Effect of Inertial Soil Structure Interaction on the Seismic Performance of Typical Low to Mid-Rise Buildings of Pakistan

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I certify that this research work titled "*Effect of Inertial Soil Structure Interaction on The Seismic Performance of Typical Low to Mid-Rise Buildings of Pakistan*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Copyright Statement

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Abstract

Low to mid-rise reinforced concrete (RC) frame buildings are commonly constructed in the urban areas of many developing countries including Pakistan. In conventional modeling practice for the analysis and design of these buildings, the code-prescribed equivalent static force procedure is used while assuming the fixed-base support conditions of a linear structural model. Several studies, however, have shown that consideration of foundation flexibility and the soil-structure interaction (SSI) can significantly influence the predicted seismic performance of buildings. This study is focused on the seismic analysis of typical low- to mid-rise buildings in Pakistan while considering the effects of SSI and foundation flexibility. Using 3 existing case study buildings and considering all the soil types prescribed by BCP 2007, the SSI effects are modeled following the local practices. The seismic performance is predicted in terms of Time Period, Maximum Lateral Deflection, Story Drift, overturning Moment and Base Shear. It is shown that depending upon the soil stiffness and structural characteristics of buildings, the consideration of SSI effects and foundation flexibility can significantly affect the prediction of seismic demands. The result also emphasizes the need to develop simple guidelines for considering SSI effects in the modeling, analysis, and design of typical low- to mid-rise RC buildings in Pakistan.

Keywords – Soil-Structure Interaction, Low to mid-rise buildings, RCC Buildings, ETABS, Seismic Analysis

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List of Abbreviations

FEMA	Federal Emergency Management Agency
NIST	National Institute of Standards and Technology
BCP	Building Code of Pakistan
UBC	Universal Building Code
ASCE	American Society of Civil Engineers
SSI	Soil Structure Interaction
ELF	Equivalent Lateral Force
FE	Finite Element
RC	Reinforced Concrete
IMRF	Intermediate Moment Resisting Frame
SSSI	Structure Soil Structure Interaction
MRF	Moment Resisting Frame
RSA	Response Spectrum Analysis
LTHA	Linear Time History Analysis
NLTHA	Non-Linear Time History Analysis

List of Notations/Symbols

L	Length of Raft Footing
B	Width of Raft Footing
Υ_Z	Equivalent Radius
V_{s30}	Shear Wave Velocity
ρ	Density of Soil
G	Shear Modulus of Soil
μ	Poisson's Ratio
K	Modulus of Subgrade Reaction
S_A	Soil Profile (Hard Rock)
S_B	Soil Profile (Rock)
S_C	Soil Profile (Very Dense Soil/Soft Rock)
S_D	Soil Profile (Stiff Soil Profile Type)
S_E	Soil Profile (Soft Soil Profile Type)

Chapter – 01

Introduction

1.1 Background

Pakistan is the 5th most populated country in the world. According to World Bank's Report, the Human Density of Pakistan was 275 persons per square kilometres in 2018. It became 287 in 2020. With new policies from the Government of Pakistan, the vertical growth of buildings is gaining popularity. Most of the tall buildings constructed in Pakistan fall under the category of low to mid-rise buildings. Designing buildings that are safe for humans is a challenge for structural engineers. Earthquakes are common in some regions of the country. Pakistan has some active fault zones with a potential for high seismic activity.

Pakistan is geographically overlapping with Eurasian and Eurasian tectonic plates, where the Sindh and Punjab province lie in the north-west corner of the Indian Plateau while the Eurasian plateau lies with Balochistan and most of the Khyber Pakhtunkhwa. Gilgit-Baltistan and Azad Kashmir are located on the edge of the Indian plate and prone to severe earthquakes whenever two tectonic plates collide. Pakistan is thus faced every year by many moderate to severe earthquakes, especially in the North and West regions. Examples include the 7.6-magnitude Quetta earthquake in 1935, the 8.0-magnitude Makran earthquake in 1945, the Pattan earthquake of 6.0 magnitude in 1974 and the latest 7.6-magnitude Kashmir earthquake that occurred on the 8th of October 2005. A strong aftershock of 6.4 magnitudes was observed after the big earthquake. According to the EERI special report prepared in 2006 about 87,000 people were dead, 138,000 people were seriously wounded and about millions were displaced. In addition, nearly 70 per cent of services such as water, power, transportation, public health and communication have been demolished. According to a 2005 research carried out by Durrani, Pakistan had to face an economic loss of more than $5 billion due to this earthquake. Likewise, several earthquakes were recorded afterwards; one of the severe earthquakes was the recent Kashmir earthquake 2019, the earthquake struck Pakistan on the 24th of September. It's a shallow earthquake of magnitude 5.8 Mw, while its epicentre was in the vicinity of Mirpur (Pakistan). On the 29th of September, an IFRC disaster assessment study verified 40 deaths and over 646 harmed individuals. A significant to moderate damage to residences, commercial buildings, and other facilities in Mirpur district is triggered by the severe earthquake**.**

According to (FEMA, 2009) When ground motions interact with a structure, the response of a structure is affected by interactions between three linked systems: the structure, the foundation and the soil underlying and surrounding the foundation. So, we can define Soil-Structure Interaction (SSI) as "The process in which the response of the soil influences the motion of the structure and vice versa". Soil-Structure Interaction (SSI) is categorised into two types as Inertial Interaction and Kinematic Interaction. The scope of this research is limited to Inertial Interaction only. Past research has shown that soil media under the foundation of a building have a considerable effect on the seismic performance of the building. With an increase in soil deformability of soil under the structure, the time period of buildings increases and alters the seismic performance of buildings. This effect of soil media is more prominent in low to mid-rise buildings as compared to high-rise buildings.

After the deadliest earthquake of 2005, the Building Code of Pakistan (BCP) was developed to improve the building design practices in Pakistan. BCP 2007 divided the whole country into five seismic zones as 1, 2A, 2B, 3 and 4 as per UBC 97 guidelines. Zone 4 being the most dangerous with the highest earthquake activities. Building Code of Pakistan (BCP) has also presented 5 different types of soils as representative of local soil conditions of the country. $S_{A,}$ $S_{B,}$ $S_{C,}$ $S_{D,}$ and S_E are the soil types present in the building code. Soil flexibility increases as we move from S_A to $S_{E.}$ S_A represents hard rocks and S_E represents loose soil. Some past earthquakes have taken many lives because of the collapse of structures. It is important to design buildings that can withstand earthquake forces. Incorporation of soil stricture interaction effects on structural modeling and analysis can provide a better understanding of the seismic performance of a structure.

1.2 Problem Statement

Pakistan is situated in an earthquake-prone region and has been affected by a number of seismic events. Low to midrise buildings are mostly designed and constructed in Pakistan without considering the base flexibility. As SSI have a great influence on the seismic performance of such structures. So, a study is required to understand the effect of local soil conditions on the ground motion amplification and the seismic performance of typical building structures of Pakistan.

1.3 Methodology

To better understand the topic and to narrow down the idea, an extensive literature review was conducted. After the literature review, a work plan was prepared to accomplish the set objectives. As the subject work is related to the real structures, designed, and constructed in Pakistan, a data collection was performed. The working drawings from different design offices were collected and analyzed. After the analysis of collected data, three buildings with a 4, 8 and 11 number of stories were selected. All the buildings had raft footing. These buildings were modeled in ETABS using the Finite Element Modeling approach.

The initial model was modeled without a substructure. Fixed support under all the columns was assigned following the local design practice. The next model was prepared including the raft footing of the buildings as part of the superstructure in ETABS. Five more building models were prepared for each building containing soil springs underneath raft footing. Each one of these five models represented one of the soil types presented in the Building Code of Pakistan (BCP 2007).

A detailed calculation was performed to calculate the soil properties of each soil type and was incorporated by using an area spring containing soil properties under the raft footing. After finalizing all the models, Seismic Analysis was performed by using Modal Analysis and Equivalent Lateral Force (ELF) procedure. The Equivalent Lateral Force procedure is used in Pakistan for seismic analysis of buildings. The same analysis was performed and key parameters for local and global response were evaluated. After extracting the results for each building model, a comparative analysis was performed to understand the performance of each building model. A set of conclusions was drawn based on the results of the comparative analysis.

1.4 Objectives

The following objectives are achieved in this research work.

1. To review various soil modeling techniques and identify a practical scheme which can be easily integrated in local practice.
2. To study the effect of modeling the foundation geometry and soil stiffness on the modal properties of typical low- to mid-rise RC buildings
3. To study the effects of varying soil conditions on the seismic responses of three case study buildings (4 story, 8 Story and 11 Story).

1.5 Scope of this Research Work

Low to mid-rise buildings are mostly constructed in Pakistan. Design engineers ignore the effect of soil-structure interaction during the modeling of structures. The linear static procedure, ELF is used to analyze the seismic performance of buildings. ELF cannot incorporate the kinematic interaction effect of soil. The idea of this research is to understand the effect of soil modeling on the seismic performance of buildings and to identify a practical scheme which can be easily integrated into local practice.

For this purpose, the scope of this research is limited to the Inertial soil structure interaction only. The performance of typical low to mid-rise buildings on varying soil conditions of Pakistan is assessed by using ELF analysis. The low to mid-rise buildings are modeled using five different soil types as presented by BCP 2007. ELF analysis is performed to understand the seismic performance of buildings. Based on the comparative analysis a set of conclusions are drawn.

1.6 Organization of Thesis

This thesis consists of five chapters. The organization of these chapters is given below.

Chapter – 01: The first chapter introduces the soil structure interaction and its effects on seismic performance of buildings. A concise overview of the seismicity of Pakistan is also discussed. The latter half of this chapter describes the Problem Statement, Methodology, Objectives and Scope of this Research Work.

Chapter – 02: The second chapter consists of Literature Review. It describes the overview of past research work describing the advancements about Soil Structure Interaction. This chapter also includes a comparison of famous soil modeling techniques along with their merits and demerits followed by structure analysis techniques used in this research.

Chapter – 03: The third chapter contains the methodology adopted to achieve the research objectives. It contains the characteristics of all the building models used in this research work. A detail discussion on parameters of soil used in modeling its effect under raft footing are discussed. At the end of this chapter, all the parameters used in analysis of structures are discussed.

Chapter – 04: Results of Modal and ELF analysis are discussed in this second last chapter.

Chapter – 05: A set of Conclusions followed by Recommendations are part of this chapter.

Chapter – 02

Literature Review

A summary of past research carried out on soil-structure interaction is presented here. The extensive study of this research provides us with an insight into historic development in the field of soil-structure interaction. A summary of past research carried out by various researchers is provided here followed by a concise discussion about the different soil modeling techniques presented in the literature.

2.1 Past Research Work on Soil Structure Interaction

In 2008, Garcia et al. [01] performed a study on the effect of soil structure interaction of a seven-story RC frame structure with shear walls. The dynamic analysis of the building on a fixed base and on a flexible base, considering soil-structure interaction, was carried out. The results showed that by considering soil-structure interaction, the damping and time period of the structure was increased. Soil structure interaction decreased the horizontal spectral acceleration values decreasing the seismic demands.

In 2017, Tomeo et al. [02] investigated the effect of Soil-Structure interaction on the seismic performances of 2D reinforced concrete moment resisting frames, which were investigated by means of non-linear dynamic analysis. In this study design level of structures, SSI effect modeling techniques, and soil properties were varied. Structures of 8 and 4 floor designed for gravity load according to Italian code (NTC-9) and Soil classes suggested by Eurocode 8 were taken as reference. This study showed that considering SSI effects, the FEM model can lead to reductions up to 50% in terms of maximum inter-story drift ratio and up to 20% in terms of maximum base share with respect to the Fixed Based Model.

In 2008, Mylonakis et al. [03] Studied the seismic demands variation due to SSI effects. In this study they found that the SSI does not always reduce the seismic demands and ignoring this effect is not always a conservative approach. They found that an increase in fundamental natural time-period due to SSI for a moderately flexible structure, may have a detrimental effect on the imposed seismic demands in certain seismic and soil environments. This conclude that ignoring SSI effect is not always conservative.

In 2016, Behnamfar et al. [04] Performed seismic vulnerability analysis considering SSI using nonlinear modeling of both structure and its underlying soil. RC buildings with 3, 5, 6, 8, 9 stories hight, resting on soft and very soft soil once with moment resisting frame and once with shear walls were considered. Non-linear dynamic analysis is conducted once for fixed based and once for flexible-based buildings. After the analysis plastic hinge rotation, story drift and maximum base shear were calculated. The analysis results showed that SSI effect decreases the plastic hinge rotation in the building, but it was also observed that plastic hinge rotation was increased considerably in the lower third of the building. This effect was more prominent in case of building model with shear wall. This effect occurred due to an increase in drift at lower stories because of the compatibility of foundation movement with lateral displacement. These observations conclude that the performance level of structure members of both type of structural systems becomes worse because of SSI.

