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Numerical Study of the Dynamic Behavior of a Reinforced Concrete Structure Considering Soil -Structure-Interaction

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Abstract

The dynamic response of structures during seismic events is significantly influenced by the interaction between the structure and the supporting soil known as Soil Structure Interaction (SSI). This thesis investigates the effects of SSI on the seismic behavior of reinforced concrete frame buildings using linear dynamic analysis methods. The study aims to highlight the importance of incorporating SSI into structural analysis as neglecting it can lead to unsafe or overly conservative designs.

To achieve this , two numerical models were developed using SAP2000: a fixed base model and a flexible base model incorporating the Winkler spring approach to simulate soil flexibility. The influence of SSI was assessed through three types of dynamic analyses: modal analysis, response spectrum analysis, and linear time history analysis. Key parameters such as the subgrade reaction modulus (ks) and foundation thickness were varied to evaluate their impact on the structural response.

The results demonstrate that SSI significantly affects the natural period, lateral displacement and overall dynamic behavior of the structure. Flexible base models exhibited increased displacements and longer natural periods compared to fixed base models especially for softer soils. These findings underscore the necessity of considering SSI in seismic design particularly for buildings on flexible soil profiles.

This thesis provides valuable insights into the role of SSI in seismic performance evaluation and reinforces the need for its inclusion in both design practice and seismic code development.

Keywords: Soil-Structure Interaction (SSI) seismic response, reinforced concrete frame, SAP2000, Winkler model, subgrade reaction modulus, fixed base, flexible base , dynamic analysis.

الملخص

يتأثر السلوك الديناميكي للهياكل خلال الزلازل بشكل كبير بالتفاعل بين المنشأة والتربة الداعمة، والذي يُعرف باسم تفاعل التربة مع المنشأة (SSI). تهدف هذه الأطروحة إلى دراسة تأثير SSI على الاستجابة الزلزالية لمباني الهياكل الخرسانية المسلحة ذات الإطارات، باستخدام طرق التحليل الديناميكي الخطي. وتبرز هذه الدراسة أهمية أخذ SSI بعين الاعتبار في التحليل الإنشائي، حيث إن تجاهله قد يؤدي إلى تصميمات غير آمنة أو مفرطة في التحفظ.

تم تطوير نموذجين عدديين باستخدام برنامج SAP2000: نموذج ذو قاعدة ثابتة، ونموذج ذو قاعدة مرنة يأخذ في الاعتبار مرونة التربة من خلال استخدام نماذج نوابض وينكلر. تم تقييم تأثير SSI من خلال ثلاثة أنواع من التحليل الديناميكي: التحليل النمطي، تحليل طيف الاستجابة، والتحليل الزمني الخطي. كما تم تغيير بعض المعاملات الرئيسية مثل معامل رد فعل التربة (ks) وسُمك الأساسات لدراسة تأثيرها على الاستجابة الزلزالية.

أظهرت النتائج أن SSI يؤثر بشكل كبير على الفترة الطبيعية، والإزاحة الجانبية، والسلوك الديناميكي العام للمنشأة. حيث أظهرت النماذج ذات القاعدة المرنة إزاحات أكبر وفترات طبيعية أطول مقارنة بالنماذج ذات القاعدة الثابتة، لا سيما في حالة الترب الطرية. وتؤكد هذه النتائج على ضرورة تضمين تأثير SSI في التصميم الزلزالي، خصوصًا للمباني المشيدة على تربة مرنة.

توفر هذه الدراسة رؤى مهمة حول دور SSI في تقييم الأداء الزلزالي، وتدعم الحاجة إلى أخذه بعين الاعتبار في الممارسات التصميمية وتطوير الأكواد الزلزالية.

الكلمات المفتاحية: تفاعل التربة مع المنشأة (SSI)، الاستجابة الزلزالية، الخرسانة المسلحة، SAP2000، نموذج وينكلر، معامل رد فعل التربة، قاعدة ثابتة، قاعدة مرنة، التحليل الديناميكي .

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Chapter I : Generality of soil structure interaction

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General Introduction

General Introduction

When a structure is subjected to seismic loading, its response is not only influenced by its own dynamic characteristics but also by the behavior of the soil it rests upon.

The complexity of the soil-structure interaction problem lies in the integration and coupling of the two elements: the soil and the structure. This phenomenon describes the effects that occur at the contact interface between the soil mass and the structure. Therefore, in the analysis of dynamic response, not only the structural properties must be considered, but also the properties of the underlying soil.

Soil-structure interaction can contribute to either amplifying or reducing the dynamic response of the structure. The seismic behavior of a structure depends on the seismic motion imposed by the ground, the dynamic response of the structure, the performance of the foundations during and after the earthquake, and the resistance capacity of the superstructure. Considering the characteristics of the soil, which play a significant role in the structural response, is thus particularly important in the study of soil-structure interaction effects on the seismic response of a structure.

The study of SSI has become increasingly important, particularly in the context of earthquake engineering, where ignoring SSI can lead to under- or overestimation of seismic demands on structures.

In this study , the influence of Soil-Structure Interaction (SSI) on the dynamic response of a reinforced concrete frame-type building is examined through linear dynamic analyses performed using the SAP2000 software. Three analysis approaches were adopted: modal analysis, response spectrum analysis, and linear time history analysis. Two numerical models were developed: a fixed-base model and a flexible-base model incorporating the Winkler spring approach. To clearly present the content of this study and organize it in a systematic manner, this work is divided into several chapters as follows:

Chapter 1 : introduces the fundamental concept of Soil-Structure Interaction (SSI). It outlines the key mechanisms of SSI, inertial and kinematic interactions and highlights their impact on the dynamic response of structures. The chapter also presents various analytical and numerical methods used in SSI analysis such as the Winkler model, p-y method, and Finite Element Method (FEM) and summarizes commonly used SSI models .

Chapter 2 : focuses on a comparative review of major international codes and standards, presenting how soil-structure interaction (SSI) is addressed in seismic design. It highlights key similarities and differences in the treatment of SSI in standards such as ASCE 7-22, ASCE 41-17, and JSCE 15, as well as codes like Eurocode 8 and IS 1893.

Chapter 3 : provides a comprehensive literature review of previous studies on soil-structure interaction (SSI) in seismic design. It analyzes experimental, analytical, and numerical research focused on the effects of SSI on reinforced concrete structures. This chapter synthesizes past findings to underscore the importance of SSI in seismic analysis and design .

Chapter 4 : presents a focused literature review on the Winkler foundation model and the subgrade reaction modulus (ks). It examines the development, application and evaluation of the Winkler method in soil-structure interaction modeling, emphasizing various empirical approaches to estimate ks for different soil and foundation conditions.

Chapter 5 : investigates the effect of soil-structure interaction (SSI) on the seismic response of a multi-storey reinforced concrete frame building. Using SAP2000, two numerical models fixed-base and flexible-base with the Winkler spring approach were developed to simulate the dynamic behavior under seismic loading. The chapter validates the modeling approach, details soil and foundation parameters, and applies three linear dynamic analysis methods: modal analysis, response spectrum analysis, and linear time history analysis. It assesses how varying the subgrade reaction modulus (ks) influences also explores foundation thickness on the seismic response of the structure.

Chapter I:

Generality of soil structure interaction

1.1 Introduction:

When an earthquake happens, the movement of the ground transmits to the building through its foundation (Firoozi et al, 2023) . The seismic response of building structures depends on the nature of the ground motion, the mechanical and physical properties of the structure, and those of the soil (Tamahloult, 2011) . Consequently ,the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil. This is called as soil-structure interaction (SSI) (Fu, 2018) . Soil-structure interaction (SSI) is a research field that has been thoroughly studied by numerous authors, defining practically all possible effects it can have on buildings and structures of various types (Shendkar, 2023) .The effects of soil-structure interaction (SSI) on seismic response were not seriously considered until the 1971 San Fernando earthquake and the beginning of nuclear construction in California. The catastrophic consequences of several recent earthquakes in different regions of the world have posed a serious problem to civil engineering structural engineers in consulting firms. This problem has focused on how to take into account the effect of soil-structure interaction (SSI) on the final seismic behavior of structures when an earthquake occurs (Tamahloult, 2011).

1.2 Soil-Structure Interaction :

Soil-Structure Interaction (SSI) is a critical field of study in applied mechanics that examines how the interaction between a structure and its foundation soil influences seismic response. Over the last thirty years, researchers and engineers have displayed a keen interest in how soil-structure interaction (SSI) affects the seismic response of structures (Abdulaziz et al, 2023) . It is a discipline of applied mechanics concerned with the development and investigation of theoretical and practical methods for the analysis of structures subjected to dynamic loads, taking into account the behavior of the foundation soil (Arabi & Boulefred 2015) . Soil-Structure Interaction (SSI) is an important factor on the seismic behavior of structure and an outstanding factor that affects both linear and non-linear performance of any structure, It has a significant detrimental effect on the behavior of structures, specifically tall or massive structures, resting on soft soil and structural safety could not be assured by eliminating this phenomenon. (Fathi et al, 2020) . Also soil-structure interaction (SSI) can make a substantial difference in how buildings behave during earthquake shaking and how they should be designed . (Fema, P-2091) .

1.3 Mechanisms of Soil-Structure Interaction :

From a geotechnical perspective, SSI occurs as seismic waves propagate through the soil-structure system, influencing structural response through multiple mechanisms. These include :

1.3.1 Seismic Wave Propagation: SSI occurs as seismic waves travel through the soil-structure system, influencing structural response through:

- **a) Wave Dispersion:** Foundation disperses incident waves.
- **b) Wave Transmission**: Seismic waves are transmitted to the superstructure.
- **c) Energy Radiation**: Vibrational energy is radiated back into the ground.

1.3.2 Key Factors: The extent of SSI effects depends on:

a) Stiffness of the soil and structure.
b) Characteristics of the seismic load.

To better understand this mechanism SSI, a visual representation is often helpful. This section introduces Figure 1, which illustrates a typical SSI scenario involving a raft-type foundation supported by piles embedded in layered soil. This figure highlights how seismic waves travel through the soil and affect the structure, providing a clear depiction of the SSI problem.

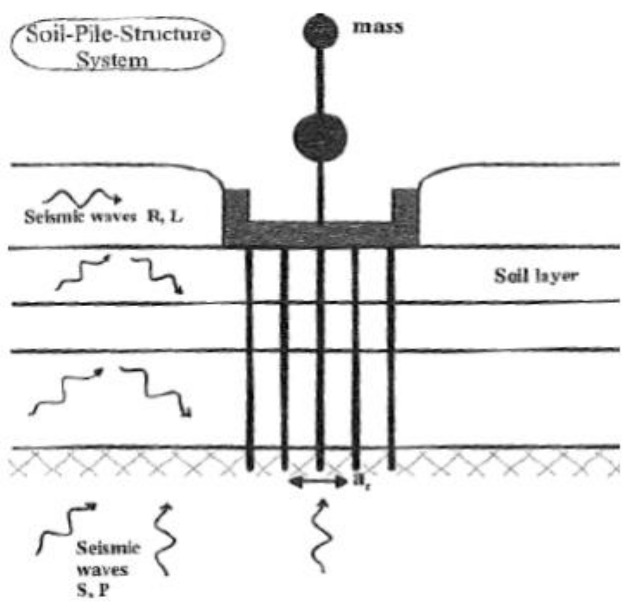


Figure 1.3 Illustration of the SSI

The layer of soil around the structure is subjected to several types of seismic waves:

- Shear waves: S waves
- Primary Waves: P waves
- Surface waves: Rayleigh Waves (R-Waves) or Love Waves (L-Waves)

As seismic waves travel through the soil layers, these waves induce motion in the soil, which in turn affects the piles and ultimately the structure above. The nature of these waves is dictated by seismic conditions, the geometry, stiffness, and damping of the soil play a crucial role in modifying their behaviour under seismic loads (Baghdadi 2015) . In the case of pile-supported foundations, additional complexity arises as the piles interact with the propagating seismic waves beneath the base slab. This interaction can further alter the foundation-level motions, modifying the input motions at the base of the structure.

The response of a structure to seismic action depends on many parameters such as:

- The nature of seismic movement .
- The dynamic properties of the construction .
- The dynamic properties of the soil .

The combined impact of these factors results in free-field ground motion, which subsequently alters structural response. Specifically, foundation flexibility and differences between free-field and foundation motion affect structural accelerations. Consequently, a precise evaluation of inertial forces and displacements necessitates a rational approach to addressing SSI effects.

1.4 Inertial and Kinematic Interaction :

Structure on soil exhibits two kinds of interaction effects known as kinematic and inertial effects.

1.4.1 Inertial interaction : refers to the dynamic interaction between a structure, its foundation, and the surrounding soil due to the inertia developed in the structure during seismic excitation.This interaction occurs because the vibrating structure generates base shear, moment, and torsional forces, which in turn induce displacements and rotations at the soil-foundation interface characteristics of inertial interaction :

- ***Period Lengthening*** **:** The building's natural period increases due to the flexibility of the foundation.
- ***Radiation Damping*** : The damping in the soil-structure system caused by the generation and propagation of waves away from the foundation, which result from dynamic displacements of the foundation relative to the free-field displacements.
- ***Soil Damping*** **:** The hysteretic (material) damping of the soil, similar to inherent viscous damping in the superstructure, but independent of the flexible-base period of the structure**.**

1.4.2 Kinematic interaction

: refers to the modification of free-field ground motion due to the presence of a structure's foundation. Free-field motion is the ground motion at the surface in the absence of a structure and its foundation. When considering soil-structure interaction (SSI), the structural response differs from that based on free-field motion alone.

Kinematic interaction is independent of the structure's mass and is influenced by factors such as its geometry, foundation embedment the composition of incident free-field waves, and the angle of incidence of these waves. It can generally be neglected for structures without embedded foundations and when subjected to vertically propagating shear waves.

Kinematic interaction alters free-field ground motion, transforming it into foundation input motion due to spatial variations in seismic waves. This interaction consists of two primary effects :

- ***Base-Slab Averaging:*** Spatially varying ground motions within the building footprint are averaged out due to the stiffness and strength of the foundation system. This averaging effect reduces the variability of ground motions experienced by the foundation.
- ***Embedment Effects:*** Foundation-level motions are reduced because ground motions typically decrease with depth below the free surface. For embedded foundations, these results in lower amplitudes of motion compared to the free-field surface motions.

When analysing the seismic behaviour of structures, kinematic and inertial effects associated to soil–structure interaction (SSI) affect the dynamic characteristics of the interacting system and influence the ground motion around the foundation.

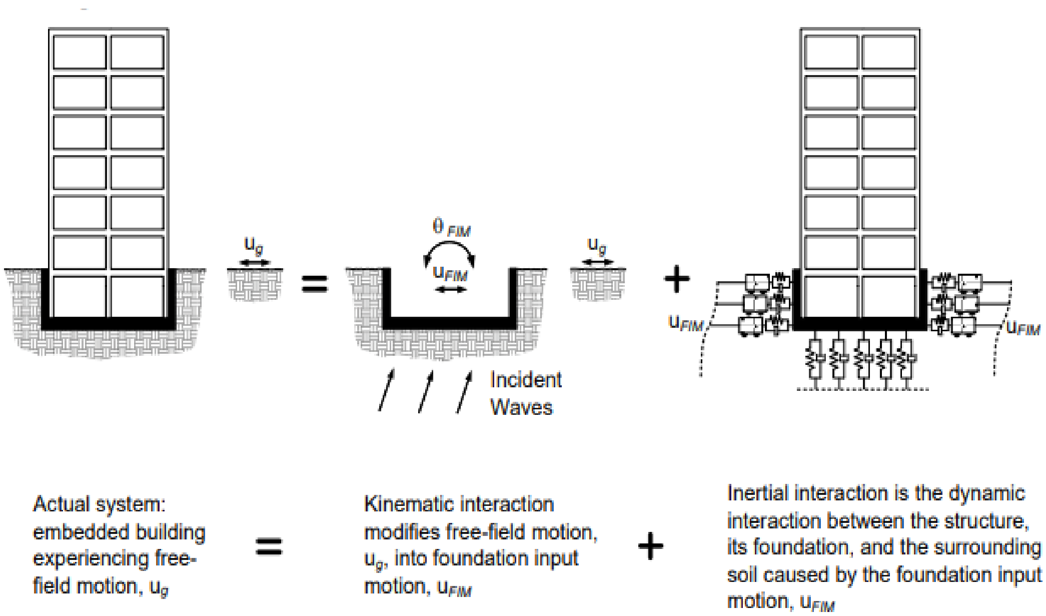


Figure 1. 4 Illustration of free-field motion and its relationship to kinematic interaction and inertial interaction (Fema P-2091)

1.5 Factors Influencing Seismic Response :

The seismic response of a structure is influenced by a combination of factors, including the properties of the soil layers, local site conditions, and SSI effects. the Shema below show this factor . The figure below summarizes these key factors.

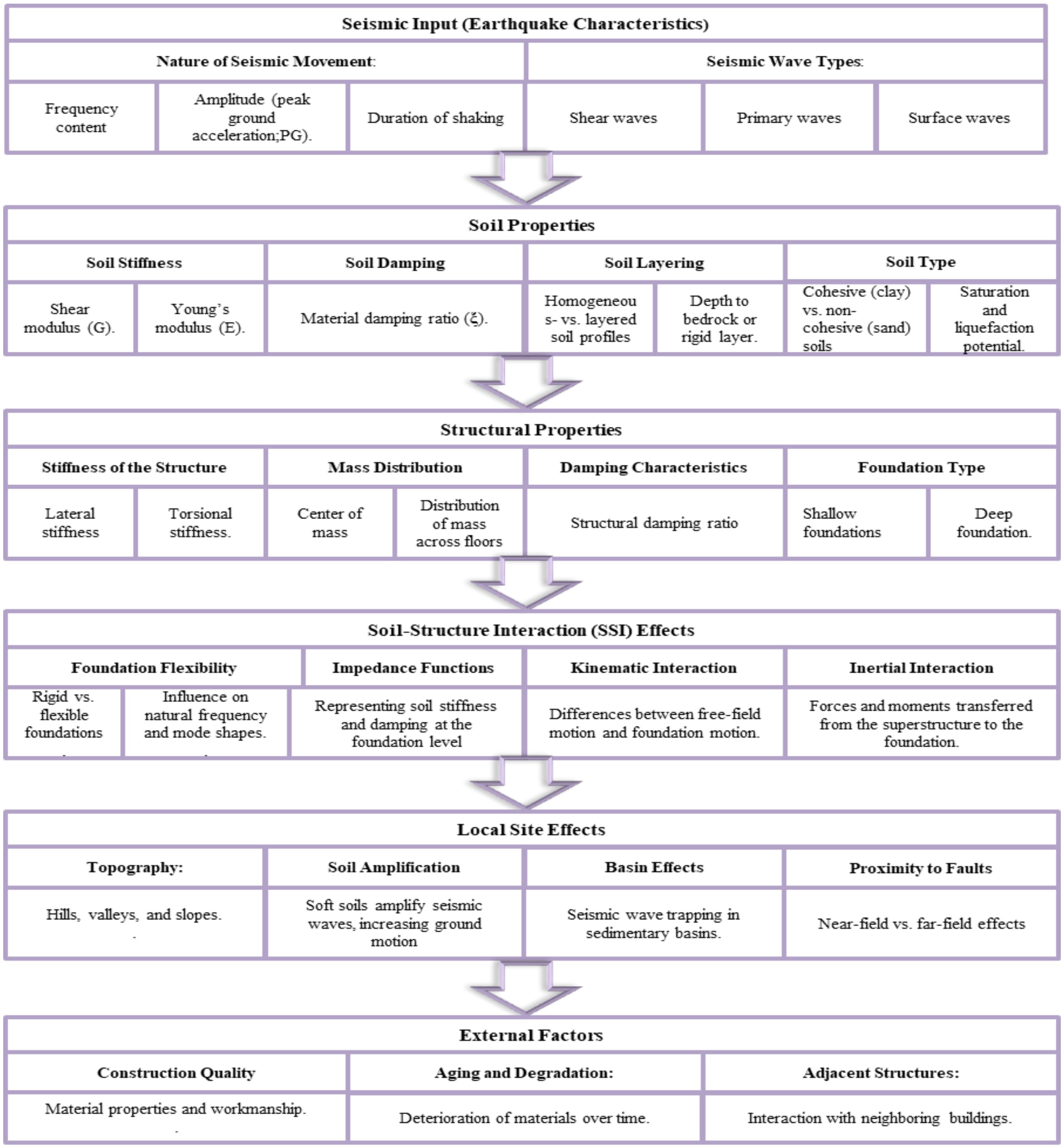


Figure 1.3 Key Factors Influencing the Seismic Response of Structures

1.6 Modern Seismic Design Codes and SSI

Modern seismic design codes acknowledge the importance of Soil-Structure Interaction (SSI) and provide guidelines for incorporating its effects into structural analysis. But unfortunately, code provisions relating to soil-structure interaction nowadays are still very limited, and straightforward procedures to account for soil-structure interaction in design are not included in most codes.

1.7 Effects of SSI:

Soil-structure interaction (SSI) plays a crucial role in seismic analysis, influencing the dynamic characteristics of structures and their response to ground motion. (Khalil et al.2007)

In general, the ISS trains:

- An elongation of the vibration period of the first mode in particular, which can cause a variation either increasing or decreasing the value of the acceleration depending on the zone where we stand on the elastic spectrum.
- A significant damping (radiative damping + damping specific to the soil material) since it is always greater than that of the structural materials. Not taking it into account leads to overestimating the response.
- A rotation of the foundation that can significantly alter the calculation of the modal deformation and thus the distribution of accelerations along the height of the structure.
- A ground movement at the base of the structure assumed to be identical to that in free field; in common cases, this approximation is considered acceptable.

SSI is often considered beneficial; that taking into account the SSI generally allows for a reduction in stresses through dissipation at the ground level and a more favorable spectral reading.

Indeed, it can be seen in Figure 2 that taking the ISS into account allows for an increase in the natural oscillation period of the structure, which in most cases decreases the value of the seismic response. Moreover, in this same figure, it can be seen that with greater damping, the response is also weaker.

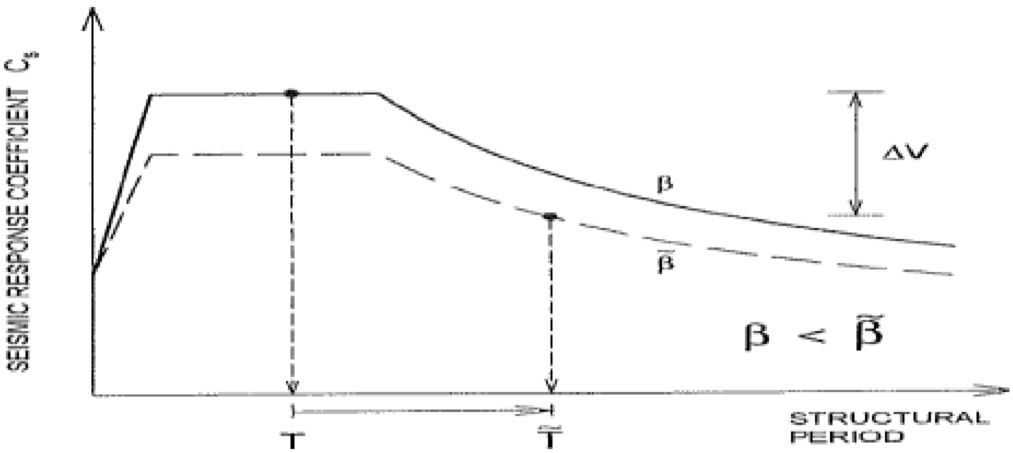


Figure 1. 4 Spectral lecture showing the effects of considering the SSI

Case studies from earthquakes such as the Bucharest 1977, Mexico City 1985, and Kobe 1995 events demonstrate that SSI can sometimes be detrimental, leading to unsafe structural performance and foundation failure, particularly for structures founded on soft soils (Mylonakis & Gazetas, 1998). Soft soils amplify seismic waves and increase the deformation of structures, whereas firm soils may reduce base shear (Li et al., 2014).

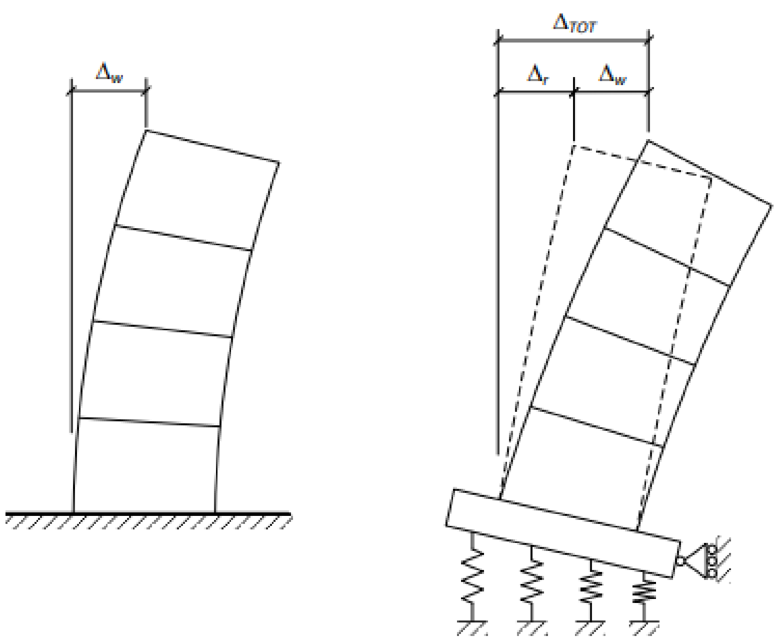


Figure 1. 5 A structure where soil flexibility will have a significant impact on the lateral displacement and fundamental period of the structure. (Fema P-2091)

The effect of soil-structure interaction (SSI) on the seismic response of buildings is evident in the cracking pattern of the shear walls. Research has demonstrated that SSI can significantly change these patterns, depending on the stiffness of the foundation and the type of soil. Rigid/strong foundation structures experience high base shear forces, causing shear wall damage, while flexible/weak foundations allow for foundation yield and rocking, which protects the shear walls

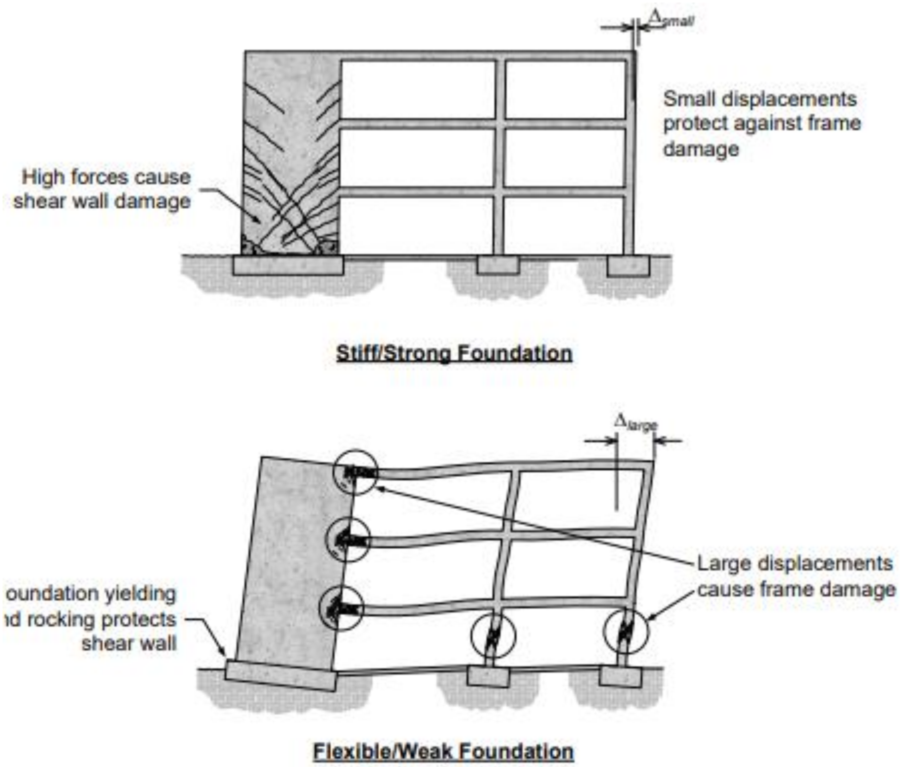


Figure 1. 6 The significant impact of soil flexibility on a reinforced concrete shear wall system (ATC, 1996).

Recent studies indicate that its effects can be detrimental, especially for buildings on soft soil. Neglecting SSI in seismic design can lead to unsafe structural performance and foundation failure (Ali et al 2023).

This soil-structure interaction is more or less significant depending on several factors:

- Soil Type: Soft soils tend to amplify seismic waves, while firm soils may reduce base shear.

- Structural Characteristics: Tall and heavy structures experience greater SSI effects than short and light ones.
- Foundation Mode (Foundation Impedance): The type of foundation affects how energy is dissipated at the ground level.

1.8 Method of analysis of SSI problems :

Over the years, numerous methods for analyzing soil-structure interaction (SSI) have been developed, primarily falling into two main groups: direct method and substructure methods (Medina et al 2013). For a better understanding, Figure 1.2 shows the possible combinations that can arise in solutions for SSI problems.

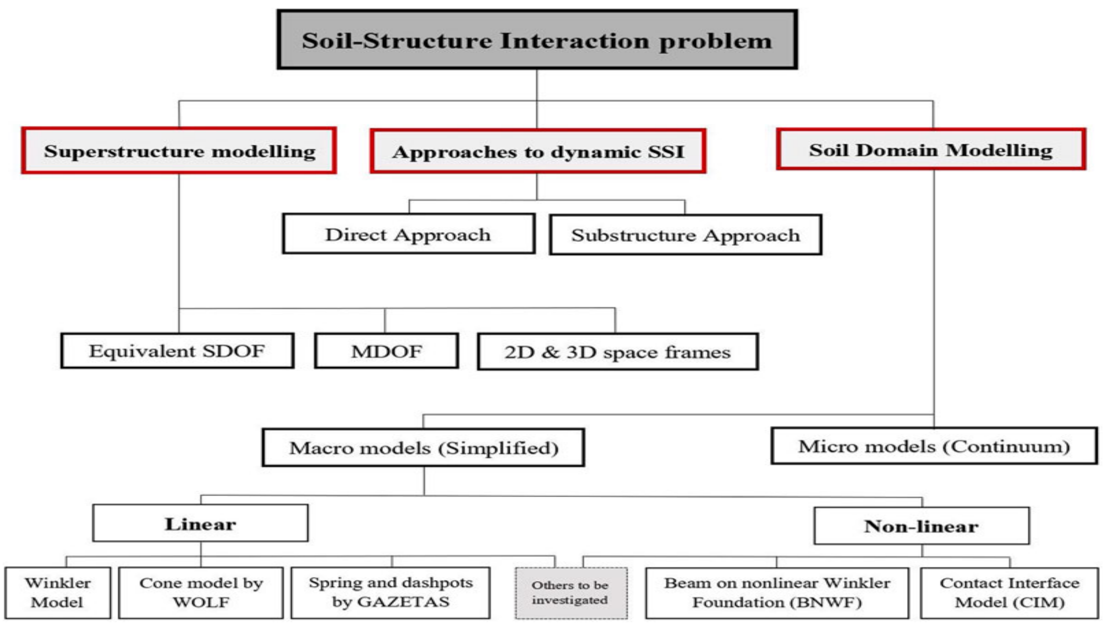


Figure 1.7 Overview on Soil-Structure Interaction problem

1.8.1 Direct method:

The direct approach is the most rigorous method for solving SSI problems, particularly for complex structural geometries and non-linear soil modeling, where both the soil and the structure are modeled using finite elements within the same system. In this approach, the soil modeling extends sufficiently around and beneath the building to account for site properties, and seismic waves are imparted at the soil boundary, exciting the soil elements, which in turn excite the structure, allowing for a comprehensive analysis of their interaction as a complete system. As schematically depicted in Figure 7, the soil is often represented as a continuum (e.g., finite elements) along with foundation and structural elements, transmitting boundaries at the limits of the soil mesh, and interface elements at the edges of the foundation.

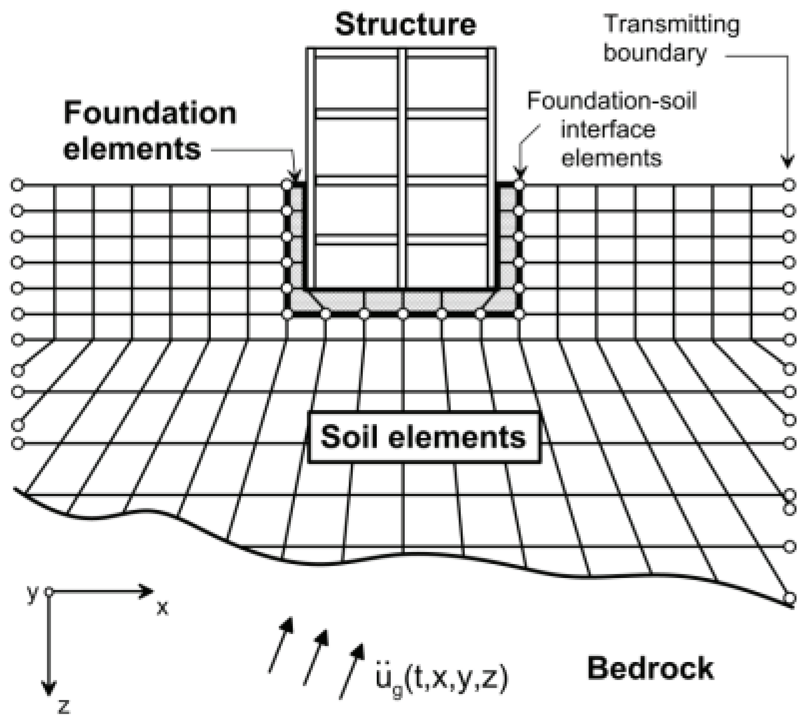


Figure 1. 8 Schematic illustration of a direct analysis of soil-structure interaction using continuum modelling by finite elements. (NIST, 2012).

1.8.2 Substructure approach

The substructure approach, also known as the indirect method, involves considering the soil and structure separately, solving them independently, and combining their effects using superposition principles to determine the final seismic response of the structure (Kramer, 1996) . This method partitions the SSI problem into distinct parts that are combined to formulate the complete solution, allowing inertial and kinematic interactions to be addressed separately using impedance and transfer functions, respectively. The solution of SSI problems with the substructure approach is broken down into three main steps as depicted in Figure 8 :

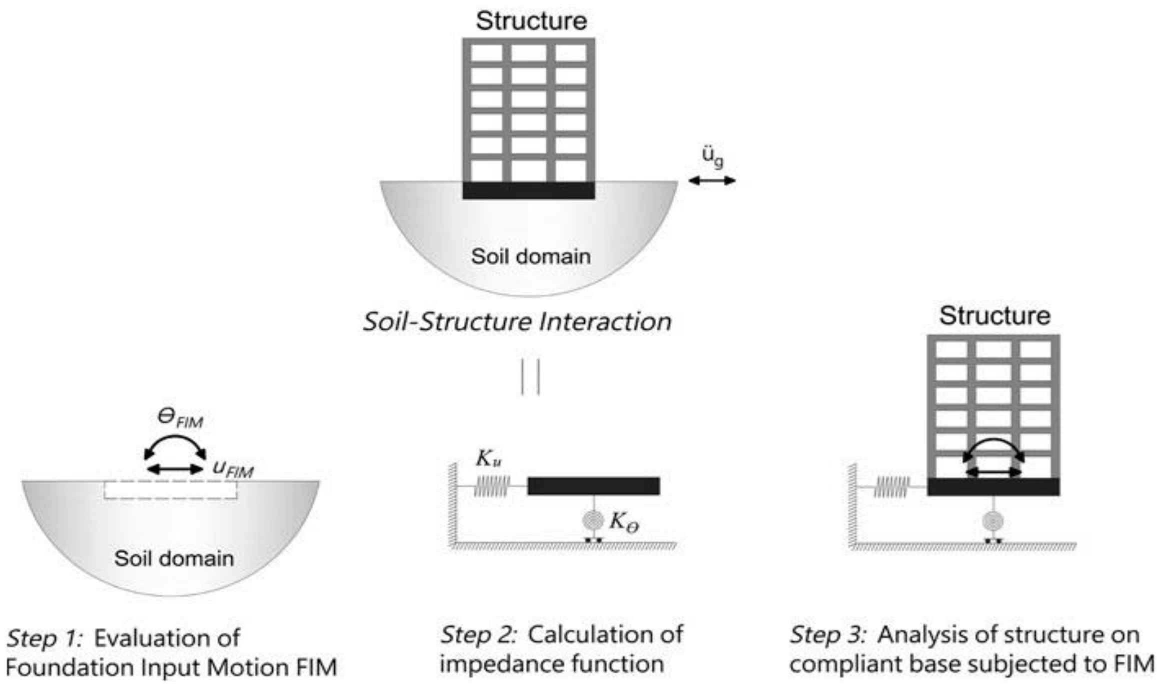


Figure 1. 9 Substructure approach to the analysis of the soil-structure interaction problem. (Stewart &Kramer, 2004)

1.9 Different Analysis Methods

Analytical methods for predicting lateral deflections, rotations, and stresses in soil-structure interaction (SSI) can be classified into three main methods: Winkler method , P-Y Method and Elastic Continuum Approach (Yesane et al 2016) .

1.9.1 Winkler model

The Winkler model is the most recognized and commonly employed foundational model for SSI analysis by structural engineers, being the oldest and simplest method to model the subgrade, consisting of an infinite number of springs on a rigid base (Shendkar 2023).

Elastic models based on this idealization represents the soil medium as a system of identical but mutually independent, closely spaced, discrete, linearly elastic springs (Chandra 2014) meaning that soil deformation due to applied loads is limited only to the loaded regions, and the soil is considered elastic.

In this model, the soil medium is represented by linearly elastic springs that are distributed independently and discretely in close spaces along the foundation area, as shown in Figure 9 .

