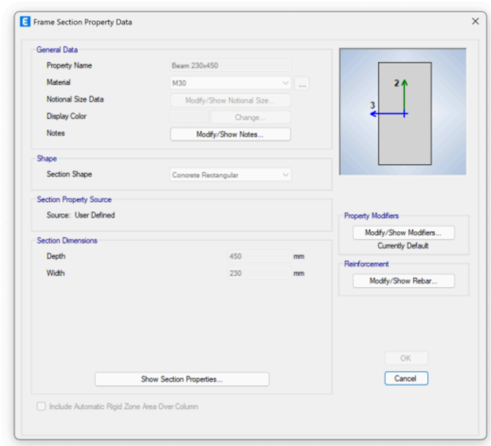



**Fig. 3.7. Property Assign for Beam 230x450**

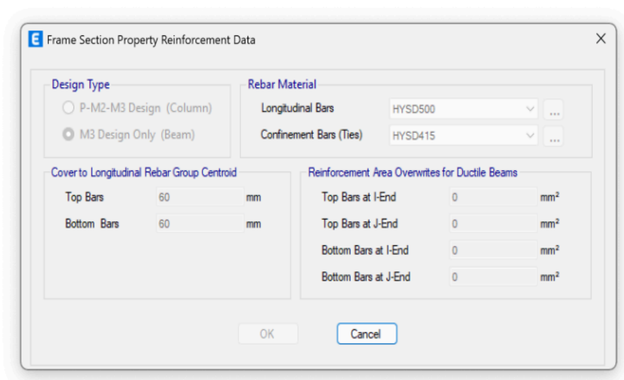



**Fig. 3.8. Reinforcement Property Assign for Beam 230x450**

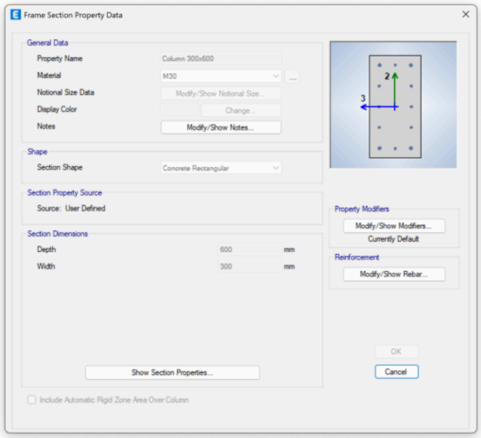



Fig. 3.9. Property Assign for Column 300x600

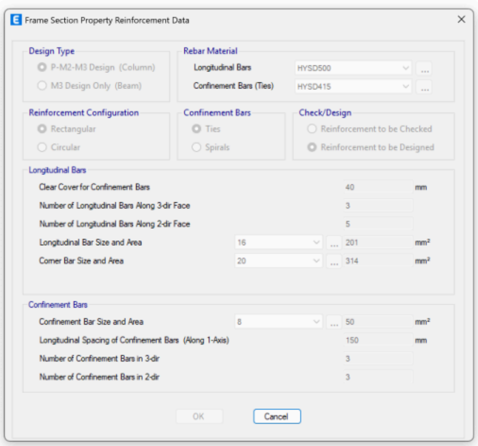



Fig. 3.10. Reinforcement Property Assign for Column 300x600

## 3.4. SLAB PROPERTY

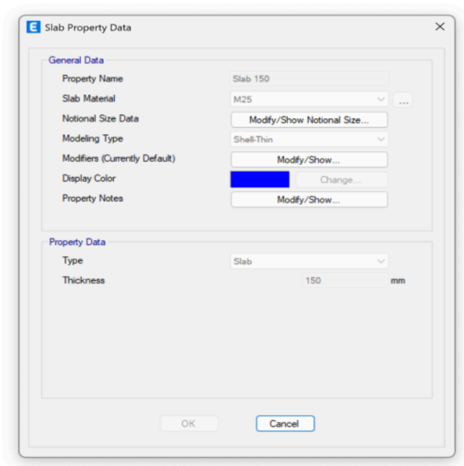



Fig. 3.10. Property data of Slab 150

## 3.5. SHEAR WALL PROPERTY

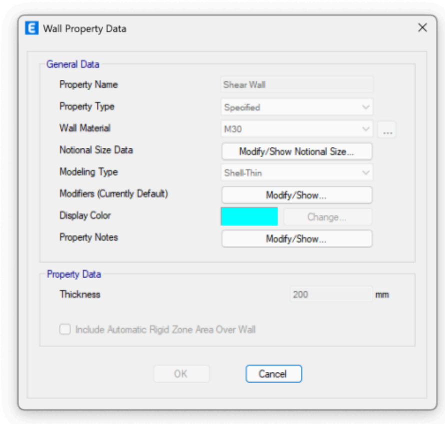



Fig. 3.11. Property data of Shear Wall 200

## 3.6. RESPONSE SPECTRUM FUNCTION

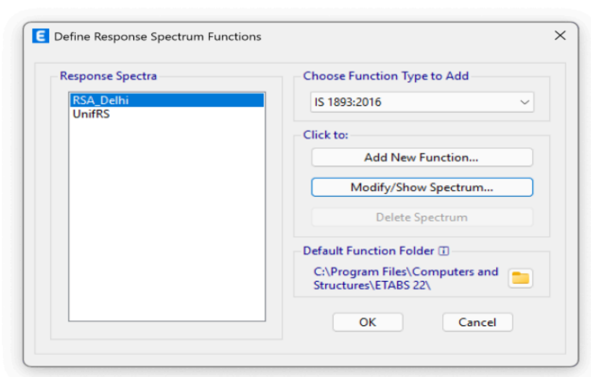



Fig. 3.12. Response Spectrum Function

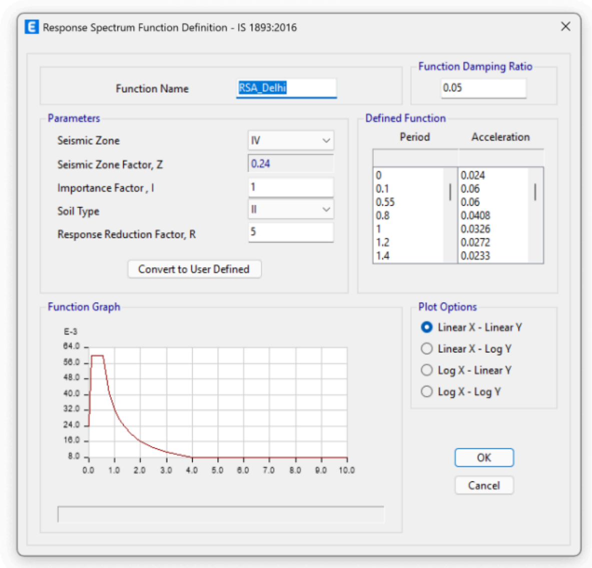



**Fig. 3.13. Response Spectrum Function Definition As per IS 1893:2016**

## 3.7. MASS SOURCE FUNCTION

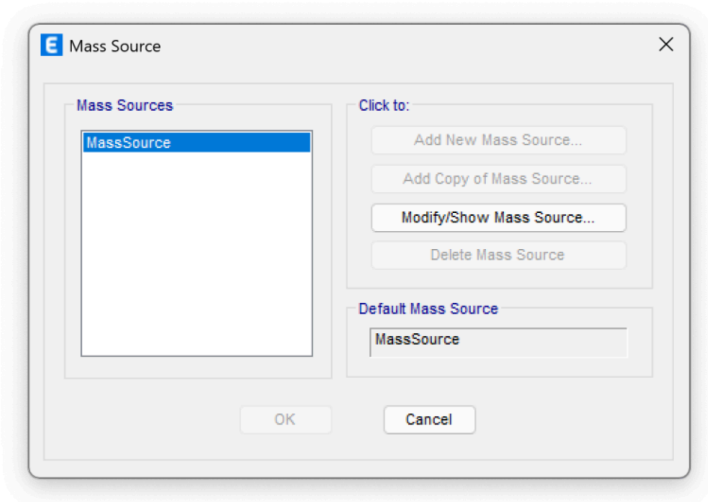



**Fig. 3.14. Mass Source Function**

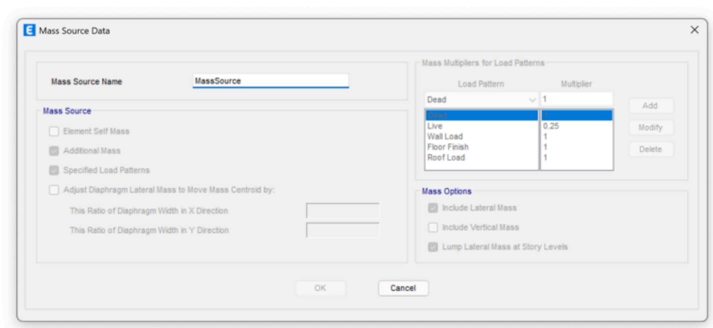



**Fig. 3.15. Mass Source Data**

## 3.8. LOAD CASES

### 3.8.1. Static Loads

The following static load cases are defined for the tower and basement structure

