INFLUENCE OF SOIL-STRUCTURE INTERACTION ON SEISMIC PERFORMANCE OF TALL BUILDINGS

M.Tech (Structural Engineering)

A DISSERTATION SUBMITTED
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
STRUCTURAL ENGINEERING

by

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CANDIDATE'S DECLARATION

I, **Ashish Yadav**, hereby declare that the work which is being presented in dissertation entitled "**Influence of Soil-Structure Interaction on Seismic Performance of Tall Buildings**" which is submitted by me to thein partial fulfillment of the requirement for the award of the degree of **Master of Technology**, submitted in the Department of Civil Engineering, Delhi Technological University, Delhi is an authenticate record of my own work carried out during the period from 2024 to 2025 under the supervision of **Shri Gokaran P. Awadhiya**.

The matter presented in the dissertation has not been submitted by me for the award of any other degree or any other institute.

Candidate's Signature

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

Signature of Supervisor (S) **Signature of Examiner**

CERTIFICATE

Certified that **Ashish Yadav (2K23/STE/09)** has carried out their research work presented in this dissertation entitled **"Influence of Soil-Structure Interaction on Seismic Performance of Tall Buildings"** for the award of **Master of Technology** from the Department of Civil Engineering, Delhi Technological University, Delhi; under my supervision. The dissertation embodies results of original work, and studies are carried out by the student himself and the contents of the dissertation do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University.

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ABSTRACT

The interaction between a building and the supporting soil plays a critical role in determining structural behavior, especially during seismic events. This project focuses on evaluating the **Soil-Structure Interaction (SSI)** effects for a G+14 reinforced concrete building with a basement, situated in Delhi — a region classified under Seismic Zone IV according to IS 1893 (Part 1): 2016. While conventional analysis often assumes a fixed support at the foundation level, such assumptions can overlook the influence of soil flexibility on a building's dynamic response.

Using ETABS 20, the structure is modeled to include both the superstructure and basement levels. Soil flexibility is accounted for by introducing equivalent spring constants that simulate the supporting ground's response under load. These constants are based on assumed geotechnical conditions typical of Delhi's subsoil. The study examines how variations in soil stiffness affect key structural parameters such as lateral displacement, base shear, time period, and inter-story drift.

Response spectrum analysis is used to compare the seismic behavior of the fixed-base model with that of models incorporating SSI. It is observed that neglecting soil compliance may result in either underestimating or overdesigning structural components. The study also provides insight into how SSI affects basement wall behavior due to lateral earth pressures.

In conclusion, this research demonstrates the significance of including soil-structure interaction in high-rise structural models, especially for earthquake-prone zones. It also recommends the integration of structural software like ETABS with geotechnical tools such as PLAXIS for more refined SSI studies in future research.

Keywords: Soil-Structure Interaction, Seismic Load, Response Spectrum, Modal Analysis, Modal Mass Participation, etc.

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ASHISH YADAV

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION & SYMBOL

ETABS	:Extended Three-Dimensional Analysis of Building System
SSI	:Soil-Structure Interaction
RC	:Reinforced Concrete
FEM	:Finite Element Method
NBWF	:Nonlinear Beam on Winkler Foundation
SBSI	:Soil-Basement-Structure Interaction
ATC	:Applied Technology Council
NIST	:National Institute of Standards and Technology
NEHRP	:National Earthquake Hazards Reduction Program
IS	:Indian Standard
DBE	:Design Basis Earthquake
HYSD	:High Yield Strength Deformed (Steel Reinforcement)
UDL	:Uniformly Distributed Load
DL	:Dead Load
LL	:Live Load
EL	:Earthquake Load
Vs	:Shear Wave Velocity
T	:Time Period
R	:Strength Reduction Factor
kn	:Normal Stiffness Modulus
kt	:Shear Stiffness Modulus
tv	:Virtual Thickness
α	:Mass Proportional Damping Coefficient
β	:Stiffness Proportional Damping Coefficient

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 modelling 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

- **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.
- **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
- Modelling 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.

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): Givens 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 GAP