In 2011, Menglin et al. [05] studied the concept of structure-soil-structure interaction (SSI) in their review paper on structure soil-structure interaction. The review paper presented the past research on the effect of adjacent structures and their importance on dynamic performance. The review paper also discussed the different calculation methods and available computer programs that are used in the analysis. This paper mentioned the limitations of the current study and identified some important problems for further research in this field.

In 2017, Papadopoulos et al. [06] Studied the modal characteristics of frame structures considering the soil-structure interaction. Modal characteristics were computed using PE-PML model for all the frame structures incorporating the soil-structure interaction effects. They found that SSI affects all modes of structure especially in vertical modes where SSI plays an important role even in the case of stiff soils. They concluded that Dynamic SSI leads to lower eigen frequencies for coupled soil-structure systems, increase in model damping ratios and complex-valued model shapes.

In 2018, Vicencio et al. [07] studied the structure-soil-structure (SSSI) interaction effects considering different parameters for two buildings under the influence of seismic excitations. Interaction between buildings with a large difference in heights, Inter-building spacing, soil type and underground motion records with Far-Field, Near-Field without Pulse and Near-Field Pulse-Like characteristics were studied. Based on the linear soil-structure-soil parametric study it is concluded that there are both the beneficial and detrimental configurations of buildings for dynamic performance. It was found that the effect of interaction is unfavorable for building 1 when building 2 is taller i.e. the power of the earthquake passed from two times or taller structure to shorter structure. As the displacement response increases up to 400%. When there is a 10% difference in height, the seismic risk is reduced of -45% for displacement response.

In 2013, Tabatabaiefar et al. [08] Studied the effect of SSI for a 10 story building consisting of frame structure having shallow foundation. The soil classes Ce, De, and Ee as per Australian standards were selected for this research work. An elastic perfectly plastic behavior of structure was considered. The building was analyzed by applying non-linear time history analysis by considering both, the elastic and inelastic behavior of structure. Model was analyzed without considering SSI (fixed base) and with consideration of SSI. The performance-based analysis results indicated that the performance level of the model resting on soil class Ce does not change and remain at life safety level while for soil class De and Ee it was increased to near collapse for both elastic and inelastic cases. Based on these observations, it was concluded that the consideration SSI effect is essential for elastic and inelastic seismic design of a frame structure resting on soil class D_E and $E_{E.}$

In 2015, Bhojegowda et al. [09] This study was carried out to understand the influence of different soil types (soft, medium and hard) on the time period of buildings with isolated, mat and pile foundations. 5, 10 and 15 stories frame with regular and Irregular plan on different soil conditions were studied. Soil was considered as non-linear, and its effect was incorporated using non-linear springs. Based on the seismic analysis of structure, no considerable variation in time period was observed for frame structure with pile foundation when compared with the fixed base structure.

In 2010, Reza et al. [10] In this research the effect of SSI are calculated for four type of structure variations resting on three different type of soils. The RC-MRFs are studied using the direct method for all type of structures under consideration subject to different time histories. The outcome of this study was in the form of a criteria for consideration of SSI for different types of soil and base shear. It was concluded that RC-MRF structures resting on soil type II are not influenced by SSI but this effect is considerable for 7 story and 3 story buildings resting on soil type III and IV respectively. A graph and a couple of formulas to get maximum elastic deflection from fixed based structures for SSI was also proposed.

In 2004, Dutta et al. [11] This study considers low-rise building frames resting on shallow, isolated and grid foundations. The study shows that the effect of soil structure interaction decreases the seismic demands for mid to high-rise buildings. SSI effect can be influenced by the frequency content of the ground motions. It was observed that the time period less than 1 sec can increase the seismic demands due to the influence of SSI. This increase in seismic demands in terms of base shear can decrease with increase in soil and structural stiffness. Structure stiffness was increased by using tie beams. There was also a change in base shear by the change in number of baye in the frame structure.

In 2010, Roy et al. [12] Studied the effect of soil flexibility by considering both elastic-plastic and degrading hysteresis behavior for lateral load resisting structure elements and sub-soil is idealized as linear and elastic-plastic in parallel. This study shows that the effect of strength and stiffness degradation can a cause considerable increase in inelastic demand as compared to the elasto-plastic counterparts. This indicates the need to purpose a lesser response reduction factor, R for former relative to latter. Also, such system resulting on shallow footings may yield from their foundation level at moderate seismic demands because of high ductility demands.

In 2016, YangLu et al. [13] Studied the Seismic performance of multistory shear buildings considering SSI. Different lateral seismic load patterns and ductility demands were considered for buildings with 1, 5, 10, 15 and 20 story constructed on shallow foundations with different soil classes were considered. The results of this study showed that for mid-rise buildings with small slenderness ratio, up to 60% reduction in strength and ductility demands are observed because of SSI effects. Also, the code based lateral load patterns are more suitable for the design of long period flexible base structures. For short period flexible base structures, a new trapezoidal design pattern is suggested. To consider SSI and structure yielding effects for single degree of freedom and multi-degree of freedom two modification factors RF and RM are presented respectfully.

In 2018, Tanik et al. [14] conducted a study to evaluate the effect of soil-structure interaction on seismic behavior of reinforced concrete (RC) buildings. Three buildings with 8 story, 12 story and 16 story were considered for this research work. Non-linear behavior of structural members was also considered. Two types of soil were modeled under the structures in SAP200 software. Substructure approach as suggested by NIST was considered for this work. Based on the analysis, it was concluded that as the soil stiffness increases the seismic demands also increase under the influence of soil structure interaction.

In 2018, Forcellini [15] Studied the influence of soil-structure interaction for a 4-story RC building by considering base isolation. An advanced plasticity model and non-linear hysteretic material was used to model the soil underneath the structures. Analysis was performed using OPENSEES software. Based on the results of analysis it was concluded that SSI effects are directly related to soil flexibility. An increase in SSI effects was observed as soil flexibility was increased.

In 2015, Thusoo et al. [16] Studied the influence of soil-structure interaction on mid-rise buildings by considering three soil types. Soft, Stiff and Very Stiff soil types were assumed for mid-rise buildings. Finite Element models were prepared in ANSYS v14.5 and NLTHA was performed. The results showed that Time Period and deflection of buildings increased by increasing soil flexibility. There was up to 40% increase in maximum deflection values for flexible soil conditions. There was a decrease in Base Shear values for increased flexibility conditions. Up to 30% decrease in Base Shear was observed for flexible based conditions.

In 2002, Dutta et al. [17] Studied the different modeling approaches available for the consideration of soil-structure interaction. In this research different simplified approaches were modeled, and results of the seismic analysis were compared with a fixed based and complex and more accurate model. Based on the comparison results, the Winkler approach of incorporation of soil-structure interaction using soil springs was recommended. This approach is simple and easy to practice for practising engineers. It incorporates soil behaviour using spring elements.

In 2019, Star at al. [18] performed a parametric study on the system identification of data recorded during forced vibration tests. They found that these data records provide a useful tool for evaluating modal frequencies and damping ratios. These modal frequencies and damping ratios can be used to understand the influence of SSI on the structures under consideration. It was concluded that different variations of soil modeling presented by NIST provide a reasonable accuracy of seismic response in terms of time period lengthening and foundation damping for both, linear and non-linear conditions. It was recommended that the model prediction techniques can provide better results by the consideration of gapping effects at the interface of soil and foundation.

In 2019, Arias et al. [19] proposed an easily programable and easy to understand method to understand the effect of SSI for multiple degree of freedom systems. This method provides a considerable accuracy. Soil with shear wave velocity from 100 m/s to 750 m/s was considered. A two-layered soil foundation that includes a semi-space and a 30-m layer on which the structure is founded was considered. Different Soils according to their stiffness, from soil class E to soil class B as per NEHRP were modeled using Spring and Dashboards. This research presented a simple expression for the estimation of SSI effect on the response of each mode.

In 2019, Asli et al. [20] studied the performance of one direct and two substructure approaches. Three types of soil including soil type B, soil type C and soil type D as per classification of EC8 were considered. In this research Direct, BNWF and Cone Model were prepared in OpenSeas software. A comparison of inter story drift ratio results was drawn and it showed that BNWF model was closer to FE model. It was concluded that the BNWF model with non-linear springs presents more accurate performance in comparison with cone model with linear springs.

In 2019, Singh et al. [21] analyzed the critical behaviour of RCC frame structures with and without a shear wall on hard, medium and soft soil strata subjected to seismic loading. 5 different models of a 9 story RCC Building with different locations of shear wall were prepared in ETABS. Hard, Medium and Soft soil was modeled under the footing of the building to incorporate the effect of SSI. Pushover Analysis was performed and results for lateral displacement, base shear and story displacement were compared. It was observed that displacements in hard soil are less than medium and soft soil for all the schemes of shear wall. It was concluded that the type of soil influences the seismic performance of a building.

In 2019, Sadek et al. [22] performed a study on the influence of soil-structure interaction on the seismic performance of shear walled structures by considering soil non-linearity. A 10 story 3D Numerical Investigation was performed using FLAC3D software. elastic and elastoplastic behavior of the soil was considered. It was concluded that soil non-linearity should be considered for the seismic analysis of structures constructed in moderate to severe seismic environments. It is because this research study indicates that SSI effects change the seismic response of structures ate foundation level and also reduce the lateral seismic demands considerably. A considerable change in superstructure movement was also recorded by the consideration of soil structure interaction effects.

In 2019, Anwar et al. [23] studied two models with SSI modelled using an indirect approach, and two models with SSI modelled using a direct approach. 5 and 14 Story buildings with soft soil, stiff soil and rock as per NEHRP soil profile type classification were considered. Direct and Indirect modelling approaches presented by NIST were considered and both buildings were analyzed using DEEPSOIL and SAP2000 software. Based on comparative analysis of story shear, story moment, roof acceleration story displacement and story drift results, it was concluded that the dynamic behavior of a structure can be more accurately studied by considering SSI effects and 3D modelling of surrounding soil instead of idealizing the base of the structure with rigidly fixed support condition.

In 2018, Bolisetti et al. [24] analyzed a single-story, steel moment-resisting frame structure laid on footings along with a two-story shear wall building built on a basement using dense, dry nevada sand with a relative density of 80%. Both structures were modeled using Direct modeling approach (DM approach) prescribed by NIST using SASSI and LS-DYNA software. SASSI is used for linear SSI analysis and for low-intensity earthquakes. Nonlinear analysis was performed using the time-domain finite-element code, LS-DYNA. Results showed that the equivalent-linear and nonlinear responses were significantly different. It was found that for intensive shaking, the nonlinear effects, including gapping, sliding and uplift, are highest in the immediate vicinity of the boundary of soil-structure. Such effects cannot be considered if linear techniques are used.

In 2018, Cayci et al. [25] found the effect of soil-structure interaction on seismic behavior of RC buildings by considering the nonlinear properties of the structural members. Substructure approach of NIST was used to model a two-dimensional 16-story, 12-story and 8-story reinforced concrete (RC) frame buildings. Two types of soil with different stiffness were taken into account during nonlinear time history analyses. It was found that the effectiveness of SSI is related to the height/width ratio of superstructures, roofs and displacement profiles. The dynamic amplification due to the frequency content of surface motion is more effective especially for structures with lower H/W ratios. It was found that seismic demands tend to decrease for SSI models as stiffness of the soil decreases.

In 2018, Karthika et al. [26] analyzed a ten (G+10) and twenty story (G+20) building. Area springs were included in the local vertical axis to make the foundation flexible. It was done to create the effect of soil structure interaction. Area springs are usually used in case of raft or mat foundations.

The comparative study of the fundamental time period, lateral displacement, story drift, lateral deflection and seismic base shear showed that the SSI have an influence on the dynamic behavior of the building, and it needs to be incorporated in the design of earthquake-resistant buildings for better seismic performance.

In 2019, Far et al. [27] identified and proposed a precise and reliable computation method and modelling technique to study the dynamic influence of soil structure interaction for structures resting of soft soils. Comparison of Winkler spring model, Lumped parameter on elastic half-space, and Numerical methods (Substructure and Direct) was drawn. It was concluded that the Fully Non-linear Computational Method and Direct approach is most accurate for soft soils.

In 2016, Bhojegowda et al. [28] studied the buildings with different foundation conditions. For this purpose buildings with isolated, mat and pile foundations were selected for different soil conditions. 5 story, 10 story and 15 story's frames with regular and Irregular plans were considered. different soil conditions as soft, medium and hard were considered and the non-linear behaviour of the soil was considered using non-linear springs. It was concluded that there was a little variation in time period for the frame model with a pile foundation of a flexible base as compared with the fixed base model.