- **Dead Load (DL)** – It represents the self-weight of the structural components like beams, columns, shear walls, slabs.
- **Live Load (LL)** – Live load is imposed on the structure based on IS 875-Part II. The load is applied as area loads to all the typical floors except the roof.
- **Floor Finish** – In accordance with IS 875 (Part I), a uniform area load of 1.2 kN/m² is applied to all floors of the structure..
- **Wall Load** – Element load is applied on beams for the partition walls as the partition doesn't significantly affect the stiffness of the structure but increases the mass. For the external walls an UDL of 7.4 kN/m is applied on the beams and for internal walls an UDL of 4.4 kN/m is applied.
- **Roof LL** – Uniform floor load of 3 kN/m² is applied on the roof of the structure in accordance with IS 875 (Part II).
- **Parapet wall load –** Element load of 4.4 kN/m is applied on the exterior beams of the roof.
- **Earthquake Loads (EL) –** Seismic forces are applied in accordance with the equivalent static method outlined in IS 1893-2016. The calculation of base shear according to equivalent static method is as follows –

**Table 3.2. Seismic parameters (IS 1893-2016)**

| Zone | IV |
|---|---|
| **Soil conditions** | Medium stiff soil |
| **Structure** | Residential and commercial |
| **Type of frame in X direction** | Building with Ductile Structural Walls |
| **Type of frame in Y direction** | Building with Ductile Structural Walls |
| **Hazard level** | DBE |
| **Zone factor** | 0.24 |
| **Z** | 0.18 |
| **$R_X$** | 4 |
| **$R_Y$** | 4 |
| **Importance factor** | 1.2 |

### 3.8.2. Design Base Shear

$$V_B = A_h * W \tag{1.1}$$

where, $V_B$ = Base shear on the structure

6
$W$ = Seismic weight of the structure
$A_h$= Design horizontal seismic coefficient given in equation 1.2

$$A_h = \frac{\frac{Z}{2} * \frac{S_a}{g}}{\frac{R}{I}} \tag{1.2}$$

For the calculation of base shear, the ground floor is designated as the lowest story, while the roof is treated as the highest story. The mass source in the structure is defined as *Load to Mass* option in ETABs to calculate the effective seismic weight with the factors shown in Table 3.3.