- 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

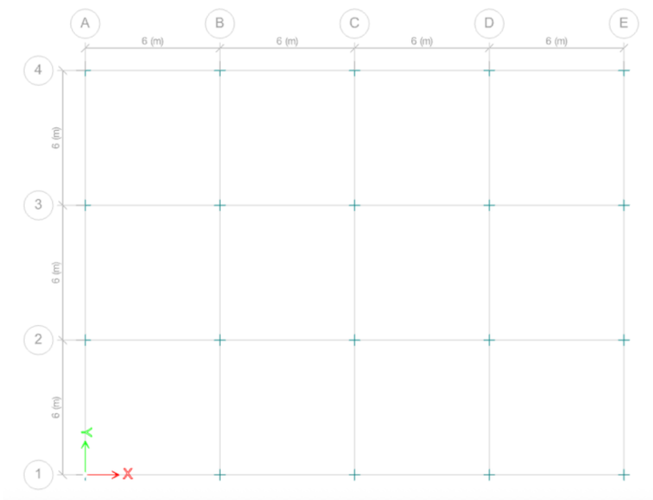


Fig. 1: Top View of G+14 Tower

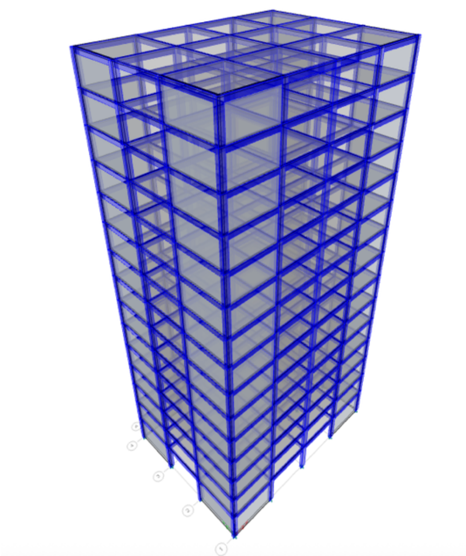


Fig. 2: 3D View of G+14 Tower

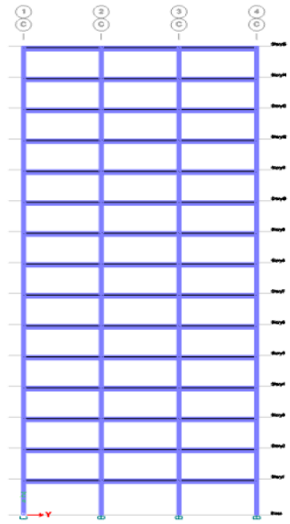


Fig. 3: Elevation View of G+14 Tower

Table 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

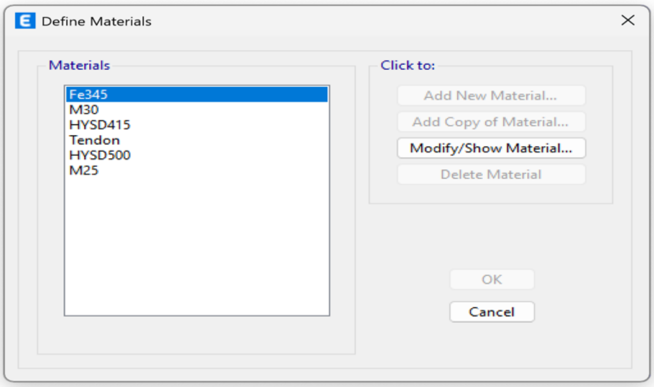


Fig. 4: Define Materials

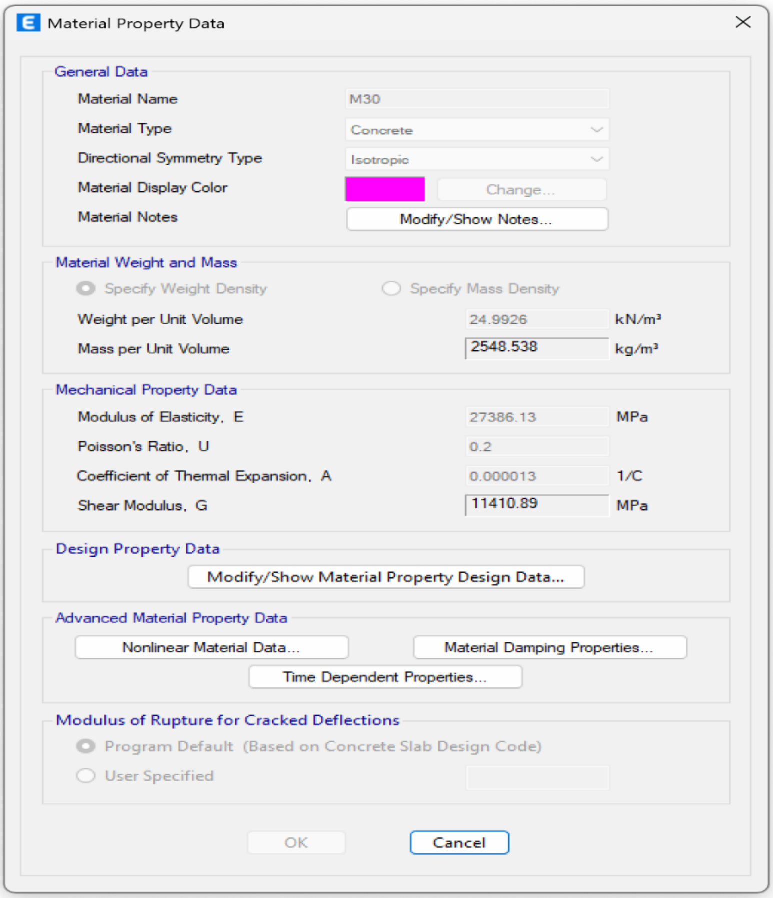


Fig. 5: Property data of Material M30

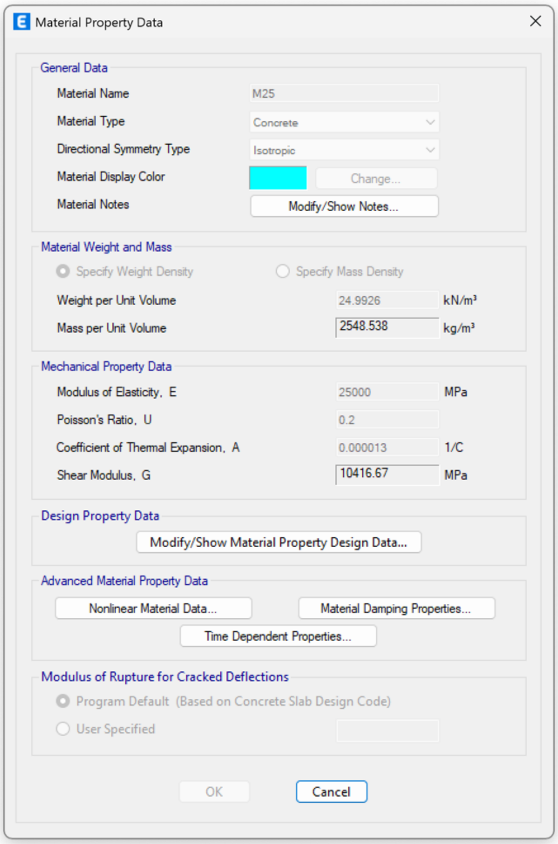


Fig. 6: Property data of Material M25

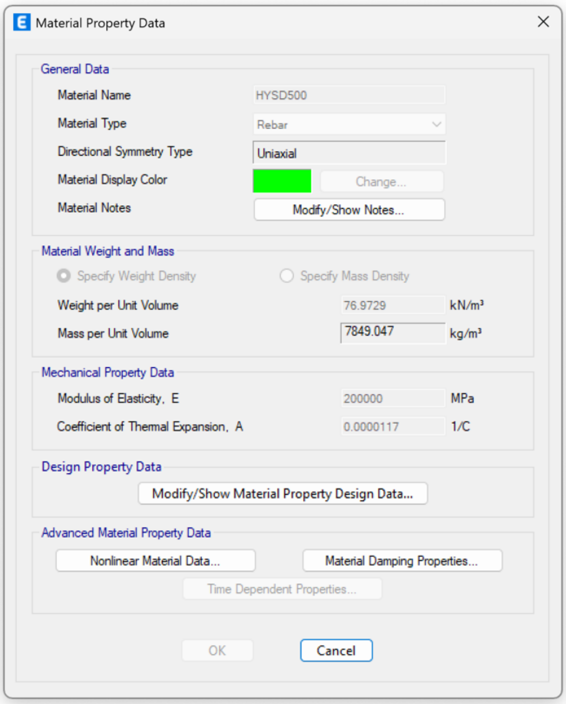


Fig. 7: Property data of Material HYSD500

3.3. SECTION PROPERTY

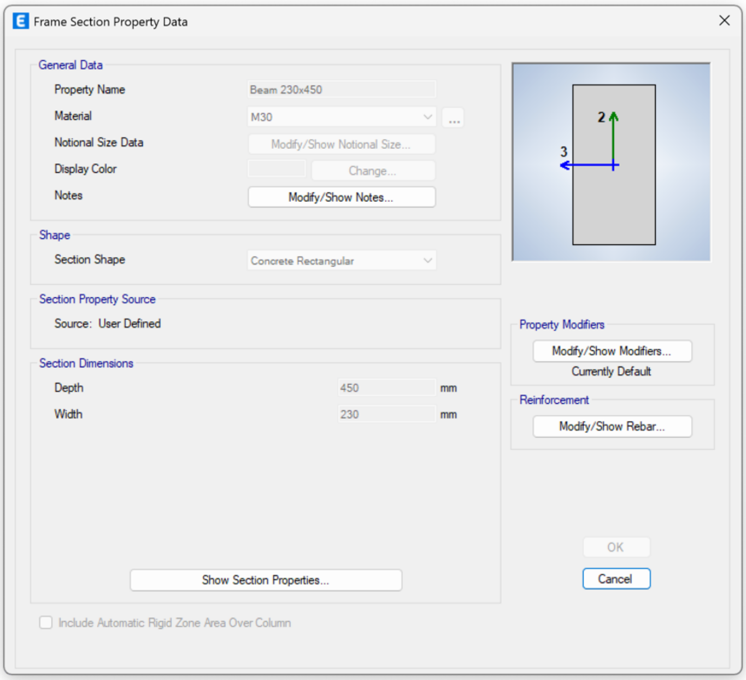


Fig. 8: Property Assign for Beam 230x450

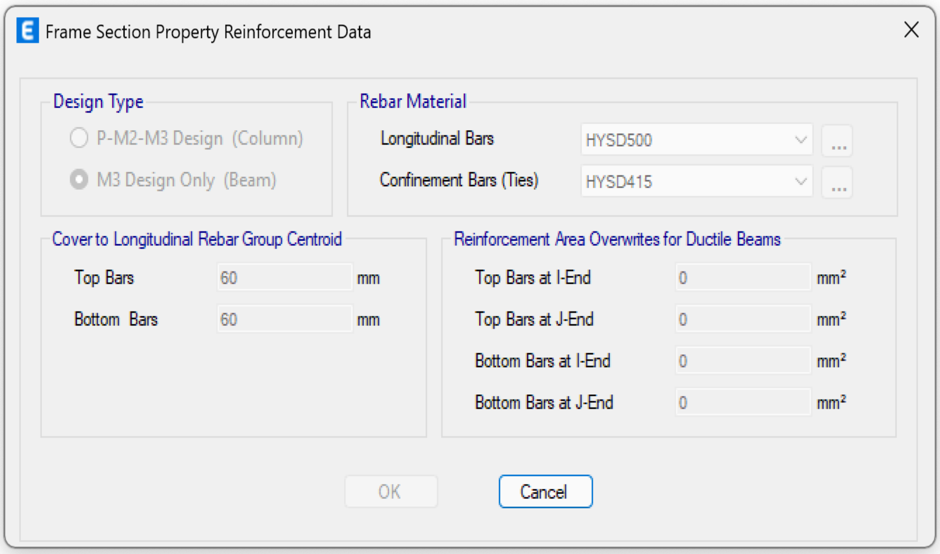


Fig. 9: Reinforcement Property Assign for Beam 230x450

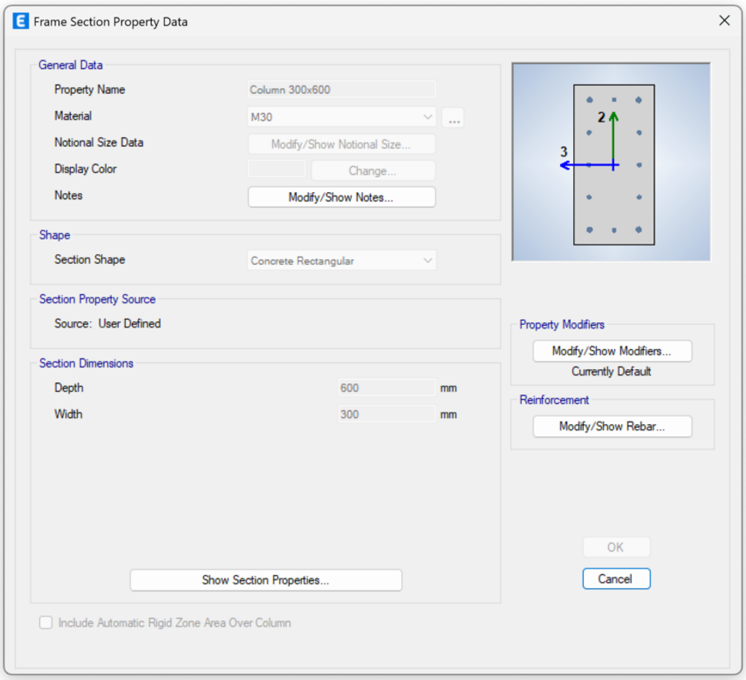