In 2013, Sáez et al. [29] studied two (2 and 7 story) RC moment-resisting frame buildings founded on a homogeneous sandy soil. There were two hydraulic conditions considered, dry and fully saturated soil conditions. The effect of SSI was considered under the influence of time histories, both hydraulic conditions were studied. 2D FE model was composed of superstructure, substructure and soil underneath substructure over a bedrock. GEFDyn software is used for the modeling and analysis of models. Based on comparative analysis of results, it was concluded that, If the soil is fully saturated, inelastic DSSI will be invariantly favorable or negligible. If the soil is in dry condition, results will present more dispersion.

In 2012, Saad et al. [30] studied the seismic behavior of RC buildings with multiple underground stories. Five, ten, fifteen and twenty-story building models were prepared. The local seismic conditions of Beirut were considered for the analysis. The SSI effects were modeled in SAP2000 by multi-linear kinematic plastic link property. The soil class C and D were considered as per ASCE 7-05. Soil class C refers to very dense soil or soft rock and soil class D refers to stiff soil. The seismic response of buildings in terms of inter-story shears, base shear, and overturning moments were studied. Based on the comparative analysis of results, it was concluded SSI influence the low-rise buildings by increasing story shear and moment demands significantly. The effect of SSI is more prominent in case of buildings constructed in softer soils.

In 2010, Tabatabaiefar et al. [31] studied four RC models, consisting of 3, 5, 7 and 10 stories. Soil class II, soil class III and soil class IV as per Iranian Standards were considered for this research. The direct Method of modeling SSI is considered as per NIST guidelines using SAP2000. It was observed that soil structure effects were prominent for soils with shear wave velocity less than 600 m/s. It was concluded that considering SSI in seismic design, for buildings with more than three and seven stories on soil with Vso175 m/s and 175oVso375 m/s, respectively, is essential. By considering SSI effects for this category, safer and economical structures can be designed and built.

2.2 Soil Modeling Techniques

Over the years, researchers have attempted to improve the soil modeling techniques to better understand the response of Soil-Structure Interaction. There are a number of methods or techniques that are being adopted for this purpose. These techniques vary in the level of complexity and accuracy. Some of the famous techniques among researchers are discussed here. The following figure represents the Winkler Approach of Soil Springs. Soil is idealized as a spring element containing the stiffness of the soil medium. These soil springs are placed under the foundation by idealizing the soil medium under the foundation as homogeneous. These springs are restrained at the base by a rigid layer as shown in fig below.

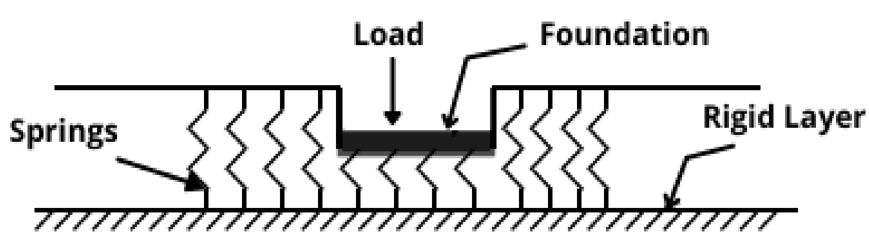

Figure 2-1: Winkler foundation [32]

In the Elasto-plastic approach, the non-linear behavior of soil is modeled using an elastic spring along with a plastic element. Elastic spring is also called Hookean Spring that monitors the deformation within the elastic range. When deformation enters in plastic range, a plastic element monitors the soil deformation effect. The combined effect of these elasto-plastic elements is presented in St. Venant Unit as shown in the fig below.

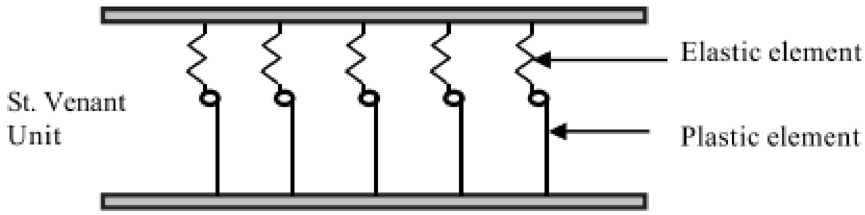

Figure 2-2: Elasto-plastic model[33]

The real behavior of soil is always time-dependent to some extent depending on the permeability of the soil. This effect is modeled using a Viscoelastic Model. There are several schemes of such models presented in research, but the Kelvin model is considered superior of all. It contains a parallel arrangement of spring and dashpot as shown in the figure below.

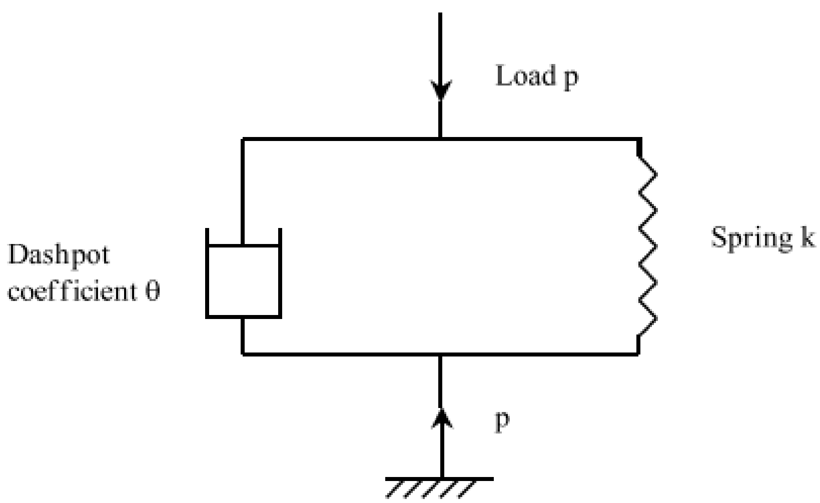

Figure 2-3: Viscoelastic model[34]

Other than these models, there is the Finite-Element Model, Continuum Model and some Modified versions of the Winkler Approach. Based on the comparison of the level of complexity and accuracy of results Winkler approach is recommended to use in design offices instead of a fixed base condition. The present practice in design offices generally adopts a fixed base consideration for structural analysis and design. In this context, the Winkler model, though oversimplified, seems adequate and suitable for its reasonable performance and simplicity.

NIST published a detailed report in 2012 on SSI and presented the following 5 approaches to incorporate SSI effects. These Modeling approaches vary depending on the configuration of the building. 2B is suggested by NIST for buildings with raft footings. It consists of a number of equally spaced springs representing the soil underneath the foundation. These springs are assigned modiolus of subgrade reaction as representative of stiffness of soil. This approach is also called the Winkler approach. Horizontal springs are recommended to incorporate the embedment effect. These are normally used for Buildings with Piles footing. The following fig shows these approaches.

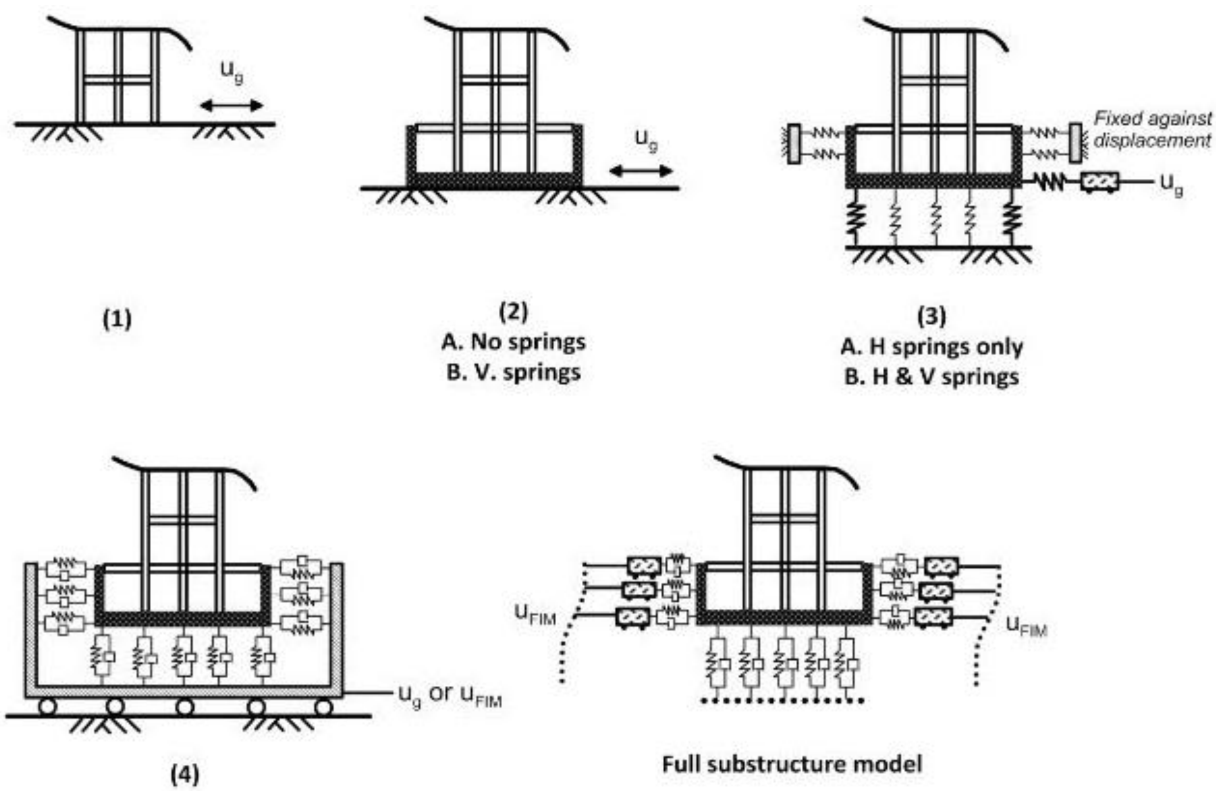

Figure 2-4: Modeling approaches suggested by NIST in 2012[35]

2.3 Methods of Analysis

The following two methods are adopted for the seismic analysis of building models under consideration.

2.3.1 Modal Analysis

Modal Analysis is a technique used to determine a structure's vibration characteristics like Natural Frequency, Mode shapes and Modal participation factors. It is the most fundamental of all the dynamic analysis types. The benefit of Modal Analysis is that it gives en35gineers an idea of how the design will respond to different types of dynamic loads. It is because the vibration characteristics determine how the structure will respond to any type of dynamic load. A schematic illustration of Modal Analysis showing the first three modes is shown in Fig below.

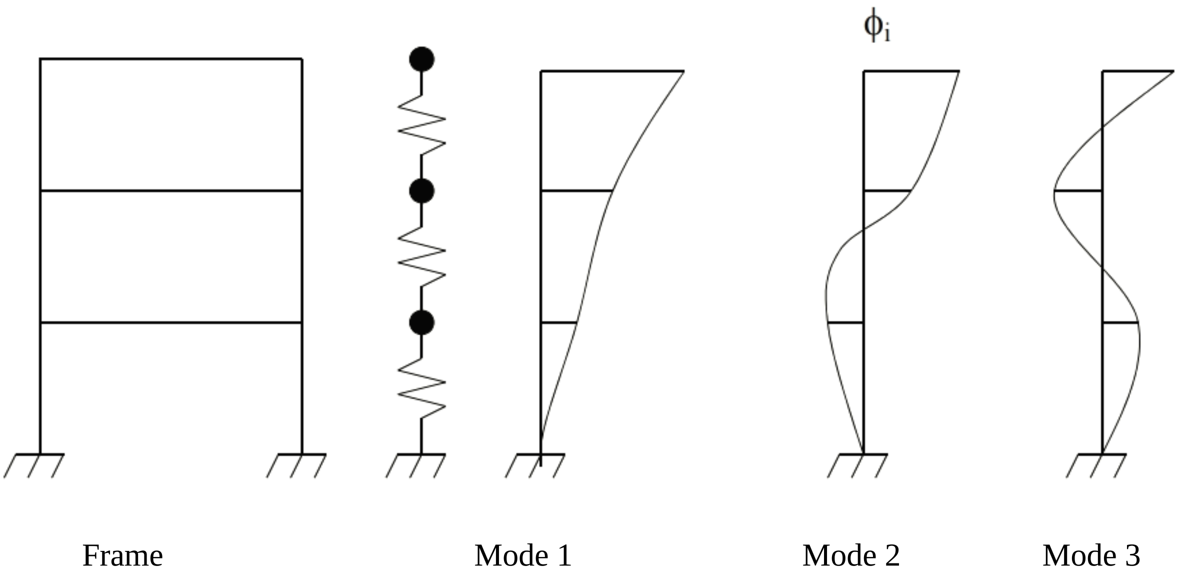

Figure 2-5: Schematic illustration of Modal Analysis

There are many other analysis procedures such as Equivalent Lateral Force (ELF), Response Spectrum Analysis (RSA), Linear Time History Analysis (LTHA), Non-linear Time History Analysis (NLTHA) and Pushover Analysis but since this study is focused on local practices of Pakistan. We will discuss ELF only. ELF is widely used in the Pakistani local market for seismic analysis of buildings. It can only capture the elastic behavior of structures under linear loading conditions.