**Table 3.3. Load to Mass factors for mass source definition**

| Load case | Factor |
|---|---|
| **DL** | 1 |
| **LL** | 0.25 |
| **Floor Finish** | 1 |
| **Wall Load** | 1 |
| **Parapet Wall** | 1 |

20
Total effective weight for X-direction seismic loads ($W_x$) = 47879.90 kN
Total effective weight for Y-direction seismic loads ($W_y$) = 47879.90 kN
From **IS 1893-2016**, fundamental period for buildings with RC structural walls can be expressed as

$$T_a = \frac{0.075h^{0.75}}{\sqrt{A_w}} \geq \frac{0.09h}{\sqrt{d}} \tag{1.3}$$

6
where,
$h$ = height of the building = 60 m
d = base dimension of the building at the plinth level along the considered direction of earthquake shaking

$$A_w = \sum_{i=1}^{Nw} \left[ A_{wi} \left\{ 0.2 + \left( \frac{L_{wi}}{h} \right)^2 \right\} \right] \tag{1.4}$$

17
$A_{wi}$ = Cross-sectional area of $i^{th}$ shear wall in first story of building.
$L_{wi}$ = Length of $i^{th}$ shear wall in the considered direction of shaking.
$N_w$ = No. of shear wall in the considered direction of shaking.

From **IS 16700-2023**, the fundamental natural period for a structure with height more than 50 m shall not exceed,

$$T_a = 0.0675 h^{0.75} \tag{1.5}$$

From IS 1893-2016, $\frac{S_a}{g} = 0.938$ for both X and Y direction. Equation 2.1 gives the value of Design Base Shear, **$V_{BX}$ = 1616.69 kN and . $V_{BY}$ = 1616.69 kN.**

## 3.9. MODELING OF SOIL

The structure from ETABS is imported into the geotechnical software PLEXIS and the boundary conditions from the structure are removed. The continuum soil is modelled using 3D elements with 3 DOFs per node. The soil domain extends to five times the length and breadth of the structure, while the depth is three times the maximum dimension of the structure in plan. The basement plan measures 65 m in length and 52 m in breadth, leading to a corresponding soil domain with dimensions of 325 m in length and 260 m in breadth. The vertical extent of the soil domain is taken to be 200 m. Figure 0.1 shows the continuum soil domain along with the tower and embedded basement. Soil is modelled using linear elastic material and a uniform soil layer of 200 m is used for analysis. Three soil models are made with three different properties shown in Table 0.1.

The first type of soil represents rigid rock which also helps in simulating the rigid base condition of the structure. The other two soil properties represent medium stiff and soft soil conditions.

A raft of 1 m thickness is placed under the tower and basement structure and the columns and shear walls are imprinted on the raft. One of the most important aspects of modeling is modeling the interface element between the soil layer and the basement wall i.e. structure. Interface elements are applied based on relative stiffness between the soil and structural members. The parameters required for defining interface elements are (i) interface nonlinearities (ii) normal stiffness modulus ($k_n$) (iii) shear stiffness modulus ($k_t$) expressed below. Interface elements are used to simulate the non-compressive frictional behaviour between two different materials. Value of $k_n$ represents the degree of compenetration between the two materials at interface.

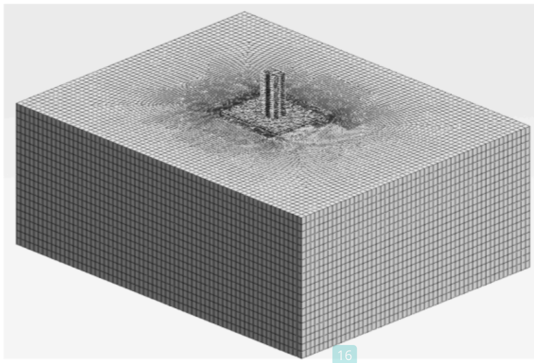


**Figure 0.1** Continuum approach of soil modeling

**Table 0.1** Soil properties for continuum modeling

| Soil types | Shear wave velocity (m/s) | Elastic modulus ($kN/m^2$) | Poisson's ratio | Unit weight ($kN/m^3$) |
|---|---|---|---|---|
| 1 | 600 | 2660550.46 | 0.45 | 25 |
| 2 | 360 | 627522.936 | 0.25 | 19 |
| 3 | 200 | 183486.239 | 0.25 | 18 |