Fig. 10: Property Assign for Column 300x600

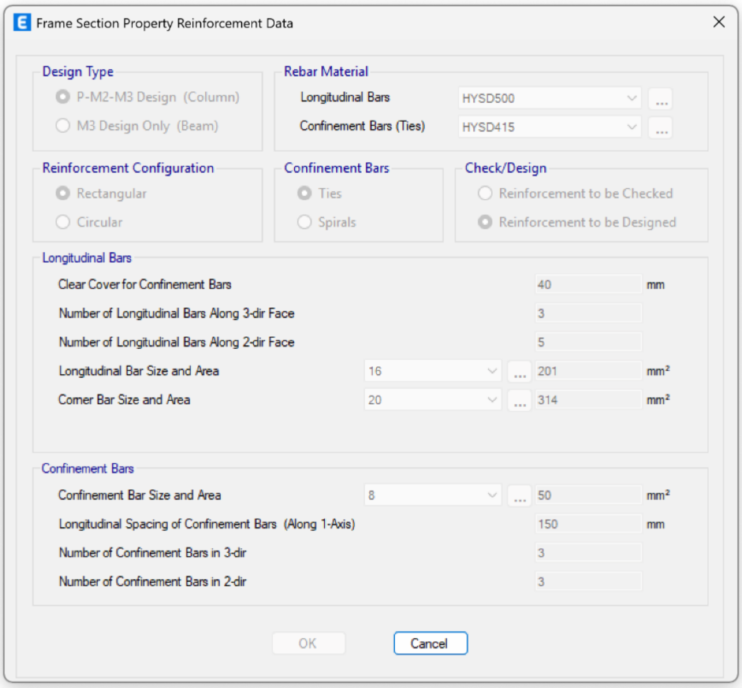


Fig. 11: Reinforcement Property Assign for Column 300x600

3.4. SLAB PROPERTY

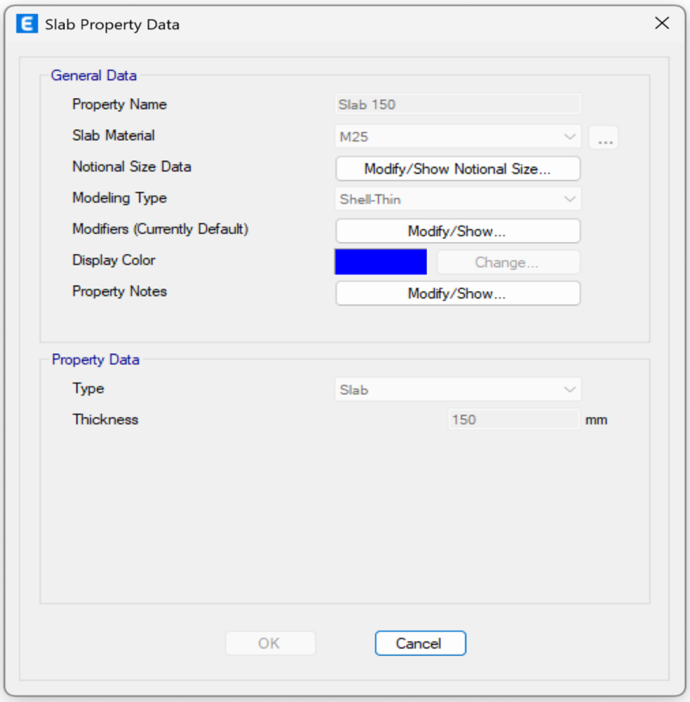


Fig. 12: Property data of Slab 150

3.5. SHEAR WALL PROPERTY

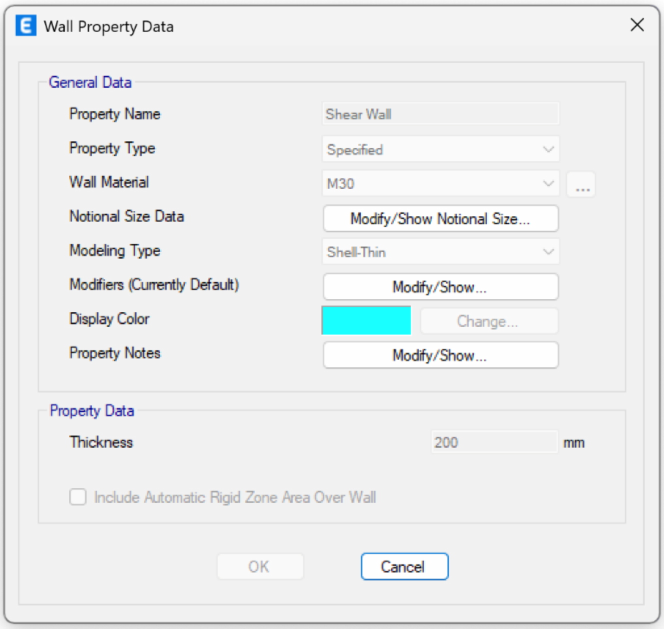


Fig. 13: Property data of Shear Wall 200

3.6. RESPONSE SPECTRUM FUNCTION

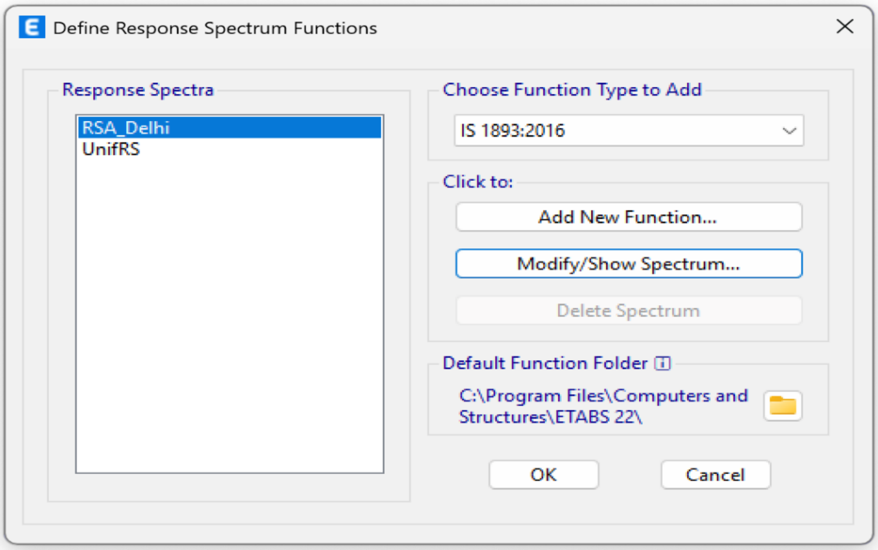


Fig. 14: Response Spectrum Function

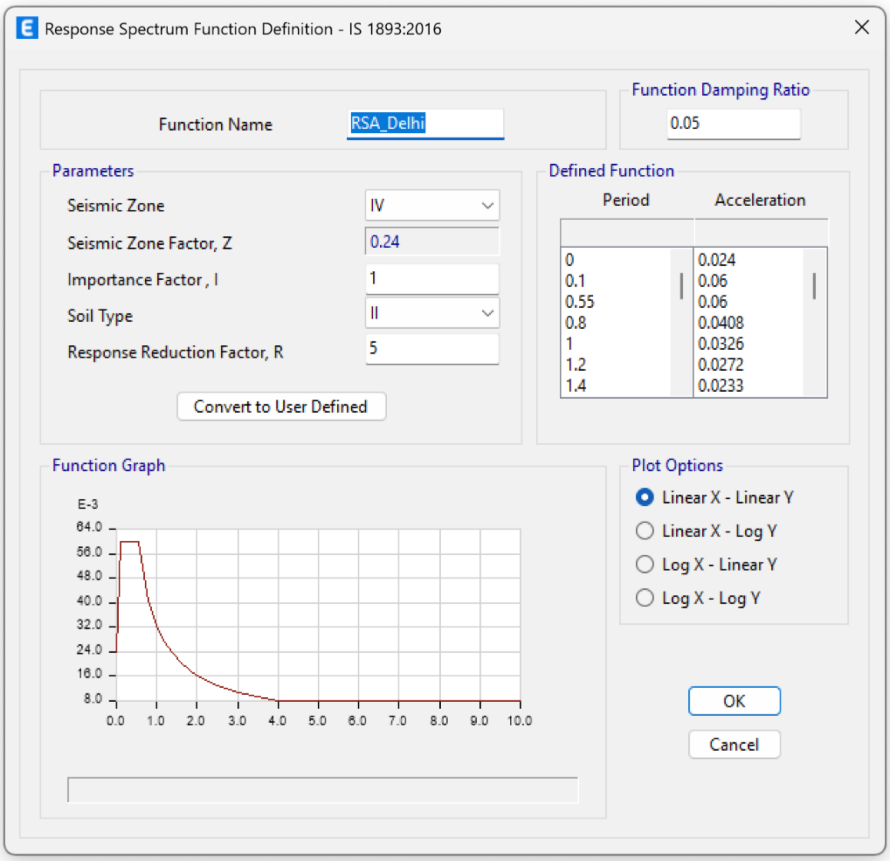


Fig. 15: Response Spectrum Function Definition As per IS 1893:2016

3.7. MASS SOURCE FUNCTION

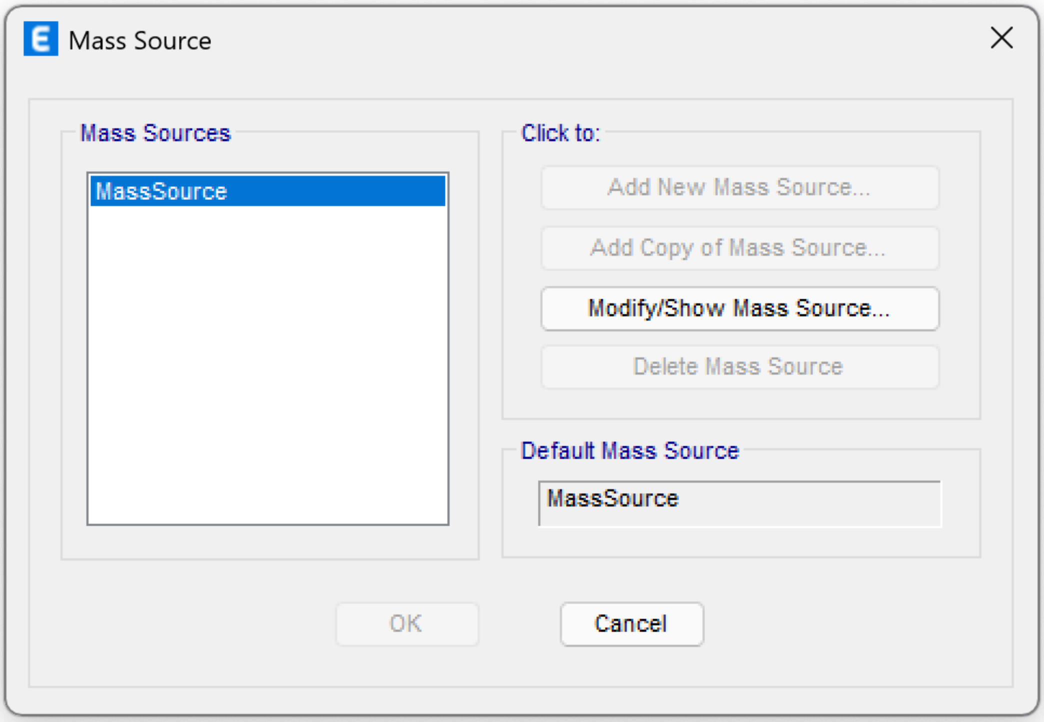


Fig. 16: Mass Source Function

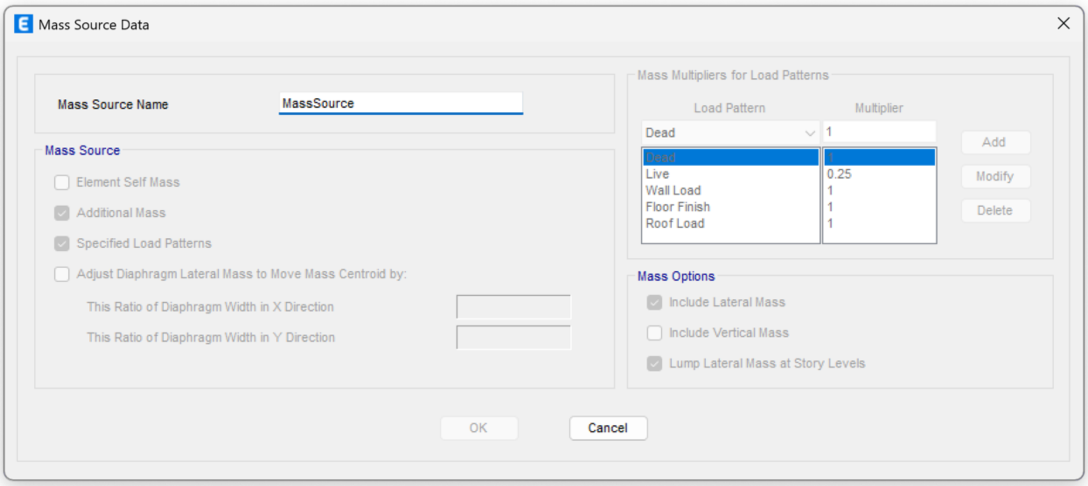


Fig. 17: Mass Source Data

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/m^2 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 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