2.3.2 Equivalent Lateral Force (ELF) Method

The equivalent lateral force method is a simplified technique to substitute the effect of dynamic loading of an expected earthquake by a static force distributed laterally on a structure for design purposes. ELF cannot account for Kinematic Interaction effects and it is widely practised in our country.

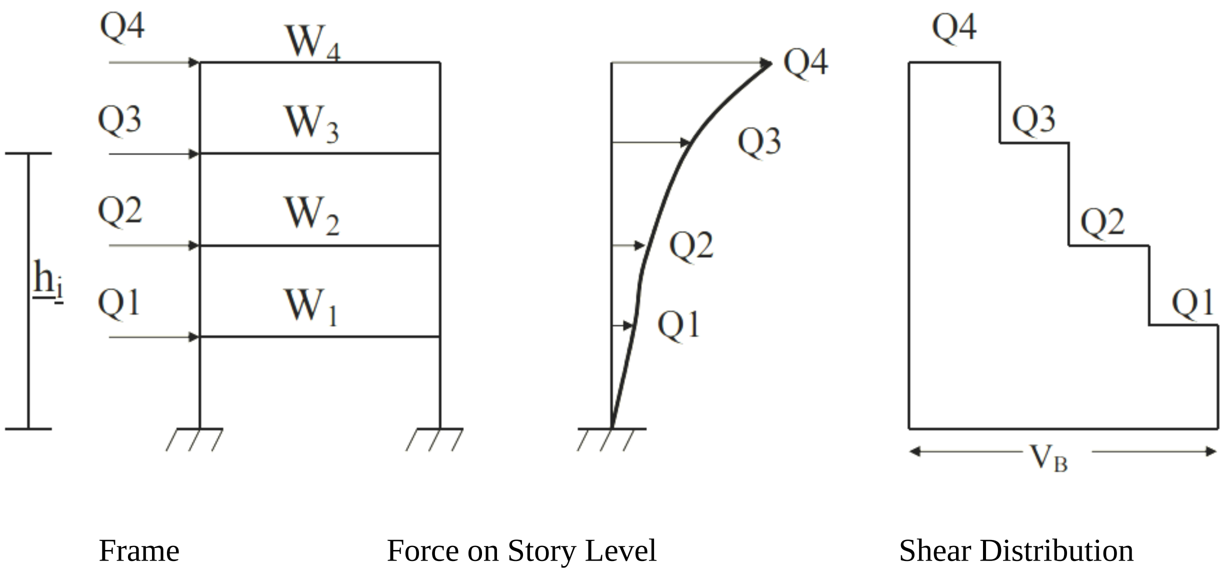

Figure 2-6: Schematic illustration of ELF Analysis

2.4 Summary

These studies indicate that SSI affects the seismic performance of buildings. This effect is more prominent in low rise buildings. The effect of SSI varies with changes in soil properties. This variation of seismic performance due to SSI can help in achieving safer and economical structures. Since Pakistan have a variety of soil types, as indicated by BCP 2007 and low to mid-rise buildings are mostly constructed in Pakistan, the effect of SSI can be prominent in such case. As there was limited research conducted previously to address this problem. Research work was required in this regard.

Chapter – 03

Methodology

A detailed study of available literature on SSI is carried out to understand the level of research already carried out. The focus of the literature review was the past research explaining the effect of Soil-Structure Interaction on low to midrise structures. It is because the focus of this research is typically low to midrise structures of Pakistan. This thorough review of available literature helped in finalizing: what soil modeling techniques are to be used, what types of analysis are to perform, and which response parameters are to monitor.

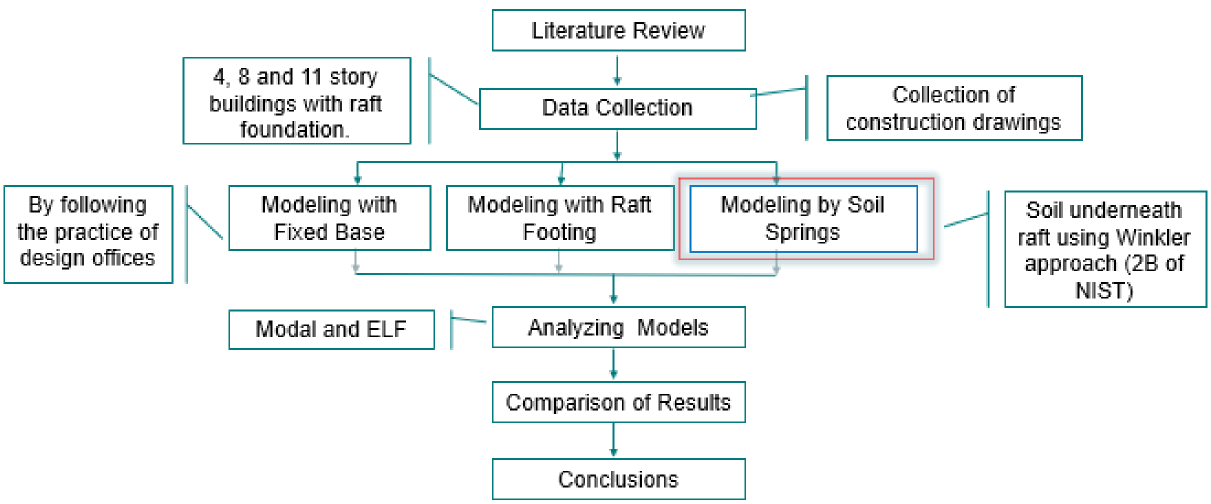

Figure 3-1: Workflow diagram

There are five different types of soils, a separate model for each soil type is prepared for all three building types. The schematic diagram is shown below.

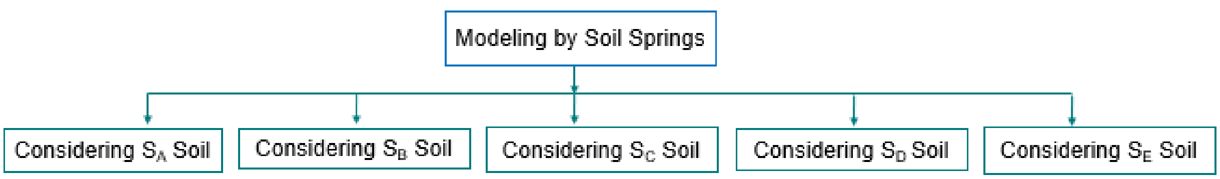

Figure 3-2: Soil modeling scheme

There are some specific terminologies devised to name the models for ease of identification. The following illustration shows the building model naming technique.

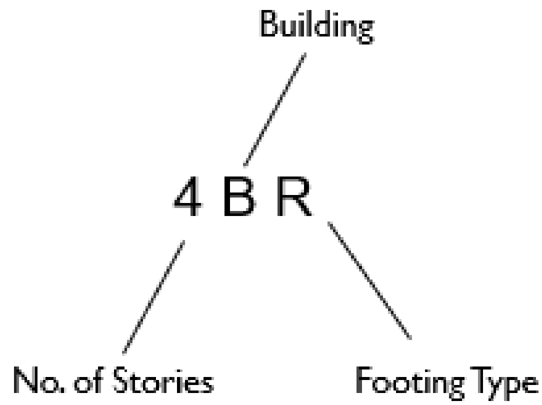

Figure 3-3: Model naming technique

3.1 Description of Case Study Buildings

There are four RC frame buildings selected for this research as representative of typical buildings of Pakistan. As the focus of this research is to analyze Low to Mid-rise RC frame building structures so, three buildings are selected for this research. Four-story, eight-story and eleven-story buildings representing the low to midrise structures of Pakistan. All these buildings were constructed on raft footing and were situated in 2B seismic zone as per UBC 97.

Since the idea was to understand the seismic performance of typical building of Pakistan. For this purpose, real building structures are considered for this project. Three buildings representing low to mid-rise buildings of Pakistan are collected from different locations of the country. One building with 4 stories is a residential plus commercial building by the name of Maryam Plaza is constructed in Rawalpindi and the other two of 8 and 11 stories by the name as Health Net Hospital and Pakistan Engineering Council Branch Office respectively are constructed in Peshawar City.

All these buildings are constructed on raft footing. The geotechnical investigation reports of these buildings suggest that the soil underneath these buildings lie in the class S_D of Building Code of Pakistan. All three buildings are situated in same seismic region with same soil type. All three buildings are designed by following the guidelines of BCP 2007, UBC 97 and ASCE 7-10 as practiced locally. Some key features of these buildings are discussed here.

3.1.1 4 Story Building Characteristics

The Building Plan and 3D view along with some key features of 4 story building are shown below.

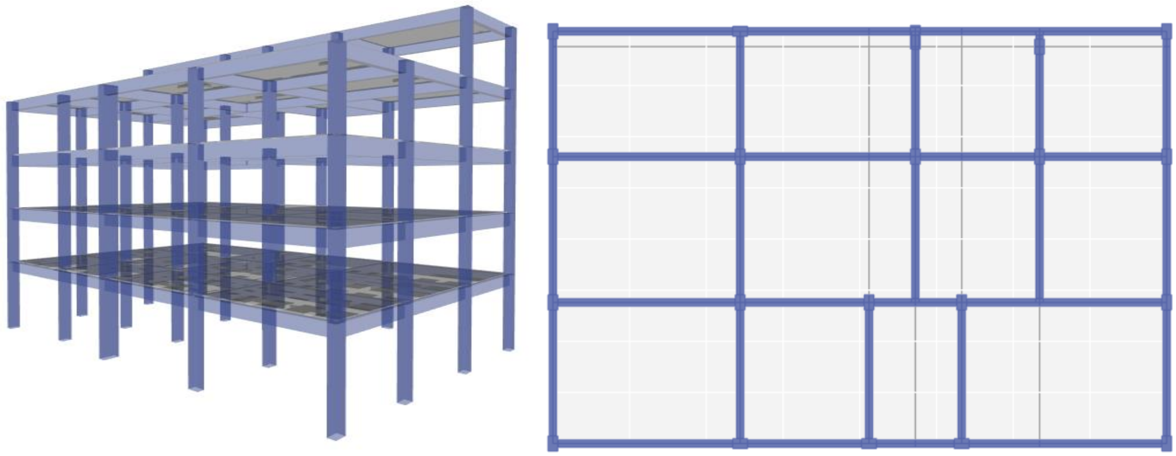

Figure 3-4: Typical Plan and 3D view of 4 story building

The following tables shows that elevation and number of story data for this 4-story building model are considered representative of typical low-rise buildings of the country.

Table 3-1: Basic structural and architectural features of 4 story building

Basic structural and architectural features of 4B	
Feature	**Particular**
No. of Stories	4
Height of each story	10.5 ft
Shape of Building	Rectangular
Type of Structural System	RC Frame
Height of Building	52.5 ft
Length of Building	61ft
Width of Building	40 ft
Height/ Length ratio	0.860655738
Height/ Width ratio	1.3125
Length/Width ratio	46.47619048
Structural Scheme	IMRF

3.1.2 8 Story Building Characteristics

The Building Plan and 3D view along with some key features of 8 story building are shown below.

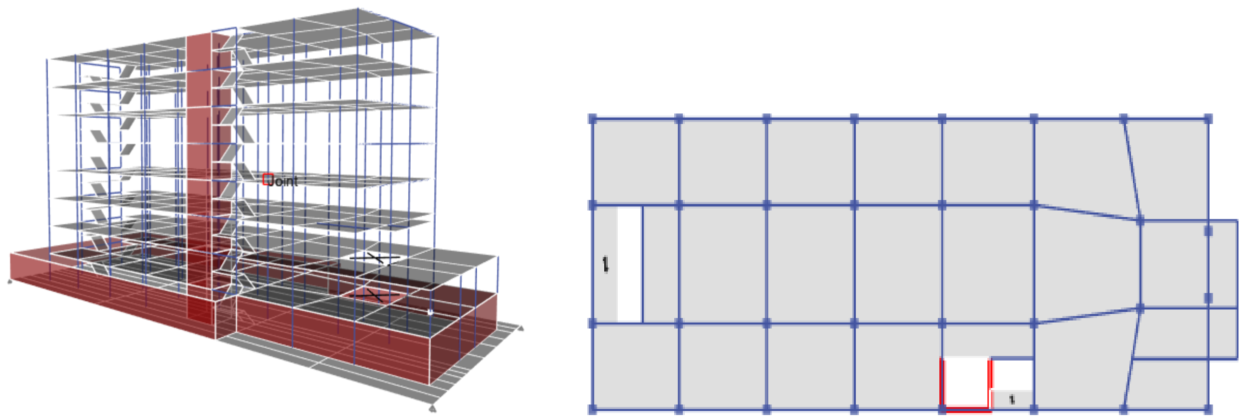

Figure 3-5: Typical Plan and 3D view of 8 story building

The following table contains the basic characteristics of 8 story building under consideration.