$$k_n = E_{oed}/t_v \qquad (2.6)$$

$$E_{oed} = 2G_i \frac{1-\nu_i}{1-2\nu_i} \qquad (2.7)$$

Where $\nu_i$ is the interface Poisson's ratio taken as 0.45 to prevent numerical errors

$t_v$ = Virtual thickness = (0.01 – 0.1)

$$G_i = R \times G_{soil} \qquad (2.8)$$

where, $R$ is the strength reduction factor.

**Table 0.2**. Strength reduction factor for different material interface

| Material | R |
|---|---|
| Sand – Steel | 0.6 – 0.7 |
| Clay – Steel | 0.5 |
| Sand – Concrete | 0.8 – 1.0 |
| Clay – Concrete | 0.7 – 1.0 |

The soil boundary is kept fixed at all free faces. To prevent the reflection of seismic waves off the building walls and floor edges, the maximum size of the finite elements was established using the frequency range corresponding to the largest amplitude in the Fourier series. This ensures that the mesh size is smaller than either $\lambda/8$ or $\lambda/10$, where $\lambda$ represents the wavelength (Kuhlemeyer and Lysmer 1973). Following this approach, the excavated area adjacent to the structure is assigned a mesh size of 2 meters, while the soil boundaries are modelled with a coarser mesh size of 5 meters shown in Figure 0.2.

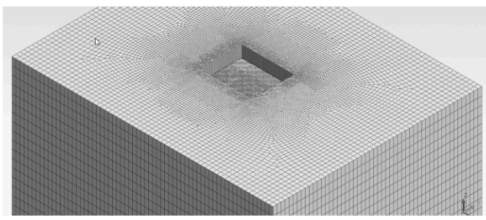


**Figure 0.2** Meshing of soil domain

The embedment of structures within soil layers has a significant impact on the ground motion records utilized for seismic analysis. Typically, deeper embedment leads to a reduction in ground motion amplitudes and may cause shifts in the peaks of response spectra, ultimately influencing the seismic performance of the structure. Consequently, it is essential to account for these variations when selecting ground motion records for analysis, as surface recordings may not accurately reflect the conditions experienced at greater depths within the soil layers.

To address this problem, DEEPSOIL is used for deconvolution of the downloaded ground motion recorded at the earth surface. The Imperial Valley ground motion is downloaded from Pacific Earthquake Engineering Research Center. (2013) *NGA-West2*

*Project Database* and is deconvoluted in DEEPSOIL using the following soil properties shown in Table 0.3.

**Table 0.3 Properties of 2D soil layer**

| | |
|---|---|
| Depth (m) | 20 |
| Unit weight (kN/m$^3$) | 18 |
| Poisson's ratio | 0.33 |
| Elastic modulus (kN/m$^2$) | 1723680 |

The soil is modelled using plane strain elements and the bottom of the soil layer is assigned with a fixed boundary. The lateral faces of the soil are provided with free field boundary conditions to avoid interference of reflected wave in the medium shown in Figure 0.3. Rayleigh damping was applied to the soil medium for performing the linear time history analysis. The frequencies of interest used for calculation of damping coefficients are 0.25 Hz and 22.5 Hz. The coefficients are $\alpha = 0.15$ and $\beta = 0.00069$. The ground motion is applied at the base of the soil column in terms of acceleration-time history shown in Figure 0.4. The acceleration response is recorded at the top of the soil column shown in Figure 0.6.