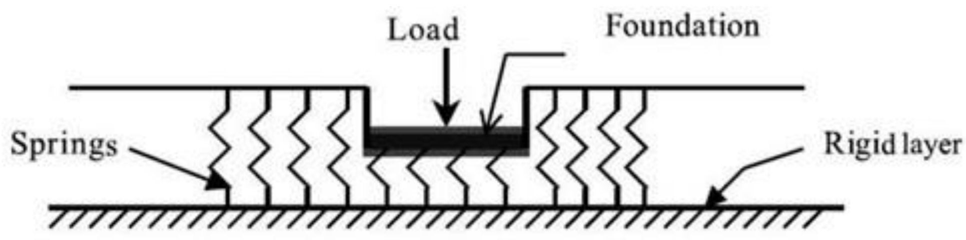


Figure 1.10 Winkler foundation model (Dutta & Roy, 2002).

since the springs are independent, the deformation of the foundation due to the applied load remains localized in the loaded region only. (Bowles, 1996). The model establishes a relationship between pressure and deflection given by Equation :

$$p = k\,w$$

Where p is applied external pressure, k is reaction modulus or subgrade modulus, and w is deflection.

1.9.2 P-y method

The p-y method is a widely a nonlinear analytical approach used for modeling soil-pile interaction under lateral loads, particularly in offshore and seismic engineering applications and is defined by a p-y curve (soil resistance p vs. lateral displacement y) . In this method, the foundation system typically pile-supported is represented using a combination of springs and dashpots distributed along the pile length . These elements simulate the lateral stiffness (p-y curves) and energy dissipation (radiation damping) due to wave propagation in the soil (Berger et al 1977) .

1.9.3 Elastic Continuum Approach

Elastic Continuum approach is a theoretical model in continuum mechanics that represents a material as a continuously distributed, deformable medium, where matter is assumed to fill space without any gaps or discontinuities. In this model, the material responds to applied loads according to well-defined stress-strain relationships. The simplest form is the linear elastic isotropic continuum**,** governed by Hooke's Law (Irgens, 2008), which assumes the same material behavior in all directions and linear response under stress (Aron et al 2012) . This model is commonly used in preliminary structural and geotechnical analyses.

1.10 Numerical methods :

The numerical simulation of soil–structure systems under dynamic loads must include both the structure and foundation to account for energy dissipation in the soil. Typical examples of the methods used for soil–structure interaction analysis are:

1.10.1 Finite element method (FEM)

The Finite Element Method is a numerical technique widely used for analyzing complex structures composed of non-homogeneous, anisotropic, and nonlinear materials with arbitrary geometries (Yazdchi et al 1999) . It divides the structure and soil into small elements to solve governing equations. FEM is widely applied in Soil-Structure Interaction (SSI) studies to model the interaction between soil and foundations also FEM can handle 3D models and dynamic analysis with high accuracy. In FE analysis, implicit and explicit dynamic analyses are used to understand the structure's dynamic behaviour.

Table 1 illustrates the use of different FE software in various SSI-related research. Software such as Abaqus, Ansys, and SAP 2000 allow users to simulate the realistic nature of soil using the geotechnical properties of the soil such as Elastic modulus, Poisson's ratio and Shear modulus etc . This software offers the capability to specify the inhomogeneous characteristics of the layered soil.

Certain limitations of FEM are as follows:

• Selection of correct element size is difficult.

• The outcomes of numerical examination of the wave propagation phenomenon are influenced by
limit conditions.

• It can achieve only approximate solutions. (Awchat et al 2022)

Table 1.1 Application of various FE software in different research related to SSI (Awchat et al 2022)

Software	Foundation	Purpose	Reference
Abaqus v.6.8	Mat Foundation	The seismic analysis of buildings on sandy soil considering SSI was performed to evaluate stress propagation, amplification, and acceleration response at the foundation and soil medium interface .	(Matinmanesha & Asheghabadib 2011)
OpenSees	Shallow Foundation	The efficiency of the base isolator evaluated on residential base-isolated buildings with SSI effects considering the non-linear behaviour of the base isolators and soil deformability effects .	(Forcellini 2017)
C++	Piled Raft Foundation	The seismic analysis of asymmetrical buildings with SSI effects observed that shape of the structure affected seismic response under the Nepal earthquake in 2015.	(Bardy & Satyam 2017)
Abaqus	Pile foundation	The FE analysis was validated using a shaking table test on the structure of soft clay.	(Al-Isawi et al 2019)
Ansys 14.5	Mat foundation	The SSI effects were evaluated on multi-story buildings and observed that with the interaction of foundation and soil elements, response of structural changes.	(Jha et al 2015)
SAP 2000	Pile foundation	High-rise building with and without soft stories considering SSI effects analysed. The seismic response and fragility curves describe various damage states to the structure evaluated.	(Samanta & Sriwastav 2018)

1.10.2 Boundary Element Method (BEM)

The Boundary Element Method is a numerical technique developed after FEM, ideal for modeling infinite or semi-infinite domains like soil in Soil-Structure Interaction (SSI) problems. Unlike FEM, BEM discretizes only the boundaries, not the entire volume, which greatly reduces computational effort. It automatically satisfies radiation conditions, making it especially suitable for seismic wave propagation in unbounded soil media. However, BEM works best for linear and homogeneous materials but its effectiveness is limited for highly nonlinear or heterogeneous materials unless combined with other methods (e.g., FEM-BEM coupling) .

1.10.3 Spectral Element Method (SEM)

The Spectral Element Method (SEM) is a numerical technique similar to the Finite Element Method but based on higher-order element theories, offering greater accuracy at high frequencies with reduced computational cost (Çağlar & Şafak 2019). SEM uses the Discrete Fourier Transform (DFT) to convert time-domain equations into the frequency domain, which helps reduce the number of elements, degrees of freedom, and computational time. Studies (e.g., Boudaa et al.) have shown that SEM converges faster than FEM and that soil properties influence vibration modes. Despite its advantages, SEM is sparsely used in earthquake engineering due to its complexity and limited adoption.

1.11Model of soil-structure interaction :

Soil-Structure Interaction (SSI) models are used to represent the interaction between the soil and the structure during seismic or dynamic loading. These models vary in complexity, ranging from simplified analytical models to advanced numerical models. Table 1.2 show a summarize and explanation of the most commonly used SSI models, their applications, and their advantages and limitations.

Table 1.2 Summary of Commonly Used Soil-Structure Interaction (SSI) Models

Model	Description	Applications	Advantages	Limitations	References
Lumped Parameter Models	Discrete springs, dashpots, and masses represent soil.	Preliminary analysis of small structures.	Simple and efficient.	Oversimplifies soil behavior.	(Wolf 1985)
Beam on Winkler Foundation	Soil modeled as independent springs.	Shallow foundations.	Simple and easy to implement.	Does not account for soil continuity.	(Bowles ,1996)
Finite Element Method (FEM)	Soil and structure discretized into finite elements.	Large and complex structures.	Accurate for complex systems.	Computationally expensive.	(Bathe, 1996)
Boundary Element Method (BEM)	Soil represented by boundary elements.	Unbounded soil domains.	Efficient for unbounded domains.	Limited to linear problems.	(Beskos, 1987)
Hybrid Models	Combines FEM for structure and BEM for soil.	Large and complex systems.	Balances accuracy and efficiency.	Requires expertise in both methods.	(Wolf, 2003)
Continuum Models	Soil treated as a continuous medium.	Complex soil-structure systems.	Accurate representation of soil	Computationally expensive.	(Gazetas, 1991)

Impedance Function Models	Soil represented by frequency-dependent stiffness and damping functions.	Dynamic analysis of structures.	Captures frequency-dependent behavior.	Requires detailed soil properties.	(Kramer,1996)

1.12 Conclusion :

Soil-Structure Interaction (SSI) is a fundamental concept in seismic analysis that reflects the complex interplay between the structural system and the supporting soil during dynamic events such as earthquakes. This chapter has provided an overview of the basics of SSI, including its mechanisms, kinematic and inertial interaction and its effects on structural performance. SSI can alter a structure's natural period, increase damping, and change stress distribution, especially on soft soils or for tall, heavy buildings. Ignoring SSI may lead to unsafe designs. Various analytical and numerical methods, such as the direct and substructure approaches, Winkler and p-y models, and FEM/BEM techniques, provide effective tools for studying SSI. Proper consideration of SSI is essential for accurate, resilient structural design in seismic regions.

Chapter II:

Review of international codes and standards for SSI

2.1 Introduction :

Soil-structure interaction (SSI) can make a substantial difference in how buildings behave during earthquake shaking and how they should be designed, and yet there is relatively little implementation of SSI effects by practicing engineers (fema 2091). Various international codes and standards have addressed the importance of accounting for soil-structure interaction effects and incorporating different methodologies, assumptions, and design requirements.

In this chapter, we will conduct a review of the provisions related to soil-structure interaction in prominent international codes and standards. A review of these codes helps to identify the similarities, differences, and evolving approaches in addressing soil-structure interaction effects.

This study examines SSI provisions in major international seismic codes, including Eurocode 8, Indian Standard IS 1893 and RPA 2024 also major standards including the American Society of Civil Engineering (ASCE) 7-22 and ASCE 41-17. The focus is on fundamental aspects such as soil classification, foundation modeling, dynamic soil-structure interaction analysis, and design considerations. Comparative studies have revealed notable differences in how these codes address SSI. The treatment of Soil-Structure Interaction (SSI) varies significantly across international seismic codes and standards.While some codes explicitly address SSI with detailed methodologies, others barely mention SSI or do not offer any specific provisions. A study of these differences is essential for advancing seismic design practices.

2.2 Review of standards :

Various international codes and standards incorporate SSI provisions , this section compares the treatment of SSI across them , examining their methodologies , assumption , and impact on structural performance .

2.2.1 ASCE/SEI 7-22 :

titled Minimum Design Loads and Associated Criteria for Buildings and Other Structures, provides comprehensive guidelines for determining design loads across various hazards, including seismic events.The standard includes provisions addressing SSI within Chapter 19: Soil–Structure Interaction for Seismic Design. This chapter recognizes the necessity of incorporating SSI effects in seismic analysis and design and introduces also methodologies for evaluating SSI, recognizing that foundation flexibility, damping effects, and kinematic interaction influence the response of structures under seismic excitation.

The incorporation of SSI in ASCE/SEI 7-22 compared to previous editions, like ASCE 7-10, wich did not explicitly include provisions for SSI effects in seismic analysis , ASCE/SEI 7-22 enhances the accuracy of seismic response predictions, aligning with global best practices in earthquake engineering .

Chapter 19 is structured into several sections, each addressing fundamental components of soil-structure interaction (SSI)

- General Requirements

Section 19.1," serves as the introductory segment of Chapter 19,." This section establishes the foundational framework for incorporating soil-structure interaction (SSI) effects into seismic design by outlining its scope, providing essential definitions, and listing the symbols used throughout the chapter .

Scope (19.1.1): This subsection delineates that Soil-Structure Interaction (SSI) may be considered in seismic design for determining earthquake forces and structural displacements, but the analysis must include:

- horizontal, vertical, and rotational flexibility of both the foundation and soil.
- both upper and lower bound estimates of soil and foundation stiffness to determine the most critical case

SSI effects are permitted only when using the nonlinear response history procedure and for sites classified as C, D, E, or F, where soil flexibility significantly impacts seismic response. However, SSI cannot be applied when using simplified analysis methods, such as the equivalent lateral force procedure or the linear dynamic procedure. Additionally, base slab averaging and embedment effects are not allowed with these simplified methods..

Definitions (19.1.2): This part includes explicit definitions of the terms relating to SSI. These definitions are important to understand the concepts and methodologies presented in the subsequent sections of the chapter.

Symbols (19.1.3): This subsection provides a list and explanation of the symbols and notations used within the general context of SSI analysis and design. Familiarity with these symbols is essential for accurately interpreting the equations and procedures outlined in the chapter.

- SSI ADJUSTED STRUCTURAL DEMANDS

Section 19.2 outlines the analytical procedures permitted for seismic design when considering Soil-Structure Interaction (SSI) effects. These procedures are essential for accurately assessing the seismic response of structures, especially when SSI is significant .

19.2.1 The Equivalent Lateral Force (ELF) procedure is a simplified method used to estimate the lateral forces induced by earthquakes on structures. When incorporating SSI, kinematic interaction effects are not permitted under this procedure, as stated in Section 19.4. However, the base shear V, which is calculated using Equation (12.8-1) in ASCE 7-22, can be adjusted for SSI as follows:

$$\tilde{V} = V - \Delta V$$

where:

- V′ = Base shear adjusted for SSI
- V = Fixed-base structure base shear (as per Section 12.8.1)
- ΔV = Reduction in base shear due to SSI effects

The reduction term ΔV is given by:

$$\Delta V = \left(C_s - \frac{C_s}{B_{SSI}}\right) W \quad \text{such that } \Delta V \leq 0.3V$$

Where :

- Cs = Seismic response coefficient considering a fixed-base structure
- C_{es}= Seismic response coefficient considering SSI effects
- B_{SSI} = Reduction factor accounting for SSI effects

- W = Seismic weight of the structure

The condition $\Delta V \leq 0.3V$ ensures that the base shear reduction does not exceed 30% of the original

(fixed-base) value, preventing unsafe reductions to ensure structural safety.

safety.

The reduction factor B_{SSI} is further defined as:

$$B_{SSI} = \frac{4}{5.6 - \ln(100\beta_0)} \leq \begin{cases} 1.4 & \text{for } R \leq 3 \\ 1.7 - \frac{R}{10} & \text{for } 3 < R < 6 \\ 1.1 & \text{for } R \geq 6 \end{cases}$$

where

β_0 : Effective viscous damping ratio of the soil–structure system, in accordance with Section 19.3.2

R **=** Response modification factor, as defined in Table 12.2-1

Section 19.2.2 focuses on the Linear Dynamic Analysis procedure for incorporating soil-structure interaction (SSI) effects into seismic design.The Linear Dynamic Procedure (LDP) is a more refined method for determining the seismic response of a structure compared to the Equivalent Lateral Force (ELF) Procedure.

In accordance with Section 19.4, the kinematic interaction effects which account for changes in ground motion due to the presence of a foundation are not permitted in the Linear Dynamic Procedure. To incorporate SSI effects, the linear dynamic analysis must be performed using a modified response spectrum. This can be done in one of the following ways:

1. Using the SSI-modified design response spectrum and MCER response spectrum, as defined in Sections 11.4.6 and 11.4.7.

2. Using an SSI-modified site-specific response spectrum, determined in accordance with Section 19.2.2.1.
3. Using an SSI-modified site-specific response spectrum, developed based on Section 19.2.2.2.

These modifications adjust the spectral response acceleration (S~a) based on the foundation flexibility and soil properties, ensuring a more accurate representation of seismic demand.

The spectral response acceleration used in design must then be adjusted by:

$$\frac{\tilde{S}_a}{R/I_e}$$

where:

- S_a = SSI-modified spectral acceleration
- R = Response modification factor (accounts for ductility)
- I_e = Importance factor (based on the risk category of the structure, as per Section 11.5.1)

This adjustment ensures that the structure's design response remains consistent with the expected inelastic behavior while considering SSI effects.

To ensure safe design, lateral force scaling follows Section 12.9.1.4, with base shear and modal base shear being adjusted for SSI. A minimum limit of 70% of the fixed-base base shear is enforced to prevent excessive reductions in seismic demand.

Section 19.2.3 of ASCE 7-22 outlines the Nonlinear Response History Procedure, which permits the inclusion of Soil-Structure Interaction (SSI) effects in seismic analysis through nonlinear response history analysis performed in accordance with Chapter 16 . The procedure mandates that acceleration histories scaled to a site-specific response spectrum modified for kinematic interaction, as per Section 19.4 or other approved methods. The mathematical model must explicitly incorporate foundation damping (Section 19.3), foundation and soil flexibility (Section 19.1.1), and kinematic interaction effects in the determination of the site-specific response spectrum.

Kinematic soil-structure interaction (SSI) effects can be incorporated into seismic analysis when acceleration histories are scaled to a site-specific response spectrum. These effects may be included in the equivalent lateral force procedure or the linear dynamic procedure as per Section 16.1.2, subject to specific limitations. If foundation damping is considered in the nonlinear model, the chosen analysis method must comply with the provisions of Sections 19.2.1 or 19.2.2 to ensure consistency and accuracy in seismic design.

- Foundation Damping Effects

Foundation damping is a direct consequence of SSI, as the interaction between the structure and soil alters energy dissipation patterns .This section focuses on the role of damping in the soil-structure system and how it influences the seismic response of a structure.

Section 19.3.1 of ASCE 7-22 addresses the effects of foundation damping in seismic design. This section states that foundation damping effects can be considered through the direct incorporation of two primary types: soil hysteretic damping and radiation damping into the structural mathematical model.

These effects can be used with either: Equivalent lateral force procedure (Section 19.2.1) or Linear dynamic analysis (Section 19.2.2).

Noticing that foundation damping effects cannot be considered in seismic analysis if any of the following conditions exist:

If the foundation system consists of discrete, unconnected footings spaced less than the larger dimension of the lateral force-resisting element.

If the foundation includes deep foundations such as piles or piers.

If the foundation system consists of flexible mat foundations classified under Section 12.3.1.3 and is not continuously connected to grade beams or other structural foundation elements.

The effective damping ratio (β_0) represents the effects of foundation damping within the soil-structure system . Section 19.3.2 provides a formulation for determining the effective damping ratio (β_0) as follow :

$$\beta_0 = \beta_f + \frac{\beta}{(\tilde{T}/T)^2_{\text{eff}}} \leq 0.20$$

Where :

β_f : the effective viscous damping ratio related to foundation-soil interaction.

β: the effective viscous damping ratio of the structure, which is taken as 5%, unless otherwise justified by analysis.

$(\bar{T}/T)$ eff: the effective period lengthening ratio, as defined in Equation (19.3-2).

The effective period lengthening ratio is computed as:

$$\left(\frac{\tilde{T}}{T}\right)_{\text{eff}} = \left\{1 + \frac{1}{\mu}\left[\left(\frac{\tilde{T}}{T}\right)^2 - 1\right]\right\}^{0.5}$$

where μ represents the expected ductility demand. For equivalent lateral force procedures and modal response spectrum methods, μ is defined as the ratio of maximum base shear to elastic base shear capacity, or alternatively, approximated as R/ Ω0 based on seismic design parameters. In response history analysis, μ is determined using maximum displacement at yield divided by the maximum displacement of the structure.

Foundation damping consists of two main components: soil hysteretic damping (β_s) wich defined in Section 19.3.5and radiation damping (β_{rd}) addressed in Sections 19.3.3 & 19.3.4. The foundation damping ratio is given by:

$$\beta_f = \left[\frac{(\tilde{T}/T)^2 - 1}{(\tilde{T}/T)^2}\right]\beta_s + \beta_{rd}$$

This equation ensures that both damping mechanisms are properly incorporated into seismic response calculations.

Also mention If the site consists of a deep uniform layer overlying a stiff substratum, the damping values are corrected to reflect wave propagation changes. The modified radiation damping is given by:

$$\beta_s' = \left(\frac{4D_s}{v_s\tilde{T}}\right)^4 \beta_s$$

This correction accounts for variations in soil layering, ensuring more accurate representation of damping effects in sites with significant soil depth differences.

Sections 19.3.3 and 19.3.4 provide a comprehensive framework for evaluating radiation damping in seismic analysis, specifically addressing different foundation geometries. Section 19.3.3 focuses on rectangular foundations, outlining the methodology to quantify energy dissipation through wave propagation into the surrounding soil .Similarly, Section 19.3.4 extends this analysis to circular foundations, adapting the radiation damping equations to reflect the geometric characteristics of circular footings.

19.3.5 this section explain that the effects of soil hysteretic damping shall be represented by the effective soil hysteretic damping ratio, βs, determined based on a site-specific study. Alternatively, it is permitted to determine βs in accordance with Table 19.3-3.

- Kinematic Interaction Effects

Section 19.4 of ASCE 7-22 addresses kinematic soil-structure interaction (SSI) effects and introduces response spectral modification factors, RRSbsa for base slab averaging and RRSe for embedment, which adjust the spectral acceleration ordinates of the response spectrum at each period. These modification factors are applicable only in nonlinear response history analysis, as outlined in Chapter 16.

Furthermore, the section specifies that these modifications must be based on a site-specific response spectrum developed in compliance with Chapter 21 and within the constraints defined in Sections 19.2.3, 19.4.1, and 19.4.2. To prevent excessive reductions in seismic demand, the product of RRSbsa×RRSe is required to be no less than 0.7, ensuring a conservative yet realistic adjustment of the seismic input motion .

19.4.1 Base slab averaging considers site-specific transfer functions to represent kinematic SSI effects. Modifications apply to:

- Structures on Site Classes C, CD, D, DE, or E.
- Foundations with structural mats or interconnected slabs ensuring lateral stiffness. The modification factor RRS_bsa is determined using Equation (19.4-1).

$$RRS_{bsa} = 0.25 + 0.75 \times \left\{ \frac{1}{b_0^2} \left[1 - \left(\exp(-2b_0^2) \right) \times B_{bsa} \right] \right\}^{1/2}$$

b_0 and B_{bsa} are parameters related to foundation size and kinematic effects

19.4.2 Embedment effects require that the response spectrum for a structure must be developed based on a site-specific study at the depth of the base of the structure. Alternatively, modifications for embedment are allowed. Modification Factor RRS_e, is given by Equation (19.4-5):

$$RRS_e = 0.25 + 0.75 \times \cos\left(\frac{2\pi\varepsilon}{T_{v,s,e}} \right)$$

where:

e = Foundation embedment depth (ft or m), with a minimum requirement of 75% of the foundation footprint at the embedment depth.

Vs,e = Average effective shear wave velocity at the foundation embedment depth, computed using site-specific studies and Table 19.3-1.

Vs, $_0$,e = Low strain shear wave velocity, determined using Equation 20.4-1.

T = Response spectra ordinate period, which shall not be taken as less than 0.20 s.

2.2.2 ASCE 41-17

ASCE/SEI 41-17, titled "Seismic Evaluation and Retrofit of Existing Buildings", represents a comprehensive and refined standard that was developed by the American Society of Civil Engineers. The standard builds upon earlier versions (ASCE 41-13 and FEMA 356) and has added new research and practice in the evaluation and retrofitting of structures.. The document contributes to structural resilience by addressing not only structural systems but also geotechnical and foundation conditions, including the important effects of Soil–Structure Interaction (SSI). ASCE 41-17 explicitly acknowledges the impact of SSI in seismic response, with detailed guidance presented primarily in:

- Section 7.2.7 – Soil–Structure Interaction
- Section 8.5 – Soil–Structure Interaction Effects

a. Section 7.2.7 – Soil–Structure Interaction

This section mandates that SSI effects must be evaluated for buildings where such interaction leads to a significant increase in fundamental period and, consequently, an increase in spectral accelerations. For other buildings, SSI evaluation may be omitted.

The standard prescribes the use of an explicit modeling procedure to evaluate SSI effects. This involves developing a mathematical model that accounts for both the flexibility and damping of foundation elements. The stiffness parameters must align with the provisions of Section 8.4. Importantly:

For Linear Static Procedure (LSP) and Linear Dynamic Procedure (LDP), the effective damping ratio of the structure–foundation system (denoted as β_SSI), calculated per Section 8.5.2, may be used in lieu of modeling individual foundation elements.

For Nonlinear Dynamic Procedure (NDP), the damping of foundation components must be explicitly included in the analytical model.

The standard also allows the general or site-specific response spectrum to be reduced due to the effects of kinematic interaction, provided it is calculated either through:

Explicit modeling of the soil–foundation–structure system, considering spatial/depth ground motion variation, or

Per Section 8.5.1, which outlines simplified methods for calculating kinematic interaction effects.

Furthermore, combination of damping effects with kinematic interaction, calculated under Section 8.5.1, is permitted with limitations.

Finally, ASCE 41-17 imposes quantitative limitations to ensure conservative design when SSI is included:

- For LSP and LDP, the maximum pseudoinertial force including SSI shall not be less than 70% of the force without SSI.
- For NSP (Nonlinear Static Procedure), the target displacement including SSI must be at least 70% of the displacement without SSI.

b. Section 8.5 – Soil–Structure Interaction Effects

This section builds on the requirement from Section 7.2.7, stating that soil–structure interaction (SSI) effects must be considered when they result in a reduction of seismic demands, particularly through kinematic interaction and foundation damping. However, it provides more than just calculation methods. The full section includes:

- Kinematic Interaction

This subsection focuses on the reduction of spectral demands due to kinematic interaction, which results from the incompatibility between free-field ground motion and foundation motion.

- Key Concepts:

SSI effects may be explicitly modeled in the structural analysis or represented via Response Reduction Spectrum (RRS) factors:

RRS bsa for base slab averaging,

RRSe for embedment effects.

These factors are multiplied with the spectral acceleration ordinates in the response spectrum to reflect reduced demands due to kinematic interaction.

The combined product must satisfy the limit:

$$\mathrm{RRS}_{bsa} \times \mathrm{RRS}_{e} \geq 0.50$$

- Base Slab Averaging

Focuses on reducing demands for buildings with large, rigid foundation slabs that average out ground motions:

- Reduction is permitted when:
  - Site class is C, D, or E.
  - Slabs are stiff and connected to the lateral-force system.
  - Foundation is stronger than vertical elements.
- The RRS factor is calculated as:

$$RRS_{bsa} = 0.25 + 0.75 \times \left[\frac{1}{b_0^2}\left(1 - \exp(-2b_0^2) \times B_{bsa}\right)\right]^{1/2}$$

Where B_{bsa} , b_0, and other parameters are defined through Equations (8-16) to (8-18).

- Embedment

defines how to calculate the embedment response reduction factor RRS_e using:

$$RRS_e = 0.25 + 0.75\cos\left(\frac{2\pi e}{T v_s}\right) \geq 0.50$$

where :

e : is embedment depth

T : is the effective period

v_s : is the shear wave velocity.

Reductions are allowed only if:

1. Site class is C, D, or E,

2. Foundation is stiff and not a flexible diaphragm,
3. Foundation is stronger than the vertical lateral-force-resisting elements.

A minimum of 75% of the foundation must be embedded at the evaluated depth. RRS_e shall not be less than the value at T=0.2 s or for 20 ft embedment.

- Foundation Damping Soil–Structure Interaction Effects

This section addresses how foundation damping effects are to be included in nonlinear analyses by defining an effective damping ratio, denoted as β_{SSI} , for the structure foundation system. This damping ratio must be calculated using Eq. (8-20) represented as:

$$\beta_{SSI} = \beta_f + \frac{\beta}{(\tilde{T}/T)^2_{eff}} \leq \mathbf{0.20}$$

Where:

- β is the effective viscous damping ratio
- βf is the foundation–soil interaction damping ratio
- T is the period with fixed base
- T~ is the period with flexible base
- μ is the ductility demand

$$\beta_f = \left(\frac{(\tilde{T}/T)^2 - 1}{(\tilde{T}/T)^2} \right) \beta_s + \beta_{rd}$$

Where:

- βs is the soil hysteretic damping ratio (from ASCE 7 Section 19.3.5)
- βrd is radiation damping (from ASCE 7 Sections 19.3.3 or 19.3.4)

The period lengthening ratio is:

$$\frac{\tilde{T}_{eff}}{T_{eff}} = \left\{1 + \frac{1}{\mu}\left[\left(\frac{\tilde{T}}{T}\right)^2 - 1\right]\right\}^{0.5}$$

Foundation damping can be accounted for in one of two ways:

Explicitly, by modeling damping at the soil–foundation interface in the analytical model.

Or implicitly, by modifying the acceleration response spectrum using β_{SSI} instead of the standard viscous damping ratio β , especially when using Linear Static Procedure (LSP), Linear Dynamic Procedure (LDP), or Nonlinear Static Procedure (NSP).

- Radiation Damping for Rectangular Foundations

This subsection presents a method to calculate radiation damping β_{rd} , which is a component of foundation damping in soil–structure interaction (SSI). Radiation damping accounts for energy dissipated into the surrounding soil due to the vibration of the foundation.

- Soil Hysteretic Damping

This section introduces hysteretic damping, which is related to energy dissipation within the soil due to its inelastic behavior.

βs (soil hysteretic damping) is obtained from Table 8-6 or similar standards.

If the soil profile includes a soft uniform layer over a very stiff base layer (e.g., a competent rock layer) .

2.3 Review of codes:

2.3.1 IS 1893

Indian Standard Criteria for Earthquake Resistant Design of Structures is the national seismic code of India, developed and adopted by the Bureau of Indian Standards (BIS). The standard is formulated by the Earthquake Engineering Sectional Committee and approved by the Civil Engineering Division Council before its official adoption. It provides guidelines and methodologies for seismic load calculations, site classification, structural design requirements, and ensuring the structural safety of buildings, bridges, industrial structures, and other infrastructure subjected to earthquakes.

The latest version is divided into five parts:

Part 1: General provisions and buildings

Part 2: Liquid Retaining Tanks—Elevated and Ground Supported

Part 3: Bridges and Retaining Walls

Part 4: Industrial structures, including stack-like structures

Part 5: Dams and Embankments

IS 1893 provides general guidelines on considering soil flexibility but does not have extensive provisions for detailed SSI analysis. To understand how SSI is considered across different structural categories, a detailed review of each part will be conducted to identify sections where SSI is mentioned and whether specific methodologies or requirements are provided.

IS 1893 (Part 1) mentions Soil-Structure Interaction (SSI) in Clause 6.1.5, defining it as the effect of the flexibility of the supporting soil-foundation system on the response of a structure. However, the code suggests ignoring SSI studies for seismic analysis and design of structures located on rock or rock-like material. It specifies that SSI may not be considered in the seismic analysis of such structures at shallow depths.

Despite acknowledging SSI, IS 1893 (Part 1) does not explicitly mention when and how to consider its effects. Moreover, the code does not provide explicit methodologies or detailed procedures for incorporating SSI into seismic analysis.

IS 1893 (Part 2) focuses on the seismic design of liquid-retaining structures such as elevated and ground-supported tanks. After review, no explicit mention is given to soil-structure interaction (SSI) or its effects within this part of the code .

IS 1893 (Part 3) addresses the seismic design of bridges and retaining walls, explicitly recognizing the influence of Soil-Structure Interaction (SSI) in Clause 4.2.4, where it states that the design of bridges is specified based on the type of foundation and soil conditions. It mentions that bridges founded on rock and medium soil, which do not liquefy or slide under ground shaking, do not require detailed soil-structure interaction (SSI) studies. However, for bridges founded on soft soils and in cases where deep foundations are used, the clause requires a detailed study of soil-structure interaction. Additionally, it indicates that SSI may not be considered for open foundations on rocky strata.

Furthermore, the clause explains that soil flexibilities are included in modeling the substructure and foundation of the bridge. SSI generally leads to a longer natural period, resulting in lower seismic forces. However, it states that considering soil flexibilities also leads to larger lateral deflections. To address this, the clause specifies that soil parameters, such as elastic properties and spring constants, should be properly estimated. In many situations, one obtains a range of values of soil properties. It recommends using the highest values of soil stiffness for calculating the natural period and the lowest values for deflection calculations. However, while the standard acknowledges the effects of SSI, it does not provide detailed methodologies or computational approaches for incorporating these effects into structural design.

IS 1893 (Part 4) Clause 9.1.1 states that soil-structure interaction (SSI) refers to the effects of the supporting foundation medium on the motion of a structure. However, the clause specifies that SSI may not be considered in seismic analysis for structures supported on rock, hard soil, or rock-like material. It further clarifies this condition by defining the threshold parameters as the standard penetration $N > 50$ (as indicated in Note 3 of Table 1) and shear wave velocity $V_s = 760$ m/s (as per Table 16).

2.3.2 Eurocode 8 (EN 1998)

is the European standard for the seismic design of structures and provides a set of guidelines for the design and assessment of buildings and civil engineering structures developed to ensure structural safety and performance under earthquake loading. It is divided into multiple parts, each dealing with specific types of structures and design considerations. Notably, Part 5 of Eurocode 8 explicitly addresses soil-structure interaction (SSI) in Clause 6, outlining conditions where SSI effects must be accounted for:

- P-Δ (second-order) effects are significant in the structure.

- Massive or deep-seated foundations, such as bridge piers, offshore caissons, and silos.

- Slender tall structures (e.g., towers and chimneys), as covered in EN 1998-6: 2004.

- Structures supported on very soft soils (shear wave velocity < 100 m/s as defined in Table 4.1), specifically in ground type S1.

Clause 6(2)P emphasizes the need to assess SSI on piles for all structures, as per Section 5.4.2.

However, while the standard mandates consideration of SSI under these conditions, it does not provide specific methods or detailed procedures for modeling or calculating these effects in seismic analysis.

Additionally, Annex D provides further information on the effects of dynamic soil-structure interaction (SSI) and its influence on the seismic response of structures. When a structure is founded on deformable ground rather than a rigid base, its dynamic behavior is significantly altered and subjected to an identical free-field excitation for the following reason:

The foundation motion of a flexibly-supported structure differs from the free-field motion and may include an important rocking component of the fixed-base structure.

The fundamental period of vibration of a flexibly supported structure will be longer than that of a fixed-base structure. Additionally, the natural periods, mode shapes, and modal participation factors of a flexibly-supported structure differ from those of a fixed-base structure.

The overall damping of a flexibly supported structure includes both radiation damping and internal damping generated at the soil-foundation interface, along with damping in the superstructure. For common building structures, the effects of SSI tend to be beneficial, as they help reduce bending moments and shear forces in superstructure members. However, for structures listed in Section 6, SSI effects may be detrimental.

2.3.3 RPA 2024

The Règlement Parasismique Algérien 2024 (RPA 2024) represents the latest evolution of Algeria’s seismic design code, intended to improve structural safety and resilience in the face of seismic hazards. It builds upon the experience from previous editions and international best practices. However, one notable limitation of RPA 2024 is the absence of a dedicated section or detailed guidance addressing Soil-Structure Interaction (SSI).

Despite the well-established influence of SSI on the seismic response of structures particularly for buildings on soft soils or with large and flexible foundations RPA 2024 does not explicitly require or regulate the consideration of SSI effects in structural design.

Given this context, it is recommended that future versions of RPA explicitly address SSI, at least by providing:

Criteria for when SSI should be considered, based on soil class, foundation type, and structural characteristics, Simplified modeling approaches for practical design . Clear guidelines for advanced numerical modeling when required.

2.4 Conclusion :

In this chapter , a detailed review was conducted of international codes and standards that address Soil-Structure Interaction (SSI) in seismic design.

The review demonstrated that the treatment of SSI varies significantly among these standards. ASCE 7-22 and ASCE 41-17 provide advanced and comprehensive provisions including both simplified and detailed modeling approaches, clear criteria for when SSI must be considered and allowances for modified damping and stiffness values. Eurocode 8 includes specific conditions under which SSI must be considered and highlights its influence on structural response, though it lacks explicit modeling procedures.

In contrast, IS 1893 offers limited guidance, mentioning SSI but not prescribing detailed methodologies or thresholds for when it must be included in design. Most notably, RPA 2024 does not contain a dedicated section on SSI, representing a significant gap given the seismic vulnerability of many Algerian regions it is strongly recommended that future versions of RPA and similar national standards incorporate explicit SSI provisions.

Chapter III:

Comprehensive Literature Review on Soil-Structure Interaction in Seismic Design

3.1 Introduction:

The accurate assessment of structural behavior under seismic loading is a critical concern in modern civil engineering especially for structures resting on varying soil conditions. Soil-Structure Interaction (SSI) has emerged as a fundamental factor influencing the seismic behavior of buildings particularly those with significant height or underground stories and those located in seismic-prone regions. Traditional structural design approaches often assume fixed-base conditions thereby neglecting the mutual influence between the foundation and the supporting soil.

In the field of geotechnical engineering, the accurate simulation of soil-structure interaction is fundamental to the reliable design of foundations. One of the oldest and most widely used methods in this context is the Winkler foundation model originally proposed by Emil Winkler in 1867. This model conceptualizes the soil medium as an array of independent linear springs each exerting a reaction force that is directly proportional to the vertical displacement imposed on it. The stiffness of these springs is defined by the coefficient of subgrade reaction (ks) a parameter that plays a central role in simplifying complex soil behaviors into manageable structural analyses.

This chapter presents a comprehensive literature review of numerous scholarly articles and research studies that investigate the effects of SSI on reinforced concrete structures. The review includes experimental, analytical, and numerical investigations utilizing advanced software tools such as SAP2000, ETABS, and STAAD.Pro. These articles are analyzed to understand the influence of subgrade modulus, foundation flexibility, soil types, etc. These parameters include time period, base shear, lateral displacement, inter-storey drift ratio, and modal behavior.

This chapter also focuses on reviewing the extensive literature surrounding the Winkler method and the critical parameter of the subgrade reaction modulus. It explores how various studies have evaluated, applied, and modified the Winkler model, especially in terms of estimating and utilizing ks for different soil types and foundation conditions.

3.2 Literature Review of Past Studies :

This section offers a review of past studies by presenting selected examples that explore the effects of Soil-Structure Interaction in seismic design.

3.2.1 Patel and Shah (2016) : conducted a comprehensive study in the seismic behavior of reinforced concrete buildings with multiple underground stories, emphasizing the effect of soil subgrade modulus variation. The objective was to evaluate the variation in maximum nodal displacement and natural time period of the structures due to changes in soil stiffness and number of underground stories.

The authors used STAAD.Pro to analyze a G+8 reinforced concrete frame with 1 to 3 underground storeys using two approaches: (1) a fixed base model, and (2) models accounting for soil flexibility through the FEMA-356 Spring Model and the Winkler Spring Model, to evaluate SSI effects on building response

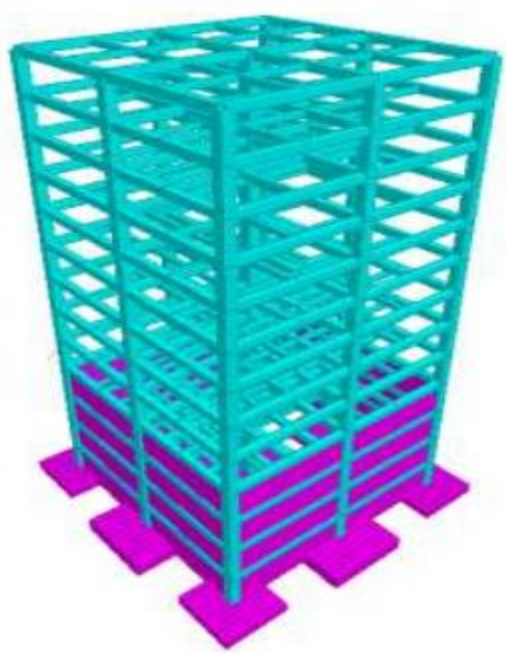


Figure 3.1 Winkler model

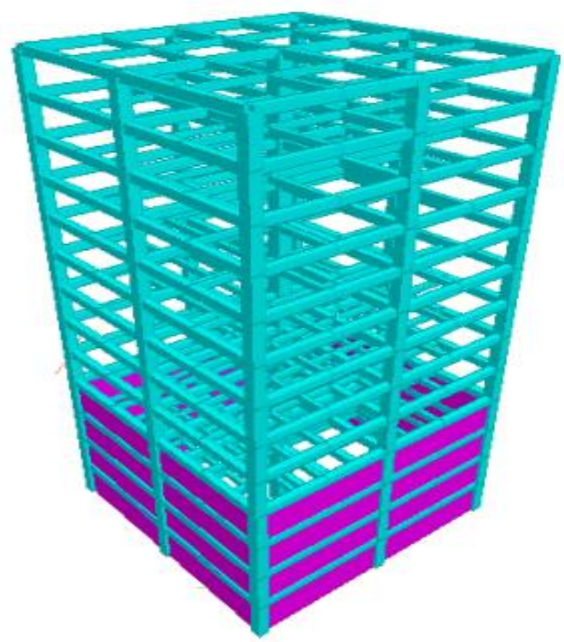


Figure 3.2 Fixed base modal

The results, in terms of displacement, as in Table 2 the Winkler Model consistently provides the highest value of maximum nodal displacement compared to other to models .Moreover, as the number of underground storeys increased, the influence of soil subgrade modulus variations reduced.