Table 3-2: Basic structural and architectural features of 8 story building

Basic structural and architectural features of 8B	
Feature	**Particular**
No. of Stories	8
Height of each story	11 ft
Shape of Building	rectangular
Type of Structural System	RC Frame with Shear Wall
Height of Building	88 ft
Length of Building	184.25 ft
Width of Building	66.5 ft
Height/ Length ratio	0.47761194
Height/ Width ratio	1.323308271
Length/Width ratio	139.234375
Structural Scheme	Dual system (IMRF with shear wall)

The basic characteristics of 11B are explained below.

3.1.3 11 Story Building Characteristics

The Building Plan and 3D view along with basic features of 11 story building are shown below.

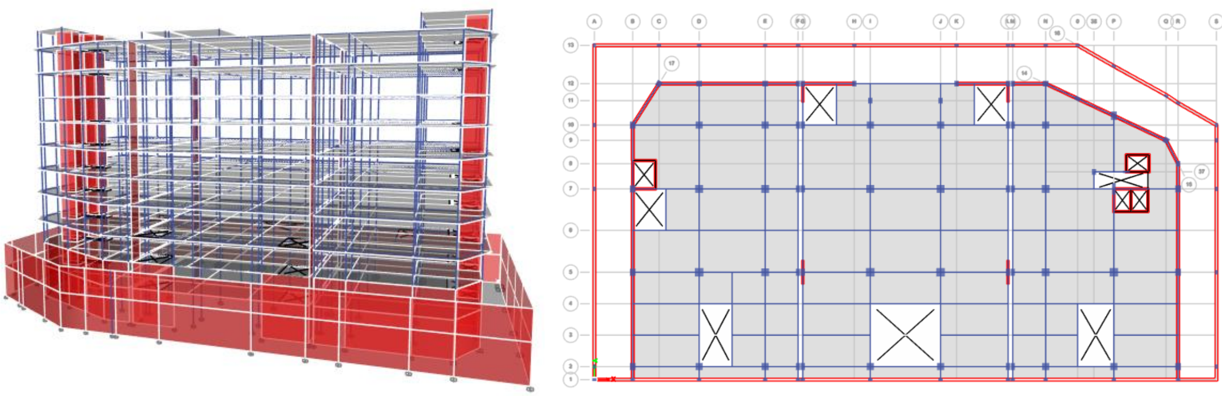

Figure 3-6: Typical Plan and 3D view of 11 story building

The following table contains the basic characteristics of 8 story building under consideration.

Table 3-3: Basic structural and architectural features of 11 story building

Basic structural and architectural features of 11B	
Feature	**Particular**
No. of Stories	11
Height of Each Story	10.5 ft
Shape of Building	Rectangular
Type of Structural System	RC Frame with Shear Wall
Height of Building	115.5 ft
Length of Building	219 ft
Width of Building	174 ft
Height/ Length Ratio	0.52739726
Height/ Width Ratio	0.663793103
Length/Width Ratio	329.9220779
Structural Scheme	Dual System (IMRF with Shear Wall)

3.2 Modeling of Buildings

Selected building structures are modeled in ETABS considering fixed base structures as per the current practices. Finite element models are prepared by following the working drawings of selected buildings. Fixed support condition was assigned at the base of columns and shear walls. All the buildings were modeled using Column, Beam, Slab and Shear walls as per their respective working drawings. The following figure shows one of the building models prepared by using fixed base condition.

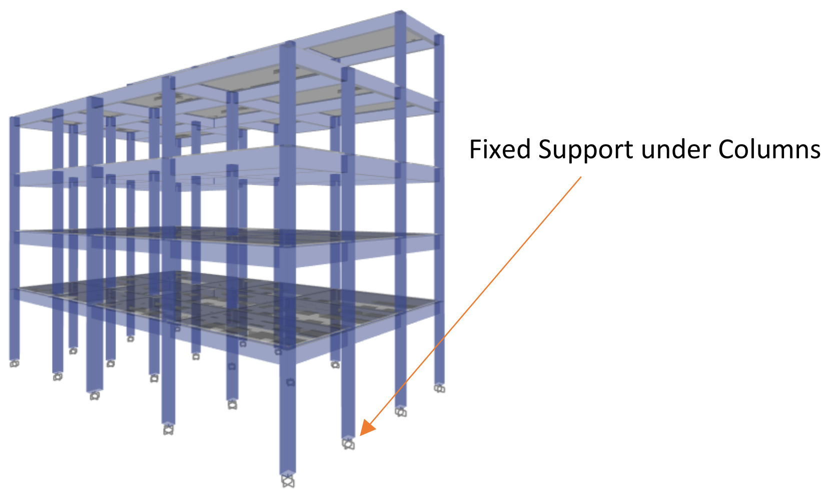

Figure 3-7: Building model with fixed base

All these buildings were designed and constructed using raft footing as foundation. All the buildings were modeled with raft footing by following the specifications of construction drawings. One of the building models prepared in ETABS using raft footing is shown below.

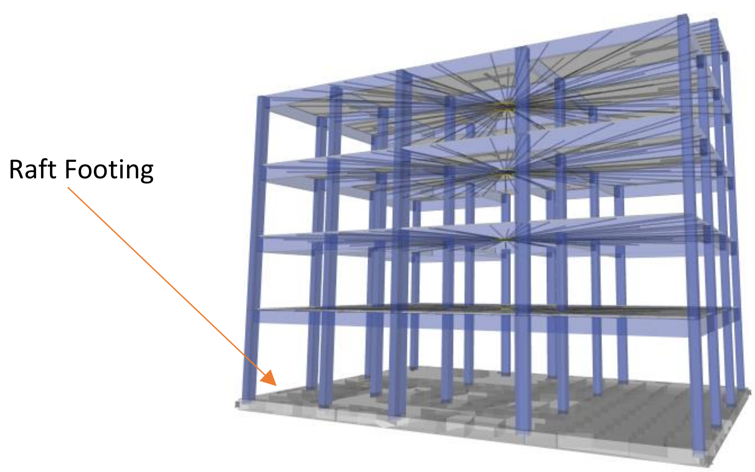

Figure 3-8: Building model with raft footing

After modeling the buildings with raft footing, the third category of modeling was done for incorporating the effect of soil underneath raft footing of each building. The detail example of soil modeling and its key parameters are presented in Annex A and Annex B. The detail discussion of soil modeling is discussed in next section.

3.3 Soil Modeling Characteristics

After completing the finite element model of all three building types with raft footing, the next step was to model the effect of soil under the foundation. There are different approaches used to incorporate the effect of soil under the footing. Based on the literature review, the Winkler approach is finalized to use for soil modeling. Soil is modeled using Area springs under the raft footing. Raft slab has meshed to 1 x 1 mesh size and each mesh is assigned an area spring containing modulus of subgrade reaction of soil. Soil properties are obtained from the geotechnical investigation report. Modulus of subgrade reaction for area springs was calculated using Richart and Lysmer Model. Area springs are assigned under the raft footings as suggested by Winkler Approach. Five soil types mentioned here are taken from the building code of Pakistan. Following is the table of soil types for BCP 2007.

Table 3-4: Soil profile type of BCP 2007

Soil Profile Type	Soil Profile Name/ Generic Description	Average Properties for Top 30 M (100 ft) of Soil Profile		
		Shear Wave Velocity, v_s m/sec (ft/sec)	Standard Penetration Tests, N [or N_{CH} for cohesionless soil layers] (blows/foot)	Undrained Shear Strength, s_u kPa (psf)
S_A	Hard Rock	>1,500 (>4,920)	-	-
S_B	Rock	750 to 1,500 (2,460 to 4,920)		
S_C	Very Dense Soil and Soft Rock	350 to 750 (1,150 to 2,460)	>50	>100 (>2,088)
S_D	Stiff Soil Profile	175 to 350 (575 to 1,150)	15 to 50	50 to 100 (1,044 to 2,088)
S_E[1]	Soft Soil Profile	<175 (<575)	<15	<50 (<1,044)
S_F	Soil requiring Site-specific Evaluation. See 4.4.2			

1 Soil Profile Type S_E also includes any soil profile with more than 3 m (10 ft) of soft clay defined as a soil with a plasticity index, PI > 20, $w_{mc} \geq 40$ percent and s_u < 25 kPa (522 psf). The Plasticity Index, *PI*, and the moisture content, w_{mc}, shall be determined in accordance with the latest ASTM procedures.

Richart and Lysmer presented a formula for the calculation of modulus of subgrade reaction. The modulus of subgrade reaction calculated using these formulas is used in springs as representative of stiffness of soil under the foundations. Following is the Table representing the equations used to calculate the modulus of subgrade reaction.

Table 3-5: Richart and Laysmer model to calculate soil spring values

Direction	Spring Values	Equivalent Radius
Vertical	$K_Z = \frac{4Gr_z}{(1-\vartheta)}$	$r_Z = \sqrt{\frac{LB}{\pi}}$
Horizontal	$K_x = K_y = \frac{32(1-\vartheta)Gr_x}{(7-8\vartheta)}$	$r_Z = \sqrt{\frac{LB}{\pi}}$
Rocking	$K_{\emptyset x} = \frac{8Gr_{\emptyset y}^3}{3(1-\vartheta)}$	$r_{\emptyset x} = \sqrt[4]{\frac{LB^3}{3\pi}}$
	$K_{\emptyset y} = \frac{8Gr_{\emptyset x}^3}{3(1-\vartheta)}$	$r_{\emptyset y} = \sqrt[4]{\frac{LB^3}{3\pi}}$
Twisting	$K_{\emptyset z} = \frac{16Gr_{\emptyset z}^3}{3}$	$r_{\emptyset z} = \sqrt[4]{\frac{LB^3+BL^3}{6\pi}}$

The soil properties are represented by "*G*" in the above formulas. This term is calculated by multiplying soil density with respective shear wave velocities V_{S30}. The density of individual soil can be calculated by dividing the unit weight of soil by gravitational factor "g".

"r_z" represents the equivalent radius of rectangular raft footing. L and B are the length and width of raft footing under the structure. Soil stiffness factor K can also be obtained from the modulus of subgrade reaction obtained from the plat load test at the site. The values of modulus of subgrade reaction calculated at the site is considered more accurate as it represented the exact stiffness of site under consideration.

In this study, the plate load test results for each type of soil condition were not available so richart and laysmer model was used to calculate the approximate soil stiffness values of each type of soil mentioned in the Building Code of Pakistan.

The following table contains the values of modulus of subgrade reaction calculated for all the building models under consideration.

Table 3-6: Calculated values of subgrade reaction for different soil types

Modulus of subgrade reaction, K (KN/M3)			
Soil Type	4B	8B	11B
S_A	401986	901343	1587222
S_B	120134	269369	474345
S_C	80859	181305	319268
S_D	20792	46621	82097
S_E	4852	10878	19156

As there were five different types of soil and we had three different building models. Each building was modeled with every soil type. Fifteen building models were prepared to represent each soil type for each one of the building models. The following is the representation of a building model with soil springs under the raft footing.

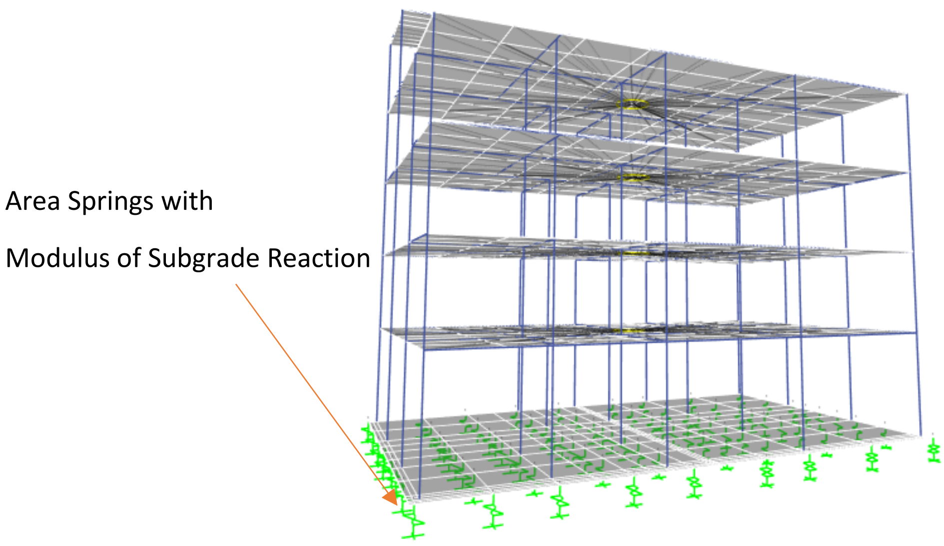

Figure 3-9: Building model with Area springs under raft footing

3.4 Analysis of Buildings

All the building models are analyzed using Modal Analysis and Equivalent Lateral Force (ELF) method. Modal Analysis is used to monitor the geometric properties of the model. The modal analysis provides time period variation of buildings with change in soil stiffness at the base. ELF provided the seismic performance and demand parameters such as story drift, lateral displacement, overturning moment, and base shear etc. Following tables contains the key features used in the analysis of all the buildings under consideration.