**Figure 0.3** 2D soil column with free field boundary

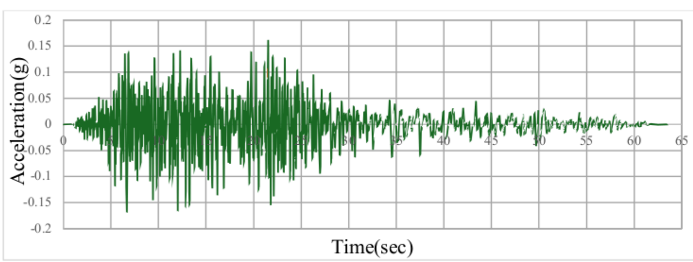



**Figure 0.4** Imperial Valley recorded ground motion

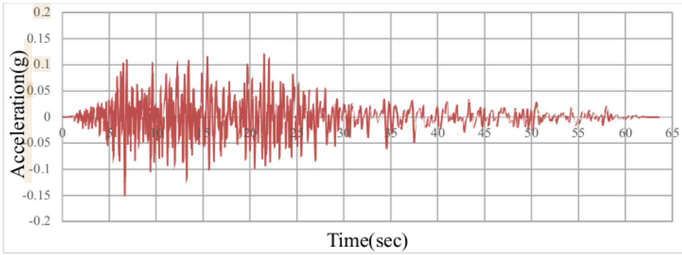



**Figure 0.5** Deconvoluted Imperial Valley motion using DEEPSOIL

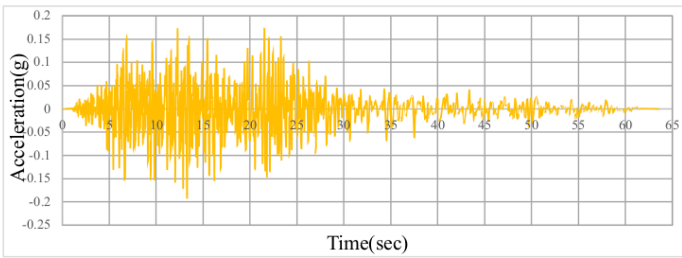



**Figure 0.6** Acceleration recorded at the top of soil column from PLEXIS

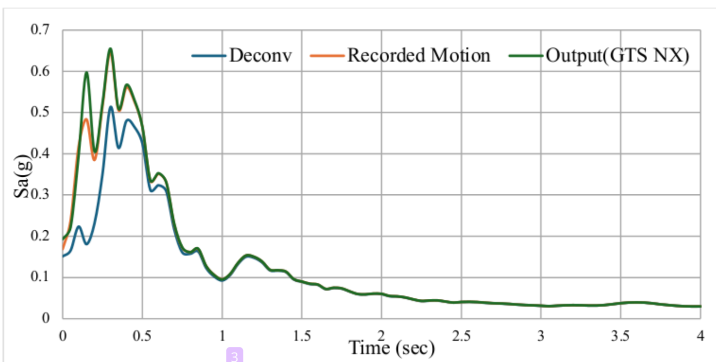



Figure 0.7 **Comparison of response spectra of mentioned ground motions**

The response spectra for the three ground motions were generated using Seismosignal, revealing that the deconvoluted motion exhibited lower intensity compared to the actual recorded motion. Additionally, the motion recorded at the top of the soil column closely mirrored the recorded motion, which is consistent with expectations.

## 3.10. METHODOLOGY OF ANALYSIS

- **Equivalent Static Analysis**

The linear static analysis method is appropriate for simpler and more regular structures, as it primarily considers only the fundamental mode of vibration. In this approach, it is assumed that the total seismic action can be represented as equivalent static lateral forces applied to the structure. The design horizontal seismic coefficient, as specified in equation 2.2, corresponds to a design basis earthquake with a return period of 475 years. The results obtained from this analysis are discussed in detail in **Error! Reference source not found.**.