However the result reveal that the the FEMA Spring Model gives a higher time period compared to both the Fixed Base Model and the Winkler Spring Model when the soil subgrade modulus is

2750 kN/m³. However, when the soil subgrade modulus increases to 4500 and 6250 kN/m³, the Winkler Model shows a higher time period.

The authors concluded that the impact of soil subgrade modulus is more pronounced in softer soils, significantly affecting storey shear and moment demand, especially for low-rise structures. They emphasize that soil stiffness and foundation flexibility, combined with the number of underground levels, are critical factors in capturing accurate seismic responses in structural analysis.

3.2.2 Joy et al.(2016) : presented a study about evaluating the structural vulnerability of buildings to damage during earthquakes using pushover analysis using a finite element-based structural analysis program SAP2000, while incorporating the effects of Soil-Structure Interaction (SSI)

To substantiate their approach, the authors provided a detailed review of relevant literature. Foundational contributions by Ghobarah , Hasan et al. , and Zou & Chan were referenced, each of which emphasized performance-based seismic design using nonlinear pushover techniques. Additionally, studies such as those by Halkude et al. , Yesane et al. , and Noorzaei et al. were cited to highlight the critical role of SSI, showing that ignoring SSI can lead to an underestimation of seismic demand.

The authors define pushover analysis as a nonlinear static procedure that requires determining three primary elements: capacity, demand, and performance. As shown in Figure 3, they explain elements that are essential for evaluating seismic performance.

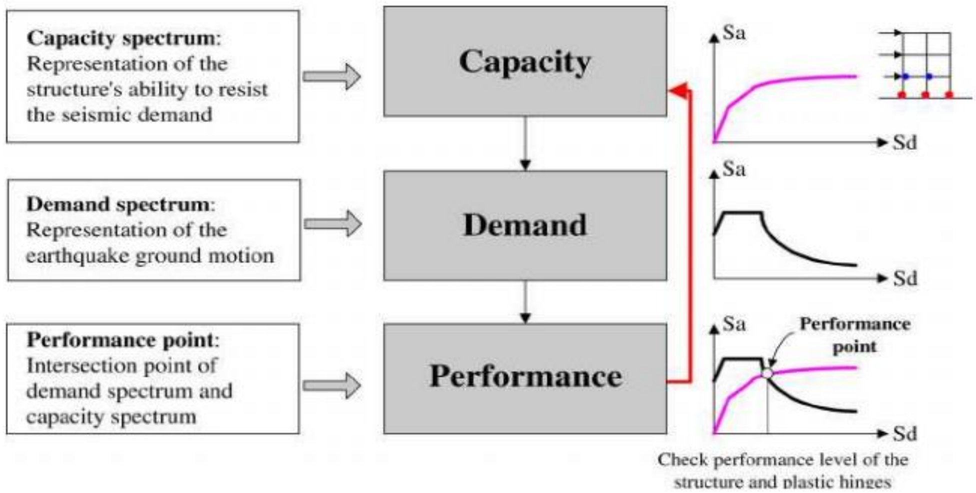


Figure 3.3 Pushover analysis procedure

The authors adopted Richart and Lysmer's modified Winkler hypothesis , representing the soil as a point with six spring stiffness values, as shown in Table 1.

Table 3.1 Soil spring value as per Richart and Lysmer

Direction	Spring values	Equivalent radius
Vertical	$K_z = \frac{4Gr_z}{1-\nu}$	$r_z = \sqrt{\frac{LB}{\pi}}$
Horizontal	$K_x = K_y = \frac{32(1-\nu)Gr_x}{(7-8\nu)}$	$r_x = \sqrt{\frac{LB}{\pi}}$
Rocking	$K\phi_x = \frac{8Gr_{\phi x}{}^3}{3(1-\nu)}$	$r_{\phi x} = \sqrt[4]{\frac{LB^3}{3\pi}}$
	$K\phi_y = \frac{8Gr_{\phi y}{}^3}{3(1-\nu)}$	$r_{\phi y} = \sqrt[4]{\frac{LB^3}{3\pi}}$
Twisting	$K\phi_z = \frac{16Gr_{\phi z}{}^3}{3}$	$r_{\phi z} = \sqrt[4]{\frac{LB^3 + BL^3}{6\pi}}$

To validate their approach, a 10-storey building was modeled in SAP2000 with fixed column bases. Using the standard pushover procedure , results were compared with Shinde et al. and showed excellent agreement in performance points (Table 2)

Table 3.2 Performance point of the 10- storey building.

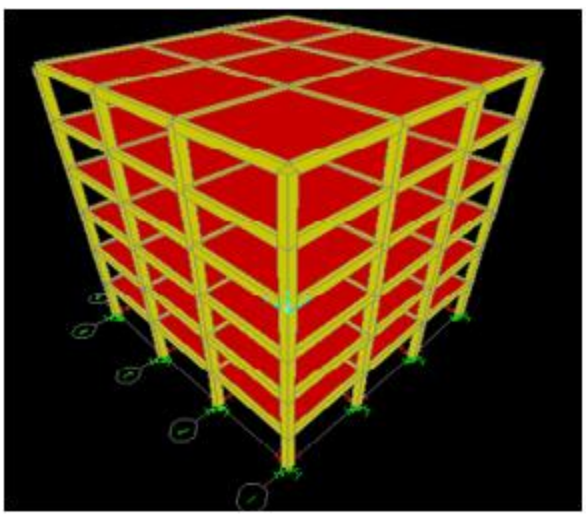
	Base shear (kN)	Displacement (mm)
Shinde *et al.* [13]	903	21.9
Present study	903.3	20.9

Three building models of varying heights G+3 (Model I), G+5 (Model II), and G+9 (Model III) were modeled with fixed base support, and pushover analysis was carried out. The model descriptions used are presented in Table. In order to incorporate SSI in the present model, Richard and Lysmer model is incorporated.. Three types of soil were considered, and their properties are listed in Table 3.

Table 3.3 Soil properties.

Type of soil	S.B.C of soil (kN/m^2)	Young's modulus (kN/m^2)	Poisson's ratio	Shear Modulus (kN/m^2)
Soft	100	12000	0.45	4137.93
Medium soil	150	35000	0.4	10714.28
Hard	250	200000	0.3	76923.08

Default hinges of M3 and P-M3 were assigned to beams and columns, respectively. Figures 4 and 5 illustrating the structural model and typical hinge formation for Model II during pushover analysis.



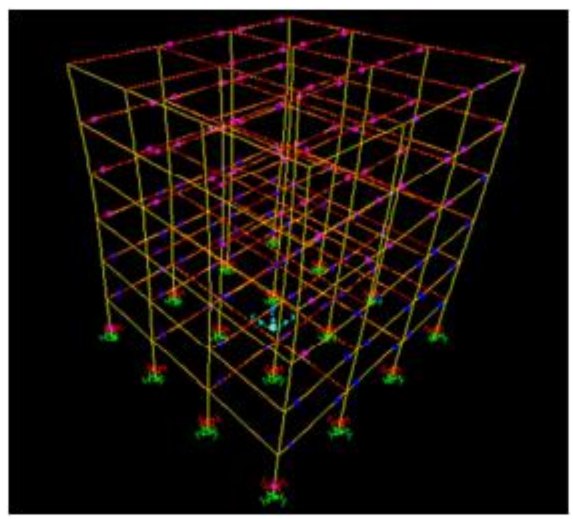


Figure 3.4 Fixed base model II **Figure 3.5** Hinge formation for model II.

The seismic analysis focused on base shear and displacement at the performance point, evaluated across different soil types as well as under fixed base conditions. The results are illustrated through the pushover curves shown in the following figures.

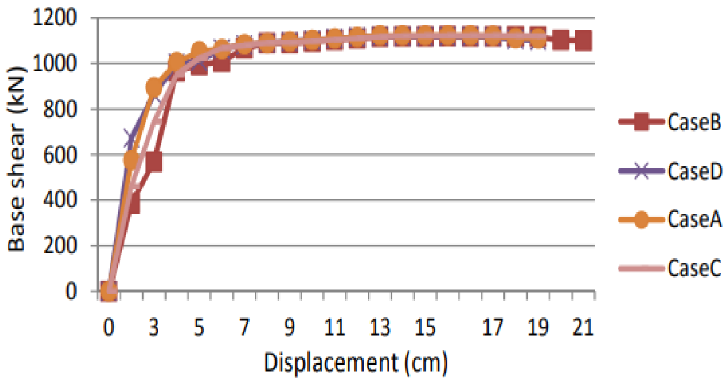


Figure 3.6 Pushover curves of model I.

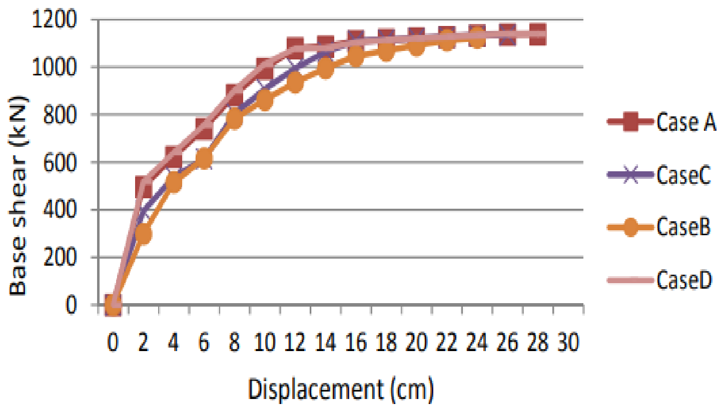


Figure 3.7 Pushover curves of model II.

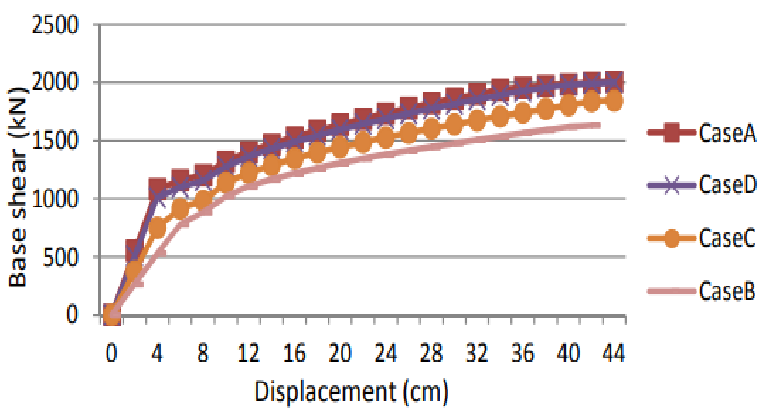


Figure 3.8 Pushover curves of Model III.

in Figures. 6, 7, and 8 the base shear at the performance point of each structure is influenced by the type of supporting soil. For Models I and II, the variation in base shear across different soil conditions is minimal. However, in Model III, the variation in base shear is r is observed to be higher due to the increased sensitivity of taller buildings to soil flexibility. Under fixed support conditions, roof displacement remains low, but it increases notably as the soil changes from hard to soft strata .

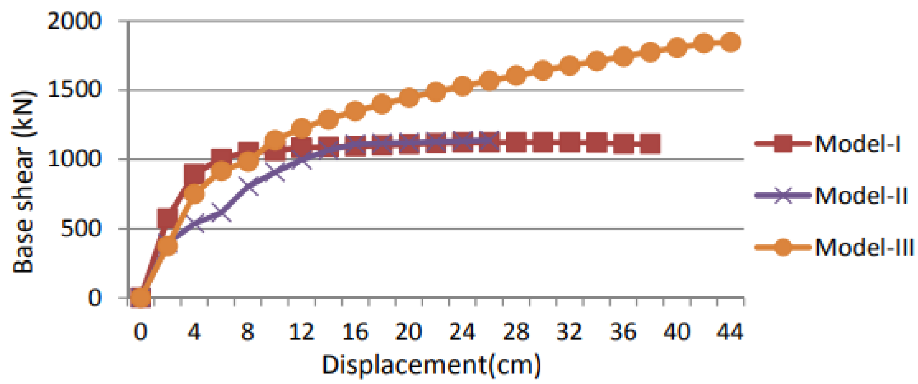


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Figure 3.9 Pushover curves for buildings on medium soil.

Figure 9 shows that under medium soil conditions, Model III exhibits the highest base shear and displacement due to the increased sensitivity of taller buildings to soil flexibility. Model II shows moderate response, while Model I remains the stiffest with minimal displacement, as shorter buildings are less sensitive to soil flexibility. Incorporating SSI through pushover analysis provides a more refined understanding of seismic response compared to models with fully restrained (fixed base) supports.

The authors proved , through this study, the importance of considering soil-structure interaction in performance-based design of buildings. They suggested that the model could be further improved by incorporating the nonlinear properties of soil better accord for the reality.

3.2.3 Verma et al. (2022) : investigated the effects of Soil-Structure Interaction (SSI) on the seismic response of multi-storey buildings through a comparative study using both fixed and flexible base analyses, implemented using the Winkler and Soil Continuum approaches. Their study focused on how SSI influences key structural response parameters, including time period, modal mass participation, base shear, lateral displacement, storey drift, and inter-storey drift ratio. The buildings were modeled using the finite element-based software SAP2000, and the equilibrium equations were solved using the by Hilber-Hughes-Taylor (HHT) method .

The authors validated their numerical model using a 10-storey residential building designed per Indian standards . Nonlinear time history analysis with El-Centro ground motion showed close agreement with Farqaleet , with only 1.52% variation in time period and 4.71% in roof displacement.

For the main analysis, three RC buildings (G+6, G+8, G+10) were studied under fixed and flexible base conditions to assess SSI effects. The flexible base was modeled using the Winkler and Soil Continuum approaches . Soil was meshed using eight-noded isoparametric solid elements, while structural members were modeled with homogeneous shell elements.

Dynamic analysis was carried out to evaluate the structural response parameters such as :

- Time period : Figures 10, 11, and 12 show the variation of the time period with all mode numbers for the G+6, G+8, and G+10 buildings considered in the study. It observed a decrease over the first three modes, then abruptly changes, with higher values in taller buildings (G+10) and under SSI due to reduced stiffness

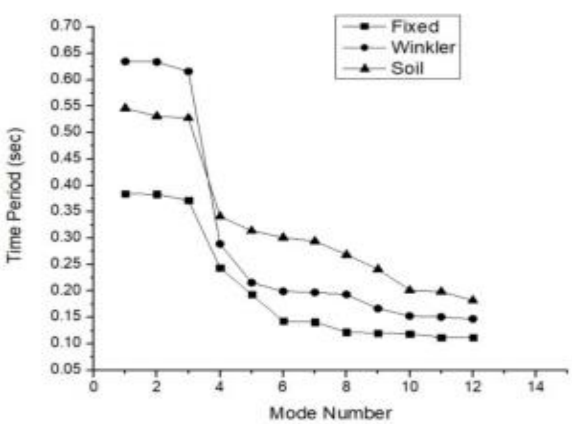


Figure 3.10 Time period vs. mode number for G+6

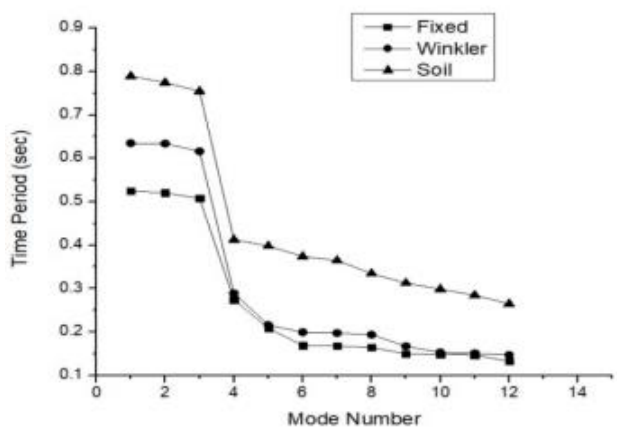


Figure 3.11 Time period vs. mode number for G+8

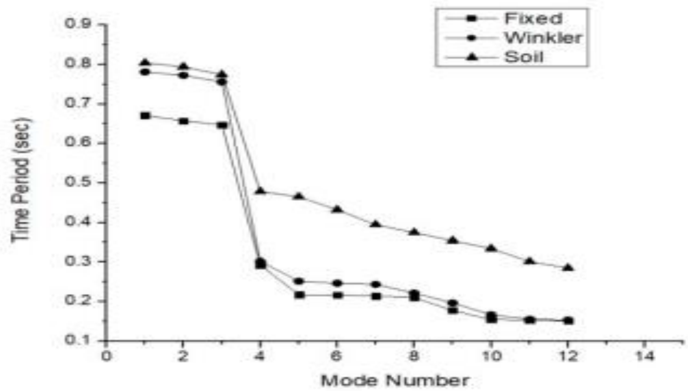


Figure 3.12 Time period vs. mode number for G+10

- Base shear : Figure 13 shows the maximum base shear for buildings under different base conditions . The results show that base shear highest in the G+10 building due to increased seismic weight, while SSI conditions reduce base shear as flexibility decreases accelerations .

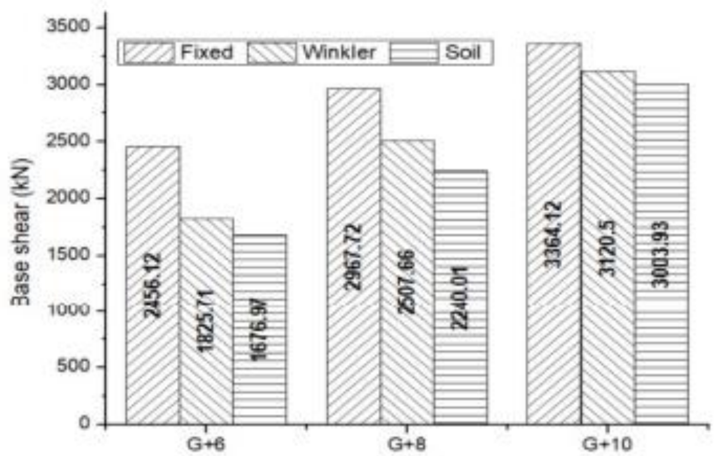


Figure 3.13 Base shear of buildings

- Lateral displacement : Figures 14, 15, and 16 show the lateral displacement of buildings under different base conditions. The results indicate that displacement is higher in SSI conditions due to increased flexibility but remains within IS code limits (H/500) for all building models :

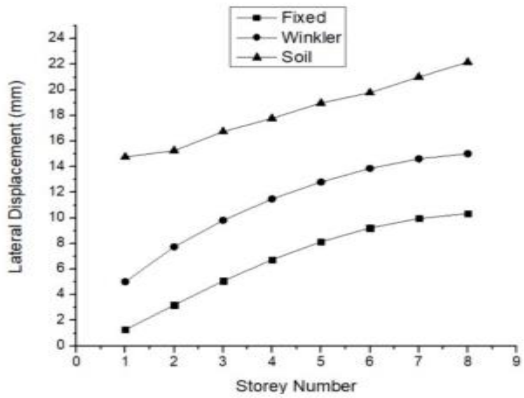


Figure 3.14 Lateral displacement of G+6

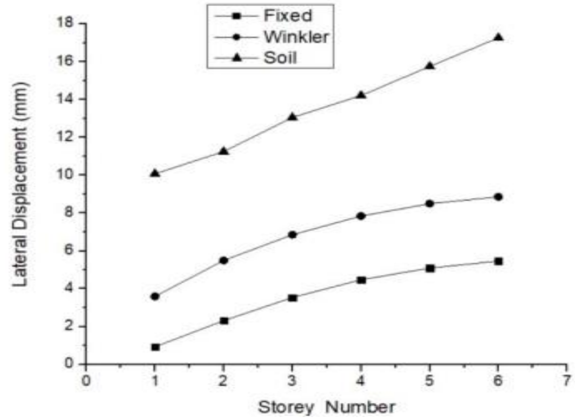


Figure 3.15 Lateral displacement of G+8

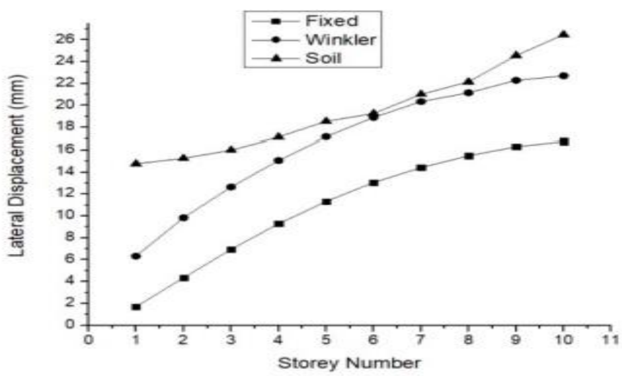


Figure 3.16 Lateral displacement of G+10

conducted a comprehensive study to evaluate the influence of Soil-Structure Interaction (SSI) on the seismic performance of multi-storey buildings using both Winkler and Soil Continuum models. Their findings show that SSI models contribute to a larger time period and lateral displacement, while resulting in reduced base shear compared to the fixed base model. The inter-storey drift ratio pattern of the fixed base model was found to be closer to that of the Winkler model.

3.2.4 Kharade and Nagendra (2015): thoroughly discussed the phenomenon of Soil-Structure Interaction (SSI), defining it as the mutual influence between a structure, its foundation, and the supporting soil. They emphasized that while SSI is often overlooked in conventional design especially for light buildings on hard soils its influence becomes critical for heavy and tall structures resting on soft soils. The authors provided multiple references to previous research studies that focused on understanding the effects of SSI on structural response, and they suggested that ignoring SSI can be dangerous and may lead to an underestimation of seismic demand. The authors also referred to the nonlinear behavior of soils and explained how their response under seismic loads can amplify or significantly alter structural performance.

In their study, they followed a systematic methodology to investigate the effects of Soil-Structure Interaction (SSI) on the seismic performance of a G+12 reinforced concrete moment-resisting frame using ETABS 9.7.4 software. Two structural configurations were analyzed: Buildings without fixed base (soft and hard) , Buildings with flexible base on a raft foundation where SSI effects were modeled using soil springs derived from Richart and Lysmer's approach .

The structural components, including beams, columns, slabs, and shear walls, were modeled with appropriate finite element techniques. Material properties included M35 grade concrete and Fe500 steel, the Figures 17 and 18 provide 3D visualizations of the studied buildings :

Figure 3.17 3D rendering view of building with fixed base in ETABS

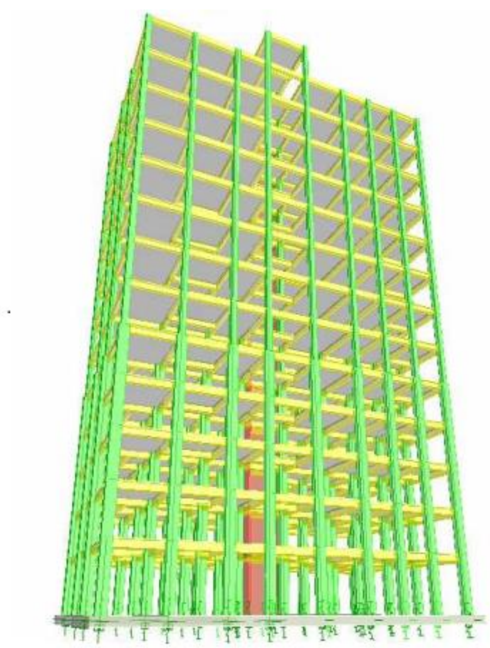


Figure 3.18 3D rendering view of building with raft foundation and applied soil springs in ETABS

Analyzing all the models using response spectrum analysis, the results were evaluated in terms of four key parameters: lateral displacement, story drift, base shear, and natural time period. Each parameter is illustrated through its respective graph as follows:

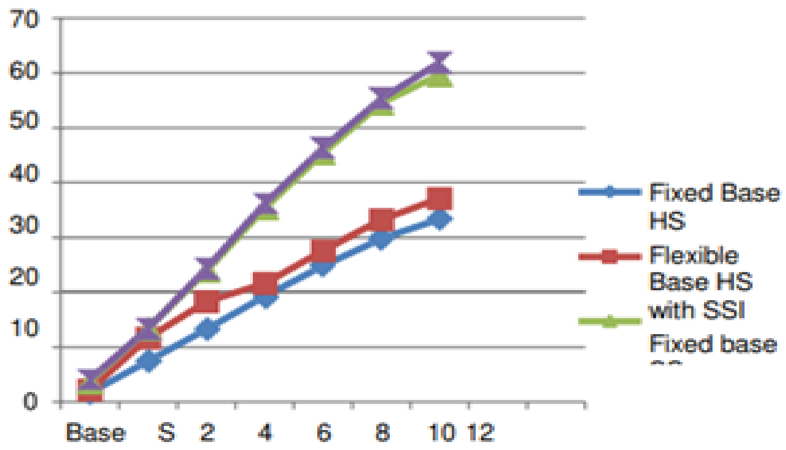


Figure 3.19 Variation of lateral displacement (mm) with floor level in X direction

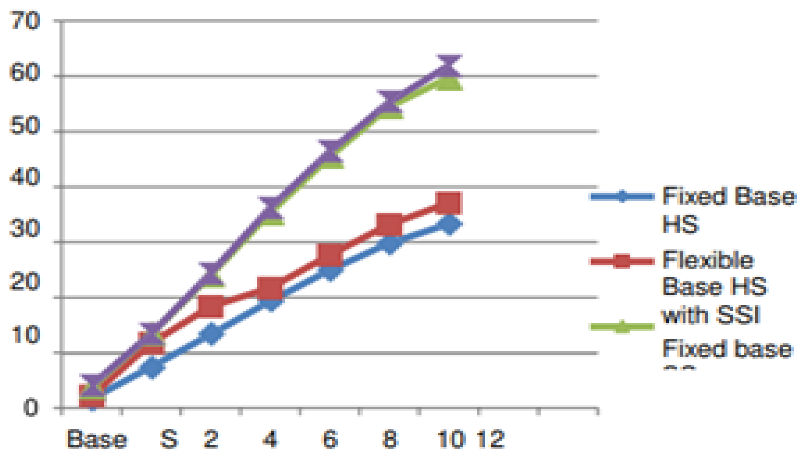


Figure 3.20 Variation of lateral displacement (mm) with floor level in Y direction

The values of lateral displacement (in mm) with floor level in the X direction increased slightly by around 5–10% under soil-structure interaction (SSI) conditions compared to the fixed base case.

In the Y direction, lateral displacement increased by about 4–5% with SSI.

- **Time Period :** The time period of the building, with mode numbers for Zone IV, increased slightly by about 1–2% under SSI conditions compared to the fixed base model.

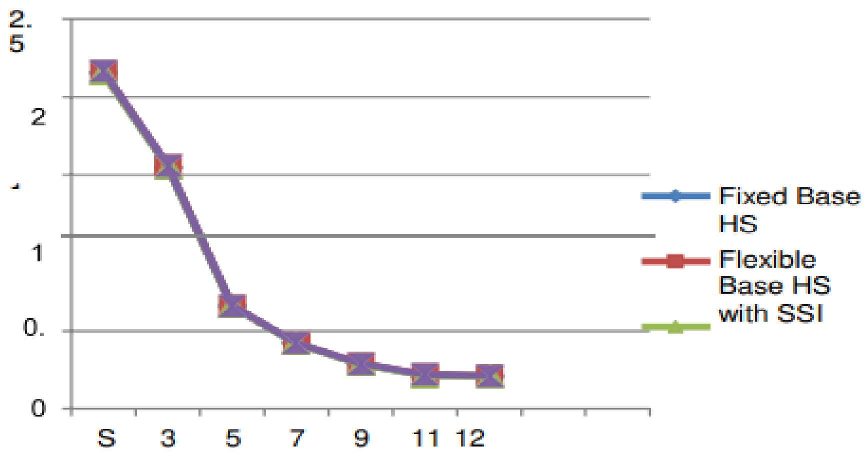


Figure 3.21 Time Period vs Mode Number

- **Base Shear**: from the figures below it was found that the base shear in both X and Y directions remained nearly the same for both fixed and flexible base conditions, as there was no increase in the seismic weight of the building.

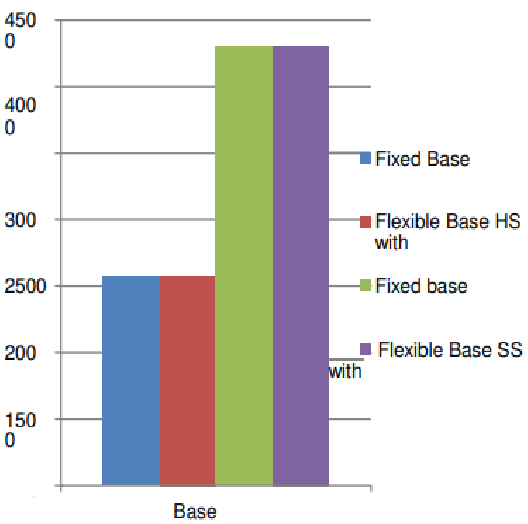


Figure 3.22 Variation of base shear (kN) of of buildings in X direction

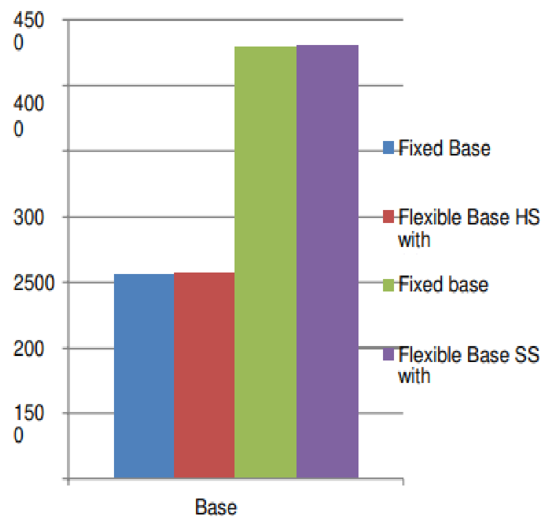


Figure 3.23 Variation of base shear (kN) of buildings in Y direction

The study concluded that the variation of storey drift is parabolic, with maximum drift in the middle storeys, and this drift magnifies when SSI is considered. It was found that lateral displacement is greatest at the top storeys and increases under SSI conditions. Although base shear remains nearly the same in both fixed and flexible base cases due to unchanged seismic weight, the natural time period increases slightly with SSI. The response of tall buildings on soft soil showed a significant increase, attributed to the flexibility introduced at the base, highlighting the considerable impact of SSI on seismic behavior.

3.2.5 Thaiba and Sebastian (2017) : investigated the influence of Soil-Structure Interaction (SSI) on the free vibration characteristics of multistorey buildings. Their research focused on analyzing modal frequencies of structures supported by raft foundations, using both the Winkler spring model and the elastic continuum model to simulate soil behavior. In developing their methodology, Thaiba and Sebastian referenced several foundational works that emphasize the significance of considering SSI in structural dynamics.

For the study they modeled symmetrical space frames with 2 bays in both X and Y directions, and storey heights of 2, 5, and 8 using SAP2000 finite element software. The material and geometric properties of the building frames, raft, and soil mass are detailed in Table 1, including beam and column dimensions, raft thickness, and the modulus of elasticity for concrete. For the soil conditions, three types hard, medium, and soft were considered.

The SSI was modeled using two main approaches Winkler Approach when the soil is represented by equivalent springs with six degrees of freedom (DOF), calculated using formulations developed by Gazetas . Elastic Continuum Approach The soil is treated as a 3D elastic continuum, modeled using eight-noded brick elements figure . The block size is kept sufficiently large (32 m × 32 m × 16 m) to minimize boundary effects, based on standard assumptions such as lateral offset being at least 1.5 times the width of the building.

These formulations are integrated into a complete 3D structural model, depicted in Figures 24 (a, b, c) corresponding to fixed support, Winkler spring model, and continuum model respectively .

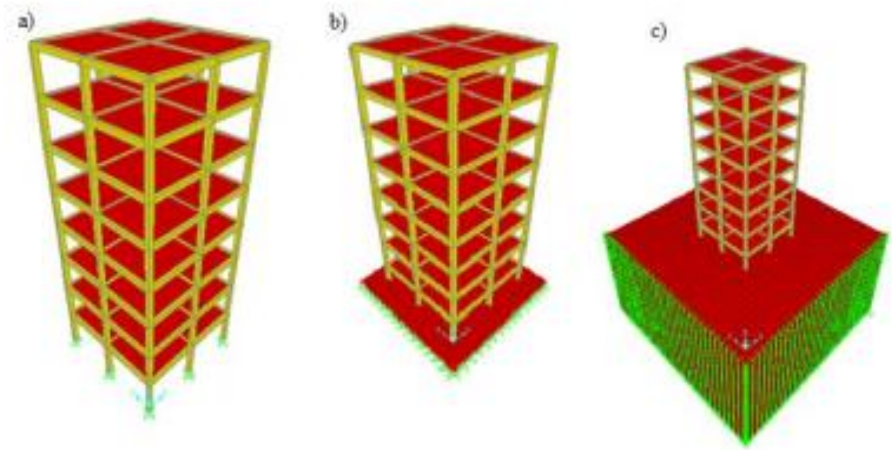
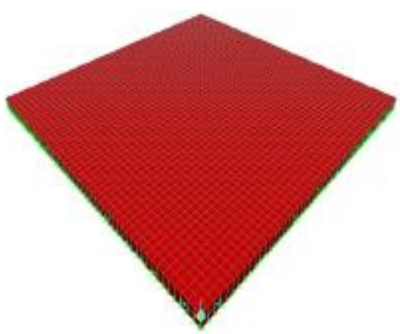


Figure 3.24 Frame with a) fixed support, b) Winkler model and c) continuum model

Their methodology validated by performing a numerical analysis of a square raft foundation using SAP2000 software. The SSI model of raft is shown in Figure 25 . The deflection result of 10.8 mm visualized in Figure 26, closely matched the result from Fraser et al (10.7 mm), confirming the reliability of the adopted modeling approach.



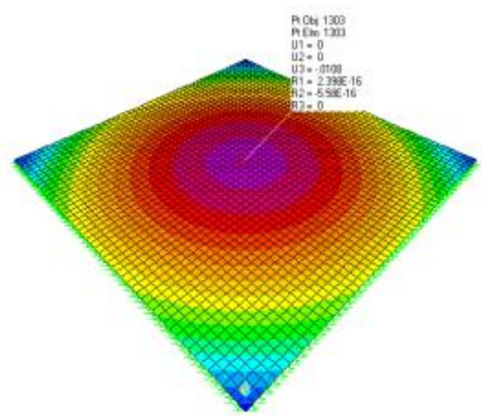


Figure 3. 25 Raft with spring model (Winkler model)   **Figure 3.26** The deflection contour of raf

After performing the soil-structure interaction analysis using the two approaches and the dynamic behavior of the building frame was assessed through modal analysis using SAP2000. The frequencies observed were: Fixed base: 0.3539 Hz , Winkler model: 0.3352 Hz and Continuum model: 0.3318 Hz The results reveal that the modal frequency under interaction analysis is lower than that of the non-interaction case (i.e., frame with fixed base), indicating the effectiveness of soil-structure interaction

The parametric study of soil structure interaction is carried out using the Winkler approach, as it is simpler compared to the continuum approach. The analysis is performed on RCC framed structures with raft footing. A comparison is made between fixed and flexible base conditions across different soil types as shown in Table 4.

Table 3.4 Frequency of building frame with different support condition

Frame	Frequency [Cyc/sec]			
	Fixed	Winkler (spring model)		
		Hard soil	Medium soil	Soft soil
Bay 2 × 2 × 2	1.8757	1.727	1.609	1.330
Bay 2 × 2 × 5	0.6164	0.5975	0.5724	0.5125
Bay 2 × 2 × 8	0.3539	0.3520	0.3352	0.3001

Thaiba and Sebastian concluded that SSI leads to a decrease in modal frequency. In this study, free vibration analysis considering SSI is carried out by comparing fixed and flexible supports. The frequency decreases in SSI analysis compared to non-interaction analysis. The parametric study shows that modal frequency reduces with increase in storey height, and soil type significantly affects the frequency, decreasing from hard soil to soft soil.

3.2.6 Awchat and Monde (2021) : investigated Soil-Structure Interaction (SSI) effects on a G+10 RC building through finite element analysis in SAP2000, comparing fixed-base and SSI models under El-Centro excitation. Their results showed SSI significantly increased inter-story drift (up to 95%) and lateral displacement, particularly in high-seismic zones (III-V), potentially compromising structural safety. The study found SSI amplified time periods and spectral responses while demonstrating the limitations of Winkler models compared to finite element analysis. Based on these findings, the researchers recommended incorporating SSI in seismic design, especially for soft soil conditions, and suggested further studies on P-delta effects and multi-directional ground motions.

They analyzed G+10 reinforced concrete (RC) frames located in seismic Zones II, III, IV, and V of India. To incorporate the effects of Soil-Structure Interaction (SSI), two models were developed: Model-1 represents a building with a fixed base (without SSI), and Model-2 represents a building with a mat foundation resting on soft soil. Both models were created in SAP2000 v.20 and are shown in Figures 27.a and 27.b, respectively.