Table 3-7: Important factors considered for analyses of buildings

Important factors for analysis of 4B	
Feature	**Particular**
Concrete Design	ACI 318 -08
Loading Criteria	ASCE 7-10
Seismic Design	UBC 97
Soil Conditions Data	BCP 2007
Soil Class	SD
Frame Type	IMRF
Importance Factor	1
Overstrength Factor	3
Seismic Analysis Type	ELF
Response Modification Factor (R)	5
Masonry Infills	Not Modeled

Chapter – 04

Results and Discussion

This chapter contains a detailed discussion on the results obtained from the seismic analysis of all the building structures. All the linear elastic models for all three buildings are analyzed using Model Analysis as per the guidelines of ASCE 7-10. After that displacement-based linear static seismic analysis ELF is performed. Following are the results obtained from the above-mentioned analysis procedures.

4.1 Modal Analysis Results

To start the structural evaluation, first, the elastic model of the case study building is subjected to the Eigen-value analysis to determine the natural periods of vibration, natural frequencies and vibration mode shapes. The mass matrix of the structure included the mass corresponding to the dead load and 25% of the live load in accordance with ASCE 7-10. For the construction of the mass matrix, the lumped mass approach is used with story masses lumped at the centre of mass of each floor level. The rigid diaphragm assumption is used in the linear elastic model while excluding the vibration modes in a vertical direction.

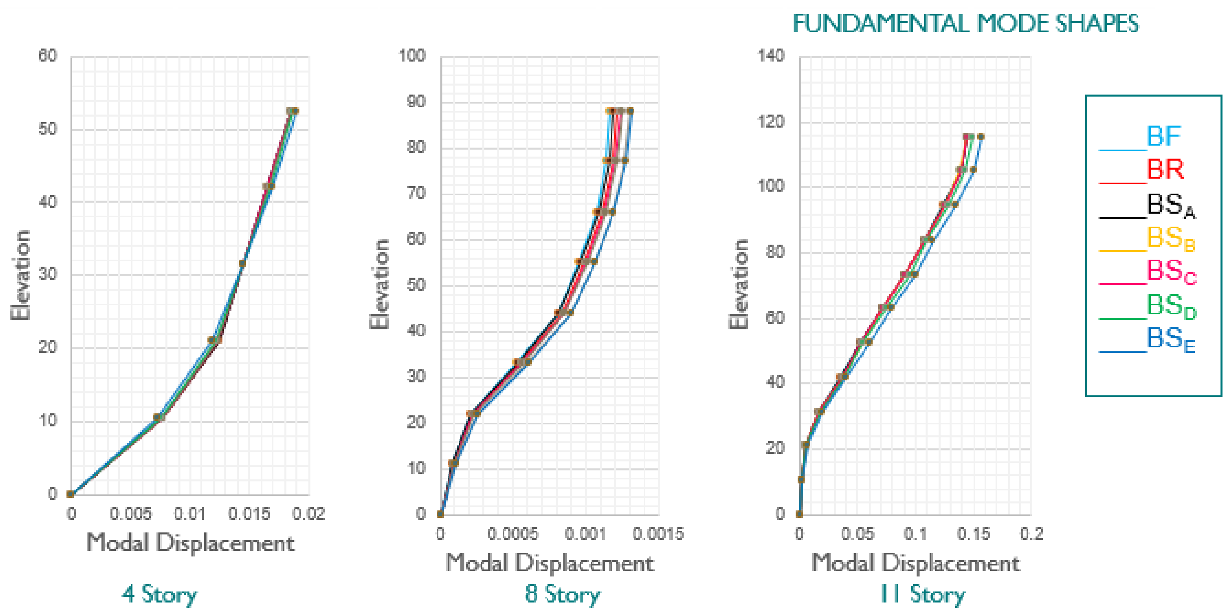

Figure 4-1: Fundamental mode shapes of all models

These are Mode shapes for Fundamental Mode in X-direction for all three buildings. A mode shape is a deformation that the buildings would show when vibrating at the natural frequency. The fundamental time periods for each building are tabulated below.

Table 4-1: Fundamental time periods variation of buildings

Fundamental time period (Sec)			
Foundation Type	4B	8B	11B
BF	0.862	1.124	1.845
BR	0.869	1.126	1.846
S_A	0.881	1.127	1.88
S_B	0.89	1.134	1.91
S_C	0.894	1.138	1.94
S_D	0.918	1.159	1.96
S_E	0.973	1.207	1.98

The following graph shows the variation time period for the first 10 modes. These graphs show time period variations for all the models. The graph is drawn by taking mode number at x-axis and time period at y-axis. The variation from BF to BS_E is shown in percentage for each building under consideration.

Figure 4-2: Fundamental time period variation of buildings

It is observed that only the 1st two-mode show a considerable change in time period. Among these, the 4 story model shows a maximum increase in time period for S_E soil type. The change in Time period for 8 and 11 story buildings is almost the same. This shows that base flexibility has a considerable effect on low rise buildings and have little effect on mid-rise buildings.

4.2 Equivalent Lateral Force (ELF) Results

As this research focuses on the inertial interaction of soil with structures, some Global and Local seismic responses affected by inertial response are studied here. ELF is performed for all the buildings models and the results are calculated for Global responses of Maximum Story Displacement, Maximum Story Drift, Story Shear, Base Shear and Overturning Moments. The Local Response of Column Shear in 2-2 and Column Shear in 3-3 direction are also calculated. The results of all these factors are discussed below.

4.2.1 Comparison of Maximum Story Displacement Results

The following Tables contain the results of Maximum Story Displacement for all Building Models. Maximum story displacement for all the variations of the foundation is tabulated here. The tabulated values are also displayed graphically for a better understanding of performance trends. Maximum Story Displacement for 4 story building for all 7 types of foundation conditions is given below.

Table 4-2: Maximum story displacement for 4 story building

Maximum story displacement for 4B (in)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	0	0	0	0	0	0	0
10.5	0.4	0.292	0.297	0.298	0.299	0.301	0.314
21	0.6	0.487	0.492	0.494	0.495	0.502	0.53
31.5	0.81	0.59	0.597	0.603	0.606	0.623	0.67
42	0.93	0.69	0.702	0.71	0.714	0.74	0.8
52.5	0.97	0.76	0.766	0.776	0.78	0.81	0.89

Similar to the above table of Maximum Story Displacement for 4 story building, the results for 8 story and 11 story buildings are also tabulated below.

Table 4-3: Maximum story displacement for 8 story building

Maximum story displacement for 8B (in)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	0	0	0	0	0	0	0
11	0.45	0.3	0.35	0.37	0.38	0.42	0.47
22	0.9	0.77	0.82	0.93	0.96	1.04	1.08
33	1.33	1.23	1.32	1.44	1.48	1.56	1.68
44	1.97	2.01	2.06	2.13	2.16	2.27	2.39
55	2.78	2.82	2.85	2.96	2.99	3.03	3.14
66	3.5	3.54	3.63	3.7	3.74	3.82	3.94
77	4.1	4.13	4.22	4.31	4.35	4.44	4.56
88	4.5	4.55	4.68	4.74	4.79	4.85	4.96

Results for 11 story building with all the foundation variations are given below.

Table 4-4: Maximum story displacement for 11 story building

Maximum story displacement for 11B (in)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	0	0	0	0	0	0	0
10.5	0.101	0.098	0.099	0.101	0.113	0.126	0.144
21	0.238	0.215	0.218	0.22	0.25	0.29	0.32
31.5	0.386	0.37	0.38	0.42	0.45	0.49	0.52
42	0.5	0.52	0.56	0.59	0.62	0.66	0.7
52.5	0.712	0.75	0.78	0.81	0.84	0.88	0.92
63	0.93	0.95	0.99	1.02	1.05	1.09	1.13
73.5	1.16	1.19	1.21	1.24	1.29	1.33	1.37
84	1.34	1.38	1.42	1.45	1.49	1.53	1.57
94.5	1.52	1.56	1.59	1.62	1.65	1.69	1.74
105	1.63	1.68	1.73	1.75	1.78	1.82	1.88
115.5	1.84	1.87	1.91	1.93	1.96	2.01	2.03

Graphical Representation of Tabulated values is given below.

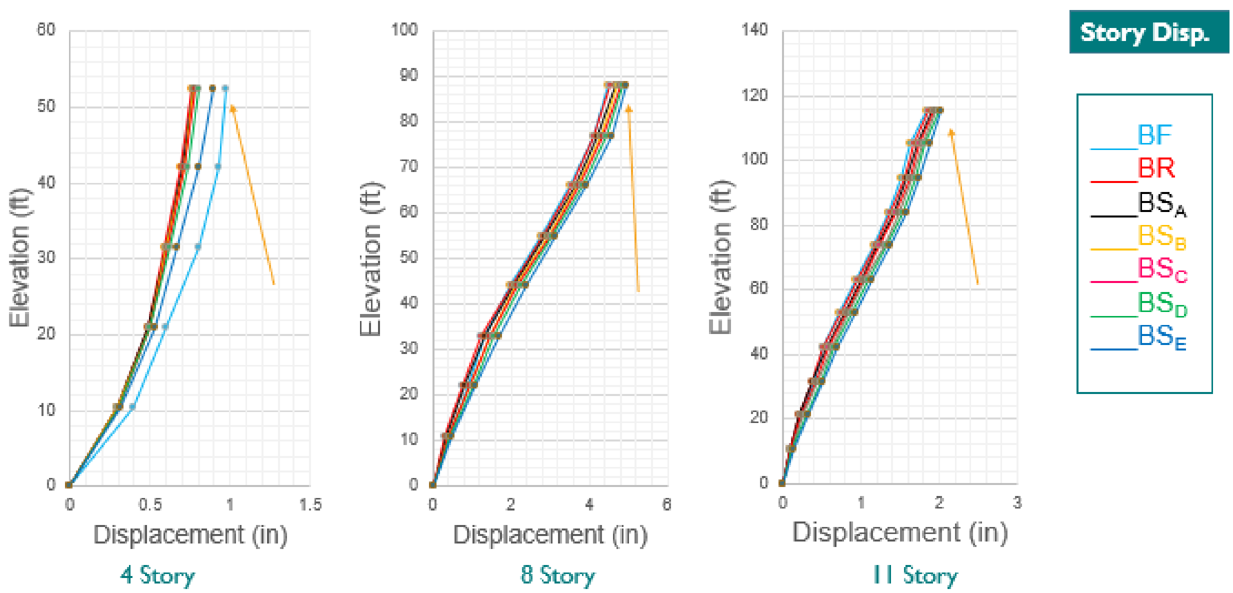

Figure 4-3: Story displacement comparison of buildings

The maximum variation of Story Displacement is observed for the top story in all the buildings. Among all the models, maximum variation is observed in model BF, BR and BS_E. The Story Displacement results for the top story of BF, BR and BS_E along with the percentage of their variations are presented below for better visualization.