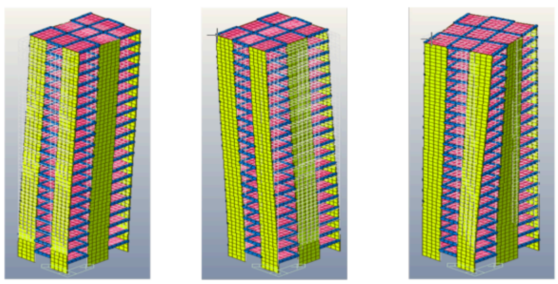
- **Response Spectrum Analysis**

To achieve a more accurate assessment of seismic forces and structural responses in complex structures, it is essential to consider higher modes through dynamic analysis methods. IS 1893:2016 recommends considering modes up to 90% mass participation or a frequency limit of 33 Hz. The structure in this report attains 90% mass participation in $8^{th}$ mode. Therefore, a linear response spectrum analysis is performed on the specified structure considering first 8 modes, in accordance with the guidelines set forth in the relevant clauses of Indian standard codes and practices. The findings from this analysis are detailed in 4.

# CHAPTER 4

# RESULTS AND DISCUSSION

The dynamic properties obtained from the analysis procedures mentioned in chapter 2 are discussed in this chapter. Figure 0.8 shows the first three fundamental mode shapes of the fixed base tower structure. From eigenvalue analysis of the model 90% mass participation is attained in the 8$^{th}$ mode.



(a) (b) (c)

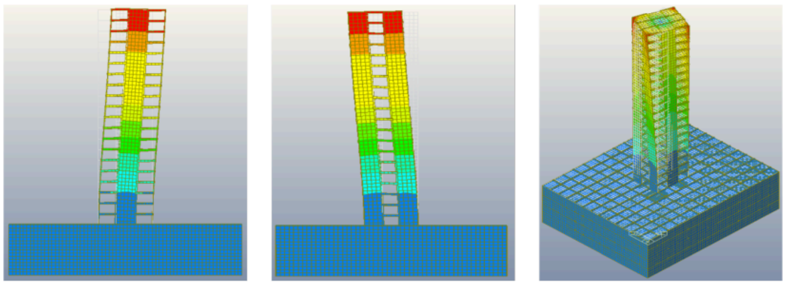
**Figure 0.8** Mode shapes of fixed base tower in: (a) translation in X; (b) translation in Y; and (c) Rotation about Z

**Table 0.4** Dynamic properties of the fixed base tower

| **Mode No.** | **Direction** | **Period (s)** | **Frequency** | | **Modal mass participation** | |
|---|---|---|---|---|---|---|
| | | | **(Hz)** | **(rad/s)** | **(%)** | **(T)** |
| Mode 1 | Translation in X | 2.68 | 0.37 | 2.34 | 71.19 | 3409.71 |
| Mode 2 | Translation in Y | 2.54 | 0.39 | 2.47 | 70.89 | 3395.19 |
| Mode 3 | Rotation about Z | 1.86 | 0.54 | 1.86 | 69.98 | 120219 |

Table 0.4 shows the fundamental period and mass participation for the first three fundamental modes obtained from eigen value analysis.

Figure 0.9 shows the first three fundamental mode shapes of the fixed base tower structure along with basement levels.



(a) (b) (c)

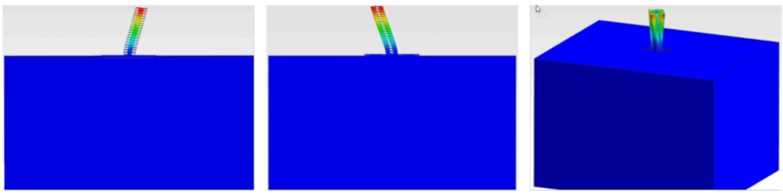
**Figure 0.9** Mode shape of tower and basement with fixed base: (a) translation in X; (b) translation in Y; and (c) Rotation about Z

Table 0.5 shows the dynamic structural properties of fixed base tower and basement structure. Upon comparing the results for the tower alone and the combined tower and basement system, it was observed that the inclusion of the basement leads to an increase in both the fundamental period and the modal mass participation. However, the first three fundamental modes remain unchanged in their directional characteristics.