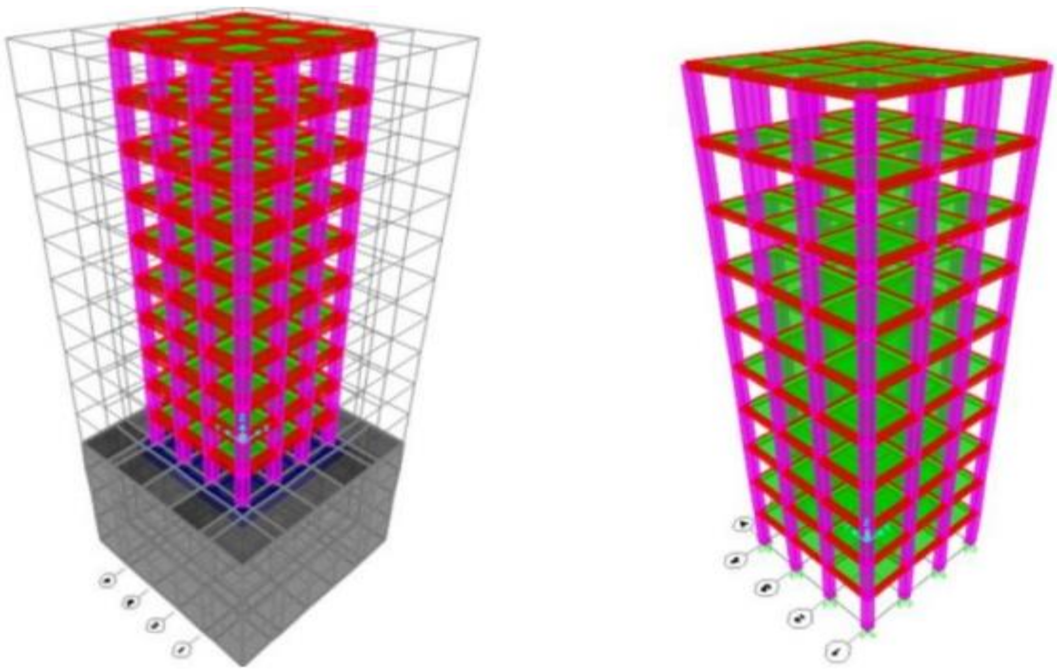


Figure 3.27 Model of a structure (a) with soft soil and mat foundation (b) with fixed base

The frames were modeled as moment-resisting with three bays, using 3 m storey height and bay width. Design followed Indian codes (IS-875, IS-456:2000, IS-1893:2016), with M25 concrete and Fe500 steel. Hysteresis behavior used the Takeda model for concrete and the kinematic model for steel (Figures28 and 29).

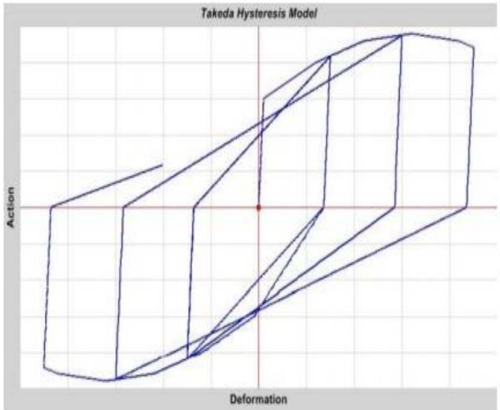


Figure 3.28 Takeda Hysteresis Model

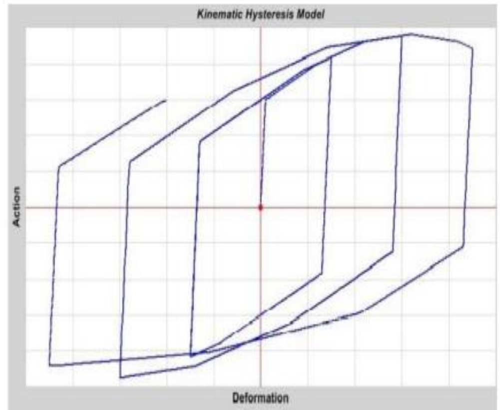


Figure 3.29 Kinematic Hysteresis Model

Dynamic analysis was conducted to account for lateral loads, and Time-history analysis was performed using El-Centro earthquake data. This method provided both linear and non-linear responses under seismic excitation and specific time periods. Figure 5 presents the El-Centro acceleration-time history used in the analysis.

The results of the study focus on the following key aspects:

- **Lateral Storey Displacement :** SSI effects amplified lateral displacements by 47-95% across seismic zones, with greater increases (60-95%) in higher zones (III-V), confirming soil flexibility significantly impacts structural response, as validated by Chore's findings of 56-98% increase.

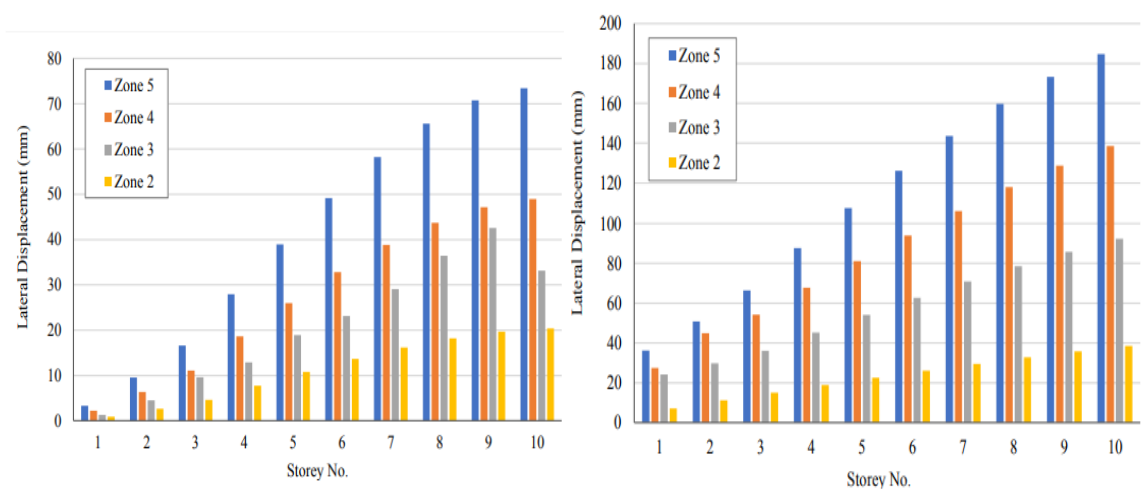


Figure 3.30 lateral storey displacement and storey number in various seismic zones (a) without SSI; (b) with SSI

Awchat and Monde analyzed spectral acceleration and spectral velocity to assess the effect of Soil-Structure Interaction (SSI) during the El-Centro earthquake ,.They defined the fundamental natural period as the time required by a building to complete an oscillation cycle, an inherent property of the structure. When considering SSI, the time period increased, indicating an increase in ductility demand. The results align with Singh & Mala's study on a G+9 building, which showed that time period increases when SSI effects are considered due to the soil's flexibility. Figure 31 illustrate the effect of SSI on the time period.

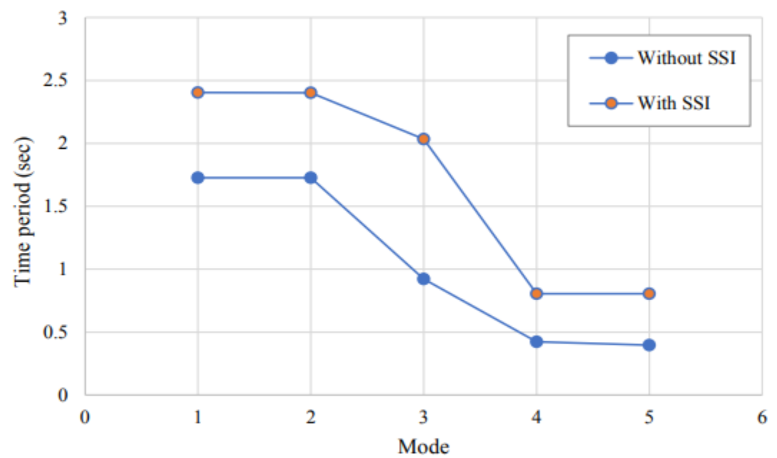


Figure 3.31 Variation of Time period (sec) in different modes without and with SSI effects

Awchat and Monde conducted a study to analyze the seismic parameters during the El-Centro earthquake, considering the effect of Soil-Structure Interaction (SSI). They compared models with and without SSI across various seismic zones in India, focusing on parameters that follow :

- Inter-storey drift was higher in buildings with SSI, and Zone II and III buildings were safe without SSI. However, with SSI, Zone III, IV, and V buildings suffered light to moderate damage.
- Lateral storey displacement increased from Zone II to V, with SSI causing a 47–87% increase in Zone II, and up to 95% in Zones III, IV, and V.
- Spectral acceleration showed a decrease with increasing damping, and increased with SSI, especially in Zone V. It peaked at a time period between 0.3 to 0.6 sec.
- Time period and ductility demand increased with SSI, caused by soil flexibility.

The study concluded that including SSI is essential, particularly for soft soils in Zones III, IV, and V. Mitigation measures like base isolators or dampers were recommended, along with further studies to include experimental work and realistic forces like pounding.

3.2.7 Abdel Raheem et al. (2022) : This study investigated SSI's critical role in the seismic response of RC buildings with raft foundations, demonstrating that neglecting SSI especially on soft soils leads to unsafe designs by misrepresenting energy transfer. Using 3D FEM and multiple analysis methods (static, spectrum, nonlinear time-history), it compared SSI and fixed-base models in terms of drift, displacement, and internal forces, while evaluating ECP-201 provisions and alternative approaches for improved accuracy.

Abdel Raheem et al. conducted an extensive investigation into the seismic response of multi-story buildings considering Soil-Structure Interaction (SSI), where they explicitly utilized three seismic analysis methods:

- Equivalent static load (ESL) method

The authors apply the Equivalent Static Load (ESL) method, in accordance with ECP-201 , to compute the seismic base shear force where seismic base shear Fb. This methodology and its components are illustrated in Figure 32, which shows the design response spectrum curve used for the case study.

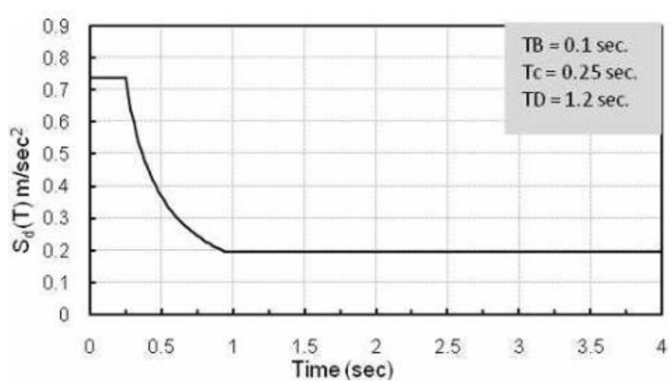


Figure 3.32 ECP-201 design response spectrum

- Modal response spectrum (RS) method

The method is applicable for all types of buildings. They highlight that RS analysis includes enough modes to capture at least 90% of the structure's mass in each of two orthogonal directions. They further explain that ECP-201 incorporates a damping coefficient into the response spectrum equations, thus eliminating the need to manually specify a damping ratio in the RS analysis.

- Nonlinear time history (TH) method

Nonlinear time-history analysis is by far the most comprehensive method for seismic analysis. Unlike the response spectrum method, nonlinear time-history analysis does not assume a specific method for mode combination.

They also presented a finite element modeling approach that includes:

- Target multi-story MRF building description

the building environment in Egypt had extensively utilized medium-rise R.C. buildings having twelve stories." They chose two typical buildings with six and twelve stories, "essentially bi-symmetric in plan" with 5 m bays and 3 m story height, shown in Figure 33. Structural elements were designed per ECP-203 and ECP-201, with slab thickness 15 cm, beam section 30×60 cm, and columns 0.6×0.6 m and 0.8×0.8 m. Materials used include C250 concrete and St52 steel, with concrete density 2.5 t/m³, and live load = 0.2 t/m².

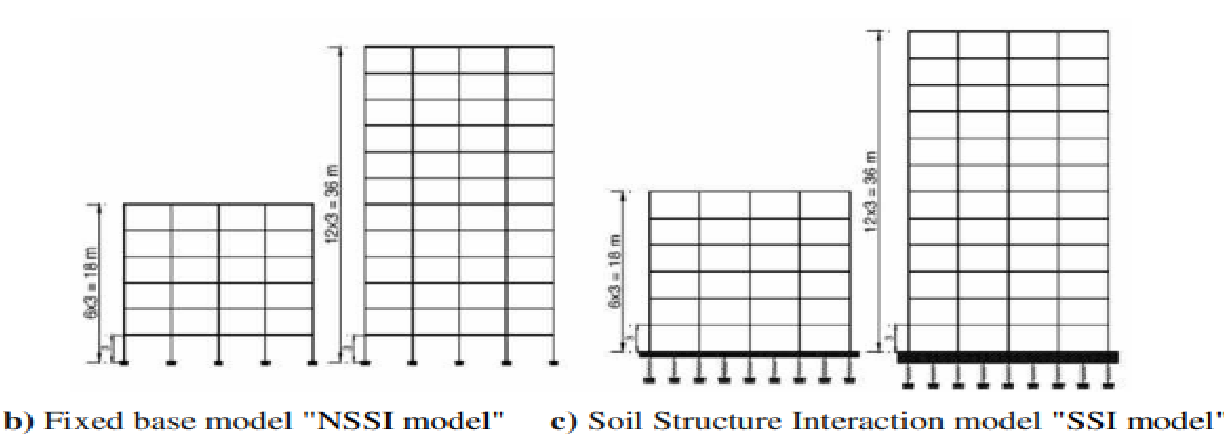


Figure 3.33 Schematic of 6-story and 12-story buildings' models

- Raft foundation and underneath soil conditions

focus on raft foundation "with thickness equal to 0.6 m for 6-story building and 1.0 m for 12-story building." Soil is modeled using the Winkler Spring approach, with modulus of elasticity 24480, 12240, and 6120 t/m² for stiff, medium, and soft soils.

- Finite element modeling

The mathematical model captures spatial distribution of mass and stiffness, sufficient for dynamic response analysis. Modeled in ETABS 9.7, the 3D structure uses frame elements (beams/columns), shell elements (slabs/raft), and spring elements (soil).

- Input seismic excitation

Ground motion properties are influenced by fault mechanism, propagation, and site amplification. Due to Egypt's moderate seismicity and limited records, nine earthquake records from seven events are used, aligned with design force requirements.

A parametric study investigates the effects of design parameters including soil condition (soft, medium, stiff), number of stories (6- and 12-story), raft foundation flexibility, and boundary conditions at foundation level .Beam, slab, and column sections are constant, with a rigid diaphragm assumption. Soil spring stiffness is based on soil modulus of elasticity. To study SSI effects, comparisons are made between the two models in the parameters below :

- Natural vibration analysis :

Vibration period (T) is key for seismic design, with empirical formulas underestimating actual periods especially on soft soils where SSI increases T. While ECP-201 claims height alone determines T, analysis shows soil stiffness significantly lengthens periods in 6- and 12-story buildings. Softer soils reduce spring stiffness, further amplifying this effect.

- Seismic response analysis:

They evaluate the seismic response of multi-story buildings by analyzing

a. Story lateral displacement response **:** SSI models (Figs 34-35) show consistently greater displacements than NSSI cases, with softer soils amplifying effects; TH analysis yields higher/more realistic values than ESL/RS, revealing nonlinear height-dependent growth (peaking at lower stories) that intensifies with reduced soil stiffness in both 6- and 12-story buildings.

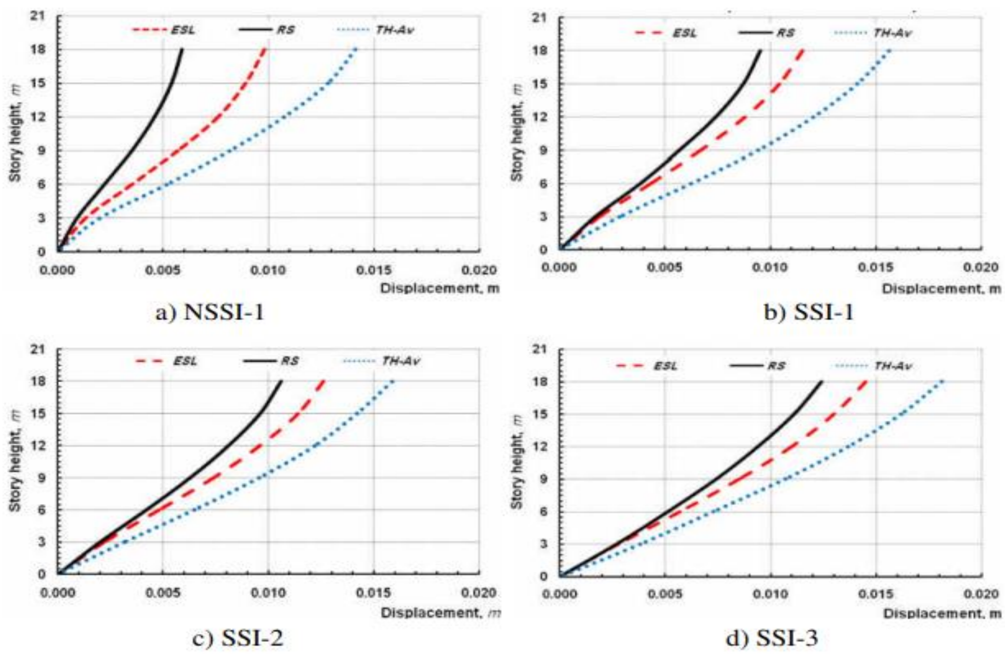


Figure 3.34 Story lateral displacement responses of 6-story building

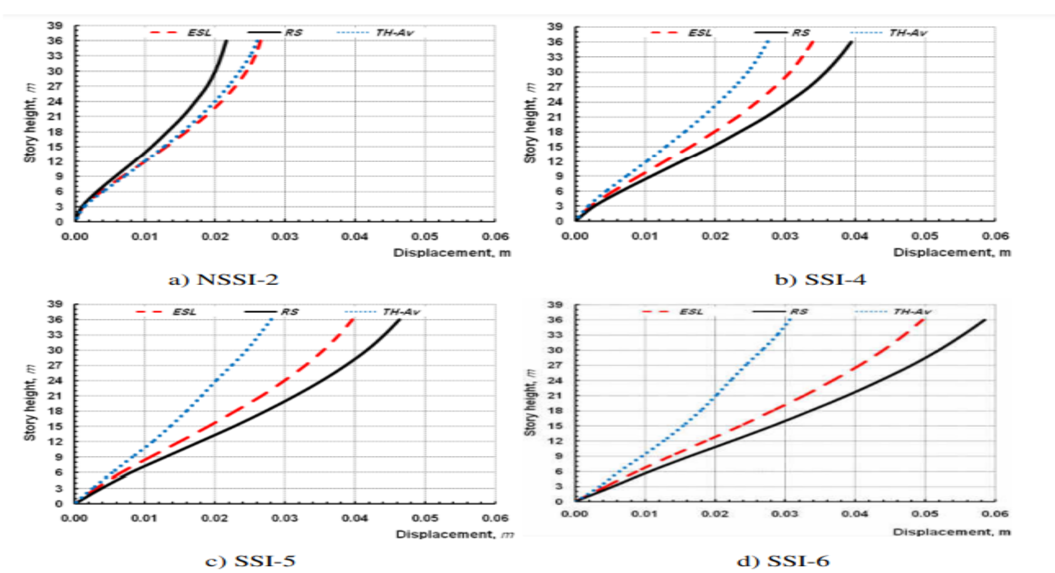


Figure 3.35 Story lateral displacement responses of 12-story building

b. Story shear force response **:** Figs. 35-36 demonstrate soil-dependent story shear variations: ESL remains constant (6-story:121.64t, 12-story:186.24t), RS increases with softer soils (12-story up to 234.93t), while TH decreases (6-story:198.62-178.57t; 12-story:211.5-185.41t), with RS response ratios peaking at 1.54 versus TH's 1.2-1.17 decline.

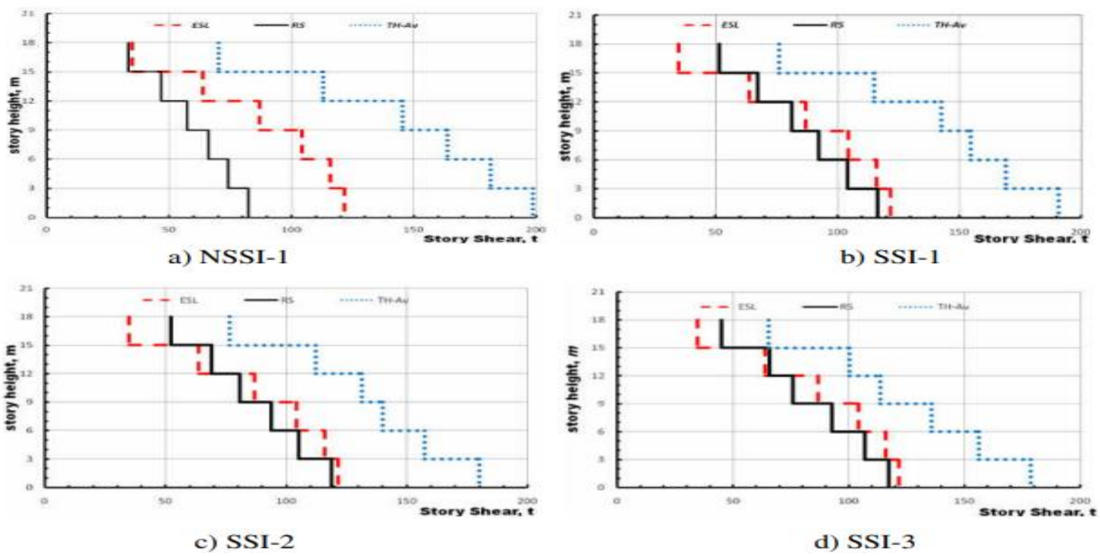


Figure 3.36 Story shear force responses of 6-story building

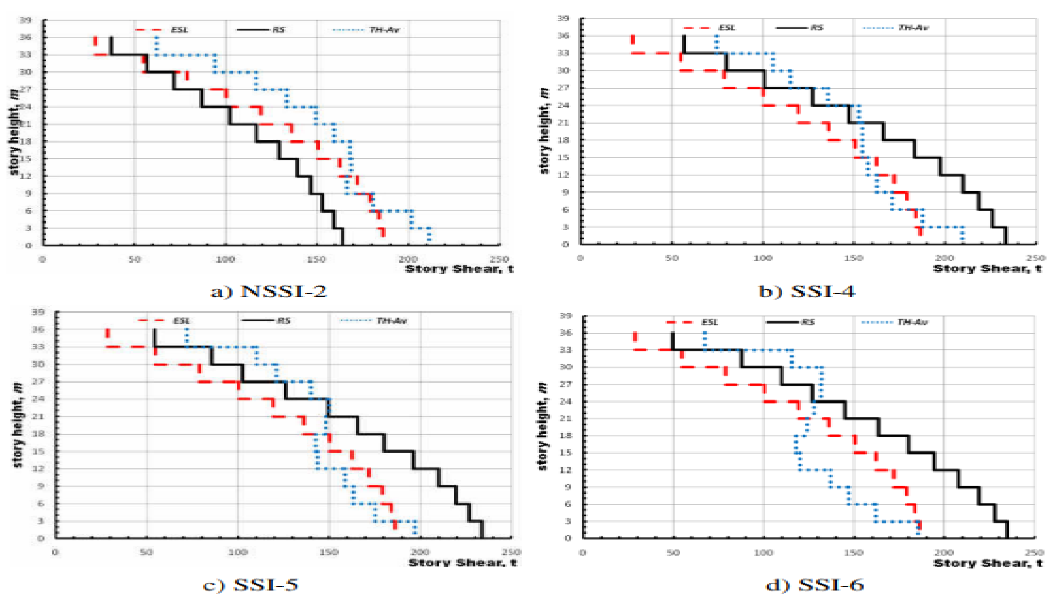


Figure 3.37 Story shear force responses of 12-story building

They concluded that incorporating soil-structure interaction (SSI) is essential for accurate seismic design of mid-rise moment-resisting frame (MRF) buildings, especially on soft soils. The study showed that SSI increases the fundamental period, lateral displacements, and inter-story drifts, particularly as soil stiffness decreases and building height increases. ESL methods ignore SSI effects, while RS and TH methods show significant sensitivity. Neglecting SSI can lead to over- or underestimation of seismic demands, making conventional fixed-base design potentially unsafe for buildings on flexible soils.

This chapter also a focuses on reviewing the extensive literature surrounding the Winkler method and the critical parameter of the subgrade reaction modulus. It explores how various studies have evaluated, applied, and modified the Winkler model, especially in terms of estimating and utilizing ks for different soil types and foundation conditions.

3.3 Subgrade Reaction Modulus (ks) :

The subgrade reaction modulus, symbolised as ks is a fundamental parameter in soil-structure interaction modeling that represents the stiffness of the soil supporting a foundation. It is defined as the ratio of the contact pressure exerted by the soil to the corresponding vertical displacement of the foundation surface typically expressed in units of force per unit volume (e.g., kN/m^3).

Various studies have proposed empirical relationships to estimate the modulus of subgrade reaction based on soil characteristics and test results. Table 1 summarizes these commonly used formulas for determining the subgrade reaction coefficient ks :

Table 3.5 Modulus of subgrade reaction formulas, ks

Source of formula	Suggested formula
Winkler (1867)	$ks = \frac{q}{\delta}$
Biot (1937)	$ks = \frac{0.95\,Es}{B(1-\upsilon_s^2)}\left[\frac{Es\,B^4}{(1-\upsilon_s^2)EI}\right]^{0.108}$
Terzaghi (1955)	$ks = ksp\left(\frac{B+B_P}{2B}\right)$
Vesic (1961)	$ks = \frac{0.65\,Es}{B(1-\upsilon_s^2)}\sqrt[12]{\frac{Es\,B^4}{EI}}$
Meyerhof and Baike (1965)	$ks = \frac{Es}{B(1-\upsilon_s^2)}$
Selvadurai (1984)	$ks = \frac{0.65\,Es}{B(1-\upsilon_s^2)}$
Bowles (1996)	$ks = 40\,SF\,qa$
Bowles (1998)	$ks = \frac{Es}{B(1-\upsilon_s^2)mI_sI_F}$
Daloglu et al. (2000)	$ks = \frac{0.78\,Es}{B(1-\upsilon_s^2)}\left[\frac{Es\,B^4}{EI}\right]^{0.0938}$
Liu (2000)	$ks = \frac{0.74\,Es}{B(1-\upsilon_s^2)}\left[\frac{Es\,B^4}{EI}\right]^{0.0903}$
Fischer et al. (2000)	$ks = \frac{0.82\,Es}{B(1-\upsilon_s^2)}\left[\frac{Es\,B^4}{EI}\right]^{0.0973}$
Yang (2006)	$ks = \frac{0.95\,Es}{B(1-\upsilon_s^2)}\left[\frac{Es\,B^4}{EI}\right]^{0.108}$
Henry (2007)	$ks = \frac{0.91\,Es}{B(1-\upsilon_s^2)}\left[\frac{Es\,B^4}{EI}\right]^{0.1043}$
Arul et al. (2008)	$ks = \frac{0.87\,Es}{B(1-\upsilon_s^2)}\left[\frac{Es\,B^4}{EI}\right]^{0.1008}$

3.4 Literature Review on the Application and Evaluation of the Winkler Method and Subgrade Reaction Modulus :

This section reviews important studies on the Winkler method and the influence of the subgrade reaction modulus (ks).

3.4.1 Özkan et al. (2023) : conducted detailed comparative study on the behavior of raft foundations on sandy soils by utilizing two analytical methods: the Winkler method and the Pseudo-coupled method. emphasizing that foundation settlements in buildings were depend by a variety of soil parameters, these parameters introduce complexity during the calculating process . As a practical solution, finite element methods often employ the subgrade reaction coefficient to simplify the founadation solution.

In their study, they analyzed a raft foundation of a 10-story symmetrical building using the two methods that are mentioned earlier : the Winkler and the Pseudo-coupled approaches. The building, shown in Figure 38, features a square raft foundation measuring 36 m × 36 m with a thickness of 75 cm, and its floor plan is presented in Figure 39. To evaluate and compare the two methods, the authors modeled the building's foundation across four distinct sandy soil types, classified according to Eurocode 8, with two soils falling under Class C and the other two under Class D . For each soil type, the raft foundation was divided into six regions (one, two, three, five, seven, and ten regions), resulting in a total of 24 different analysis cases, all conducted using ETABS software.

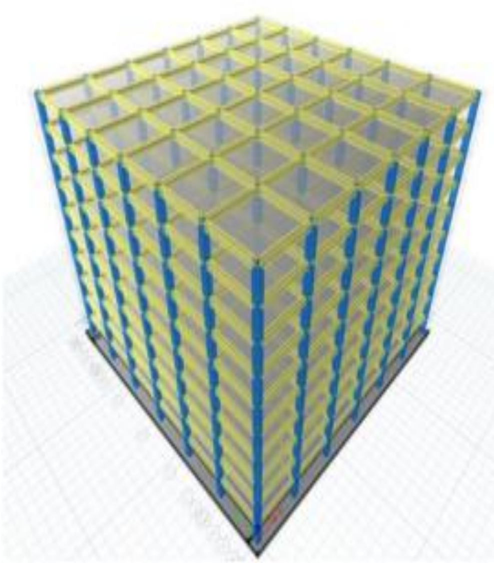


Figure 3.38 The perspective view of 10 story building

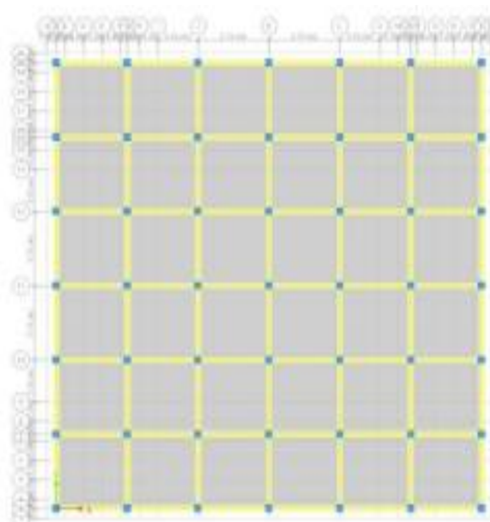


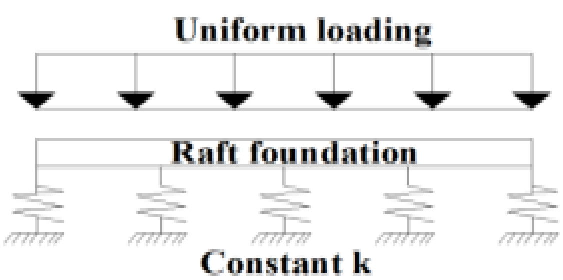
Figure 3.39 The floor plan of the building

As explained by Özkan et al., the soil layer beneath the raft foundation was modeled using springs in both the Winkler and Pseudo-coupled methods. In both approaches, the stiffness of the springs, which is defined as the coefficient of subgrade reaction (k), is the most important parameter in the analysis calculated by using the Equation 1 :

$$k = \frac{q}{s} \left(\frac{kN}{m^3}\right)$$

where k is the coefficient of subgrade reaction, q is the base pressure, and s is the settlement resulted from base pressure.

In the Winkler method, as the authors describe, each spring is considered independent. All springs have the same coefficient of the subgrade reaction of the soil layer,this method, illustrated in Figure 40. Considering the real conditions, the shape of the raft foundation becomes dishing shape after it is subjected to uniform loading (Figure 41)



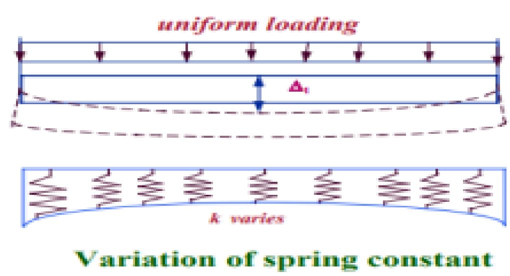


Figure 3.40 Winkler spring method **Figure 3.41** Dishing shape of raft foundation

(Subramanian et al. 2005)

However , in the Pseudo-coupled method each spring affects the surrounding springs . While the most affected springs are situated in the center region of the raft foundation, the less affected are positioned at the corner region .

In their analysis, the suggested raft was meshed into parts based on the number of regions in each model. For each case, settlement and base pressure were calculated using Equation 1 , assuming homogeneous and infinite soil depth.

Initially, the Winkler method was applied to analyze the raft foundation for all soil layers. Then, the Pseudo-coupled method was used by dividing the raft into 2, 3, 4, 7, and 10 regions, as shown in Figure 42, with regions labeled A1, A2, A3, etc., each assigned different k values.

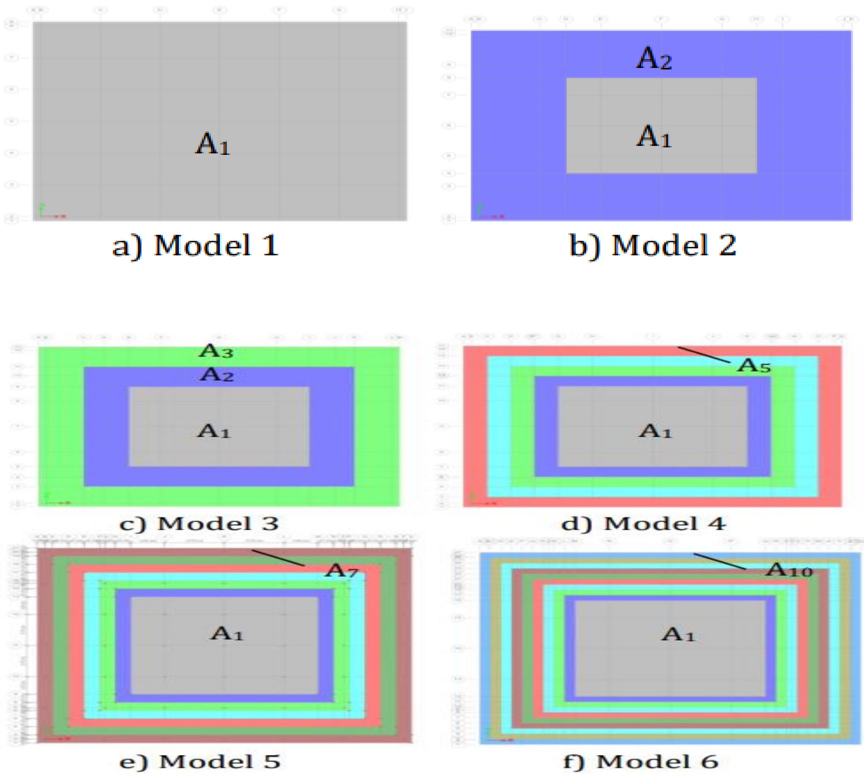


Figure 3.42 Division of the foundation into suitable regions: a) The Winkler Method and Pseudo-Coupled Method by b) 2 regions, c) 3 regions, d) 5 regions, e) 7 regions, and f) 10 regions

These k values were calculated using Equation 2 .The areas of the regions are listed , and the relationships between coefficients for different regions are expressed through Equation 3, using separate ratios for both each model and each region which should multiplied by k . The coefficients were determined from SPT-N values for sandy soils using Equation 4 .

A total of 24 analysis cases were performed, as result of these analyses , changes in foundation shape and settlements at the center and corner points were evaluated.

The results of the study are based on analyses performed using ETABS software, and were discussed under the following factors :

- Axial force and moment at column base

In the Winkler method, the axial force at the center column base is not significantly affected by soil class (Figure 43).

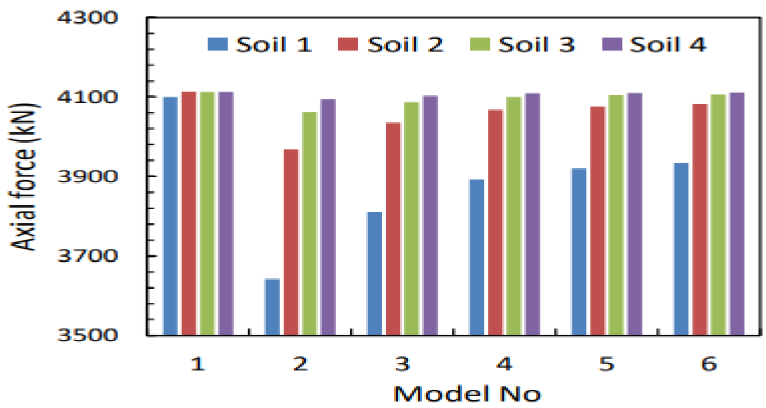


Figure 3.43 Axial force at center column base

However, in the Pseudo-Coupled method, axial force decreases by about 13% in Soil 1, Model 2, and increases as the number of regions in the foundation increases. For C class soils, axial force approaches the Winkler result. Due to the symmetrical square layout, no moment is transferred to the center column. The corner columns receive about one-third of the center column's axial load, and this increases with both soil bearing capacity and region number (Figure 44).