$$V_B = A_h * W \tag{3.1}$$

where, V_B = Base shear on the structure

W = Seismic weight of the structure

A_h= Design horizontal seismic coefficient given in equation 3.2

$$A_h = \frac{\frac{Z}{2} * \frac{S_a}{g}}{\frac{R}{I}} \tag{3.2}$$

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.

Table 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

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

$$T_a = \frac{0.075h^{0.75}}{\sqrt{A_w}} \geq \frac{0.09h}{\sqrt{d}} \tag{3.3}$$

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

$$A_w = \sum_{i=1}^{Nw}\left[A_{wi}\left\{0.2+\left(\frac{L_{wi}}{h}\right)^2\right\}\right] \tag{3.4}$$

A_{wi} = Cross-sectional area of ith shear wall in first story of building.

L_{wi} = Length of ith 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,

$$T_a = 0.0675h^{0.75} \tag{3.5}$$

From IS 1893-2016, $\frac{S_a}{g} = 0.938$ for both X and Y direction. Equation 3.1 gives the value of Design Base Shear, **V_{BX} = 1616.69 kN and . V_{BY} = 1616.69 kN.**

3.9. MODELING OF SOIL

The boundary conditions from the structure are eliminated after importing the ETABS structure into the geotechnical program PLAXIS. 3D elements with three degrees of freedom per node are used to simulate the continuum soil. The depth is three times the maximum dimension of the structure in plan, and the soil domain is five times the length and width of the structure. The basement plan's dimensions are 65 m by 52 m, which corresponds to a comparable soil domain that is 325 m long and 260 m wide. It is assumed that the soil domain extends 200 meters vertically. The tower, embedded basement, and continuum soil state are depicted in Fig. 18. Soil is modelled using linear elastic material and a uniform soil layer of 200 m is used for analysis.