**Table 0.5** Dynamic properties of the tower + basement (fixed at bottom)

| **Mode No.** | **Direction** | **Period (s)** | **Frequency** | | **Modal mass participation** | |
|---|---|---|---|---|---|---|
| | | | **(Hz)** | **(rad/s)** | **(%)** | **(T)** |
| Mode 1 | Translation in X | 3.18 | 0.31 | 1.97 | 20.18 | 3507.10 |
| Mode 2 | Translation in Y | 3.01 | 0.33 | 2.08 | 20.20 | 3509.80 |
| Mode 3 | Rotation about Z | 2.18 | 0.48 | 3.00 | 1.59 | 126148.75 |

The uniform soil layer is modelled using solid elements using three different properties of soil mentioned in Table 0.1. The dynamic properties obtained from eigen value analysis of the tower + basement model with soil continuum using three different mediums of soil is shown below.



(a) (b) (c)

**Figure 0.10** Mode shape of tower and basement with soil continuum: (a) translation in X;
(b) translation in Y; and (c) Rotation about Z

Figure 0.10Figure 0.10 Mode shape of tower and basement with soil continuum: (a) translation in X;
(b) translation in Y; and (c) Rotation about Z shows the first three fundamental mode shape of the integrated soil, basement and tower structure. It is seen that there is no change in the direction of mode shapes even if the fixed base is replaced with soil domain. But there are significant changes in modal mass participation and the period with the increasing flexibility of the soil medium. Table 0.6 shows the dynamic properties of the soil-structure model with increasing flexibility of soil.

**Table 0.6** Dynamic properties of the tower + basement + soil

| **Soil** | **Mode No.** | **Period (sec)** | **Frequency** | | **Modal mass participation** |
|---|---|---|---|---|---|
| | | | **(Hz)** | **(rad/s)** | **(T)** |
| $v_s$ = 600 m/s | Mode 1 | 3.16 | 0.32 | 1.99 | 3506.04 |
| | Mode 2 | 2.96 | 0.33 | 2.12 | 3501.97 |
| | Mode 3 | 2.13 | 0.47 | 2.95 | 149897.50 |
| $v_s$ = 360 m/s | Mode 1 | 3.17 | 0.31 | 1.98 | 4201.20 |
| | Mode 2 | 2.98 | 0.34 | 2.11 | 3844.71 |
| | Mode 3 | 2.13 | 0.47 | 2.95 | 239174.30 |
| $v_s$ = 200 m/s | Mode 1 | 3.20 | 0.31 | 1.96 | 7032.94 |
| | Mode 2 | 3.1 | 0.32 | 2.08 | 4917.42 |
| | Mode 3 | 2.31 | 0.43 | 2.72 | 3412661.21 |

The soil with with $v_s$ = 600 m/s represents rock which is also equivalent to the fixed base condition of the tower + basement structure. As the flexibility of the soil increases, it is seen that the mass participation in each mode increases considerably and there is also a dip in the fundamental frequency of the entire system.

The displacements from the response spectrum method in both X and Y directions are compared in all the models and represented in Table 0.7

**Table 0.7** Maximum roof displacement for response spectrum load case for different models

| **Model** | **X-Displacement (mm)** | **Y-Displacement (mm)** |
|---|---|---|
| Tower + Basement | 56.53 | 53.54 |
| Tower + Basement + Soil ($v_s$ = 600 m/s) | 57.42 | 52.68 |
| Tower + Basement + Soil ($v_s$ = 600 m/s) | 67.12 | 55.83 |
| Tower + Basement + Soil ($v_s$ = 600 m/s) | 88.45 | 64.72 |

It is seen that the displacements in the rigid rock base and fixed base modeling are almost similar and with increasing soil flexibility the max roof displacement of the structure increases.

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