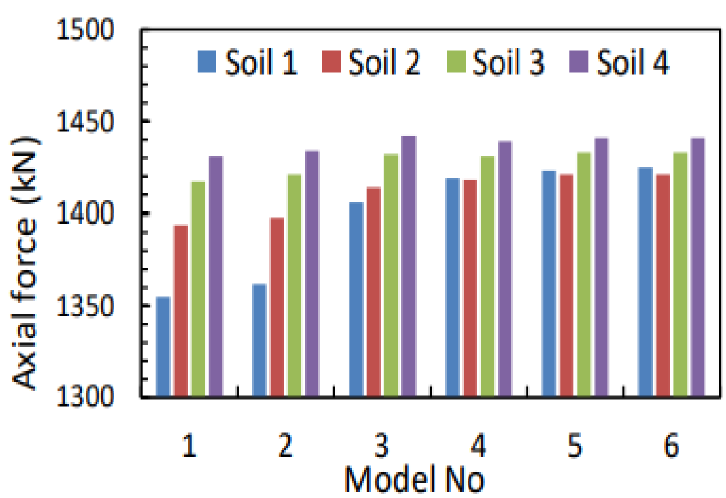


Figure 3.44 Axial force at corner column base

In contrast, moment values transferred to the corner column base decrease as region count and the bearing capacity of the foundation soil increase (Figure 45). These variations in the axial force and moment values relating to different settlements in the foundation

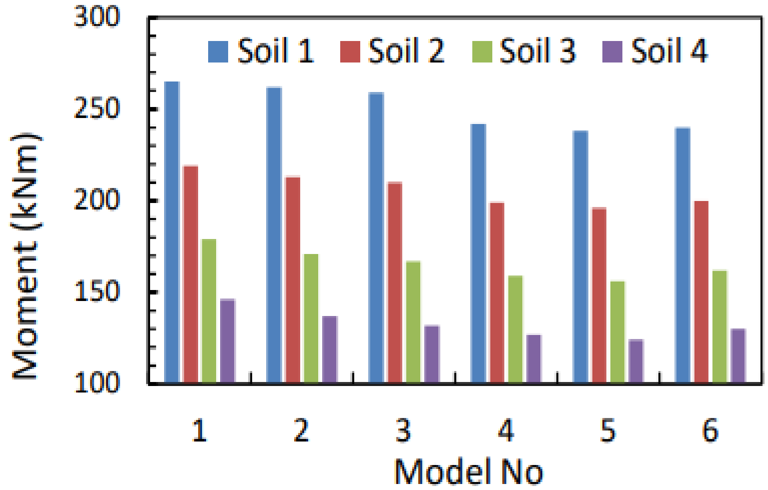


Figure 3.45 Moment values at corner column base

- Subgrade reaction coefficient

The raft foundation on sandy soils with different subgrade reaction coefficients was analyzed using six models. In Model 1, the raft foundation has one area with the same subgrade coefficient at every point. Since the foundation is square, these ratios are shown by width and length , ratios of subgrade reaction coefficients give very close values for solutions with 5 regions (Model 5) and greater regions.

- Settlements of foundation

The foundation shapes from the analyses are shown in Figures 46 and 47, and the settlements at corner and center points.

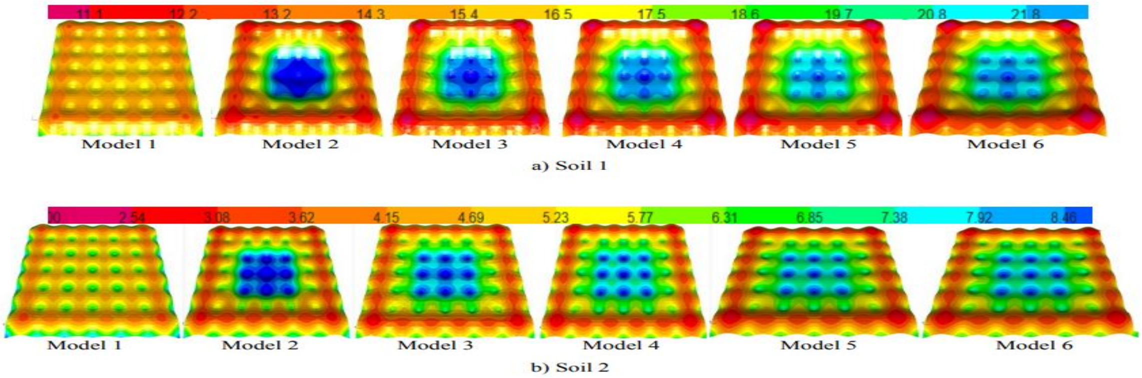


Figure 3.46 The foundation shapes designed on a) Soil 1 and b) Soil 2 (units in mm)

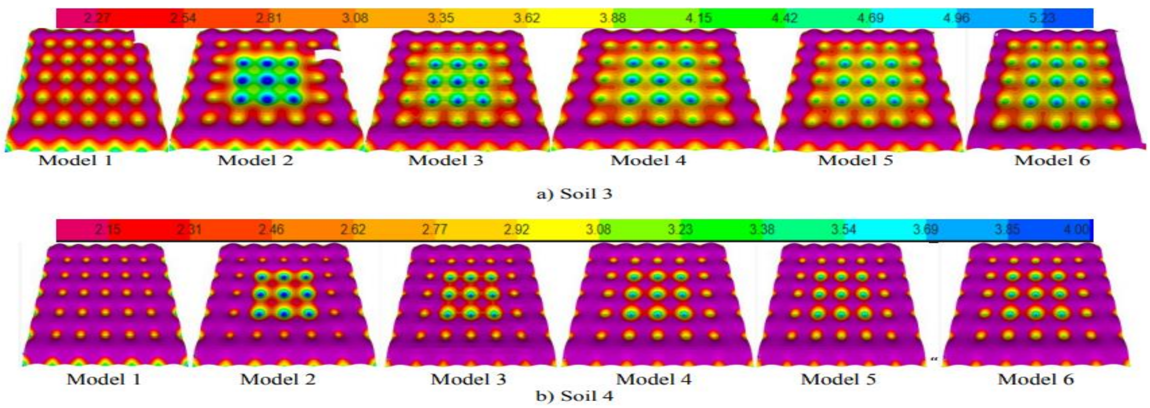


Figure 3.47 The foundation shapes designed on a) Soil 3 and b) Soil 4 (units in mm)

In Model 1 (Winkler method), all points have the same subgrade reaction coefficient.. As the subgrade coefficient increases, differential settlement decreases, and the foundation behaves more rigid. Thus, Model 1 suits rigid raft foundation analysis.

In addition ,the behavior of rigid raft foundation depends on the value of subgrade reaction of soil.

The other models were analyzed using the Pseudo-Coupled method, where the subgrade coefficient changes across regions. The raft foundation behave flexible , Model 2 gives the highest differential settlement, which decreases as the number of regions increases.

Results showed that ratios of center to corner settlement that the highest settlement ratios are obtained in Model 3 which has three different areas for all subsoil conditions, especially on Soil 1, which has the lowest stiffness for each model . These ratios decrease with increment of soil stiffness. For Model 1, the ratios < 1, and are approximately similar for all subsoil conditions.

Thus, the settlements obtained from Winkler method are suitable for rigid foundation assumption. However, the settlement ratios obtained from Pseudo-Coupled method show ratios >1, about 1.5 for Soil 1. In Figure 48, it's seen that Model 5 with 7 regions gives the lowest settlements and then increases , suggesting 7 as the optimal region number for the Pseudo-Coupled method.

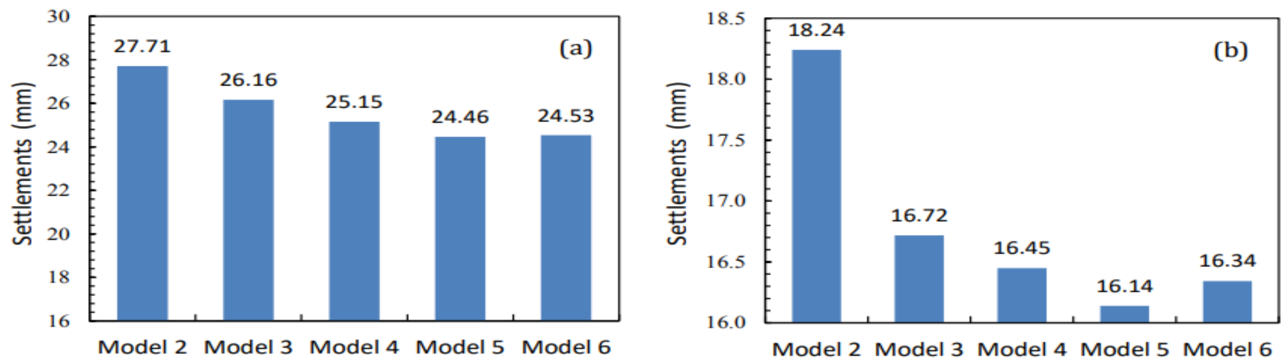


Figure 3.48 Settlements at the foundation a) corner and b) center points for subbase of Soil 1

1. Effect of local soil class

Figure 49 shows the center and corner settlement values by soil type. The maximum corner settlements for both classes C and D is calculated from Model 1, while the maximum center settlements is calculated from Model 2.

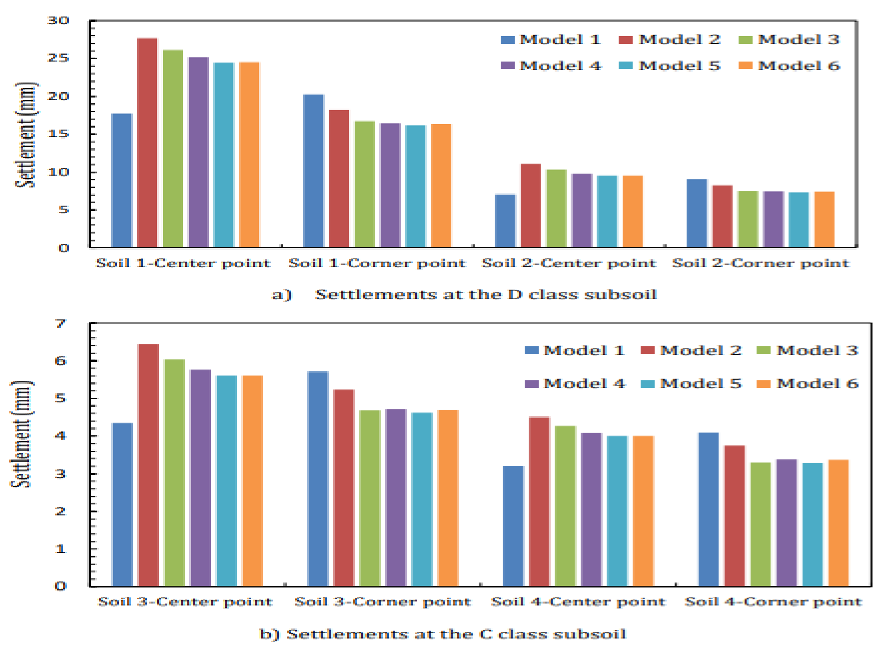


Figure 3.49 Effect of local soil class on foundation settlement

Figure 50 shows the calculated values of the differential settlement . The maximum differential settlements calculated from Model 2 on Class D soils, supporting a flexible foundation assumption. However, the minimum differential settlement on the same soils is in Model 1, supporting a rigid foundation assumption.

However, maximum values were calculated from models that were divided into three or less regions for both Soil 3 and Soil 4 , indicating Flexible foundation assumption is valid for these models . In conclusion, differential settlement decreases with increasing subgrade stiffness in this study.

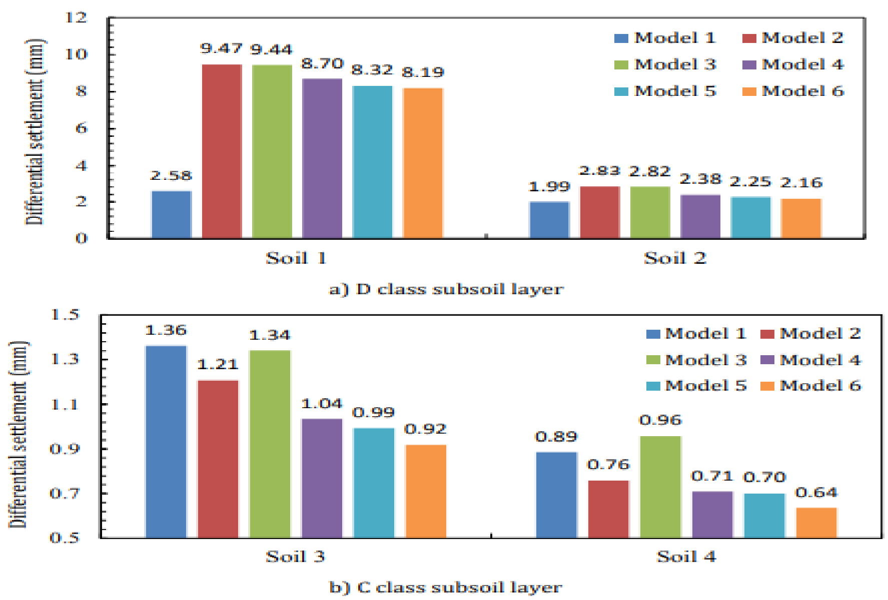


Figure 3.50 Differential settlements values considering local soil class of subsoil

The authors concluded that the Winkler method is suitable for rigid foundations on Class D soils, while the Pseudo-coupled method is more appropriate for rigid behavior on Class C soils, where the foundation can be divided into three or fewer regions. Overall, the behavior of a raft foundation whether rigid or flexible depends on the subgrade reaction coefficients of the soils beneath the structure.

3.4.2 Schepers and Appel (2017) : introduced in their study the concept of the Dynamic Winkler Foundation (DWF) as a tempting alternative due to its simplicity, but it neglects certain important peculiarities of soil-structure interaction. Hence, the coefficients of the DWF must be carefully chosen, taking into account the properties of the foundation soil, as well as the properties of the structure. As part of their study, they derive such coefficients and assess their suitability through analyses of a real-world building for which mitigation methods have been implemented.

In their study, the authors analyzed a real-world nine-storey residential building affected by subway-induced vibrations, using both numerical modeling and experimental data. The structure includes a basement, ground-floor retail space, and residential floors above, constructed with concrete and masonry walls (Fig. 51 a–c).

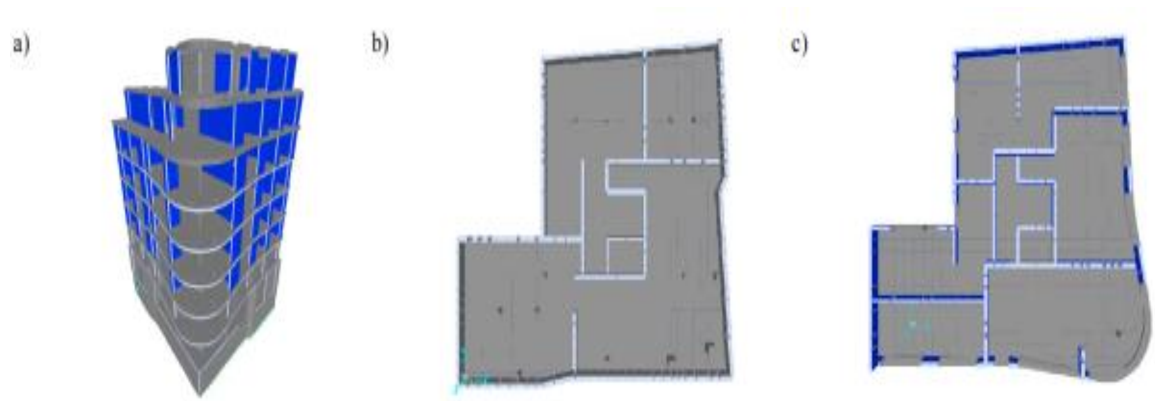


Figure 3.51 Perspective views of example building. Grey: concrete, blue: masonry. a) full model. b) plan view of foundation. c) plan view of 3rd residential floor

The building rests on a concrete slab over a homogeneous isotropic half-space, had dimensions of approximately 18 m × 18 m .Two excitation frequencies, 19 Hz and 64 Hz, were selected to represent perceivable floor vibrations and secondary noise, respectively.

The finite element model was developed in SAP2000 v17.3, consisting of 9660 shell elements, beam elements, and 9506 nodes, with the basemat modeled by 721 nodes. The Dynamic Wave Foundation (DWF) system was simulated using 1D spring-damper elements with both frequency-dependent and independent parameters. A reference solution was generated using ANSYS/SSI, which incorporated frequency-dependent dynamic soil stiffness matrices through the Boundary Element Method. As shown in Figure 52 , the reference solution demonstrated that walls significantly restrict floor displacements, especially at higher frequencies, validating the model's response to dynamic excitation.

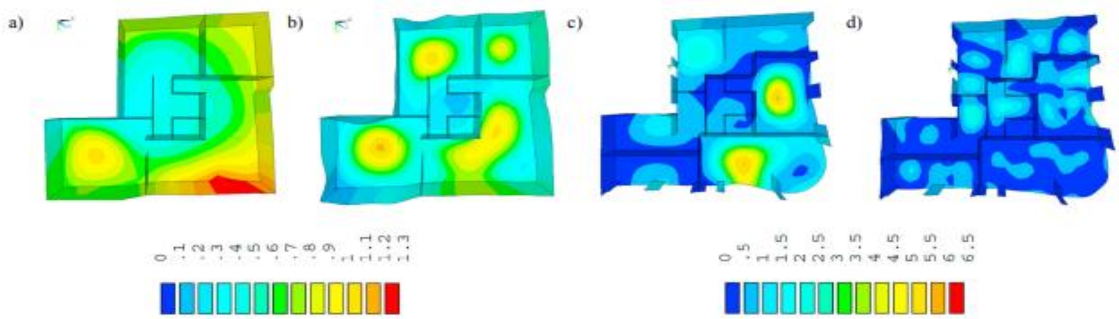


Figure 3.52 Contour plot of displacements amplitude response to a vertically propagating compressional wave of unit amplitude. (a) base slab, excitation frequency 19 Hz. (b) base slab, 64 Hz. (c) 3rd residential floor, 19 Hz. (d) 3rd residential floor, 64 Hz

In their assessment of DWF coefficient variations, the authors derived several DWF sets from the full soil stiffness matrix used in the reference solution and implemented them in **SAP2000**.

1. Frequency dependent DWF from diagonal vs. from row-sum of full soil stiffness matrix

In , they compared frequency-dependent DWF coefficients obtained from the diagonal (eq. 3) and row-sum (eq. 4) of the matrix. Results in Figure 53 show that diagonal-based DWF values significantly overestimate displacements, whereas row-sum-based coefficients result in only a slight overestimation approximately twice the reference solution.

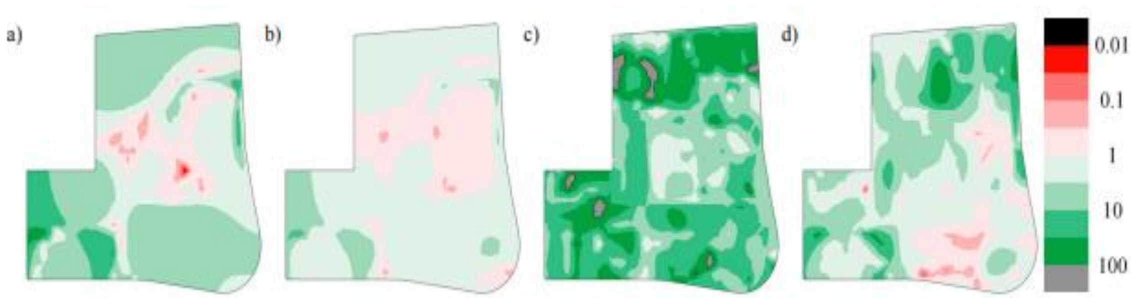


Figure 3.53 Contour plot of the ratio of displacement amplitude at the 3rd residential floor due to a vertically propagating compressional wave of unit amplitude, computed with DWF and scaled by the corresponding reference solution. (a) excitation at 19 Hz, DWF coefficients from diagonal of soil stiffness matrix, rel. Fig. 53c. (b) excitation at 19 Hz, DWF coefficients from row-sum, rel. Fig. 53c. (c)

excitation at 64 Hz, DWF coefficients from diagonal, rel. Fig. 53d. (d) excitation at 64 Hz, DWF coefficients from row-sum, rel. Fig. 53d.

- Frequency independent vs. frequency dependent DWF coefficients

The authors examined whether frequency-dependent DWFs are necessary. By applying static Winkler-like values derived at 1 Hz to both 19 Hz and 64 Hz excitations, they observed in **Fig. 54** that the displacements were considerably smaller than the reference, indicating that frequency dependency is essential for accuracy.

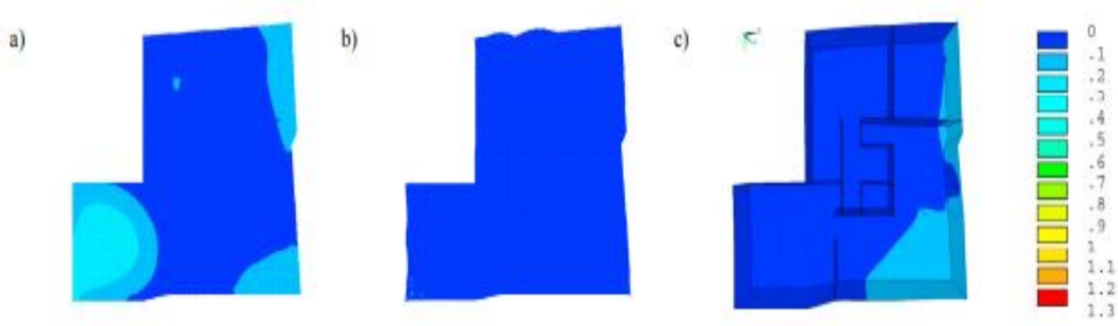


Figure 3.54 Contour plot of displacement amplitude of the base slab using frequency independent DWF. (a) excitation at 19 Hz, DWF coefficients from row-sum. (b) excitation at 64 Hz, DWF coefficients from row-sum. (c) excitation frequency 19 Hz with full quasi-static soil stiffness matrix

The authors concluded that the most reliable method for approximating the full dynamic soil stiffness matrix is by deriving dynamic Winkler foundation (DWF) coefficients from the row-sum of the soil stiffness matrix, corresponding to the relevant degree of freedom. They emphasized the necessity of considering frequency dependence in both the soil stiffness and the DWF coefficients. The DWF approach proved reliable for stiff plates, but may become partially non-conservative for more flexible ones. For future work, the authors plan to investigate different building plans and other excitation types, especially impinging Rayleigh waves.

3.4.3 Farouk et al. (2014) : studied the calculation of the subgrade reaction modulus (ks) considering the footing-soil system rigidity. They emphasized that structural engineers need an appropriate way to represent the soil in structural analysis, and that ks acts as a critical interface between geotechnical and structural engineers. While Winkler's theory is commonly used for calculating ks , wich does not consider the effect elasticity and plasticity of soils. Therefore, Farouk et al. recommended using more advanced soil models, particularly the linear elastic and elastic-perfect plastic Mohr-Coulomb models to investigate ks distribution and compared it to linear elastic analysis.

They modeled a strip concrete footing using PLAXIS 2D AE wich had constant width of 10 meters and variable thicknesses of 0.30, 0.50, 1.0, and 2.0 meters. A line load of 1000 kN/m was applied at the footing's half-width, as illustrated in Fig. 55 also they neglected the self-weight of the slab . To represent the sandy soil behavior, both linear elastic and elastic perfectly plastic (Mohr-Coulomb) models were used. The elastic model adopted a Young's modulus of 20.00 MPa, Poisson's ratio of 0.35, and a unit weight of 18.00 kN/m³. For the Mohr-Coulomb model, the angle of internal friction (φ) was set at 33°, with same parameters of the elastic linear model. Using the finite element technique authors were calibrated the horizontal and vertical boundaries conditions by applying different models with different boundaries conditions .

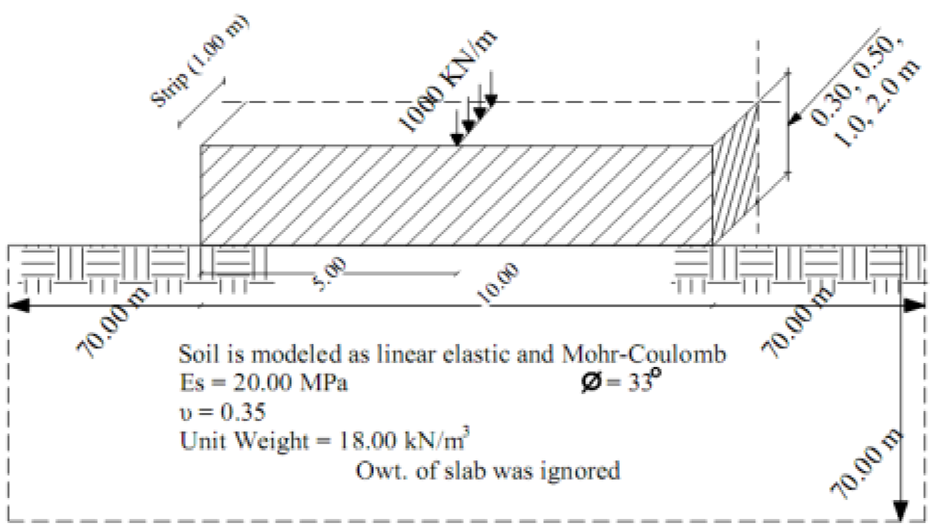


Figure 3.55 Strip footing model

After the analysis the authors discussed two effects mention below :

- Effect of Footing Thicknesses on Modulus of Subgrade Reaction (ks)

They showed that changing in footing thickness affects the rigidity of footings, which in turn affects the contact stress distribution and the modulus of subgrade reaction (ks) due to the positive relation with each other . Figure 56 shows thet for a very flexible footing (30 cm), ks is concentrated under the footing center. As rigidity increases (50 cm), ks near the edges slightly rises, with a slight decrease at the center. In semi-rigid and rigid footings (100 cm and 200 cm), ks becomes more concentrated at the edges and reduces at the footing center. Mentioning that the rigidity of the soil-footing system depends on footing dimensions, material properties, and soil parameters.

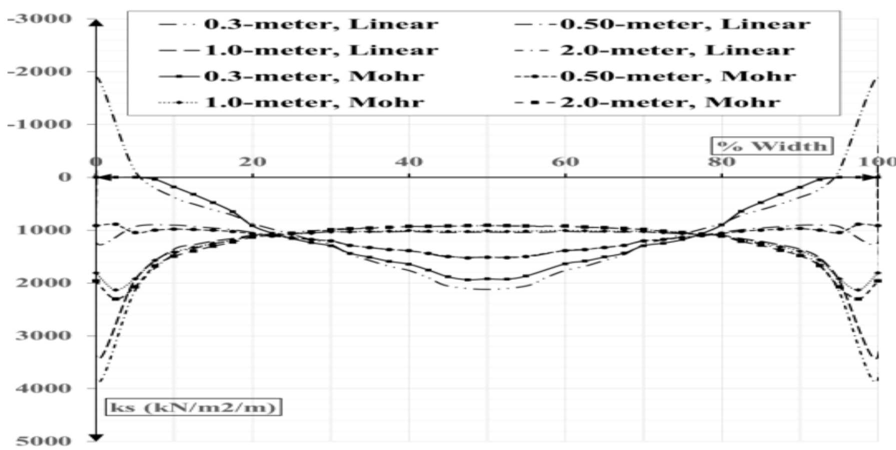


Figure 3.56 Modulus of subgrade reaction (ks) distribution under strip footing

- Effect of Soil Model on Modulus of Subgrade Reaction (ks)

The soil model significantly influences the distribution of contact stress and thus affects the modulus of subgrade reaction (ks). The elastic model increases ks concentration at footing edges and produces unrealistic tension in very flexible footings . In contrast, the Mohr-Coulomb model accounts for soil plasticity, reducing edge stress through local shear failure, which lowers ks at the edges. However, ks at the footing center remains nearly the same for both models (Figure57).

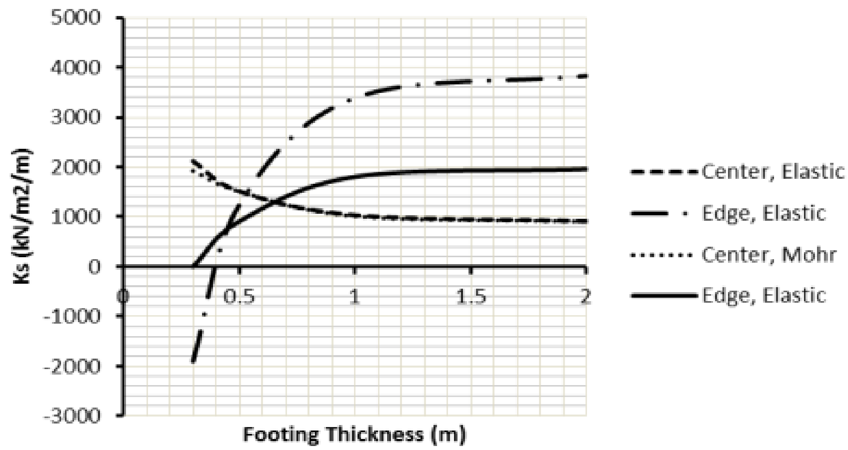


Figure 3.57 Relation between center and edge ks and footing thickness

The authors calculated the modulus of subgrade reaction (ks) considering the footing-soil system rigidity using the foundation rigidity coefficient (K), defined by the DIN Standard (2005). The dimensionless modulus of subgrade reaction (C) was calculated as

C=ks·L/ Es,

using both C and K, the relationship in Figure 58 was developed investigate the effect of the footing-soil rigidity on the subgrade reaction modulus.

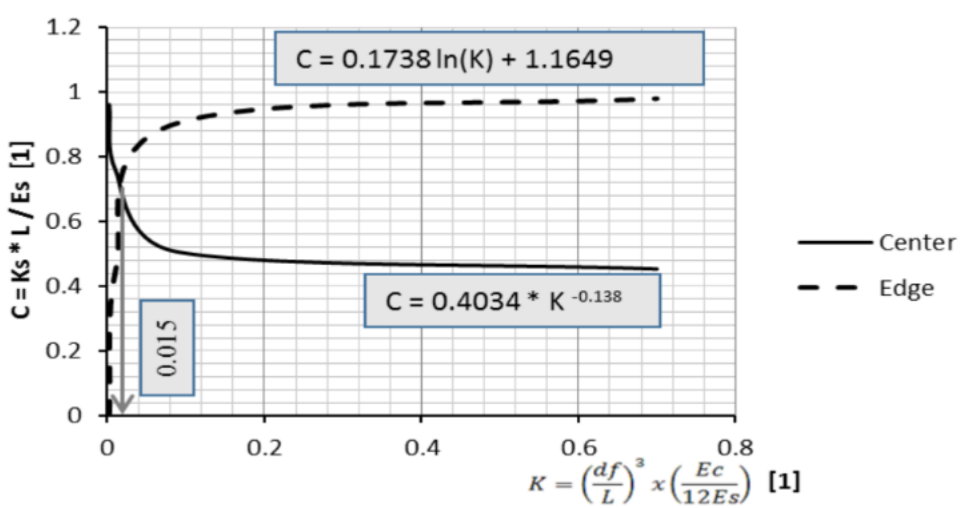


Figure 3.58 Relation between C and K for sand using Mohr model

They stated that the relation between applied stress and settlement is nearly constant within the elastic zone. Although they showed that contact stress distribution slightly varies with load level, the effect is minor and can be neglected. The modulus of subgrade reaction (ks) mainly depends on footing length, soil stiffness, and footing-soil rigidity. Using the equations, ks can be calculated effectively, and uniform distribution is valid only when rigidity is 0.015. Structural engineers can iteratively update ks values based on calculated footing loads. For accurate ks from plate load tests, plates with various rigidities and transducers are recommended. The corrected values can then be plotted. Verification using William D. C.'s test confirms Mohr model ks distribution closely matches measured stress. The study notes that standard design often results in semi-rigid footings with edge stress concentration, causing higher bending moments than predicted by uniform stress assumptions.

They concluded that the distribution of the modulus of subgrade reaction (ks) is non-uniform and directly related to the shape of the contact stress beneath footings. The variation in ks is influenced by the rigidity of the footing. For very flexible footings, ks is concentrated at the center, and it can be assumed uniformly distributed. Therefore, a modification factor to consider the soil-footing rigidity effect on plate load test results was presented.. Their measurements also showed that the actual bending moment at the footing center is higher than that predicted by standard design assumptions.

3.4.4 Farouk et al (2015) present the effect of soil structure interaction on the modulus of subgrade reaction. Many designers model footings as hinged supports or as springs with coefficient K, using equations that do not consider soil-structure interaction. The study showed that soil-structure interaction significantly affects the modulus, which is not uniformly distributed under footings .

To investigate this, they used both 2D and 3D geotechnical and structural finite element programs, two frame-soil systems were modeled .The study aimed to compare results when soil-structure interaction is considered versus when it is neglected.

Two-Dimensional Analyses:

A two-dimensional plane two-bay concrete frame was studied to evaluate the effect of soil-structure interaction on the modulus of subgrade reaction. The frame was modeled using the geotechnical finite element program PLAXIS 2D-AE, with the soil represented by a linear elastic model, as shown in Figure 59-a. The frame was also modeled using the structural finite element program SAP2000, with the footings represented as hinged supports, as shown in Figure 59-b.

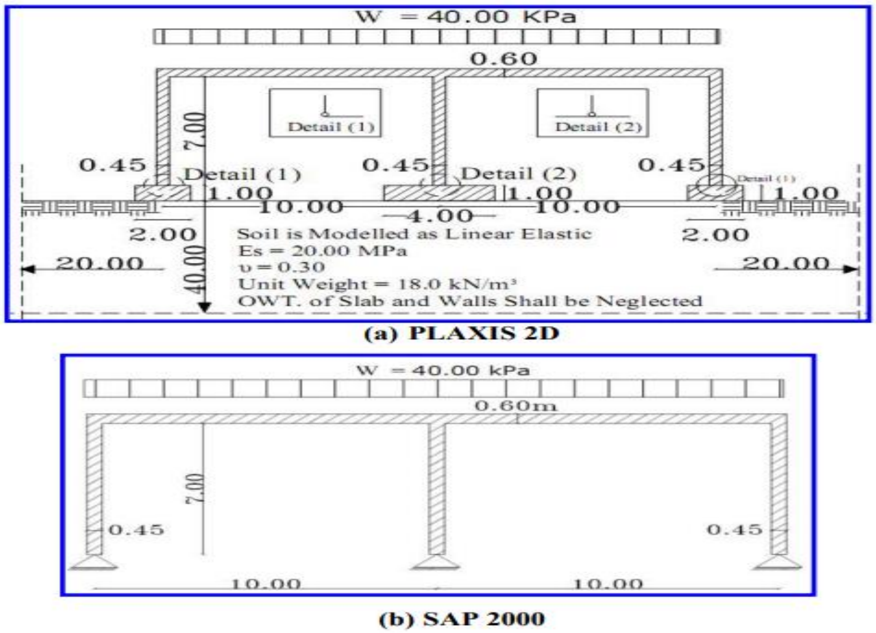


Figure 3.59 Model One

Their results showed that SSI increased the normal force in outer walls and decreased it in inner walls, reducing differential settlement without tie beams. The modulus of subgrade reaction was concentrated at footing edges, especially under superstructure rigidity (Figure 60-a, b), and differed between inner and outer footings.

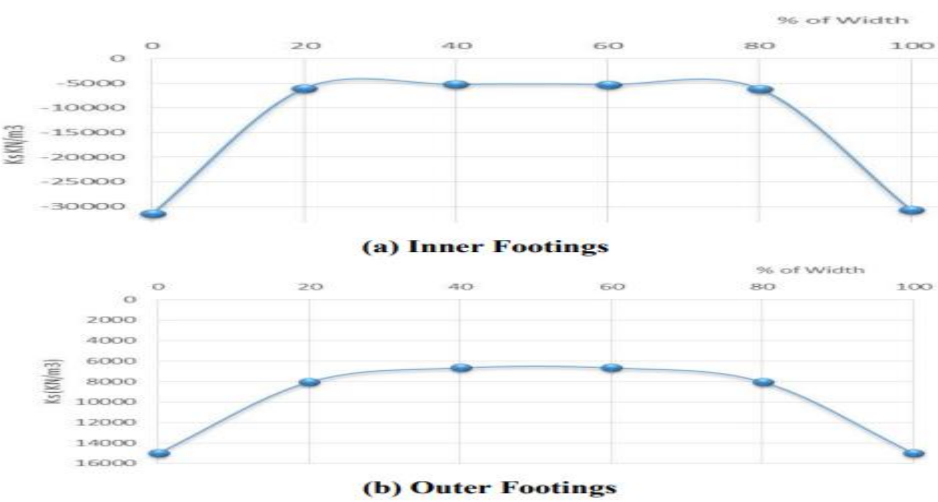


Figure 3.60 Distribution of the Subgrade Reaction Modulus

In more advanced soil models, the subgrade reaction distribution shifts inward due to soil plasticity. Results differ between inner and outer footings. Plate loading tests give a single, uniform ks value, later corrected by width and rigidity factors. However, these corrections rely on wall forces, which are affected by SSI. This circular dependency often causes designers to neglect SSI. A finite element geotechnical program is recommended to break this cycle by accurately modeling the soil–foundation–superstructure interaction.

Three-Dimensional Analyses

Analyses were carried out on a space frame (2-bay by 2-bay)–foundation–soil system of a one-story building using PLAXIS 3D 2013. The model, shown in Figure 61, included isolated footings embedded 1 meter in sand modeled with Mohr-Coulomb parameters. The slab had variable thicknesses (0.35–2.0 m) to represent different structural rigidities. Distributed loads of 10, 30, and 60 kN/m² were applied. Footing sizes were 4×4 m² (inner), 3×3 m² (edge), and 2×2 m² (corner), all 1 m thick. The columns could rotate at the base, and slabs transferred bending moments in two directions.Figure 62 shows the relation between the rigidity factor and the resulted average spring's coefficients.