The first kind of soil is a representation of stiff rock, which aids in mimicking the structure's rigid base condition. Medium stiff and soft soil qualities are represented by the other two soil attributes.

The columns and shear walls are imprinted on a raft that is one meter thick and put beneath the tower and basement structure. Modeling the interface element—that is, the structure—between the soil layer and the basement wall is one of the most crucial parts of modeling. The relative stiffness of the soil and structural parts determines the application of interface elements. 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.

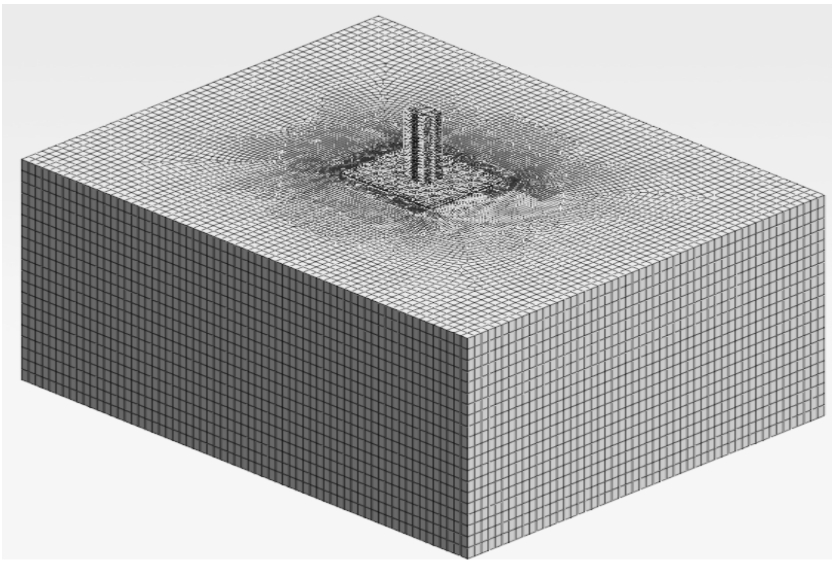


Fig. 18: Continuum approach of soil modeling

Table 4: 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

$$k_n = {E_{oed}}/{t_v} \tag{3.6}$$

$$E_{oed} = 2G_i \frac{1-\nu_i}{1-2\nu_i} \tag{3.7}$$

Where ν_i is the interface Poisson's ratio taken as 0.45 to prevent numerical errors

t_v = Virtual thickness = (0.01 – 0.1)

$$G_i = R \times G_{soil} \tag{3.8}$$

where, *R* is the strength reduction factor.

Table 5: Strength reduction factor for different material interface

Material	R
Sand – Steel	0.6 – 0.7
Clay – Steel	0.5
Sand – Concre	0.8 – 1.0
Clay – Concret	0.7 – 1.0

At every free face, the soil border remains permanent. The frequency range corresponding to the biggest amplitude in the Fourier series was used to determine the maximum size of the finite elements in order to avoid seismic waves from reflecting off building walls and floor edges. According to Kuhlemeyer and Lysmer (1973), this guarantees that the mesh size is less than either λ/8 or λ/10, where λ stands for the wavelength. This method involves modeling the soil borders using a coarser mesh size of

5 meters, as illustrated in Fig. 19, and assigning a mesh size of 2 meters to the excavated region next to the structure.

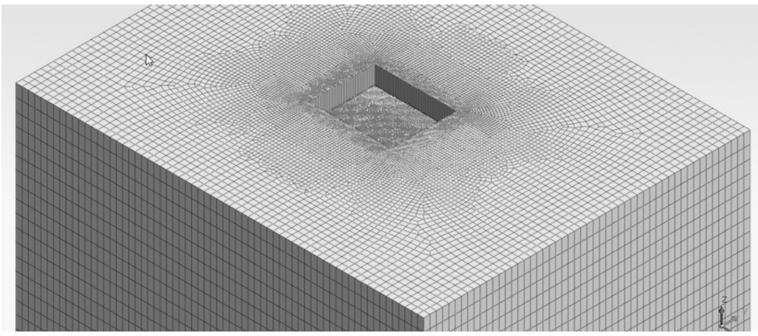


Fig. 19: Meshing of soil domain

Table 6: 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

Plane strain elements are used to model the soil, and a fixed boundary is allocated to the bottom of the soil layer. To prevent reflected wave interference in the medium depicted in Fig. 20., free field boundary conditions are applied to the soil's lateral sides. In order to conduct the linear time history analysis, Rayleigh damping was added to the soil medium. The damping coefficients are calculated using the following frequencies of interest: 0.25 Hz and 22.5 Hz. $\beta = 0.00069$ and $\alpha = 0.15$ are the coefficients. According to the acceleration-time history displayed in Fig. 21., the ground motion is applied at the base of the soil column. Fig. 22 shows the top of the soil column where the acceleration response is recorded.