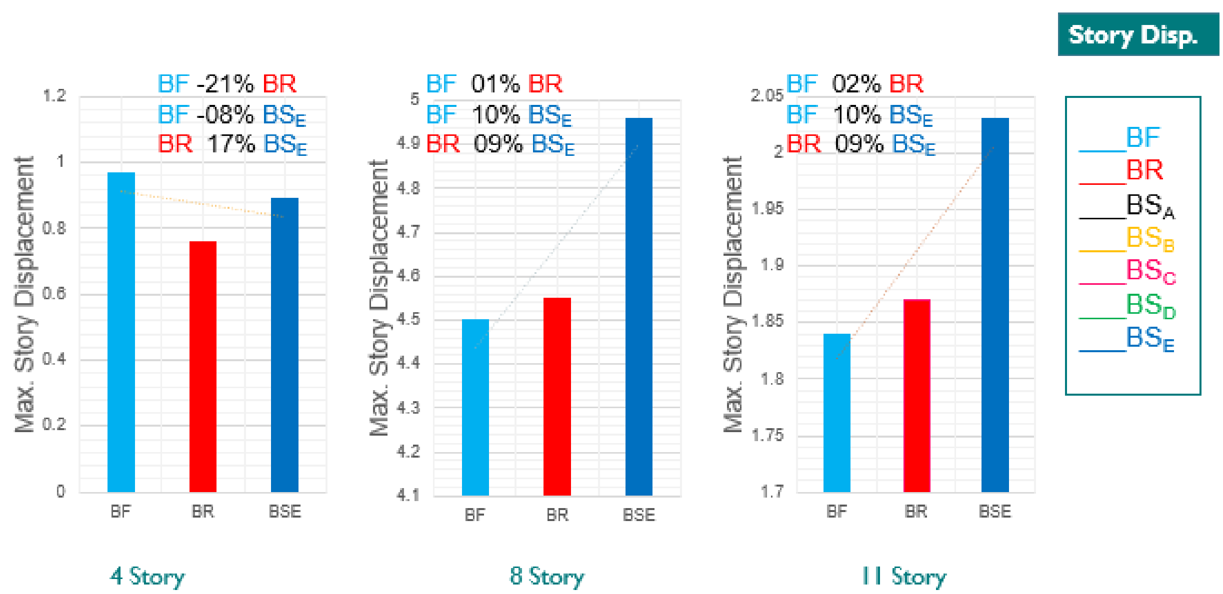

Figure 4-4: Maximum story displacement of BF, BR, and BSE

If we look at the variation from BF to BR a maximum of 21% decrease is observed in the case of 4 story building. The variation of BF to BR for 8 story and 11 story building is 1% and 2% respectively which is comparatively low. This shows that foundation modeling reduces story displacement of the low-rise building by increasing its stiffness. The effect of increased stiffness at the base in terms of story displacement is negligible in the case of mid-rise buildings.

By introducing soil springs at the base of raft footing, the story displacement is increased 17% for $BS_{E.}$ The effect of soil modeling is comparatively low in the case of mid-rise buildings. There is only a 9% change in story displacement in the case of mid-rise buildings. For story displacement results, again the maximum change is observed in the case of 4 story building and for the other two, the change is the same and comparatively low.

4.2.2 Comparison of Maximum Story Drift Results

The following Tables contain the results of Maximum Story Drift for all the Building Models. Maximum story drift for all the variations of the foundation is tabulated here. The tabulated values are also displayed graphically for a better understanding of performance trends. Maximum Story Drift results for 4 story building with all 7 types of foundation conditions are given in the following table.

Table 4-5: Maximum story drift for 4 story building

Maximum story drift for 4B							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	0	0	0	0	0	0	0
10.5	0.003894	0.001871	0.001903	0.001913	0.001917	0.001934	0.002012
21	0.003302	0.001545	0.001546	0.001553	0.001557	0.001585	0.001685
31.5	0.001731	0.000809	0.000834	0.000864	0.000879	0.000961	0.001128
42	0.001776	0.00083	0.000839	0.000852	0.00086	0.000907	0.001039
52.5	0.001073	0.000502	0.000509	0.000522	0.000529	0.000573	0.000713

Like the above table of Maximum Story Drift for 4 story building, the results for 8 story and 11 story buildings are also tabulated below.

Table 4-6: Maximum story drift for 8 story building

Maximum story drift for 8B							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	0	0	0	0	0	0	0
11	0.0024	0.0022	0.0026	0.0028	0.0028	0.0031	0.0035
22	0.0038	0.0039	0.004	0.0043	0.0044	0.0047	0.0051
33	0.0058	0.0057	0.0058	0.006	0.006	0.0062	0.0066
44	0.0061	0.0063	0.0064	0.0065	0.0066	0.0067	0.0071
55	0.006	0.0061	0.0061	0.0063	0.0063	0.0065	0.0069
66	0.0052	0.0054	0.0055	0.0056	0.0057	0.0058	0.0062
77	0.0045	0.0045	0.0045	0.0046	0.0047	0.0048	0.0052
88	0.0036	0.0036	0.0037	0.0038	0.0038	0.004	0.0043

Results for 11 story building with all the foundation variations are given below.

Table 4-7: Maximum story drift for 11 story building

Maximum story drift for 11B							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	0	0	0	0	0	0	0
10.5	0.00022	0.00018	0.00026	0.0003	0.00035	0.00039	0.00044
21	0.00065	0.00064	0.00068	0.00072	0.00078	0.0008	0.00084
31.5	0.00099	0.00095	0.00104	0.0011	0.00119	0.00122	0.00128
42	0.00125	0.0012	0.0013	0.00135	0.00141	0.00147	0.00156
52.5	0.0016	0.0015	0.00165	0.00169	0.00174	0.00178	0.00184
63	0.0017	0.0016	0.00175	0.00179	0.00184	0.00189	0.00197
73.5	0.0016	0.00156	0.00168	0.00172	0.00176	0.00181	0.00191
84	0.0014	0.00135	0.00145	0.0015	0.00154	0.00158	0.00167
94.5	0.0012	0.00125	0.0013	0.00134	0.00138	0.00143	0.00152
105	0.0011	0.00115	0.0012	0.00124	0.00128	0.00134	0.00143
115.5	0.0009	0.00095	0.001	0.0011	0.00116	0.00121	0.00132

The graphical representation of tabulated values is given below.

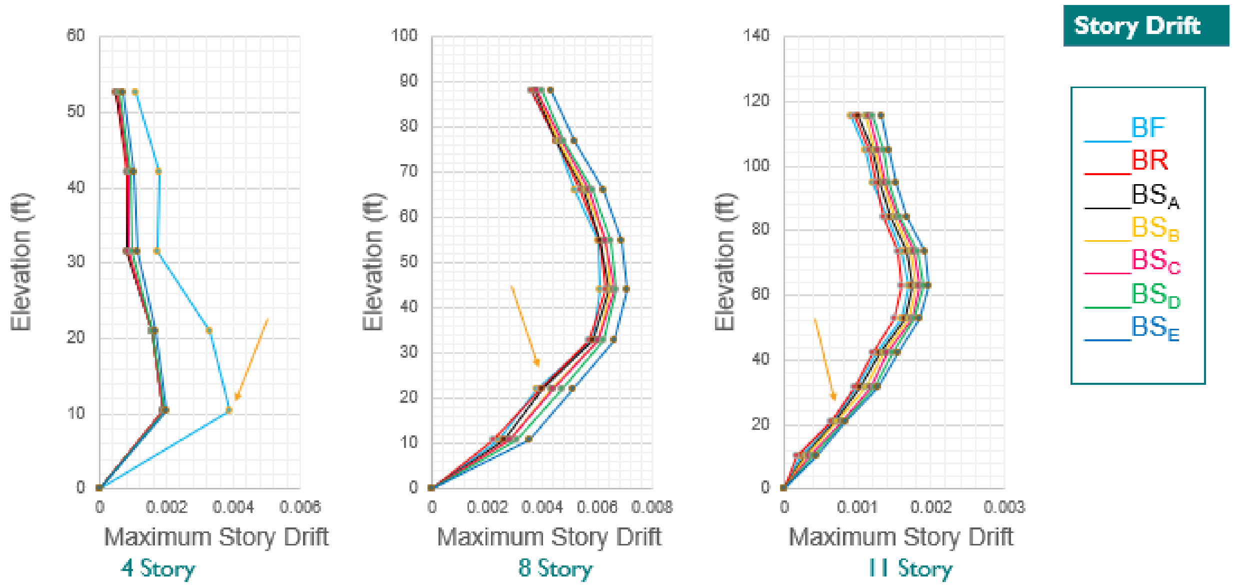

Figure 4-5: Max story drift of buildings

Among all the models, maximum variation is observed in model BF, BR, and $BS_{E.}$ The Story Drift results for lower elevation level of BF, BR, and BS_E along with the percentage of their variations are presented below for better visualization.

Figure 4-6: Maximum story drift comparison for BF, BR and BSA

If we look at the variation from BF to BR a maximum of 52% decrease is observed in the case of 4 story building. The variation of BF to BR for 8 story and 11 story building is 3% and 2% respectively which is comparatively low. This shows that foundation modeling reduces the story drift of low-rise building by increasing their stiffness. The effect of increased stiffness at the base in terms of story drift is negligible in the case of mid-rise buildings.

By introducing soil springs at the base of raft footing, the story drift of 4 story building is increased 8% for $BS_{E.}$ The effect of soil modeling is comparatively high in the case of mid-rise buildings. There is 34% for 8 story and 29% change in story drift in case of 11 story building is observed. For story drift results, the maximum change is observed in the case of 4 story building for foundation modeling and in 8 story building for soil modeling. It shows that soil modeling affects the story drift results of mid-rise buildings more. This effect reduces as we increase the story height that is why 11 story building have less variation as compared to 8 story building.

4.2.3 Comparison of Story Shear Results

The following Tables contain the results of Maximum Story Shear for all the Building Models. The maximum story Shear for all the variations of the foundation is tabulated here. The tabulated values are also displayed graphically for a better understanding of performance trends. Maximum Story Shear results for 4 story building with all 7 types of foundation conditions are given in the following table.

Table 4-8: Maximum story shear for 4 story building

Story shear for 4B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	294.5	137.44	135.65	134.3	133.7	130.2	124.68
10.5	294.5	137.44	135.65	134.3	133.7	130.2	124.68
21	270.3	126.22	124.6	123.5	122.9	119.84	114.98
31.5	221.3	103.4	102.14	101.2	100.8	98.4	94.68
42	145.5	68	67.2	66.65	66.4	64.9	62.61
52.5	45.6	21.3	21.1	20.94	20.9	20.43	19.78

Like the above table the results for 8 story and 11 story buildings are also tabulated below.

Table 4-9: Maximum story shear for 8 story building

Story shear for 8B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	2622.3	2762.2	2596.4	2544	2460	2280.93	2162
11	2622.3	2762.2	2596.4	2544	2460	2280.93	2162
22	2596	2686	2580	2530	2400	2200	2100
33	2494.5	2549.6	2460	2380	2250	2066	1956
44	2214.5	2341.5	2210	2150	2090	1825	1719
55	1981.9	2052.1	2040	1960	1830	1533	1420
66	1600.5	1670.6	1665	1605	1475	1266	1150
77	1129.5	1192.7	1192	1190	1160	980	850
88	609.4	614.2	611.3	607.8	603.5	602	560

Results for 11 story building with all the foundation variations are given below.

Table 4-10: Maximum story shear for 11 story building

Story shear for 11B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	1052.6	1052.6	1052.6	1052.6	1052.6	971.33	865.1
10.5	1051.3	1051.3	1050.2	1050.2	1050.4	969.26	863.1
21	1040.3	1040.3	1041	1041.7	1042.1	971	869.3
31.5	1020.3	1020.3	1022.2	1023.9	1024.6	966.1	872.3
42	985.7	985.7	988.8	991	992	947.5	863.2
52.5	928.3	928.3	932	934.7	935.9	905.5	834.7
63	848.8	848.8	852.8	855.6	856.6	839.4	783.8
73.5	743.7	743.7	747.1	749.6	750.7	743.5	705.3
84	610.1	610.1	612.2	616.7	614.4	613.5	594.5
94.5	445.4	445.4	447.5	451.1	453.5	448.6	436.4
105	246.6	246.6	248.9	253	254.1	249.5	238.3
115.5	42.7	42.7	43.2	48.3	42.8	41.9	39.9

The graphical representation of tabulated values is given below.

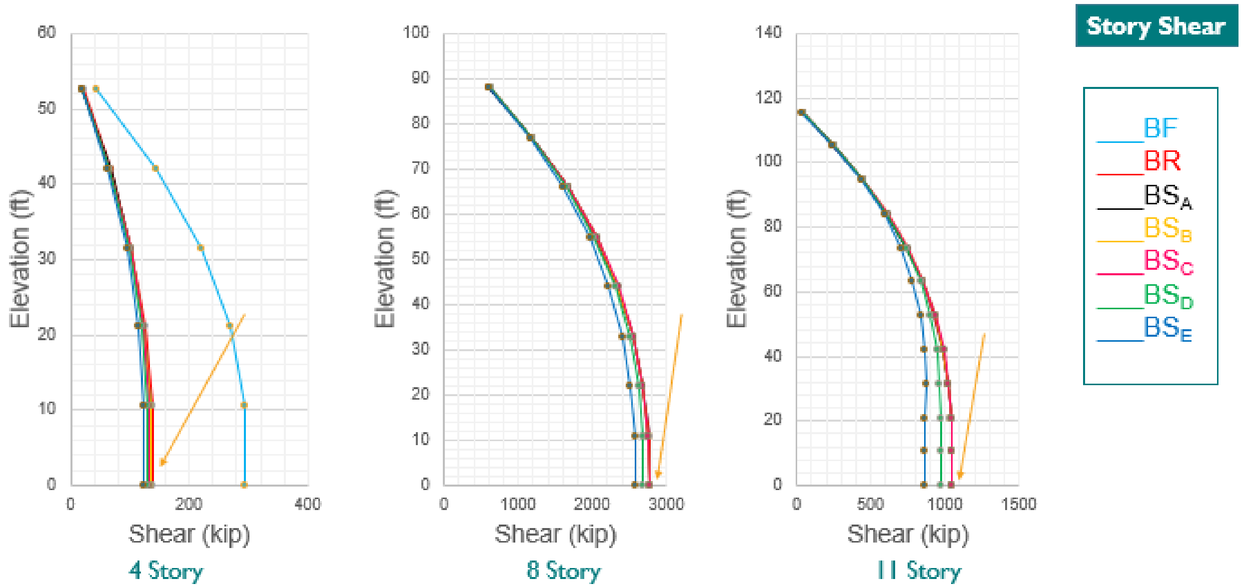

Figure 4-7: Story shear of buildings

Among all the models, maximum variation is observed in model BF, BR, and BS$_E$ at the base of the buildings. The Base Shear results for BF, BR, and BS$_E$ along with the percentage of their variations are presented below for better visualization.