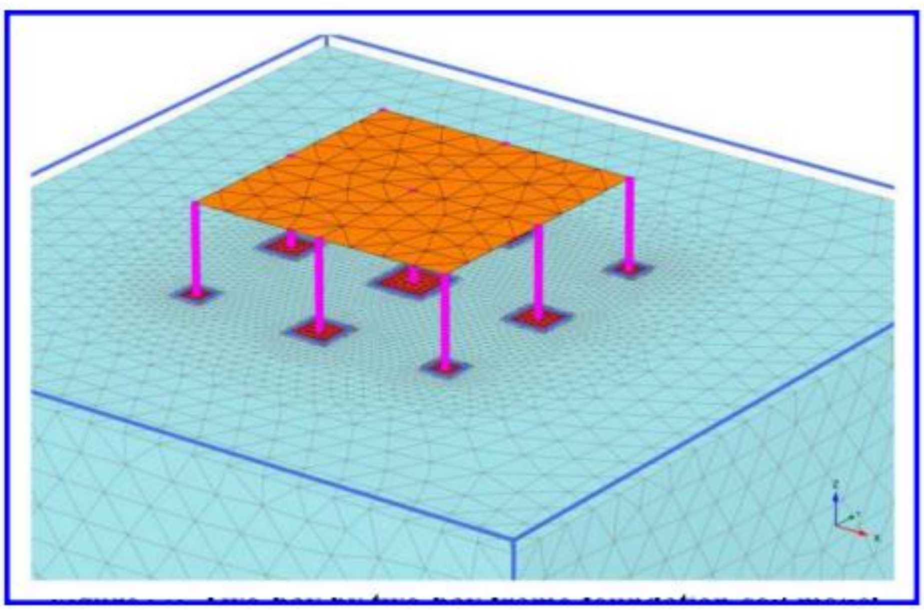


Figure 3.61 Two-bay by two-bay frame-foundation-soil model

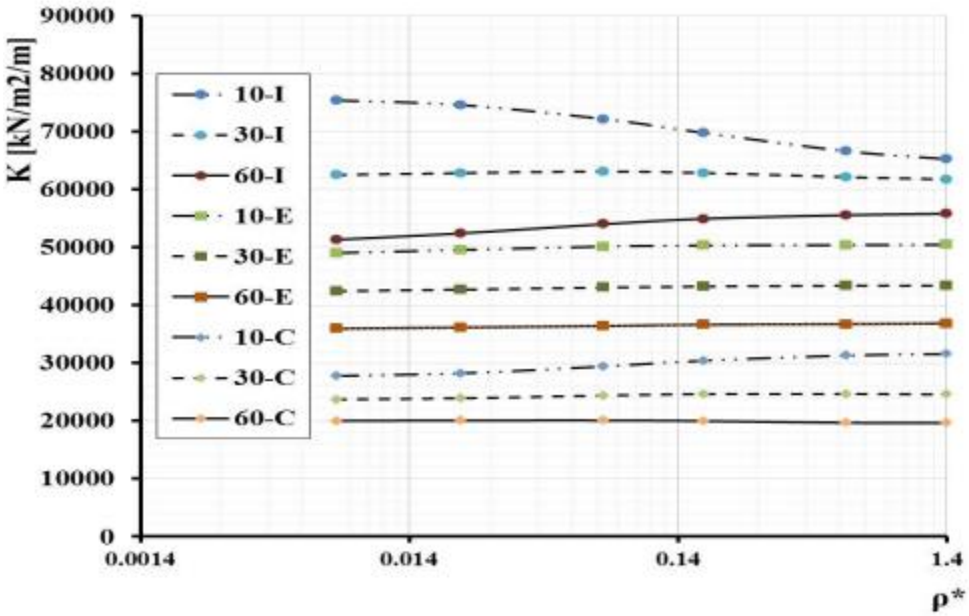


Figure 3.62 Effect of superstructure rigidity on the subgrade

It can be seen that the superstructure has a significant effect on the subgrade modulus under inner and corner footings, with no effect under external footings. The applied load levels influence the average subgrade modulus, even though footing dimensions remain constant. This variation is due to superstructure rigidity. The frame was also modeled using **SAFE V12** with the same properties, sections, and loads (Figure 63), where footings were represented as hinged supports.

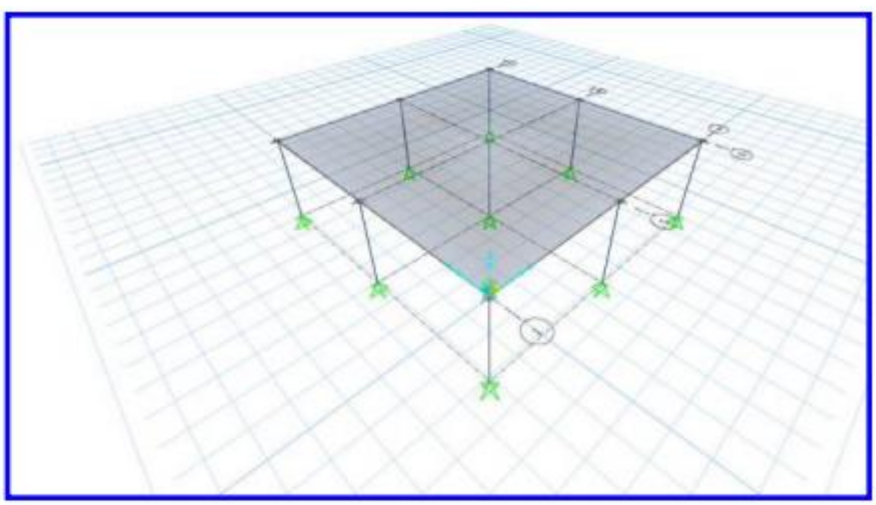


Figure 3.63 SAFE V12 frame model

The normal forces (NF) from PLAXIS and SAFE for a 10.00 kPa load are presented in Figure 64 inner and corner columns were affected, while edge columns were nearly unaffected. To validate the proposed design, average spring coefficients (K) from PLAXIS were used in SAFE, and the relation between ρ* and normal forces is shown in Figure 65. Results from both programs were close, with small differences due to using average ks in the structural model.

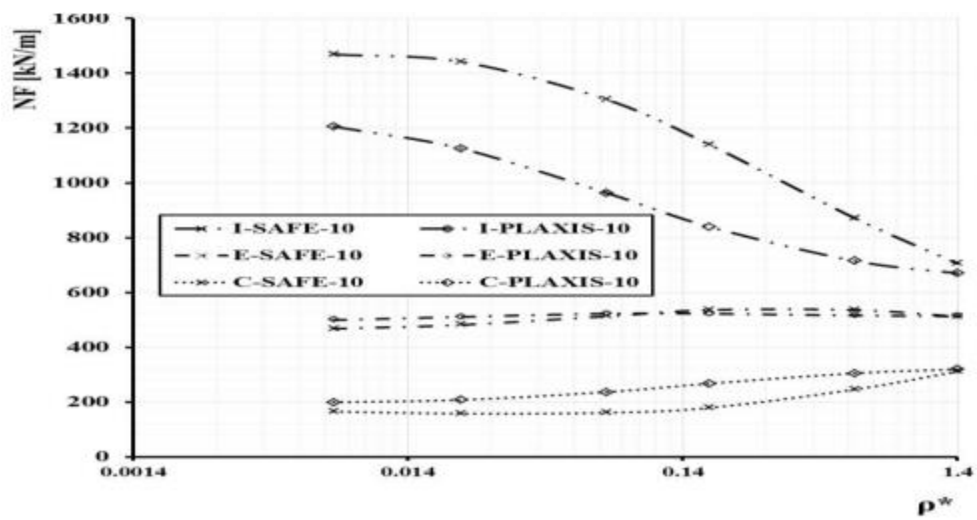


Figure 3.64 Effect of superstructure rigidity on the subgrade

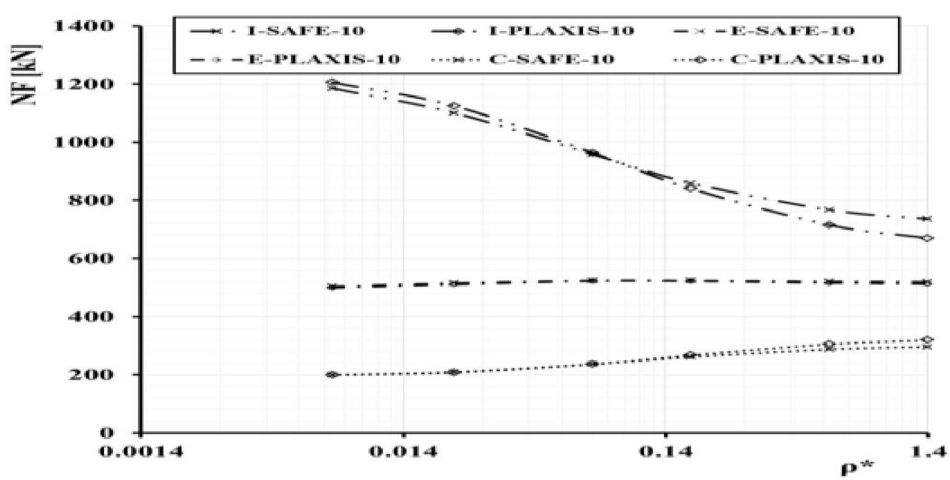


Figure 3.65 Validation of the suggested procedure for the cooperation between the geotechnical and structural engineers

Farouk et al. (2015) concluded that increasing the superstructure rigidity reduces differential settlement and raises the average contact stresses under corner footings while lowering them under inner footings. In 2-bay by 2-bay frames, edge columns are not affected by rigidity changes. Neglecting soil structure interaction (SSI) leads to higher inner column loads and lower corner column loads. Using an average ks from plate load tests without considering SSI is inappropriate. Therefore, a new advanced design procedure is suggested for special projects to account for superstructure rigidity in both geotechnical and structural analyses.

3.4.5 Teli et al (2020): conducted an analytical study to investigate the influence of foundation rigidity and the modulus of subgrade reaction on the behavior of raft foundations. The study was motivated by the need for a deeper understanding of soil–structure interaction in shallow foundations, especially in cases involving multistoreyed buildings. The authors emphasized the importance of selecting between rigid and flexible foundation models based on the relative stiffness of the structure and the supporting soil .

They employed STAAD Pro V8i, a widely used finite element-based software, to study the interaction between superstructure and foundation systems. A ten-storeyed symmetric reinforced concrete building, comprising five bays in each direction with 5 m spans and 4 m storey height, was modeled along with its raft foundation. The raft, measuring 27 m × 27 m with a 1 m offset from edge columns, was discretized into 0.5 m × 0.5 m four-noded plate elements—chosen based on prior experience. Figures 66 and 67 present the plan and 3D views of the model

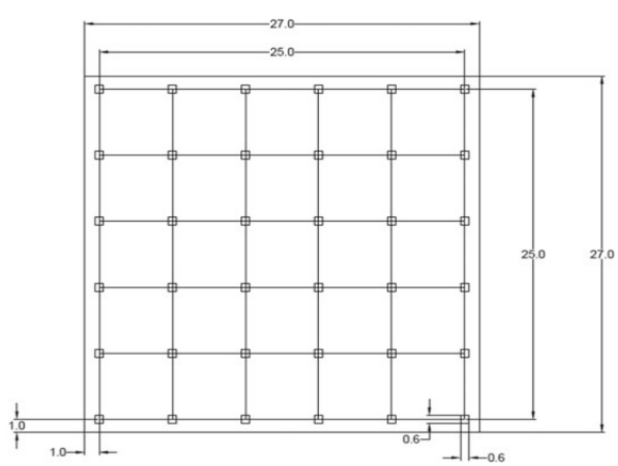


Figure 3.66 Plan dimensions of building and foundation considered in the study (in metres)

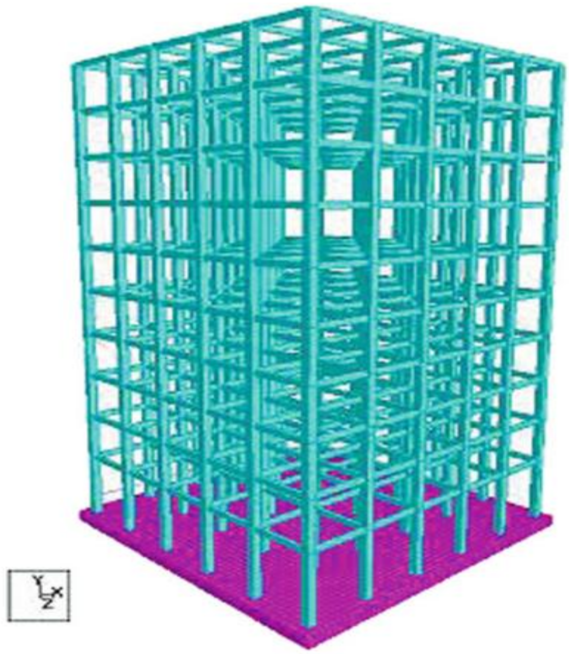


Figure 3.67 Three-dimensional view of multistoreyed building with raft foundation

The analysis accounted for dead and live loads, with beam (0.23 m × 0.45 m) and column (0.6 m × 0.6 m) dimensions considered, and 230 mm thick wall loads applied as uniformly distributed loads on beams. A live load of 4 kN/m², based on IS-875 Part-II , was applied to simulate institutional use. Soil-structure interaction was modeled by assigning vertical spring stiffness at each plate node to represent subgrade reaction . The study evaluated 25 scenarios combining five values each of raft thickness (tr) and modulus of subgrade reaction (Ks), and assessed key foundation performance parameters base pressure, settlement, shear stress, and bending moment .

They analyzed the cases by varying raft thickness (tr = 0.5 to 0.9 m) and modulus of subgrade reaction (Ks = 2000 to 12000 kN/m³). As illustrated in Figure 68 increasing both tr and Ks resulted in reduced maximum base pressure and increased minimum base pressure. The variation in base pressure, shown in Figure 69 revealed that Ks had a more pronounced influence than tr, with the highest variation (42.4%) occurring at Ks = 12000 kN/m³ and tr = 0.5 m.

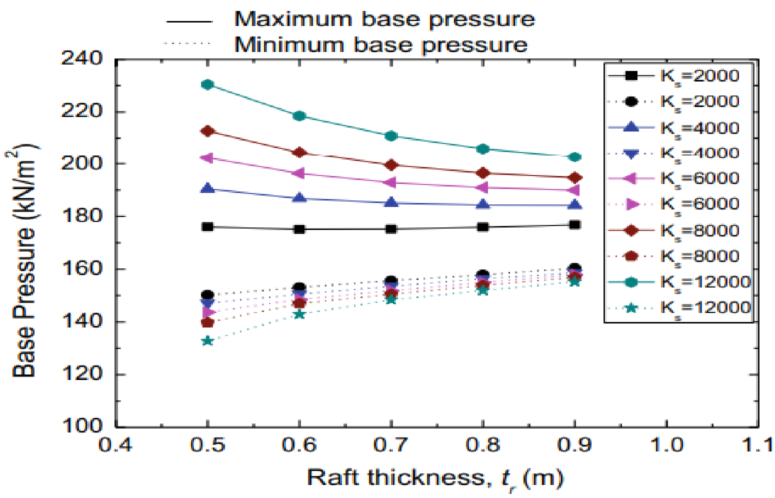


Figure 3.68 Maximum and minimum base pressure of raft foundation for different values of ‘tr ’ and ‘Ks ’

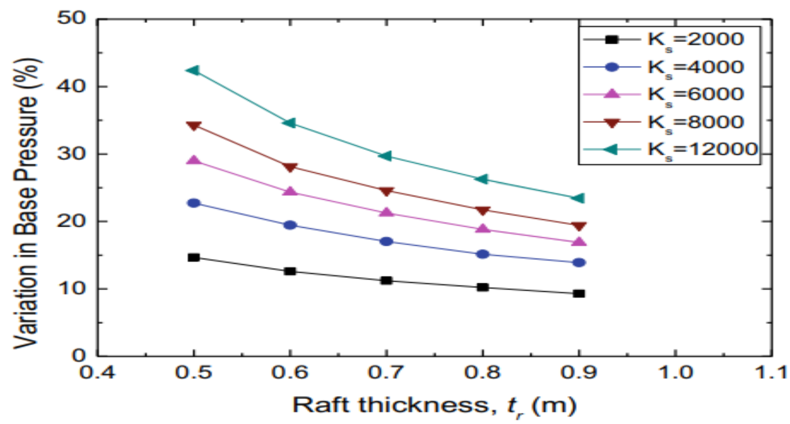


Figure 3.69 Variation in base pressure of raft foundation for different values of ‘tr ’ and ‘Ks ’

Settlement patterns (Figure 70) showed that while overall settlement decreases with increasing Ks, raft thickness has minimal impact. However, differential settlement is reduced with increased tr, as seen in Fig 71. The smallest differential settlement (3.95 mm) was observed at Ks = 12000 kN/m³ and tr = 0.9 m, while the largest (12.9 mm) occurred at Ks = 2000 kN/m³ and tr = 0.5 m. Interestingly, when expressed as a percentage of maximum settlement, a softer soil and thinner raft (Ks = 2000, tr = 0.5 m) yielded more uniform settlement (14.65%) compared to stiffer soil and thicker raft (Ks = 12000, tr = 0.9 m) with 23.44%.

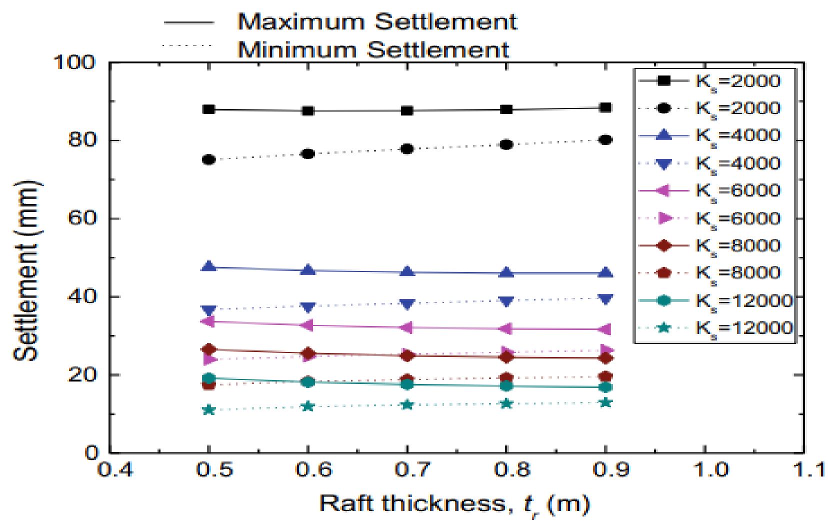


Figure 3.70 Maximum and minimum settlement of raft foundation for different values of 'tr ' and 'Ks '

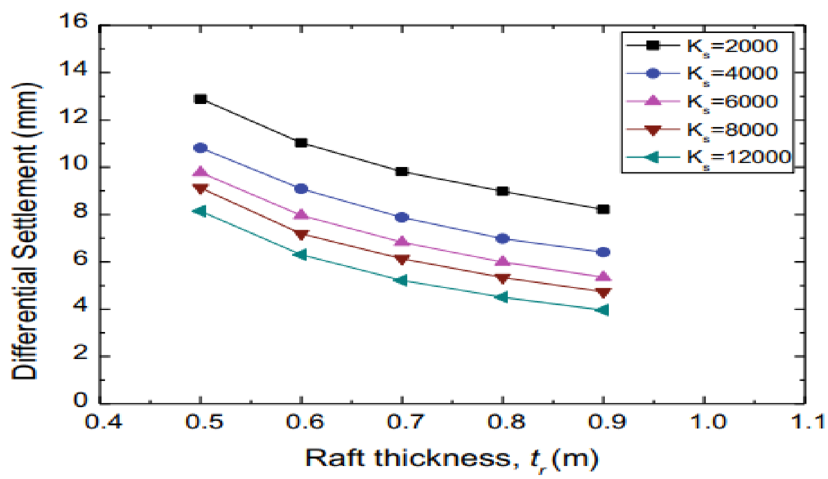


Figure 3.71 Differential settlement of raft foundation for different values of 'tr ' and 'Ks '

These findings, supported by Fig. 34, highlight that increased rigidity and stiffer subgrade lead to non-uniform settlement due to greater variation in base pressure, confirming the significant role of foundation-soil interaction in performance.

further analyzed the relative influence of modulus of subgrade reaction (Ks) and foundation flexural rigidity (EI) on base pressure variation. They introduced normalized ratios Ksn and EIn to evaluate changes against base values (Ks = 2000 kN/m³ and EI = 6.10 × 10⁶ kN·m²). Results indicated that a six-fold increase in Ks caused a 189% rise in base pressure variation, while a

5.83-fold increase in EI reduced variation by 36.59%. This demonstrates that Ks has a more dominant effect on pressure distribution than rigidity. It was inferred that improved ground (higher Ks) leads to greater base pressure variation compared to unimproved soil but compensates through reduced settlement, making Ks a key factor in raft foundation design.

To assess structural response, bending moment (Mx) and shear stress (SQx) were analyzed, as illustrated in Figures 72 and 73. The authors observed that Ks had negligible influence on both parameters, while an increase in raft thickness (tr) led to a marginal increase in Mx and a reduction in SQx. This behavior is attributed to improved load distribution and increased shear resistance area with thicker rafts. Although higher thickness adds self-weight-induced bending, the overall effect on moment remains minimal. These findings suggest that for raft design—especially where shear reinforcement is avoided—thickness should be selected considering both shear limits and structural efficiency.

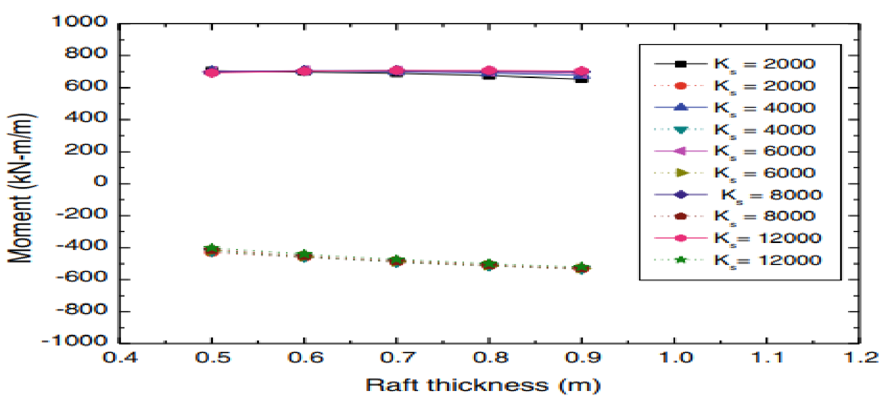


Figure 3.72 Bending moment (Mx) in raft foundation for different values of ‘tr ’ and ‘Ks ’

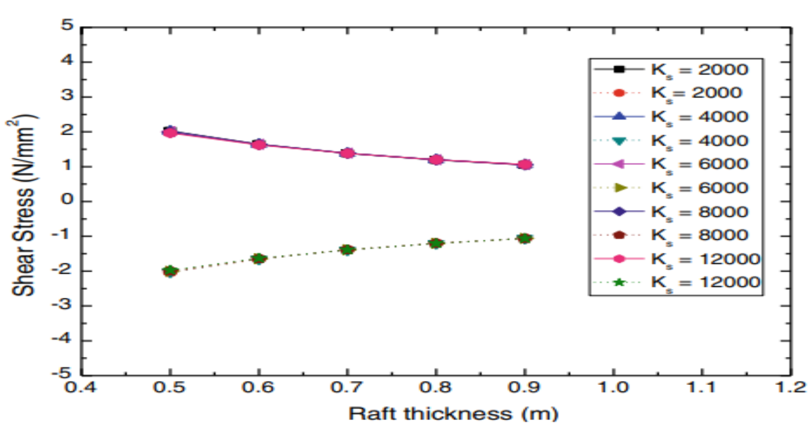


Figure 3.73 Shear stress (SQ) in raft foundation for different values of ‘tr ’ and ‘Ks ’

Noting that the use of discrete, non-interconnected soil springs in STAAD Pro limits accurate modeling of soil continuum behavior. While the raft's continuity helps distribute loads in loaded zones, this does not apply to unloaded areas beneath the raft. Additionally, the study does not consider wind and seismic effects, which the authors plan to address in future work. Despite these limitations, the research offers a clear understanding of how foundation thickness and modulus of subgrade reaction affect base pressure, settlement, shear stress, and bending moment supporting the development of a practical decision matrix for optimal raft foundation design.

It's concluded from the study that modulus of subgrade reaction has higher influence on variation in foundation base pressure as compared to rigidity of foundation. It is also noted that impact of variation in modulus of subgrade reaction on structural design of foundation is negligible. However, the rigidity of foundation influences the shear stress and bending moment in foundation. It is opined that such studies would help in developing decision matrix to account for various parameters in optimization of foundation design .

3.5 Conclusion

This chapter has provided a comprehensive review of the literature that has examined the effect of Soil-Structure Interaction (SSI) on the seismic response of reinforced concrete buildings with particular attention given to the modeling methods and the critical role of the subgrade reaction modulus (ks). Results of the studies presented in this chapter highlight the significant contribution of SSI to key structural response characteristics including natural vibration periods, base shear and lateral displacements. It has been shown that neglecting SSI in structural analysis can lead to underestimation or misrepresentation of seismic demands especially for buildings on soft soils, deep foundations or multi-story configurations.

Parametric and numerical studies including those involving elastic continuum modeling nonlinear time history analysis and variations of the Winkler model have demonstrated that SSI is a critical factor in realistic seismic design. These investigations confirm that integrating SSI into the design process is necessary for developing safe, efficient and resilient structural systems that can respond appropriately to seismic demands.

In conclusion both the effects of SSI and the application of appropriate soil modeling techniques such as the Winkler method with accurately defined ks are essential components of modern seismic design practice.

Chapter IV:

Effect of Soil-Structure Interaction on Seismic Response of Multi-Storey Frame Structure.

5.1 Introduction :

It has often been recognized that earthquake damage to buildings can be heavily affected by the underlying soil conditions. However, significant uncertainties still exist regarding the precise impact considerable uncertainties still exist regarding the contribution of the of soil-structure interaction (SSI) on the seismic response of structures. Accurate modeling of SSI requires the representation of both the structural system and the supporting soil medium. While advanced continuum-based methods such as finite element and boundary element techniques can provide detailed insights into soil behavior, their computational demands and modeling complexity often render them impractical for routine engineering applications. To address these challenges, simplified models have been developed that aim to balance computational efficiency with a reasonable approximation of soil behavior. Among these, The Winkler spring model is the most convenient representation of soil support in the domain of linear elasticity for framed structure-soil interaction analyses (Allam 1991)

This approach, proposed by Winkler (1867), idealizes the soil as a series of closely spaced, discrete linear springs, each acting independently of the others. Each spring responds only to the load applied directly above it, without influencing or being influenced by adjacent springs. The stiffness of these springs is defined by the subgrade reaction modulus (ks), which governs the soil's resistance to deformation under applied structural loads (Nisar 2024) . As illustrated in Figure 1, these springs deform proportionally to the vertical displacements they support, enabling the estimation of settlement patterns and internal forces within the foundation.

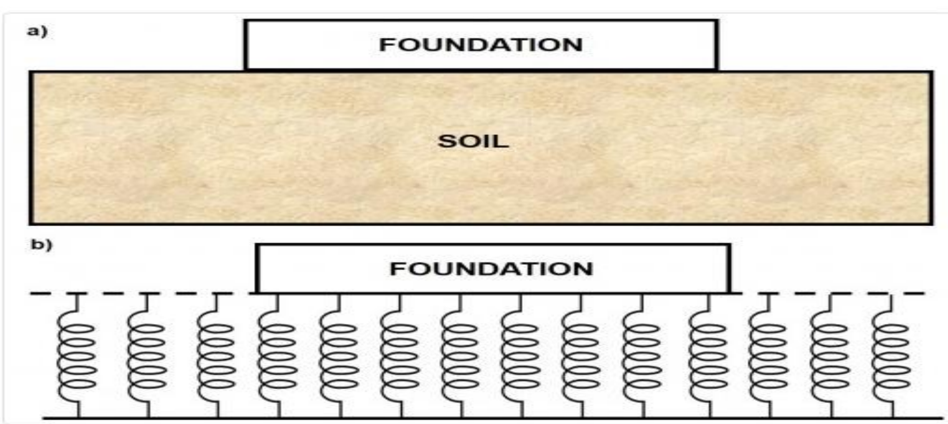


Figure 5.1: The foundation of a structure based upon a) an actual soil layer and b) a system of linear elastic springs that have replaced the ground.

While this method is computationally efficient and commonly used in software such as SAP2000, its primary limitation lies in the empirical and highly variable nature of the subgrade reaction coefficient, which is influenced by soil properties, foundation geometry, stiffness, and loading conditions (El-Garhy and Osman, 2002).

Despite its practicality and ease of use, the Winkler model exhibits several important limitations that restrict its application in complex geotechnical conditions. The key limitations are summarized as follows:

- Neglect of Soil Continuity: The model assumes independent spring action with no lateral

interaction, disregarding the continuous nature of real soils where stress and deformation propagate beyond the point of loading. This simplification can result in flawed estimates of settlement and stress fields.

- No Shear Transfer Between Springs: The formulation assumes that each spring acts independently, without any shear interaction between adjacent soil points., which can result in an underestimation of foundation stiffness and deformation, particularly for short or wide structures.

- Assumption of Linear Elastic Behavior: The soil is modeled as a perfectly linear elastic material, whereas real soils typically exhibit nonlinear responses such as plastic deformation, strain-softening, and stiffness degradation under increased loading.

- Inapplicability to Layered or Non-Homogeneous Soils: The Winkler model presumes uniform soil stiffness along the foundation. However, real soil profiles are often layered or variable with depth, which significantly influences structural response but is not captured in this model.

- Exclusion of Time-Dependent Effects: The model is limited to immediate (short-term) settlement predictions and does not consider time-dependent behaviors such as consolidation and creep, which are critical for long-term performance evaluations.

- Inaccuracy for Large or Wide Foundations: For foundations with large dimensions, the assumption of isolated springs becomes increasingly invalid, leading to underestimation of global stiffness and overestimation of settlements.

Although the Winkler foundation model has notable limitations, it was incorporated into the custom model developed in this study due to its practical applicability and the need for a simplified approach to soil-structure interaction, providing an effective solution for the specific engineering scenarios being analyzed.

5.2 Presentation of SAP2000 :

SAP2000 (Structural Analysis Program) is a structural analysis and design software program developed by Computers and Structures . It is Widely recognized in both academic and professional environments, the program offers a comprehensive suite of tools for modeling, analyzing, and designing structures under static and dynamic loads. In this study, SAP2000 is employed to model and analyze the behavior of structures under seismic excitations, considering the effects of soil-structure interaction. Its ability to integrate soil-structure interaction parameters through springs and foundation models is essential for obtaining realistic and reliable simulation results. Furthermore, SAP2000's advanced visualization and post-processing capabilities enable a detailed understanding of the structural response, making it the most appropriate choice for achieving the objectives of this study. SAP2000 analyzes and designs the structure using a model that it has defined in the graphical user interface. The model consists primarily of the following types of components :

5.2.1 Modeling Objects and Elements

In SAP2000, the physical structural members of the model are represented as "objects." Users interact with these objects using the interface, where they can draw the geometry of each member and assign properties and loads. There are several types of objects available in SAP2000, classified by their dimensional properties:

- **Point Objects**
    - *Joint objects* are created automatically at the corners or ends of other objects and are used to define supports or localized behaviors.
    - *Grounded (one-joint) link objects* model special support behaviors, such as isolators, dampers, gaps, and springs.

- **Line Objects**
  - *Frame/cable/tendon objects* represent structural elements like beams, columns, braces, trusses, cables, and tendons.
  - *Connecting (two-joint) link objects* are used to model behaviors similar to point objects but can have zero length.
- **Area Objects**
  - Used for modeling walls, floors, and other thin-walled members as well as 2D solids (plane stress, plane strain, and axisymmetric solids).
- **Solid Objects**
  - These are used for three-dimensional solid modeling, essential for capturing the full complexity of certain structural elements.

The object-based modeling approach in SAP2000 is very helpful as it decreases meshing, because the software makes automatic conversion of the object model to an element-based model during the analysis. This simplifies the modeling process and eliminates manual mesh generation, making it intuitive for users.

5.2.2 Properties and Functions

Properties in SAP2000 define the structural behavior of objects, such as material properties (i.e., concrete, steel) and section properties (i.e., rectangular, circular). Properties must be defined before they can be assigned to objects in the model.

Also, SAP2000 allows the definition of functions to describe how loads vary over time or according to specific periods. These include:

- **Response-Spectrum Functions**: Used in response-spectrum analysis.
- **Time-History Functions**: Used to model time-varying loads.
- **Steady-State Functions**: For harmonic analysis.
- **Power-Spectral-Density Functions**: Used for probabilistic loading in frequency-domain analysis.

These functions are essential to dynamic analysis,, particularly in time-history and response-spectrum studies, where the loads change over time or in response to seismic activity.

5.2.3 Load Patterns and Load Cases

In SAP2000, loads represent forces, pressures, or displacements acting on the structure. These are defined in load patterns. Load patterns can represent actions such as dead loads, live loads, wind loads, and thermal effects. Once load patterns are defined, they can be applied to objects within the model. Multiple load patterns can be applied to a single object, allowing for flexible load assignments.

A load case defines how the loads are applied to the structure and how the structural response is calculated. SAP2000 supports a variety of load cases:

- **Static Load Cases**: Traditional static analysis where loads are applied without dynamic effects.
- **Dynamic Load Cases**: Modal analysis, response-spectrum analysis, time-history analysis, and more, to model dynamic effects like seismic forces.

In addition to these, SAP2000 supports nonlinear load cases for more complex simulations such as pushover analysis, nonlinear time-history, and staged construction analysis, which considers the progressive application of loads.

5.2.4 Analysis Results in SAP2000

SAP2000 provides various graphical representations for the results of completed analyses, including:

- Deformed shapes
- Reactions and spring forces at joints
- Force and moment diagrams for frames, cables, and links
- Stress-resultant force and moment contour plots for shells
- Stress contour plots for planes, solids, and axisymmetric solids
- Design stresses for concrete shells

- Influence lines for displacements, reactions, spring forces, and forces and moments in all object types
- Virtual work plots for all object types

Deformed shapes can be animated through the status bar controls, helping to visualize and understand the structural behavior. For load cases involving multiple results (such as multiple modes or steps), users can navigate through the individual results using the scrolling controls, or view the maximum and minimum results across the steps. Additional details on the displayed results can be accessed by right-clicking on specific objects.

SAP2000 was selected for this study because it is recognized as being able to conducted specific structural analysis and design with a variety of loading conditions, including seismic loading. When comparing with other structural analysis software like ETABS, Abaqus, and Robot Structural Analysis, SAP2000 offers a unique combination of flexibility and advanced features, making it suitable for academic research and professional engineering . While ETABS is very effective specifically for the analysis and design of building structures, SAP2000 offers more extensive modeling capabilities to analyze standard building frames, and other complex structures with irregular configurations. Additionally, the program facilitates the incorporation of soil-structure interaction effects through customizable foundation springs and dampers, a critical aspect of this study.

5.3 Validation :

To verify the accuracy of SAP2000 in modeling frame elements on elastic supports, a benchmark validation example from the SAP2000 verification manual (Example 1-013) was adopted.

The case involves a simply supported beam subjected to a concentrated vertical load at its midspan, resting on an elastic foundation. The beam dimensions are 36 inches by 36 inches in cross-section and 15 feet in length, with the soil subgrade modulus specified as 800 k/ft^3. A 500 kip load is applied at the beam's center, and the self-weight is disregarded to isolate the response due to the point load . As illustrated in Figure 2 .The analytical results moment and deflection at midspan are compared with closed-form solutions based on Timoshenko's formulation (1956). Three finite element models were created with varying levels of discretization (1, 4, and 100 frame elements per span), and only bending deformation was considered by setting axial and shear stiffnesses to negligible values via property modifiers.

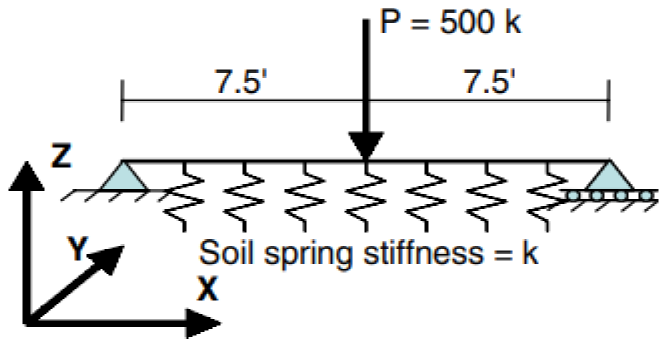


Figure 5.2 Simply Supported Beam on Elastic Foundation with Central Point Load

This validation effectively demonstrates SAP2000's capability to simulate elastic foundation behavior, bending-dominated responses, and the impact of element discretization on solution accuracy.

To elaborate on the SAP2000 simulation results, these figures are presented below in increasing order of significance:

As shown in figure 3 the undeformed shape of the beam, along with boundary and support conditions. The beam is shown as horizontally aligned and simply supported at both ends, with elastic (spring) supports distributed along its length to represent the Winkler foundation. This initial configuration provides a reference for interpreting subsequent deformation and internal force results.

Figure 5.3 Undeformed Configuration of Beam and Supports

Figure 4 displays the deformed shape of the beam under the applied central point load. As expected, the beam exhibits symmetric downward deflection with the maximum displacement occurring at midspan. The influence of the elastic foundation is visible in the way the beam is supported throughout, countering the deflection and mimicking real soil response. This confirms that the spring supports accurately model the subgrade reaction and interact with the structural behavior as intended.

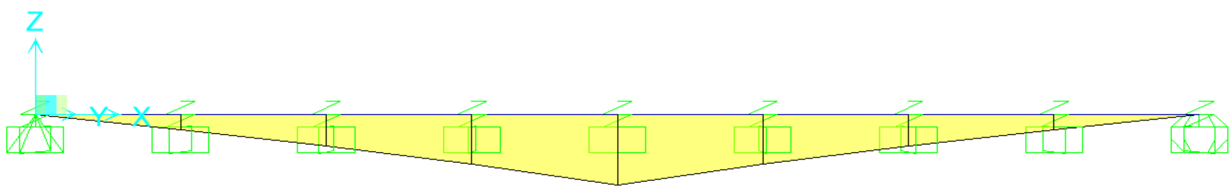


Figure 5.4 Deformed Shape Under Applied Load

The figure 5 presents SAP2000's graphical output for shear force (V2), bending moment (M3), and vertical deflection along the beam's span:

- **Shear Force Diagram (V2):** The shear force is constant along each half of the span and changes abruptly at the point load, matching expectations for a point-loaded simply supported beam.
- **Moment Diagram (M3):** The moment diagram forms a triangular profile, peaking at midspan. The maximum moment value closely aligns with the theoretical solution from Timoshenko's formulation.
- **Deflection Curve:** The deflection is symmetric, with a peak midspan displacement of approximately 1.6146 inches. This is in good agreement with the closed-form analytical solution, indicating the accuracy of the modeling assumptions and finite element mesh.