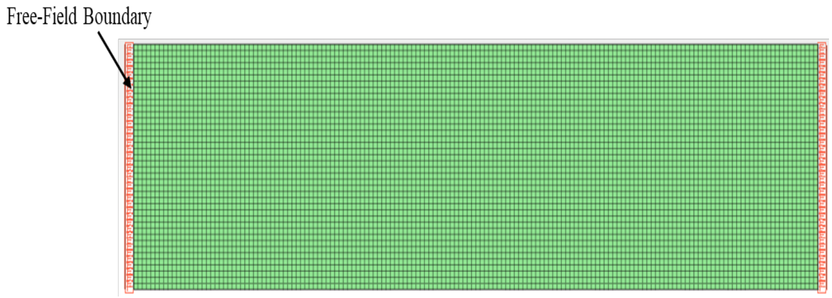


Fig. 20: 2D soil column with free field boundary

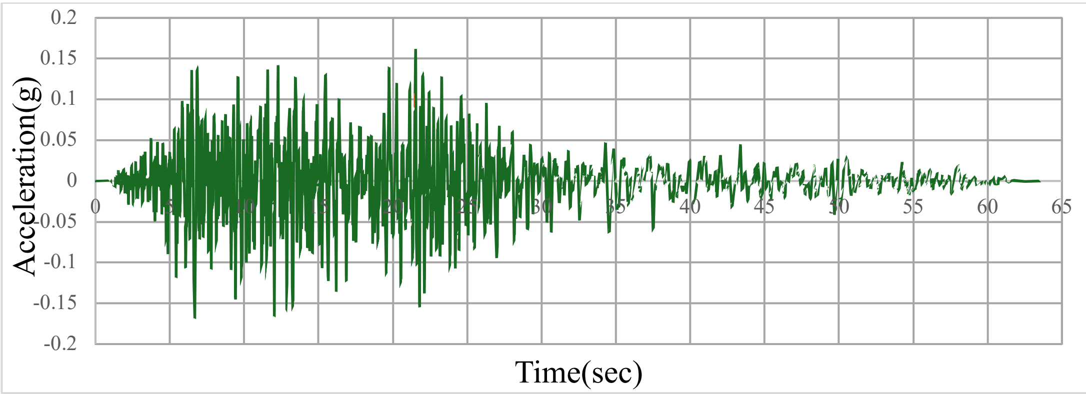


Fig. 21: Imperial Valley recorded ground motion

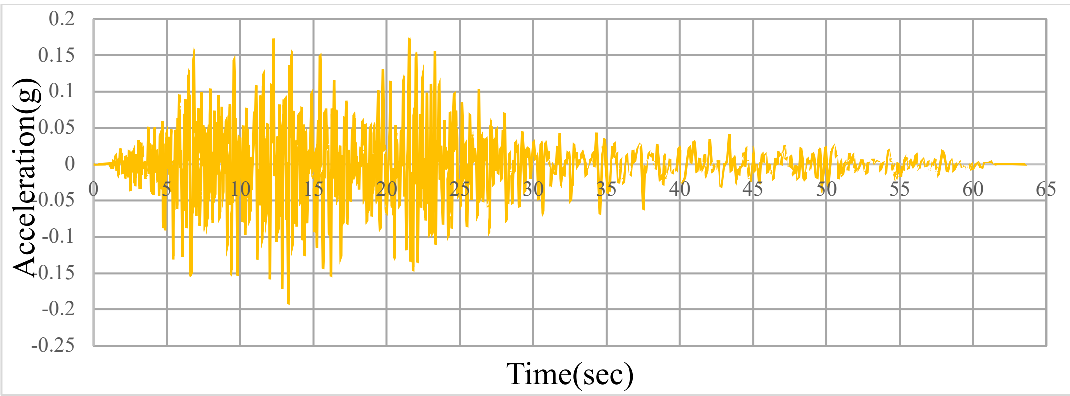


Fig. 22: Acceleration recorded at the top of soil column from PLAXIS

3.10. METHODOLOGY OF ANALYSIS

Equivalent Static Analysis

Since the linear static analysis approach mainly takes into account the fundamental mode of vibration, it is suitable for simpler and more regular structures. This method makes the assumption that identical static lateral forces imparted to the structure can be used to describe the entire seismic motion. In Equation 3.2 design horizontal seismic coefficient is equivalent to a design basis earthquake with a 475-year return time. Chapter 4 provides a detailed discussion of the findings from this investigation.

Response Spectrum Analysis

Higher modes must be taken into account using dynamic analysis methods in order to obtain a more accurate evaluation of seismic forces and structural responses in complex structures. IS 1893:2016 suggests taking into account modes with a frequency limit of 33 Hz or up to 90% mass participation. In the eighth mode, the structure in this report achieves 90% mass participation. According to the rules outlined in the relevant parts of Indian standard codes and procedures, a linear response spectrum analysis is thus carried out on the designated structure taking into account the first eight modes. The results of this investigation are explained in full in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

The dynamic properties obtained from the analysis procedures mentioned in chapter 3 are discussed in this chapter. Fig. 23 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.

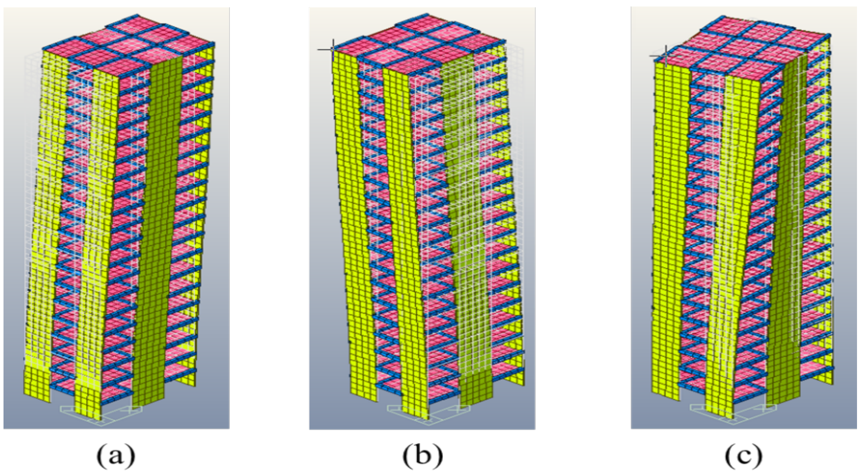


Fig. 23: Mode shapes of fixed base tower in: (a) translation in X; (b) translation in Y; and (c) Rotation about Z

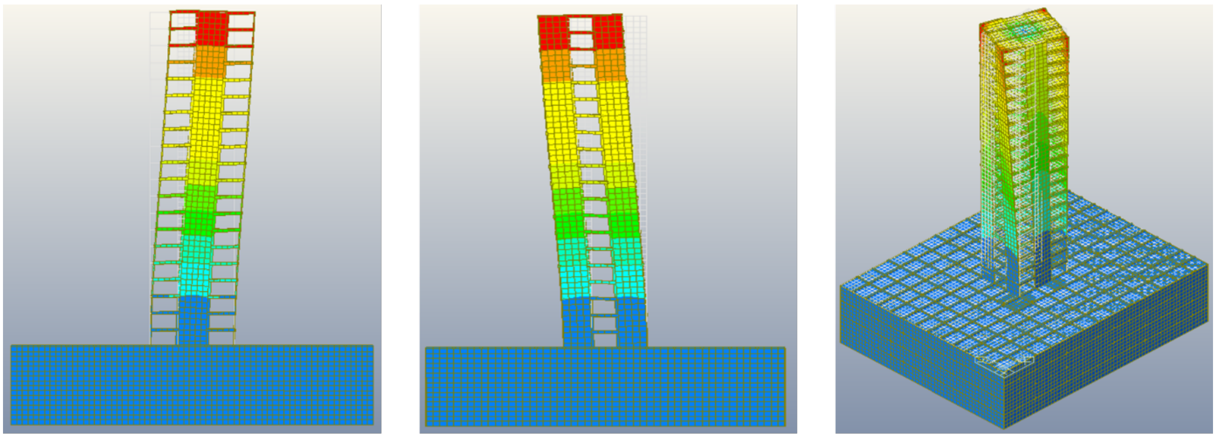
Table 7: Dynamic properties of the fixed base tower

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

Fig. 24 shows the first three fundamental mode shapes of the fixed base tower structure along with basement levels.