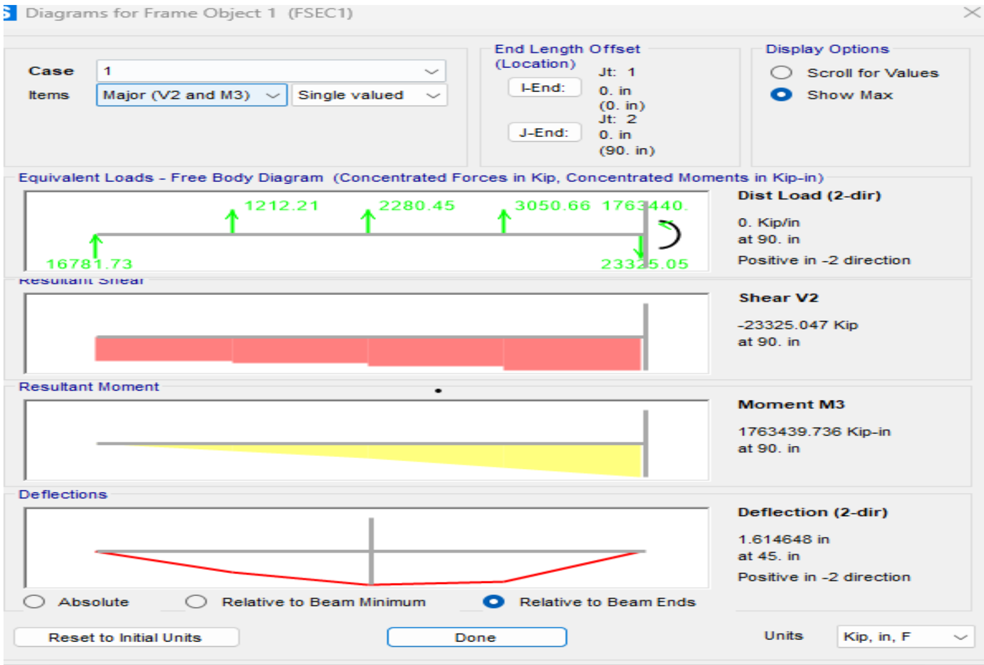


Figure 5.5 Internal Force and Deflection Diagrams (SAP2000 Output)

These simulation results affirm that SAP2000 is highly capable of modeling beam-on-elastic-foundation systems, capturing critical responses such as internal force distribution and displacement behavior. Furthermore, the ability to closely replicate theoretical benchmarks makes SAP2000 a reliable tool for more complex soil-structure interaction studies.

5.4 Numerical Modeling and Dynamic Analysis :

This part presents and analyzes the results obtained from dynamic analyses of a reinforced concrete frame-type building, with and without the inclusion of Soil-Structure Interaction (SSI). The analyses were carried out using the SAP2000 software through three linear dynamic approaches: modal analysis, response spectrum analysis, and linear time history analysis. Two numerical models were used: one with a fixed base and another with a flexible base modeled via the Winkler spring approach. The objective of this chapter is to assess the impact of SSI on key structural response parameters, including natural periods, modal mass participation, internal forces, base shear, and lateral displacements.

5.4.1 Model Description

As part of this study, two numerical models were developed using SAP2000 software to evaluate the impact of Soil-Structure Interaction (SSI) on the dynamic response of a frame-type building. The objective was to compare the vibrational behavior of the structure under two different boundary conditions: with and without considering the influence of the SSI.

The studied structure is a collective residential building located in seismic zone III, as defined by the RPA 2024 regulations (Table 3.1). It falls under usage group 2, which corresponds to buildings of normal importance, such as housing units. According to the geotechnical report, the foundation soil is classified as Site S3 (soft soil).

The building features a reinforced concrete structural system, specifically a mixed frame system with rigid masonry infill walls that partially contribute to the lateral stiffness of the structure. It consists of five levels (G+5), with a total height of 18 meters and a typical story height of 3 meters.

The structural elements are dimensioned as follows in Table 1:

Table 5.1 Dimensions of Structural Elements Used in the Building Model

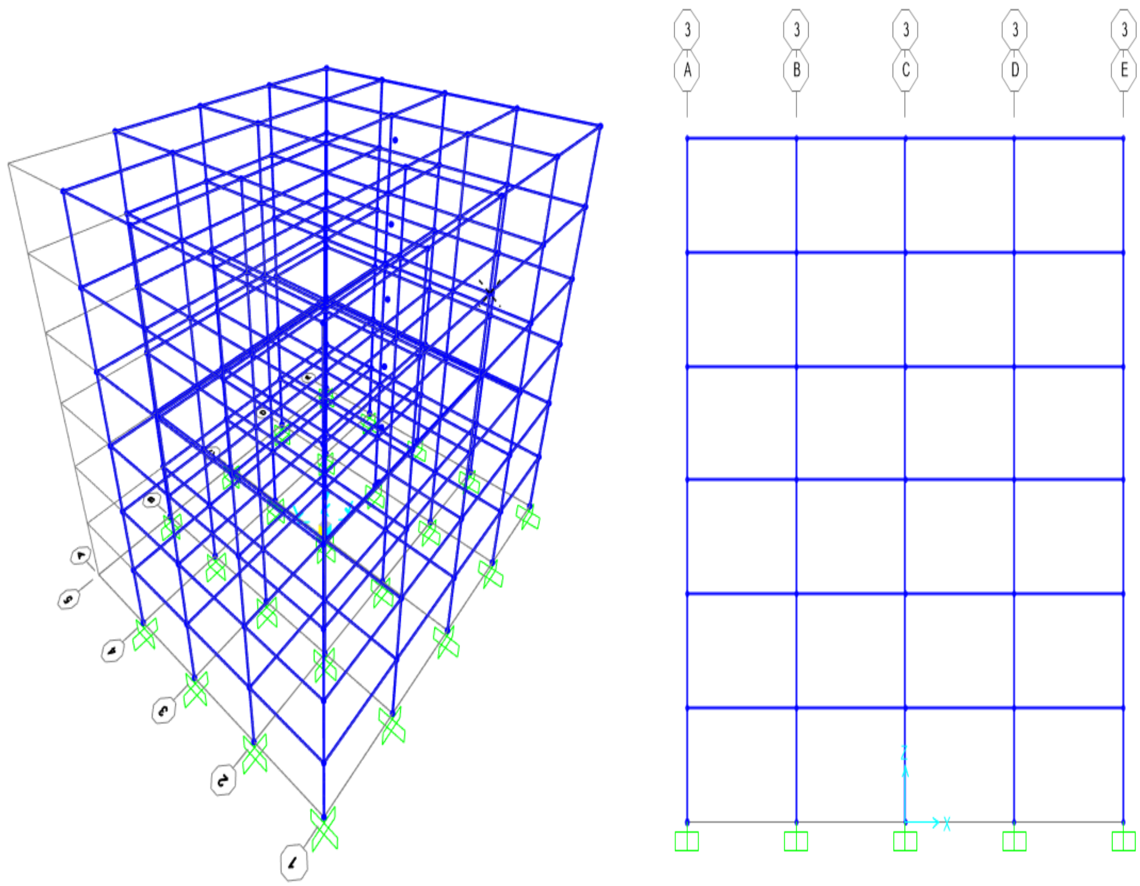
Structural Element	Dimensions
Ground floor columns	40×40 cm
Upper floor columns	35×35 cm
Primary beams	30×50 cm
Secondary beams	35×35 cm
Slab: Hollow-core slab system	(16+4 cm)

Materials used in the construction include non-cracked concrete with a characteristic compressive strength of fc28= 25 MPa, and FeE400 steel for reinforcement.

The modal analysis performed in SAP2000 enabled the investigation of how SSI affects the natural periods, frequencies, and mode shapes of the structure. The two models analyzed are described as follows:

- **Fixed-base model:**

This model assumes a completely rigid base, with no consideration of soil-structure interaction. The supports at the foundation level are modeled as fully restrained, meaning that no rotation or displacement is allowed at the base. The structure is assumed to be perfectly bonded to a non-deformable ground, providing an idealized boundary condition.

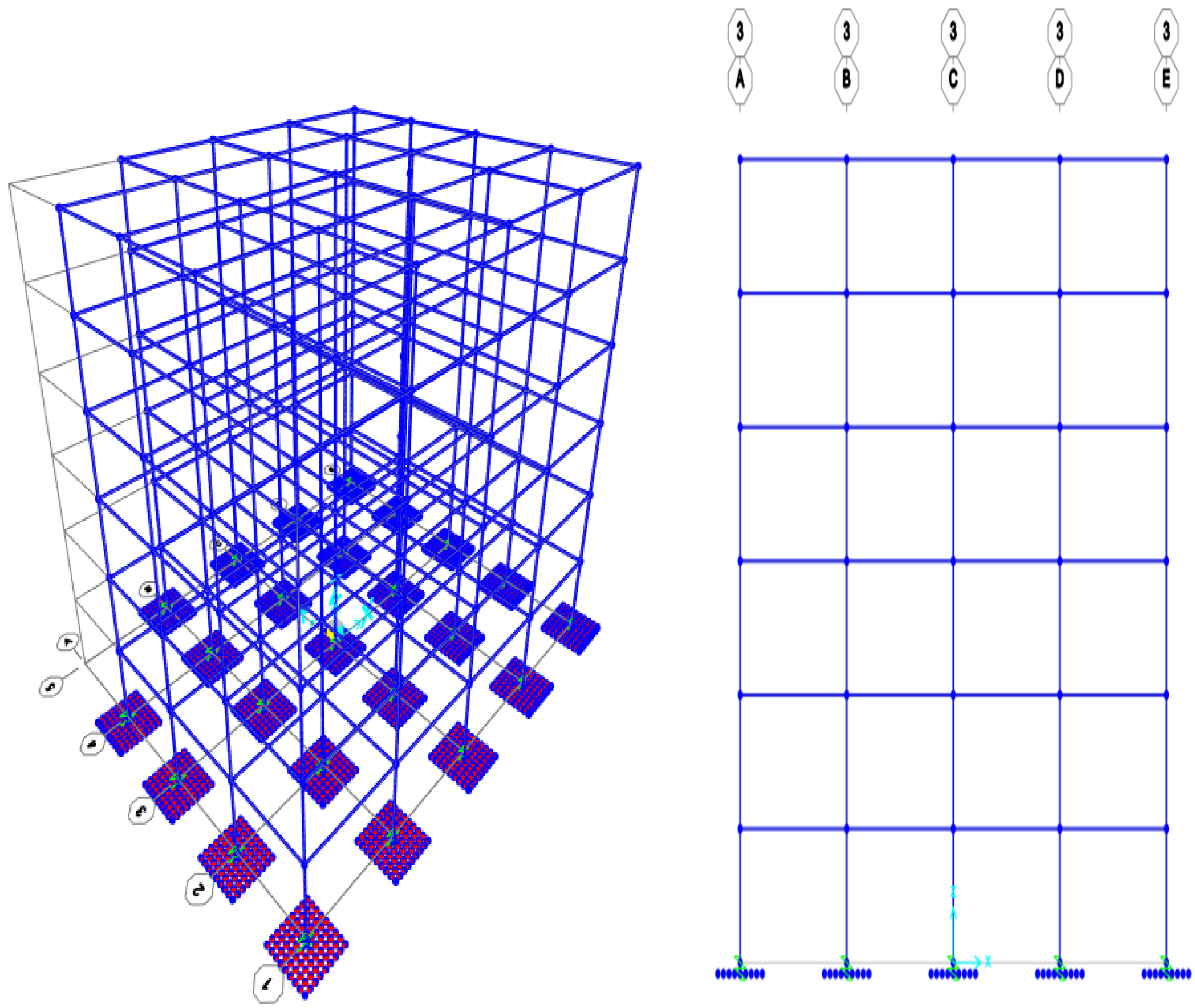


(a) (b)

Figure 5.6 : Building with fixed base modeled in SAP2000 : (a) 3D view and (b) Elevation

- **Flexible-base model (Winkler model):**

In this model, the soil is represented using the Winkler approach, which models the soil as a series of independent, linearly elastic springs. This configuration simulates the dynamic behavior of the structure while accounting for the effects of Soil-Structure Interaction (SSI). The base of the structure is supported by area springs that represent the elastic response of the SSI . These springs permit both horizontal and vertical displacements at the foundation level, providing a more realistic representation of the boundary conditions compared to the fixed-base model.



(a) (b)

Figure 5.7 Building with flexible base modeled in SAP2000 : (a) 3D view and (b)Elevation

5.4.2 Soil Parameters

The soil parameters used in the numerical modeling were derived from the geotechnical investigation report. These parameters are essential for accurately representing the soil behavior in the flexible-base model and correspond to a stiff clay soil type, as summarized in Table 2.

Table 5.2 Geotechnical Parameters of Stiff Clay Soil Used in the Numerical Model

Soil	Density (kg/m^3)	Elastic modulus (E) (MPa)	Poisson's ratio (ν)
Loose uniform sand	1470	10–26	0.2 – 0.4
Dense uniform sand	1840	34–69	0.3 – 0.45
Loose, angular-grained, and silty sand	1630	/	/
Dense, angular-grained, and silty sand	1940	/	0.2 – 0.4
Stiff clay	1730	6–14	0.2 – 0.5
Soft clay	1170 – 1490	2–3	0.15 – 0.25
Loess	1380	/	/
Soft organic clay	610–820	/	/
Glacial till	2150	/	/

5.4.3 Parameters for Winkler model

For accounting Soil-Structure Interaction (SSI) in the flexible-base model, the foundation soil was modeled using the Winkler approach, in which the soil is idealized as a series of independent, linearly elastic springs. The stiffness of these springs is represented by subgrade reaction modulus (ks), which directly impacts the structural dynamic response.

The empirical formulation suggested by Vesic (1961) was employed to calculate the subgrade modulus ks as shown below:The empirical formulation suggested by Vesic (1961) was employed to calculate the subgrade modulus ks as shown below:

$$k_s = \frac{0.65 \cdot E_s}{B(1-\nu_s^2)} \cdot \left(\sqrt[12]{\frac{E_s \cdot B^4}{E \cdot I}} \right)$$

Where:

- Es: Modulus of elasticity of the soil (MPa)
- B: Foundation width (m)
- νs: Poisson's ratio of the soil
- E: Modulus of elasticity of concrete (MPa)

- I: Moment of inertia of the footing (m^4)

The input values used in the analysis are summarized in Table 3.3.

Table 5.3 Input Parameters for SSI Modeling

Parameter	Value
Es	10 MPa
νs	0.35
B	2.0 m (square footing)
E	25 MPA
I	0.0208 m^4

From this formulation and input data, the calculated subgrade modulus was: ks=65000 kN/ m^3

5.4.4 Dynamic Analysis Methods

5.4.4.a. Modal Analysis

Modal analysis is a fundamental procedure in linear dynamic analysis used to determine the natural frequencies, mode shapes, and modal participation factors of a structure. This method assumes that the structure vibrates independently in its natural modes, allowing the dynamic response to be represented as a combination of these uncoupled modal shapes. The focus was placed on two key parameters: natural vibration periods and modal mass participation.

5.4.4.b. Response Spectrum Analysis

Response spectrum analysis is a widely adopted linear dynamic method used in seismic design to estimate the peak response of structures subjected to earthquake ground motion. This approach utilizes a predefined response spectrum to determine how different modes of the structure respond to seismic excitation. The total structural response is obtained by combining the contributions of individual mode shapes, each weighted by the spectral acceleration corresponding to its natural frequency.

In this study, the response spectrum defined by the **RPA 2024** seismic code was applied in both horizontal directions (X and Y). The resulting internal forces and moments were extracted from section cuts at the base of the structure.

The figure 8 below shows the horizontal response spectrum used for the analysis (Ex and Ey directions):

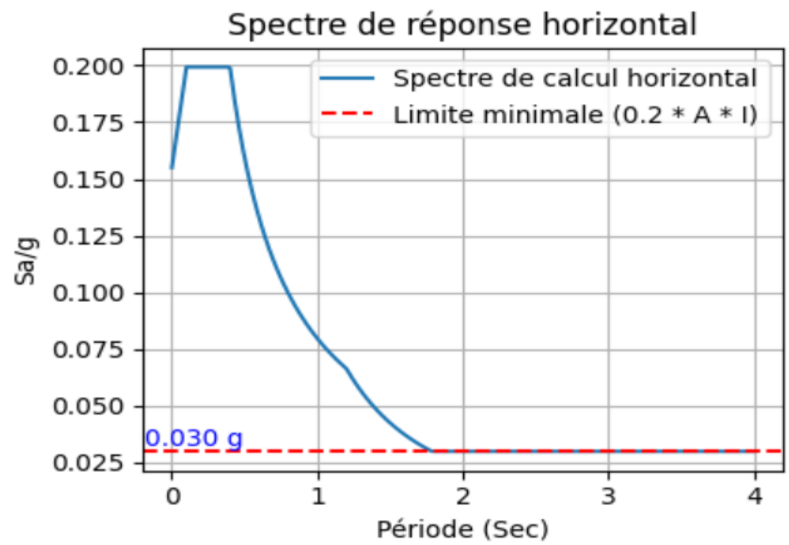


Figure 5.8 Horizontal Seismic Response Spectrum Used in X and Y Directions

5.4.4.c. Linear Time History Analysis

Linear Time History Analysis (LTHA) is a dynamic analysis method that evaluates a structure's response to a specific ground motion record over time by directly solving the equations of motion. Unlike modal or response spectrum analysis, which provide peak responses based on simplified representations, time history analysis captures the detailed evolution of structural behavior throughout the duration of an earthquake. This method is particularly valuable for understanding transient effects, peak displacements, and base shear variations under realistic seismic loading.

In this study, LTHA was performed using a ground motion record selected for compatibility with the site’s seismic and geotechnical characteristics. The record used was **ALTADENA – EATON CANYON PARK (Station Code: 24402-S0758-91179.01)**, which corresponds to an event recorded at 0° orientation. The key parameters of this record are:

- **Location**: ALTADENA – EATON CANYON PARK
- **Sampling**: 2000 data points
- **Time interval**: 0.020 seconds

- **Units**: cm/s² (acceleration)

This ground motion was applied at the base of the structure to simulate seismic excitation in the studied models.

Those three different linear dynamic methods were used to investigate :

- The influence of subgrade reaction modulus (ks) on the seismic response of the structure
- The influence of footing thickness on the seismic response of the structure.

5.4.5 Influence of Subgrade Reaction Modulus (ks)

The value of the subgrade reaction modulus (ks) plays a significant role in characterizing Soil-Structure Interaction (SSI) behavior. To assess the sensitivity of the structural response to variations in soil stiffness, two ks values were considered in this study:

- Case 1: ks = 65000 kN/m³, calculated using Vesic's equation , representing relatively stiff soil conditions.
- Case 2: ks = 1500 kN/m³, based on Terzaghi a substantially lower value proposed to simulate soft soil conditions or to reflect potential uncertainty in geotechnical parameters.

These ks values were assigned to area springs at the base of the foundation in SAP2000 .

5.4.5.a. Dynamic Analysis Results

- ➢ Modal Analysis

    - Time period

The time period plays a crucial role in assessing the lateral loads. It depends on mass and stiffness. Based on the time period, the behavior of buildings under lateral loads can be evaluated. Figure 9 illustrates the variation of the fundamental and higher mode periods for three different support conditions.

For Mode 1: It observed that the vibration time period increases when moving from the fixed-base model to the flexible-base model, with this increase being more pronounced in the case of very soft soil (Ks2). This reflects a significant effect of Soil-Structure Interaction (SSI), leading to increased system flexibility and a longer time period. Modes 2–3: The same trend continues, but the differences between the three models become less pronounced compared to modes 1 and 2. However, the time period for Ks2 remains. Modes 4–6: For higher modes, the variation between different base conditions diminishes. The time periods converge, particularly between the fixed base and ks1 models. However, the ks2 model still shows slightly higher periods

As conclusion the incorporation of Soil-Structure Interaction (SSI) leads to a noticeable increase in the natural vibration periods, especially in the fundamental mode. This effect becomes more evident as soil stiffness decreases. In the case of very soft soil (Ks2), the structure exhibits significantly greater flexibility, resulting in longer vibration periods. Conversely, when the soil is stiffer (Ks1), the dynamic behavior is close to that of the fixed-base condition. These findings emphasize the importance of considering SSI in seismic analysis, particularly for buildings constructed on soft soils

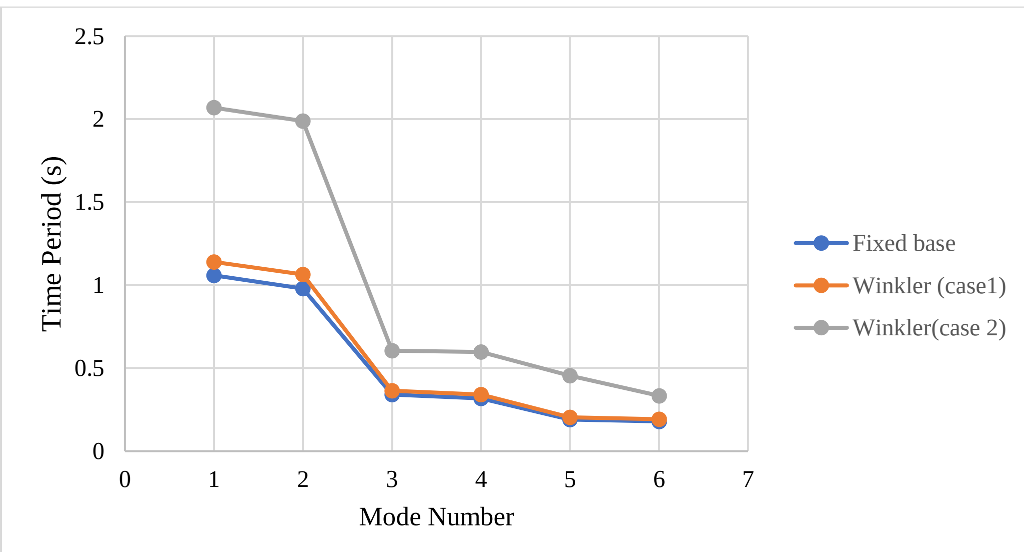


Figure 5.9 Time period vs. Mode number

- Modal Mass Participation

Table 3.5 presents the modal mass participation for the six modes under three different support conditions: fixed-base, Winkler foundation with stiff soil, and Winkler foundation with soft soil (ks = 1500 kN/m³). The results highlight the influence of soil-structure interaction (SSI) on the dynamic characteristics of the structure.

For the fixed-base model, 94.83% of the total mass is engaged within the first six modes, indicating a relatively rigid system where the majority of dynamic response is captured by the lower modes. In contrast, the Winkler model with stiff soil shows a reduced participation of 78.51% within the same number of modes, reflecting the influence of partial flexibility in the soil that redistributes modal contributions across a larger number of modes.

Interestingly, the Winkler model with soft soil (ks = 1500 kN/m³) achieves a much higher modal mass participation of 99.42% within the first six modes. This suggests that when soil flexibility increases, the structural system tends to concentrate its dynamic response in fewer dominant modes, particularly the fundamental ones.

These results highlight that it's necessary to consider soil-structure interaction effects in seismic analysis, as neglecting them (i.e., assuming a fixed base) can lead to over or underestimation of modal contributions and consequently inaccurate dynamic response predictions.

Table 5.4 Modes and mass participation

Fixed		Winkler (case 1)		Winkler (case 2)	
No. of Mode	Mass Participation (%)	No. of Mode	Mass Participation (%)	No. of Mode	Mass Participation (%)
06	94.83	06	78.51	06	99.42

- Response Spectrum Analysis

  - Internal Force Distribution from Section Cut Analysis

To evaluate the seismic response of the structure with and without Soil-Structure Interaction (SSI), section cuts were defined at the base of the structure in SAP2000. These section cuts allow for the extraction of internal forces and moments in all three global directions . In this study, particular emphasis is placed on the internal shear forces in the horizontal directions, namely:

- **F1**: Shear force in the **X-direction**
- **F2**: Shear force in the **Y-direction**

As we mention three modeling scenarios were compared:

- Fixed base (no soil flexibility)
- Flexible base with ks = 65000 kN/m³ (Winkler Case 1)
- Flexible base with ks = 1500 kN/m³ (Winkler Case 2)

For Figure 10, which illustrate the shear forces F1 and F2 in the X directions, the fixed-base model consistently shows the highest shear force values across all stories. This outcome is expected since the model assumes a completely rigid foundation that transfers seismic forces directly into the structure without any damping or deformation from the soil. In contrast, the Winkler model with a stiffer soil condition (Case 1) demonstrates a moderate reduction in shear forces, particularly in the lower stories, reflecting a more realistic soil-structure interaction. The reduction becomes much more pronounced in the softer soil scenario (Case 2), where the soil's flexibility leads to a significant decrease in the transmission of shear forces. This highlights the soil's ability to absorb and dissipate seismic energy more effectively under softer conditions.

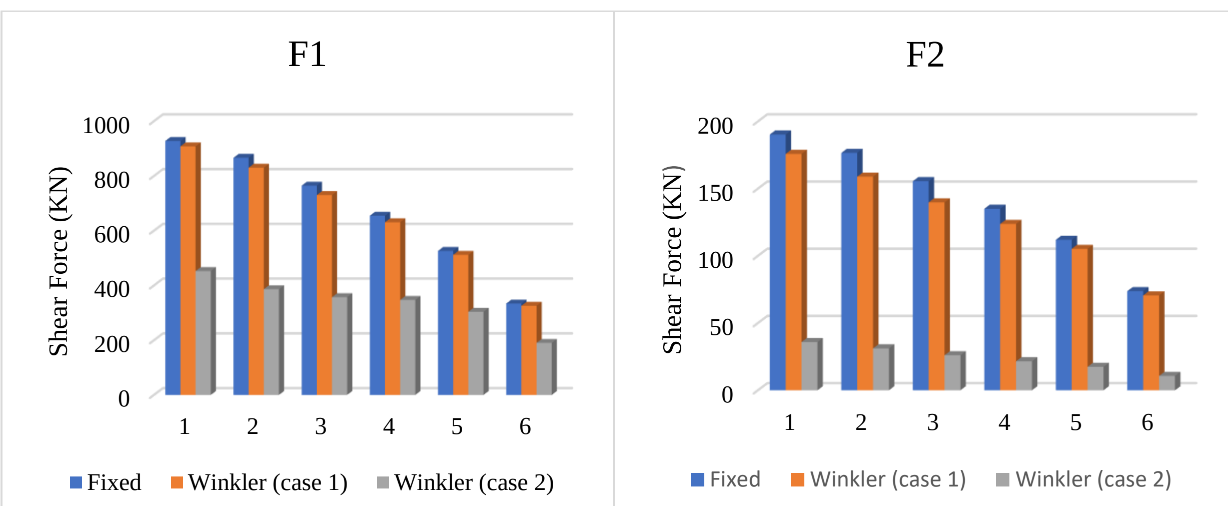


Figure 5.10 Shear Force Distribution in X Direction for Different Support Conditions

(F1, F2,)

A similar pattern is observed in the Y direction (Figure 11), where the distribution of shear forces F1 and F2 follows the same trend: the fixed-base model shows the highest values, followed by moderate reductions in the stiff-soil case, and significant decreases in the soft-soil model. This confirms that increased soil flexibility not only reduces horizontal shear forces but also amplifies vertical responses due to greater foundation deformability.

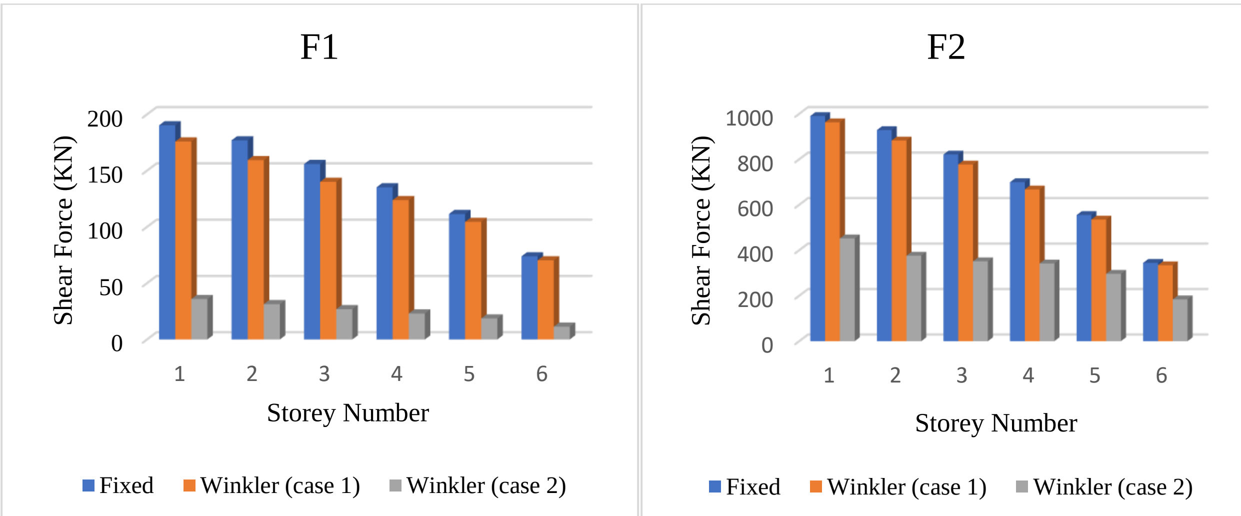


Figure 5.11 Shear Force Distribution in Y Direction for Different Support Conditions

(F1, F2)

- Base Shear

X Direction :

The base shear response of the structure in the X direction is significantly influenced by the boundary condition assumptions applied at the foundation level. The graphs for each scenario illustrate the corresponding base force and moment distributions at the base level of the structure obtained from SAP2000.

Base shear represents the total horizontal seismic force acting at the base of a structure and is a key indicator of seismic demand. Figure 12 compares the base shear response in the X direction for three different support conditions: Fixed Base, Winkler Case 1 (stiffer soil) and Winkler Case 2 (softer soil).It is observed that :

- The fixed-base model exhibits the highest base shear values, indicating that assuming a rigid connection between the structure and the ground leads to the most conservative estimation of seismic forces.
- Winkler Case 1, which represents a relatively stiff soil condition, shows a slight reduction in base shear compared to the fixed base, highlighting a moderate influence of soil flexibility.
- Winkler Case 2, representing a soft soil condition, experiences the lowest base shear values, demonstrating a substantial reduction due to increased soil deformability.

The results clearly demonstrate that as soil stiffness (case1)decreases, the base shear demand on the structure also decreases. This reduction is most significant in the case of soft soils(case 2), where soil-structure interaction (SSI) allows for greater energy dissipation through ground flexibility. Consequently, the fixed-base model, by neglecting these effects, tends to overestimate seismic demand.

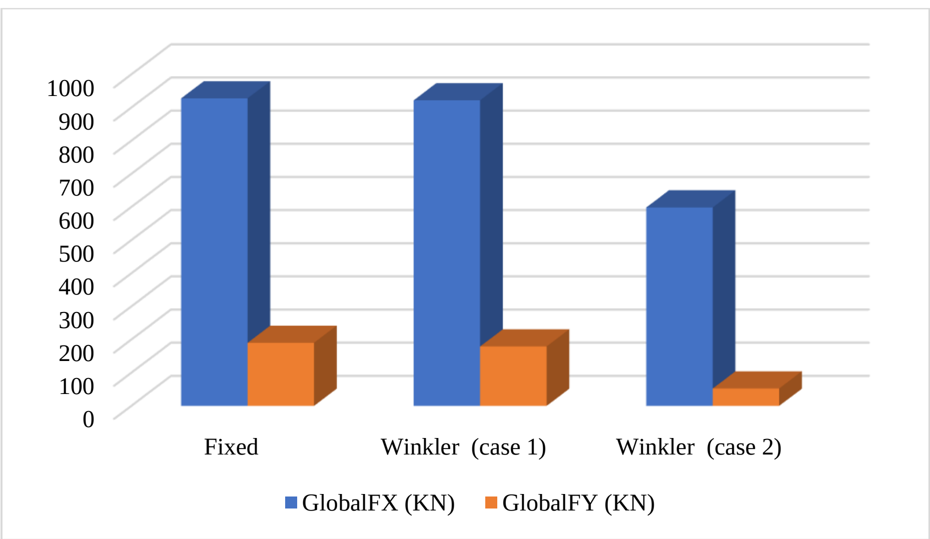


Figure 5.12 Base Shear Forces in X Direction for Different Support Conditions

Y Direction :

Figure 13 compares the base shear response in the Ydirection for three different support conditions . The force components reveal a clear influence of soil-structure interaction (SSI) on seismic response.

• The fixed-base model exhibits the highest base shear values (GlobalFY), indicating that assuming a rigid connection between the structure and the ground leads to the most conservative estimation of seismic forces in the Y direction.
• Winkler Case 1, which represents a relatively stiff soil condition, shows a moderate reduction in base shear (GlobalFY) compared to the fixed base, highlighting the partial absorption of seismic energy by the stiffer soil.
• Winkler Case 2, representing a soft soil condition, experiences the lowest base shear values (GlobalFY), demonstrating a significant reduction due to increased soil deformability and the damping effect of greater flexibility.

The results clearly demonstrate that as soil stiffness decreases, the base shear demand in the Y direction also decreases. This reduction is most notable in the case of soft soils (Case 2), where soil-structure interaction (SSI) allows for enhanced energy dissipation through ground deformation. As a result, the fixed-base model, by neglecting SSI effects, tends to overestimate seismic demand in the Y direction.

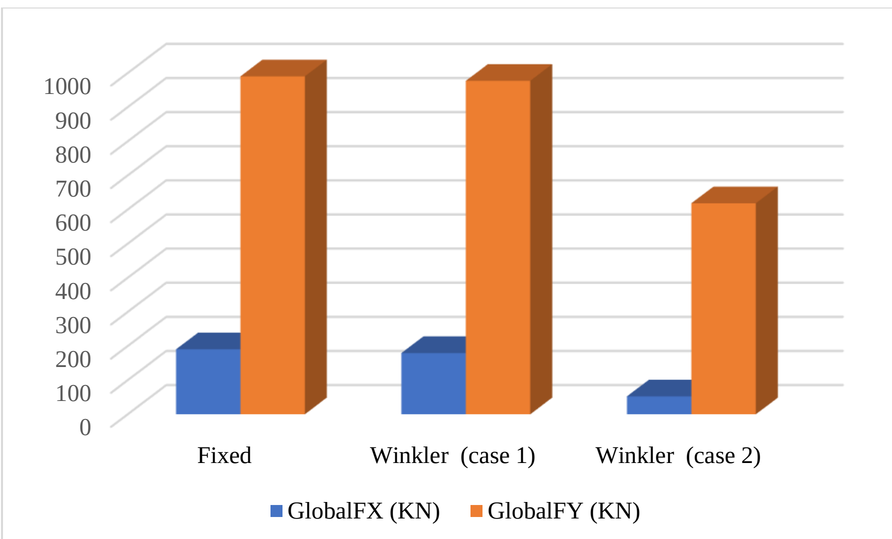


Figure 5.13 Base Shear Forces in Y Direction for Different Support Conditions

In comparing the Ex and Ey directions, the Ex direction shows higher overall base forces in the fixed-base model. However, with the inclusion of soil-structure interaction, both directions experience reductions. The reduction is more pronounced in the Ey direction, especially under soft soil conditions (Winkler case 2), indicating greater flexibility and energy dissipation. This suggests that while Ex governs the initial seismic demand, Ey is more influenced by soil flexibility, highlighting the directional sensitivity of the structure's dynamic response.

- Lateral Displacement

Lateral displacement is an absolute value of displacement of a storey under lateral forces like earthquake load, wind load, etc. It is crucial for seismic pounding effect in any seismic activity for making adequate parting between nearby structures. Larger the displacement, the less stiff is structure.

Figure 14 and 15 presents the variation of lateral displacement along the height of the building for both fixed-base and flexible-base models under seismic excitations in both the X and Y directions.

It is observed that:

• In both EX and EY directions , lateral displacement increases progressively with storey height in all three cases reflecting the typical behavior of framed structures under horizontal seismic loading.

• The fixed-base model exhibits the lowest displacement values across all storeys, indicating a stiffer structural response due to the assumption of rigid foundation conditions.

• Winkler Case 1, which incorporates a relatively stiff soil foundation shows a moderate increase in lateral displacement compared to the fixed-base model highlighting the influence of partial soil flexibility.

• Winkler Case 2, representing a soft soil condition demonstrates the highest lateral displacements with a pronounced increase in deformation especially at the upper storeys.

Overall, the results confirm that as the flexibility of the soil increases, the lateral displacement of the structure also increases. This effect becomes more significant with height reinforcing the importance of accounting for SSI in the seismic analysis of multi-storey buildings especially in soft soil conditions.

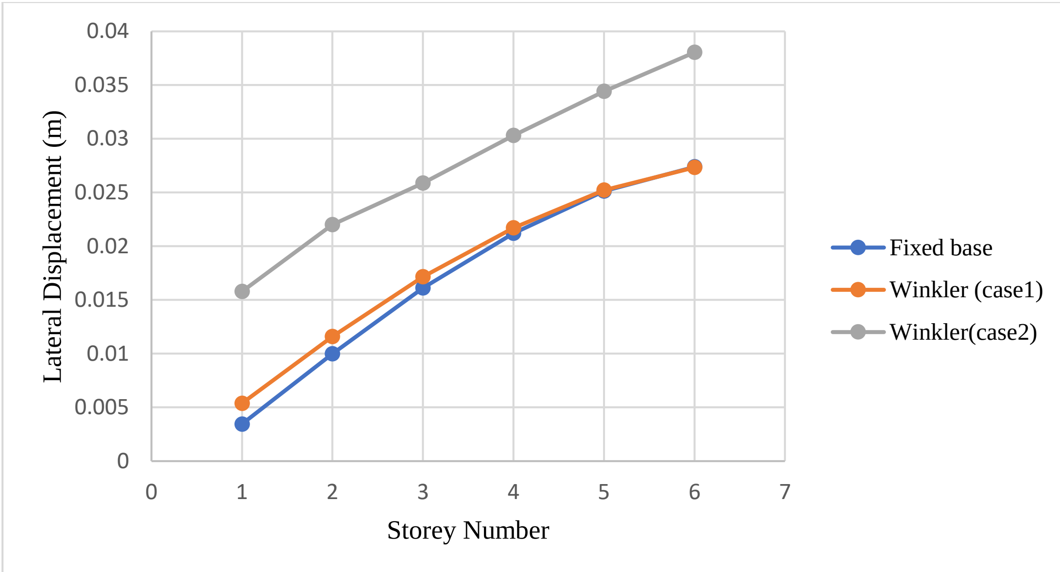


Figure 5.14 Lateral displacement vs Storey Number in X direction

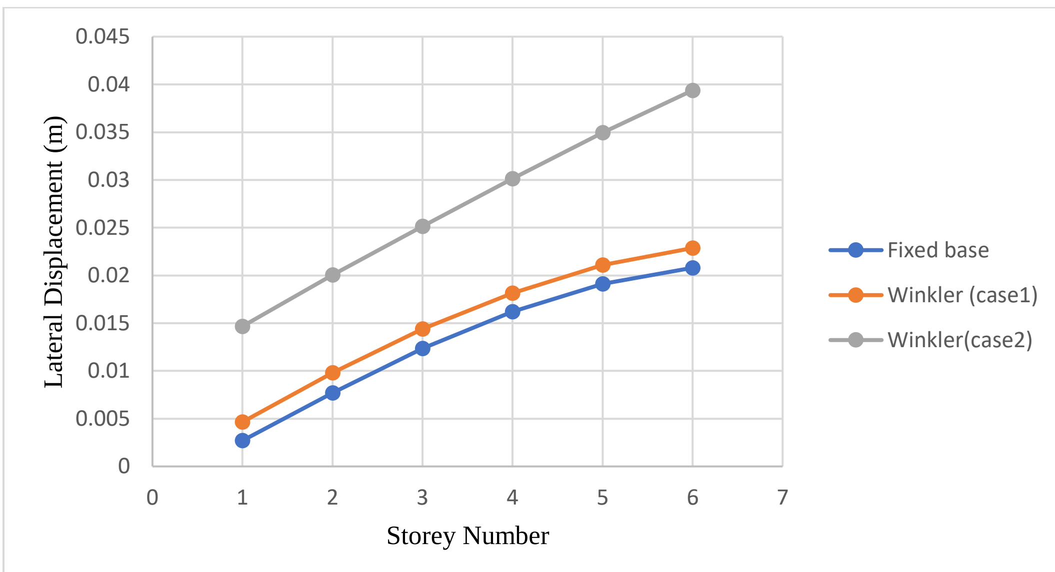


Figure 5.15 Lateral displacement vs Storey Number in Y direction

- Inter-Story Drift ratio :

Inter-story drift ratio (IDR) is an essential parameter of structural behaviour in the performance-based seismic analysis, especially for high-rise buildings. IDR is defined as the relative lateral displacement between two continuous floors divided by the same floor height.

Figure 16 illustrates the variation of Inter-Story Drift Ratio (IDR) along the height of the structure in X direction under three different support condition. The comparison revealed that

The Fixed Base model shows the lowest IDR values throughout the height of the structure, indicating a stiffer response due to the assumption of a perfectly rigid foundation. In contrast, the Winkler 1 model which likely represents soil springs with moderate stiffness demonstrates noticeably increased drift ratios particularly at mid- to upper stories. This reflects the flexibility introduced by the soil allowing greater lateral displacements. The Winkler 2 model incorporating even more flexible spring properties exhibits the highest IDRs among the three, especially in the upper stories where seismic-induced displacement demand is typically greatest.

This progressive increase in IDR from Fixed Base to Winkler 2 underscores the significance of SSI in seismic response. Neglecting SSI as in the fixed-base assumption, can lead to underestimating deformation demands. The results clearly demonstrate that incorporating realistic soil models (such as Winkler-based foundations) is essential for accurate drift prediction and safety assessment in high-rise buildings.

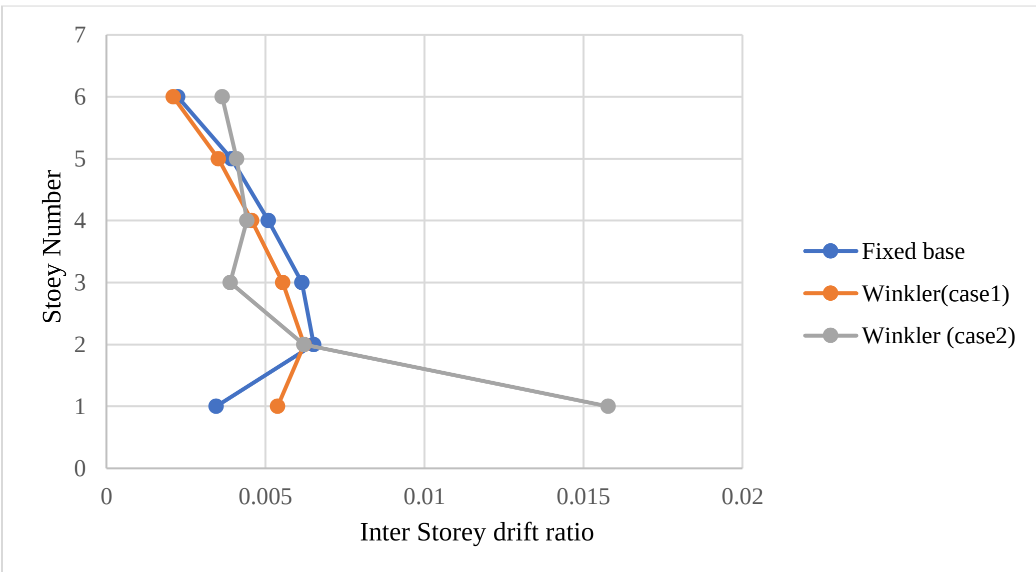


Figure 5.16 Inter-storey drift ratio vs Storey Number

- Linear Time History Analysis

Figures 17 , 18 and 19 present the time history plots of base shear response in the X-direction it was evaluated for the three foundation conditions . As shown in the time history plots, a clear trend was observed regarding the influence of soil flexibility on base shear magnitude and response behavior:

- The fixed-base model exhibited the highest peak base shear of approximately 8.48 × 10^3 kN, along with more intense and sustained high-frequency oscillations. This reflects a stiffer structural response with minimal energy dissipation.
- For Winkler foundation model with ks = 65000 kN/m^3 showed a reduced peak base shear of about 3.89 × 10^3 kN. The vibrations were noticeably less intense, and the response decayed faster compared to the fixed model, indicating moderate SSI effects.
- For the most flexible Winkler foundation case (ks = 1500 kN/m^3) ,the lowest peak base shear was recorded at around 1.27 × 10^3 kN. The response was smooth and quickly dampened, highlighting the significant influence of soft soil in absorbing seismic energy.

Overall, it was observed that increasing soil flexibility (decreasing ks) led to a substantial reduction in base shear and more damped structural responses.

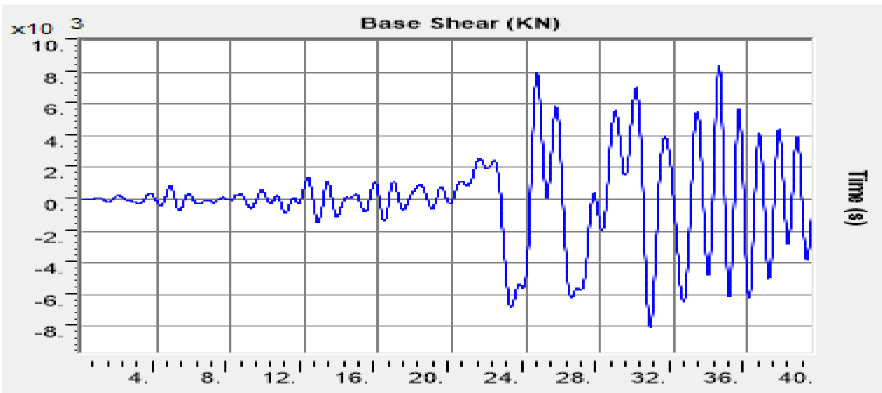


Figure 5.17 The plot of variation of Base Shear in X-Direction – Fixed Base Condition

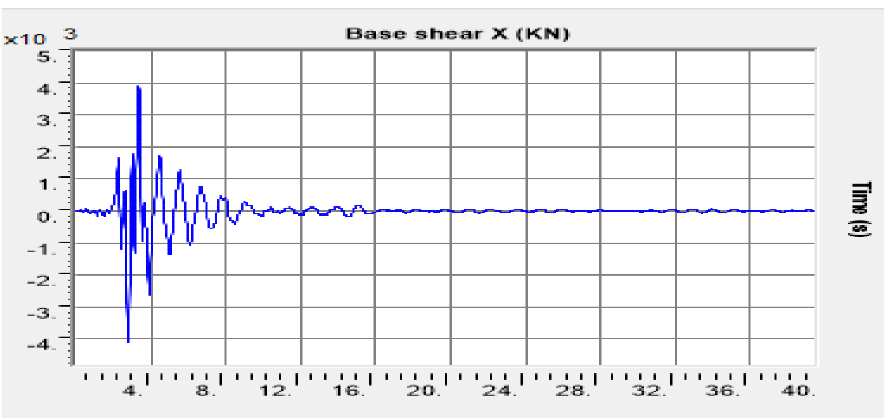


Figure 5.18 The plot of variation of Base Shear in X-Direction – Winkler (case1)

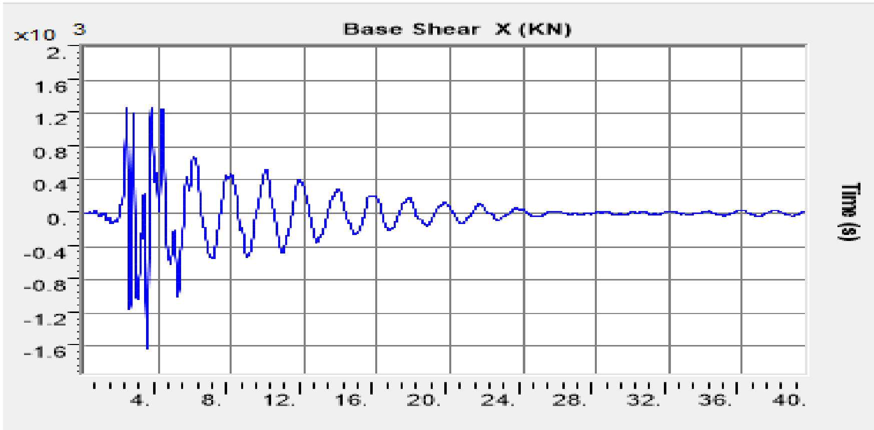


Figure 5.19: The plot of variation of Base Shear in X-Direction – Winkler (case 2)

The table below presents the minimum and maximum base shear values in the X direction obtained from the linear time history analysis for three structural model

Table 5.5 Base Shear in X-Direction (kN) for Different Models

	Base Shear X (KN)	
	Min	Max
Fixed base	-8.085 x 10^3	8.348 x 10^3
Winkler case (1)	-4.107 x 10^3	3.894 x 10^3
Winkler case (2)	-1.630 x 10^3	1.279 x 10^3

5.4.6 Influence of Footing Thickness on Structural Response

Following the investigation of the influence of the subgrade reaction modulus (ks), a second parametric study was conducted to evaluate the effect of footing thickness on the structural response under seismic loading. In this phase, the subgrade modulus was kept constant at ks = 65000 kN/m^3, representing stiff soil conditions as derived from Vesic’s formula. The aim was to isolate and analyze the impact of footing stiffness on the dynamic behavior of the structure, particularly its ability to transfer seismic loads.

Two footing thicknesses were considered:

- Case 1: Footing thickness = 0.50 m (thick footing)
- Case 2: Footing thickness = 0.15 m (thin footing)

5.4.6.a. Dynamic Analysis Results

➢ Modal Analysis

- Time period

Figure 20 compares the natural time periods of the structure for different footing conditions and a fixed-base reference across the first six vibration modes. The key observations are:

(Mode 1): The fixed-base model shows the shortest time period, indicating the highest stiffness and least flexibility. However case 1 (thick footing) results in the longest period among the three, reflecting the highest degree of flexibility and SSI influence. In case 2 (thin footing) yields a slightly longer period than the fixed-base model, indicating a modest increase in flexibility due to the inclusion of soil-structure interaction (SSI). The thicker footing adds mass and increases rotational compliance, thereby softening the overall system.

Mode 2:A similar trend is observed, with the time period increasing from fixed-base to Case 1 to Case 2. This further confirms the growing influence of footing stiffness on lower mode dynamics.

Modes 3 to 6: The differences in time periods between the three models become increasingly minor with higher modes.This suggests that footing thickness has a diminishing effect on the dynamic response as the mode number increases. Higher modes are typically governed more by local deformation characteristics than by global flexibility or foundation compliance.

Footing thickness significantly affects seismic response by altering structural flexibility. Thicker footings increase time periods in lower modes, reducing force demands but potentially increasing displacements. The effect is minimal in higher modes. Thus, accounting for footing stiffness is essential for realistic seismic analysis, especially on stiff soils.

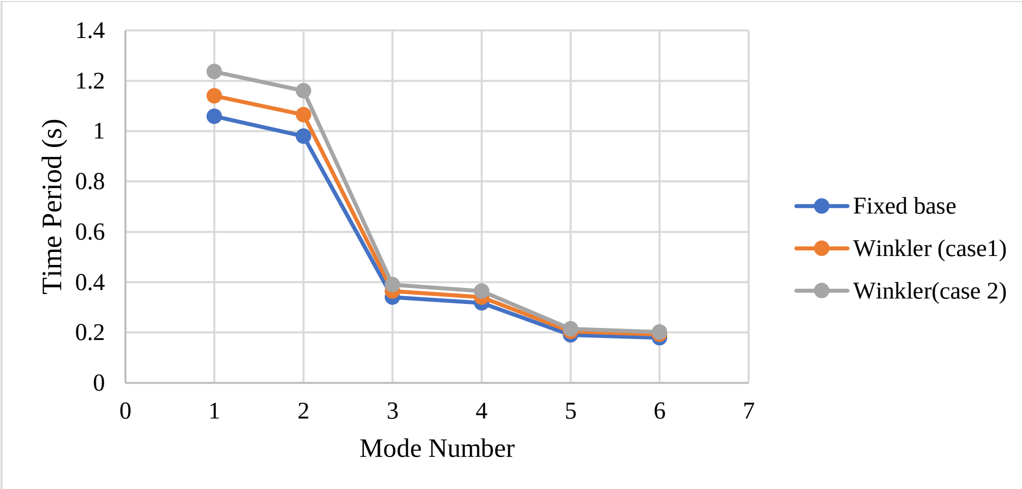


Figure 5.20 Time period vs. Mode number

- Modal Mass Participation

Table 3.5 summarizes the number of vibration modes required to achieve significant mass participation in the X-direction for the fixed-base model and the two flexible-base models (Winkler cases 1 and 2). For all three models, the first **six modes** were sufficient to capture a large portion of the total mass participation. The fixed-base model reached the highest mass participation at **94.83%** followed closely by Winkler case (2) at **93.23%** indicating similar dynamic characteristics. In contrast, Winkler case (1) showed a noticeably lower mass participation of **78.51%** for the same number of modes.

Table 5.6 Modes and mass participation

Fixed		Winkler (case 1)		Winkler (case 2)	
No. of Mode	Mass Participation (%)	No. of Mode	Mass Participation (%)	No. of Mode	Mass Participation (%)
06	94.83	06	78.51	06	93.23

- Response Spectrum Analysis

  - Internal Force Distribution from Section Cut Analysis

Figure 21 compares the internal forces F1 and F2 for a frame structure under three different foundation modeling assumptions: fixed base, Winkler case 1 and Winkler case 2. The horizontal axis represents the level number (1 to 6), while the vertical axis shows the corresponding magnitude of the internal force.

For both F1 and F2, the results consistently show that the internal forces decrease from level 1 to level 6. The fixed base model exhibits the highest force values across all levels, followed by Winkler case 1 (thick footing) and then Winkler case 2 (thin footing). This trend highlights the effect of soil-structure interaction (SSI): introducing flexibility through Winkler foundation modeling results in reduced internal forces.

This outcome confirms the significance of SSI in dynamic structural analysis. Neglecting foundation flexibility, as in the fixed base assumption, may lead to conservative estimates of internal forces. In contrast, more realistic modeling with soil springs (Winkler foundation) provides a better approximation of actual structural behavior under lateral loading.

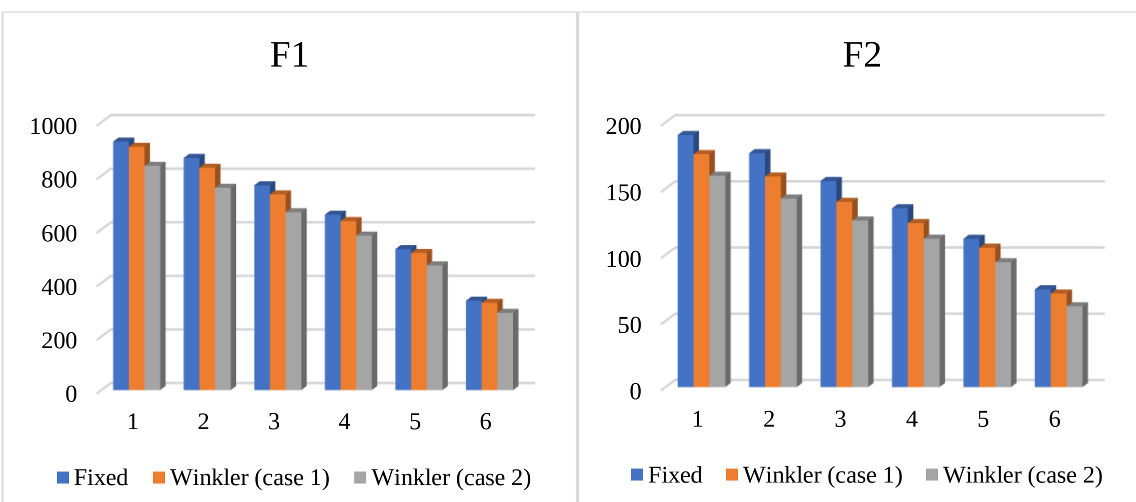


Figure 5.21 Shear Force Distribution in X Direction for Different Support Conditions

(F1, F2,)

Figure 22, which presents the results in the Y direction, exhibits a similar trend to that observed in Figure 21. The internal forces again decrease progressively from the fixed base to Winkler case 1 (thick footing) and further to Winkler case 2 (thin footing). This consistency across both seismic directions reinforces the conclusion that increased foundation flexibility relating to the footing thickness leads to a reduction in internal force demands. The alignment of results in both directions confirms the robustness of the SSI effect in dynamic response evaluation.

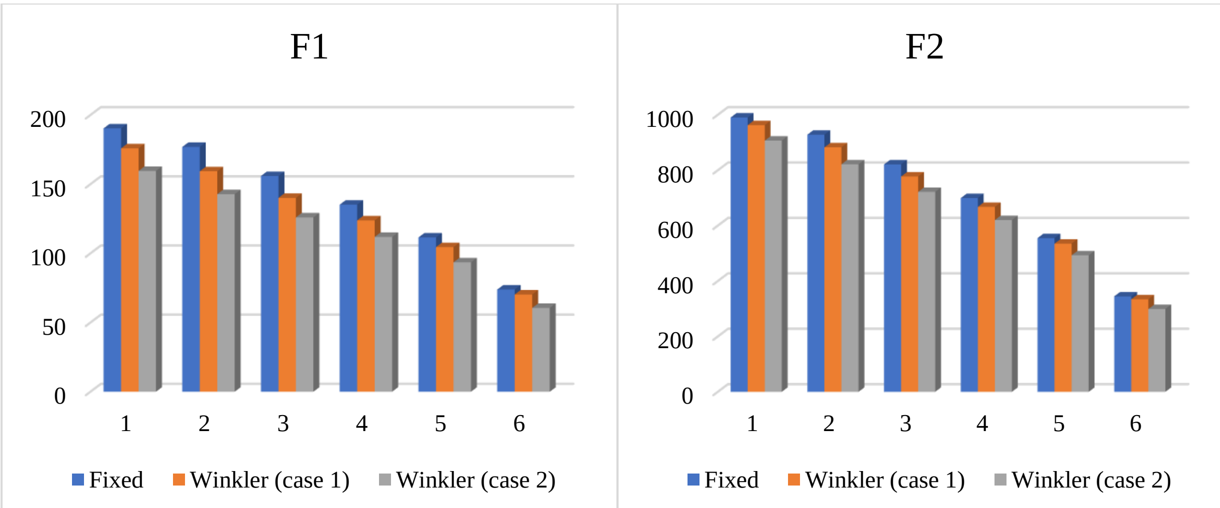


Figure 5.22 Shear Force Distribution in Y Direction for Different Support Conditions

(F1, F2,)

- Base Shear

Figure 23 presents the base shear forces in the X direction for the three support conditions .The fixed base model shows the highest base shear in the X direction . When soil-structure interaction is introduced through the Winkler model a noticeable reduction in base shear is observed. This reduction is more significant in Case 2 where the footing is thinner indicating that increased foundation stiffness helps in absorbing and redistributing seismic forces thereby reducing their impact on the superstructure. The GlobalFY component in this direction remains relatively small across all cases suggesting that seismic action is primarily concentrated in the X direction under this loading scenario.

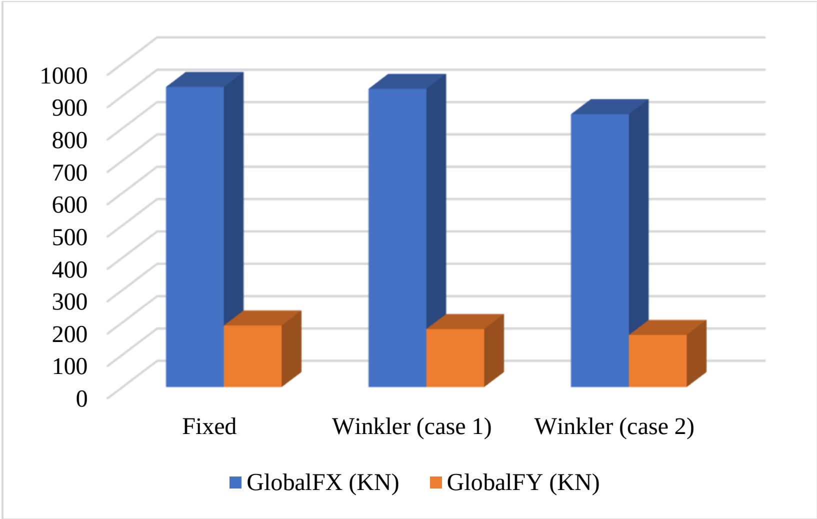


Figure 5.23 Base Shear Forces in X Direction for Different Support Conditions

Figure 24 illustrates the base shear forces in the Y direction for the same three support conditions. In contrast to the X direction the dominant component here is GlobalFY indicating that seismic forces are primarily acting along the Y axis in this case. The fixed-base and Winkler (Case 1) models display similar base shear values, showing minimal influence of footing thickness at higher stiffness. However, in Winkler (Case 2) a slight reduction in base shear is observed, again suggesting that a thinner footing can partially mitigate seismic forces. Meanwhile , the GlobalFX component remains low confirming that lateral forces in the X direction are minimal under Y direction excitation.

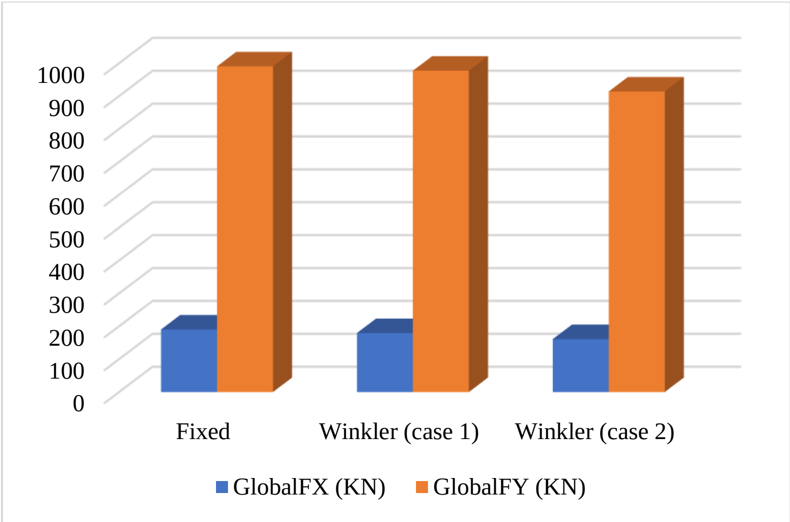


Figure 5.24 Base Shear Forces in Y Direction for Different Support Conditions

- Lateral Displacement

Figure 25 , 26 illustrates the variation of lateral displacement across the building height for three foundation conditions: fixed base, Winkler model with thick footing (Case 1), and Winkler model with thin footing (Case 2).

The trend shows in both EX and EY directions that lateral displacement increases with storey height in all cases and it is observed that : The fixed-base model exhibits the lowest lateral displacements owing to its idealized boundary condition that assumes no base flexibility. However the Winkler (Case 1) model representing a thick footing (0.50 m) shows slightly higher displacements than the fixed base. The inclusion of soil-structure interaction introduces base flexibility allowing more movement . Also the Winkler (Case 2) model which uses a thin footing (0.15 m), results in the highest lateral displacements across all storeys. The reduced stiffness of the thin footing amplifies the base flexibility leading to a greater overall deformation of the structure

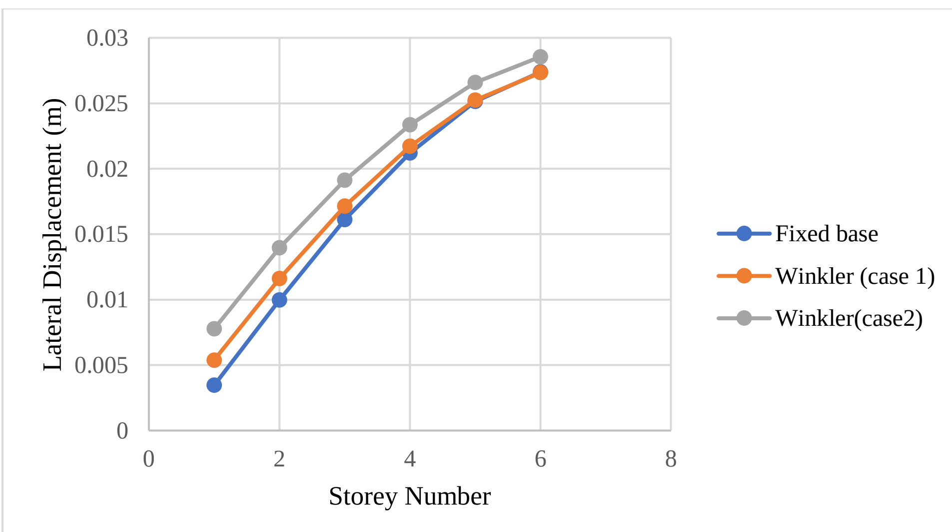


Figure 5.25 Lateral displacement vs Storey Number in X direction

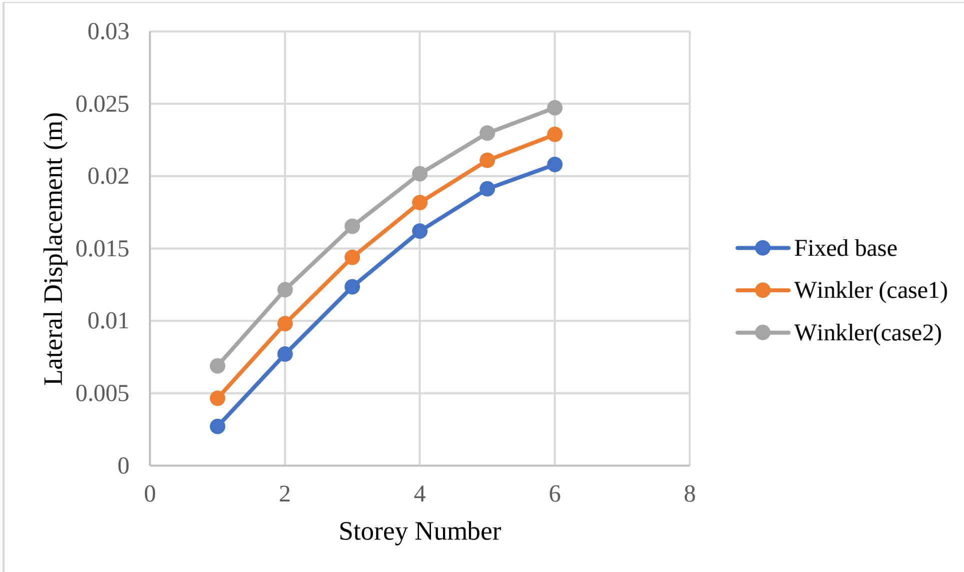


Figure 5.26 Lateral displacement vs Storey Number in Y direction

- Inter-Story Drift

Figure 21 presents the variation of inter-storey drift ratio (IDR) along the height of the building for three different foundation conditions. It is observed that the fixed base model which neglects soil-structure interaction exhibits the lowest drift values throughout the height, reflecting a stiffer system response. In contrast Winkler Case 1 (with a footing thickness of 0.50 m) and Case 2 (with a thinner footing of 0.15 m) show progressively increasing drift ratios particularly in the lower storeys . Case 2 experiences the highest drift values especially at the first and second storeys highlighting the pronounced effect of increased foundation flexibility .This comparison underscores the critical role of footing stiffness in seismic response where thinner footings lead to greater lateral deformations due to amplified SSI effects. The results demonstrate that assuming a fixed base may significantly underestimate the actual seismic demand and incorporating foundation flexibility is essential for realistic structural assessments.

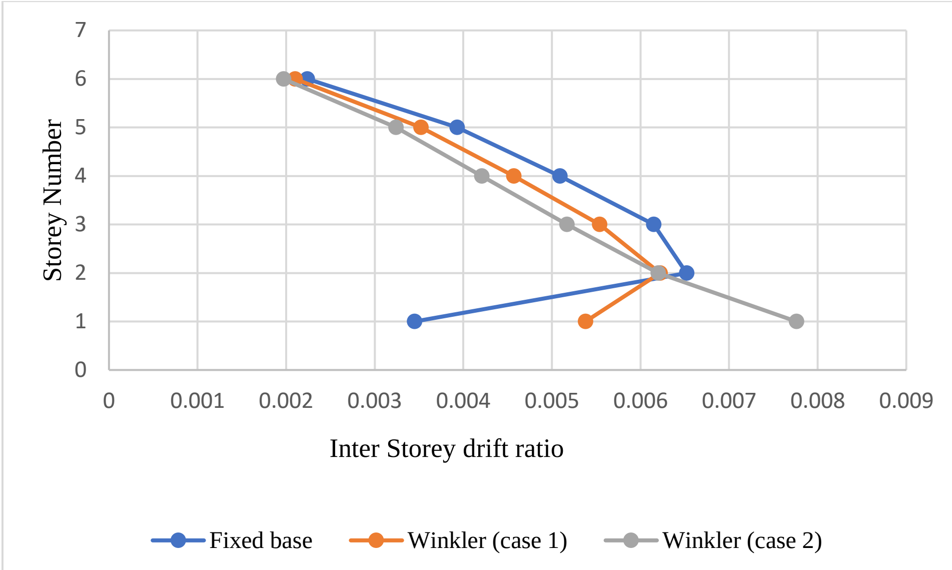


Figure 5.27 Inter-storey drift ratio vs Storey Number

➢ Linear Time History Analysis

The base shear response of the structure under seismic loading varies significantly depending on the foundation modeling as illustrated in Figures 28, 29 and 30. In the fixed base condition (Figure 26) , where the foundation is assumed to be perfectly rigid the base shear reaches its maximum values with peaks of $+8.348 \times 10^3$ kN and -8.085×10^3 kN . This represents the highest seismic forces experienced by the structure due to the complete transfer of ground motion without any energy dissipation through soil flexibility. In contrast when Soil-Structure Interaction (SSI) is incorporated using the Winkler model the base shear reduces substantially. In Case 1 (Figure 27) where the footing thickness is 0.50 m the peak base shear values drop to $+3.894 \times 10^3$ kN and -4.107×10^3 kN. This reduction is attributed to the flexibility introduced by the soil springs , thus reducing the force transmitted to the structure. Further reduction is observed in Case 2 (Figure 28) where the footing thickness is reduced to 0.15 m. Here the base shear peaks at $+3.432 \times 10^3$ kN and -3.646×10^3 kN the lowest among all three cases. This demonstrates that the combination of SSI and reduced footing stiffness leads to even greater damping of seismic forces. Overall , the comparison shows that considering SSI particularly with more flexible foundations can significantly reduce base shear providing a more realistic and less conservative seismic response than the fixed-base assumption.

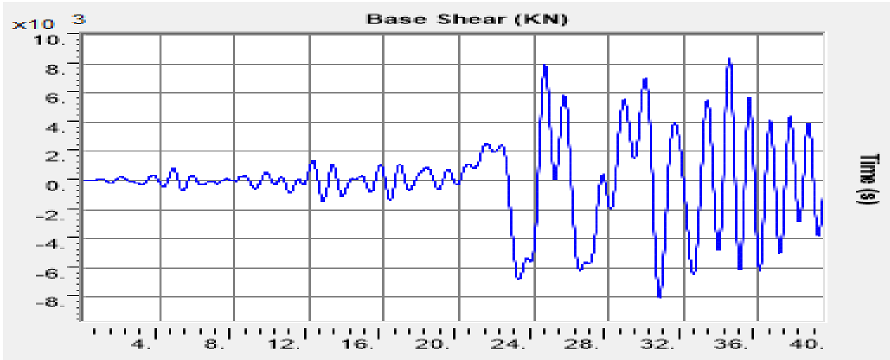


Figure 5.28: The plot of variation of Base Shear in X-Direction – Fixed Base Condition

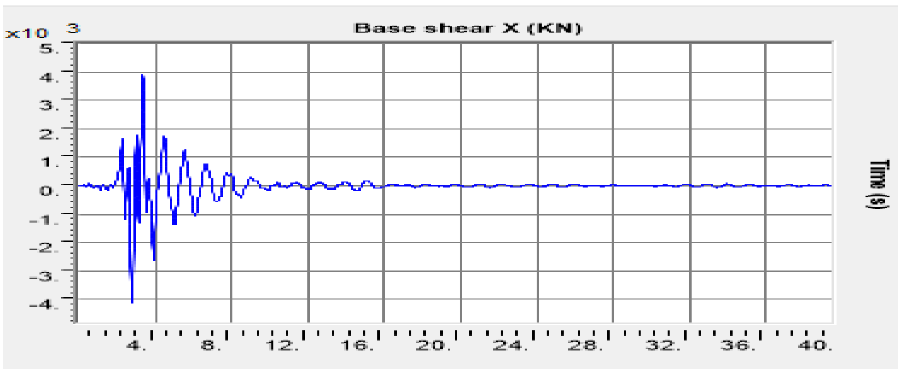


Figure 5.29 The plot of variation of Base Shear in X-Direction – Winkler (case1)

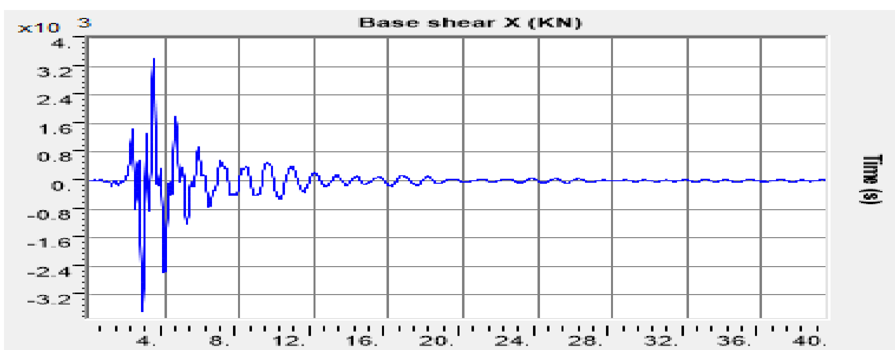


Figure 5.30 : The plot of variation of Base Shear in X-Direction – Winkler (case 2)

The table below presents the minimum and maximum base shear values in the X-direction obtained from the linear time history analysis for three structural model

Table 5.7 Base Shear in X-Direction (kN) for Different Models

	Base Shear X (KN)	
	Min	Max
Fixed base	-8.085 x 10^3	8.348 x 10^3
Winkler case (1)	-4.107 x 10^3	3.894 x 10^3
Winkler case (2)	-3.646 x 10^3	3.432 10^3

5.5 Conclusion :

This chapter has explored the influence of Soil-Structure Interaction (SSI) on the seismic response of a multi-storey reinforced concrete frame structure through a series of numerical simulations using SAP2000. Two modeling approaches fixed-base and flexible-base using the Winkler spring model were developed to assess how SSI alters the dynamic characteristics of the structure under seismic loading. The objective was to evaluate how soil flexibility alters key structural response parameters under seismic loading. Furthermore, parametric studies revealed that both the value of ks and the thickness of the foundation significantly influence the building's behavior under seismic loading. A lower ks value or thinner foundation results in greater flexibility, while higher stiffness and thicker footing help reduce deformations and increase structural stability.

General Conclusion

General Conclusion

This thesis present thesis explored the effects of Soil-Structure Interaction (SSI) on the seismic response of reinforced concrete frame buildings through comprehensive analytical and numerical studies. The research emphasized the importance of incorporating SSI effects in structural analysis particularly for buildings subjected to dynamic loading .

The study began by establishing a solid theoretical foundation of SSI, highlighting essential informations about it and discussing widely used analytical and numerical modeling approaches. Particular attention was given to the Winkler model and the subgrade reaction modulus (ks), which offer a practical yet effective means of representing soil flexibility in numerical simulations.

A critical review of international codes and standards revealed a growing global recognition of SSI's role in seismic design. However, variations in how different codes address SSI underscore the need for harmonized and context-specific guidelines that reflect local soil conditions and structural types.

The literature review chapters further illustrated the extensive research conducted on SSI effects in both linear and nonlinear contexts. Previous experimental, analytical, and numerical studies collectively demonstrate that the behavior of the supporting soil can significantly alter a structure's dynamic characteristics, particularly for tall, heavy, or foundation-sensitive buildings on soft soils.

To validate and quantify these effects, two models a fixed-base and a flexible-base were developed in SAP2000 to simulate the seismic response of a multi-story reinforced concrete frame structure. Linear dynamic analysis methods, including modal analysis, response spectrum analysis, and time history analysis, were applied to evaluate the differences between the two models. The results showed that the inclusion of soil flexibility through the Winkler spring model generally led to increased lateral displacements, elongated natural periods, and altered force distribution. Variations in the subgrade reaction modulus (ks) were found to significantly impact the structural response, and foundation thickness also played a notable role in mitigating or amplifying SSI effects.

In conclusion, the study demonstrates that Soil-Structure Interaction is a critical parameter in seismic analysis and design. It should not be neglected especially in structures resting on soft or medium stiff soils where its influence becomes more pronounced. By integrating SSI into the design process, engineers can achieve more accurate predictions of structural behavior under seismic loading, leading to safer and more efficient designs.

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