(a) (b) (c)

Fig. 24: Mode shape of tower and basement with fixed base: (a) translation in X;

Table 8 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 8: 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 6. 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.

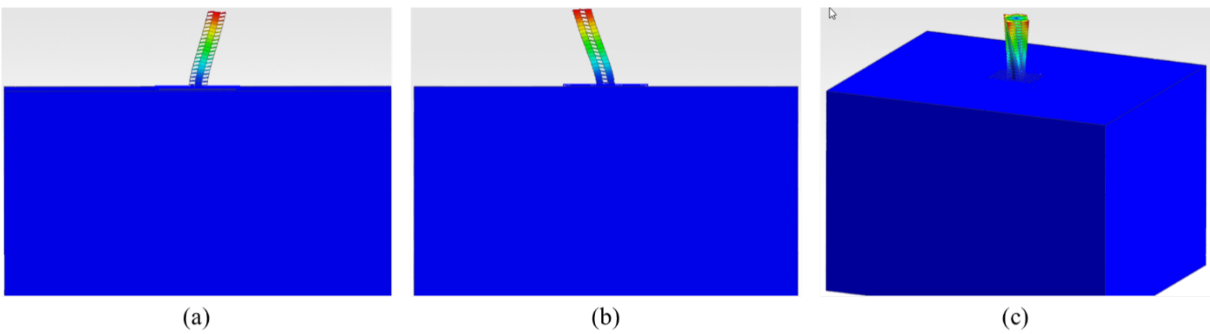


Fig. 25: Mode shape of tower and basement with soil continuum: (a) translation in X;

Fig. 25 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 9 shows the dynamic properties of the soil-structure model with increasing flexibility of soil.

Table 9: 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 10.

Table 10: 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	67.12	55.83

m/s)		
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.

CHAPTER 5

CONCLUSION

This research provides an in-depth examination of the influence of soil-structure interaction (SSI) on the dynamic behavior of a high-rise tower with a basement, using both fixed-base assumptions and continuum soil modeling approaches. The comparative analysis using ETABS and PLAXIS reveals that SSI significantly alters the structural response, especially when basement levels and varying soil conditions are considered.

The dynamic properties derived from eigenvalue analyses demonstrate that introducing basement levels increases the structure's fundamental period and reduces modal frequency. This effect becomes more pronounced when the structure is supported on medium to soft soil layers, where soil flexibility contributes to greater period elongation and increased modal mass participation. Notably, while the direction of mode shapes remains largely unchanged, the magnitude of dynamic responses shifts considerably with soil stiffness.

The displacement data further reinforce these findings. As the underlying soil transitions from rigid rock (Vs = 600 m/s) to softer conditions (Vs = 200 m/s), maximum roof displacements increase markedly—from approximately 56 mm to over 88 mm. This clearly indicates that neglecting SSI, particularly in softer soil profiles, can result in significant underestimation of lateral deformations and potential performance deficiencies during seismic events.

Moreover, the modeling of interface elements between the basement walls and soil domain played a crucial role in simulating realistic frictional behavior and stress transfer. The continuum modeling approach proved essential in capturing these effects, as it accommodates the distribution of stresses and strains within the soil body, unlike simplified spring-based models.

In conclusion, this study confirms that SSI has a considerable impact on both the global dynamic characteristics and localized displacement behavior of tall structures with basements. For structures built in seismic zones or on non-rigid foundations, it is essential to move beyond the fixed-base idealization. Integrating continuum-based SSI modeling into structural design not only enhances safety and serviceability but also aligns with the principles of performance-based engineering. The insights from this research advocate for more widespread adoption of SSI-aware methodologies in both academic research and professional practice, particularly for high-rise developments in geotechnically sensitive areas.

CHAPTER 6

FUTURE SCOPE OF WORK

While this study has comprehensively explored the role of soil-structure interaction (SSI) in high-rise buildings with basement levels using both fixed-base and continuum modeling approaches, several areas offer potential for further exploration and advancement:

1. **Nonlinear Soil Behavior and Liquefaction Effects**: The present study employed linear elastic models for soil. However, real-world seismic events often induce nonlinear behavior in soil, particularly in soft or loose strata. Future studies could incorporate advanced constitutive models capable of capturing plasticity, strain-softening, and liquefaction phenomena to better simulate extreme seismic responses.

2. **Time-History Analysis with Site-Specific Ground Motions**: Although response spectrum analysis provides valuable insights into modal behavior, it is limited in capturing transient seismic effects. Future research can utilize nonlinear time-history analysis using real or site-specific synthetic ground motions to observe structure-soil interaction under realistic dynamic loading conditions.

3. **Effect of Groundwater Table and Pore Water Pressure**: The influence of groundwater on basement walls, effective stress conditions in soil, and pore water pressure buildup during seismic shaking was not considered in this study. Future investigations can integrate hydro-mechanical coupling to evaluate how fluctuations in the water table and excess pore pressures affect basement behavior and foundation performance.

4. **SSI in Irregular and Asymmetric Structures**: This study focused on a regular tower geometry. Real-world buildings often exhibit irregularities in plan and elevation,

which may amplify SSI effects. Further work can address the implications of geometric and mass irregularities on seismic performance under SSI conditions.

5. **Comparative Evaluation of Different Foundation Systems**: While this research adopted a raft foundation, future studies may explore the comparative impact of pile foundations, combined pile-raft systems, and deep caisson foundations under varying soil profiles to determine the most effective strategies for mitigating SSI.

6. **Parametric Sensitivity Studies and Optimization**: A more systematic parametric study could be conducted to examine the sensitivity of structural response to variables such as basement depth, soil stiffness, damping ratios, and structural stiffness. These studies could be used to develop optimization frameworks for performance-based design.

7. **Inclusion of Soil Creep and Long-Term Settlement**: SSI is not only a dynamic concern but also affects long-term structural integrity. Incorporating time-dependent behaviors like soil creep and consolidation could help assess differential settlement and its impact on serviceability over the building's lifespan.

8. **Code Development and Design Guidelines**: The findings from this study can be extended to support the development of practical design guidelines or code provisions for incorporating SSI effects in seismic analysis, especially for basement structures in high-rise buildings. Future work may involve validating these recommendations through shake table experiments or field instrumentation data.

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