Figure 4-8: Maximum story shear comparison for BF, BR and BSA

If we look at the variation from BF to BR a maximum of 53% decrease is observed in the case of 4 story building. The variation of BF to BR for 8 story and 11 story building is 5% and 0.1% respectively which is comparatively low. This shows that foundation modeling reduces the Base Shear of the low-rise building by increasing their stiffness. The effect of increased stiffness at the base in terms of Base Shear is negligible in the case of mid-rise buildings.

By introducing soil springs at the base of raft footing, the Base Shear of 4 story building is decreased 9% for $BS_{E.}$ The effect of soil modeling is comparatively high in the case of mid-rise buildings. There is 21% for 8 story and 18% change in Base Shear in the case of 11 story building is observed. For Base Shear results, the maximum change is observed in the case of 4 story building for foundation modeling and in 8 story building for soil modeling. It shows that soil modeling affects the Base Shear results of mid-rise buildings more. This effect reduces as we increase the story height that is why 11 story building have less variation as compared to 8 story building.

4.2.4 Comparison of Overturning Moments Results

The following Tables contain the results of Overturning Moment for all the Building Models. Overturning Moment for all the variations of the foundation is tabulated here. The tabulated values are also displayed graphically for a better understanding of performance trends. Overturning Moment results for 4 story building with all 7 types of foundation conditions is given in the following table.

Table 4-11: Overturning moment for 4 story building

Overturning moment for 4B (kip-ft)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	10997	5135	5072.2	5025	5002.2	4880.2	4687.22
10.5	7169.2	3348.7	3308.8	3278.9	3264.5	3187.4	3066.4
21	4330.7	2023.3	2000	1982.6	1974.1	1929.1	1859
31.5	2006.8	937.8	927.5	919.7	916	896	865.1
42	479.1	224	221.6	219.9	219	214.5	207.7
52.5	0	0	0	0	0	0	0

Like the above table the results for 8 story and 11 story buildings are also tabulated below.

Table 4-12: Overturning moment for 8 story building

Overturning moment for 8B (kip-ft)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	174810	171669	175033	175186	175254	171825	165564
11	144430	144440	144653	144807	144874	142339	137245
22	114876	114886	115088	115233	115297	113545	109566
33	86812	86820	86999	87128	87185	86077	83130
44	61029	61035	61180	61285	61331	60714	58687
55	38420	38425	38529	38604	38637	38355	37109
66	19998	20001	20062	20105	20125	20035	19403
77	6822.8	6823.9	6847	6863.7	6871	6861	6651
88	0	0	0	0	0	0	0

Results for 11 story building with all the foundation variations are given below.

Table 4-13: Overturning moment for 11 story building

Overturning moment for 11B (kip-ft)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	95073	91932	95296	95449	95517	92088	85827
10.5	77090	77100	77313	77467	77534	74999	69905
21	65955	66005	66207	66352	66416	64664	60685
31.5	54878	54886	55065	55194	55251	54143	51196
42	42218	42224	42369	42474	42520	41903	39876
52.5	31979	31984	32088	32163	32196	31914	30668
63	22639	22642	22703	22746	22766	22676	22044
73.5	14490	14492	14515	14532	14539	14529	14319
84	7841.2	7846.1	7846	7831	7837	7838	7820
94.5	3012.8	3012.8	3013	3013	3013	3004	2999
105	346	347	349	350	350	348	339
115.5	0	0	0	0	0	0	0

The graphical representation of tabulated values is given below.

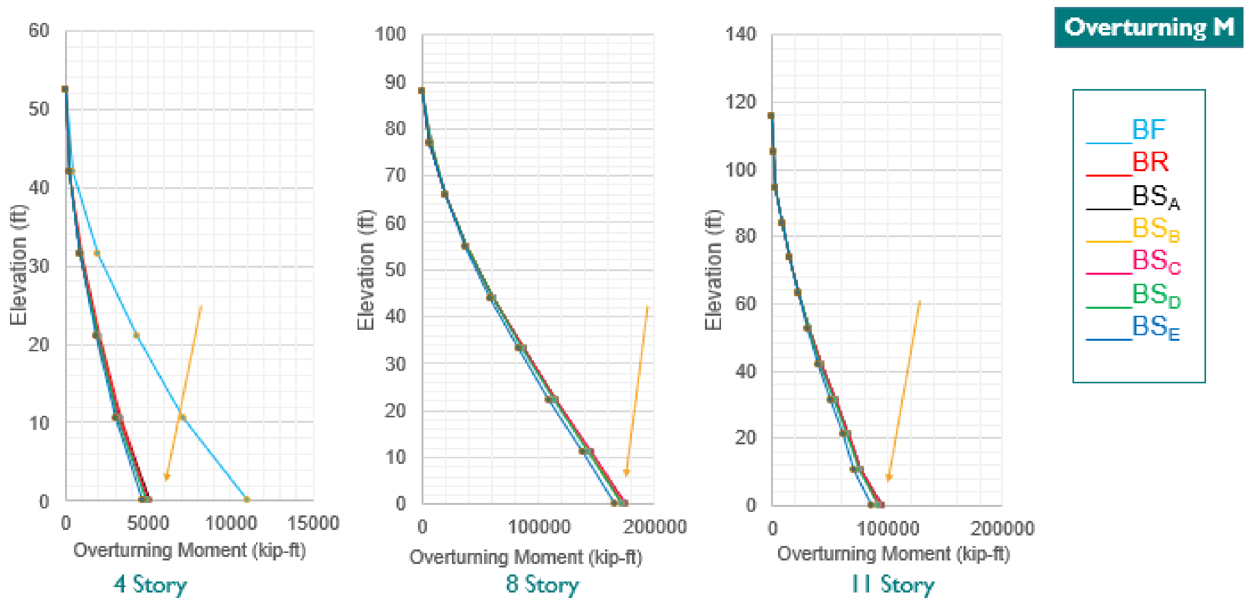

Figure 4-9: Overturning moment of buildings

Among all the models, maximum variation is observed in model BF, BR, and BS_E at the base of the buildings. The Overturning Moment results for BF, BR, and BS_E along with the percentage of their variations are presented below for better visualization.

Figure 4-10: Overturning moments comparison for BF, BR and BSA

If we look at the variation from BF to BR a maximum of 53% decrease is observed in the case of 4 story building. The variation of BF to BR for 8 story and 11 story building is 2% and 3% respectively that is comparatively low. This shows that foundation modeling reduces the Overturning Moment of the low-rise building by increasing its stiffness at the base. The effect of increased stiffness at the base in terms of Overturning Moment is negligible in the case of mid-rise buildings.

By introducing soil springs at the base of raft footing, the Overturning Moment of 4 story building is decreased 9% for $BS_{E.}$ The effect of soil modeling is comparatively low in the case of mid-rise buildings. There is 04% for 8 story and 07% change in Overturning Moment in case of 11 story building is observed. For Overturning Moment results, the maximum change is observed in the case of 4 story building for foundation modeling and similar for soil modeling. It shows that soil modeling affects the Base Shear results of mid-rise buildings more. This effect reduces as we increase the story height that is why 8 story and 11 story building have less variation as compared to 4 story building.

4.2.5 Local Response of Structures

To capture the local response of structures under seismic loadings, an external column for each building is selected. Columns selected for the local response for each building are shown below.

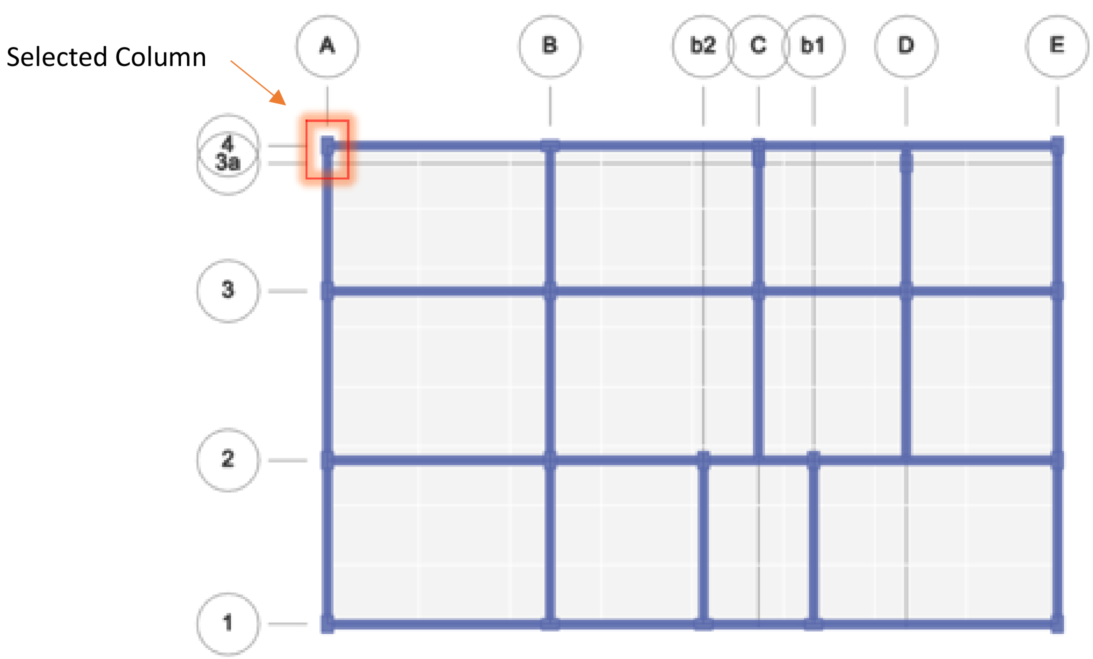

Figure 4-11: Typical Plan of 4 story building

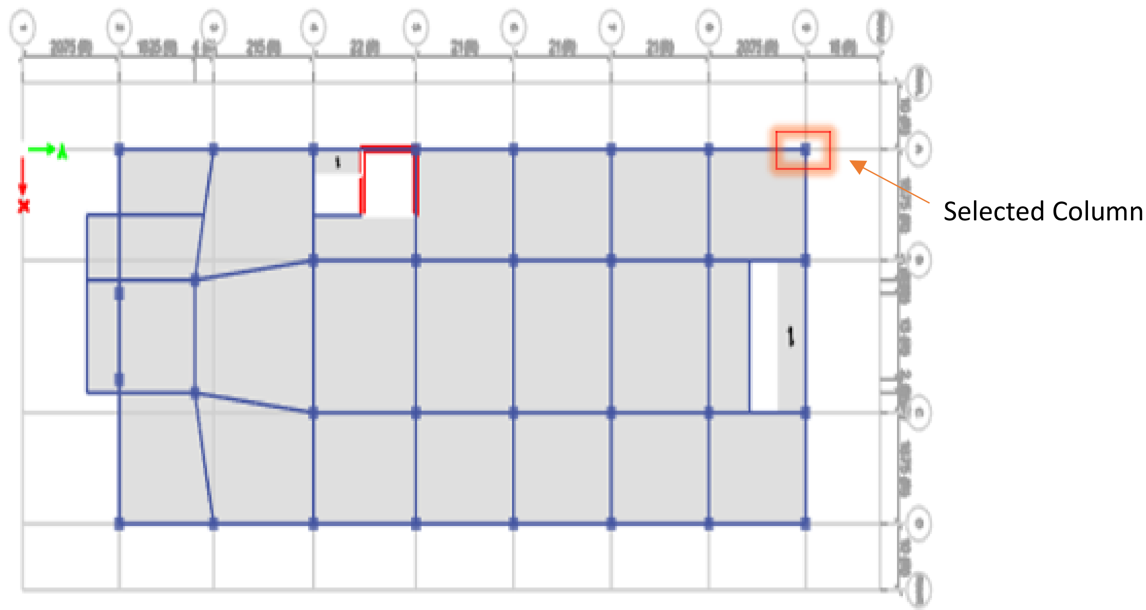

Figure 4-12: Typical Plan of 8 story building

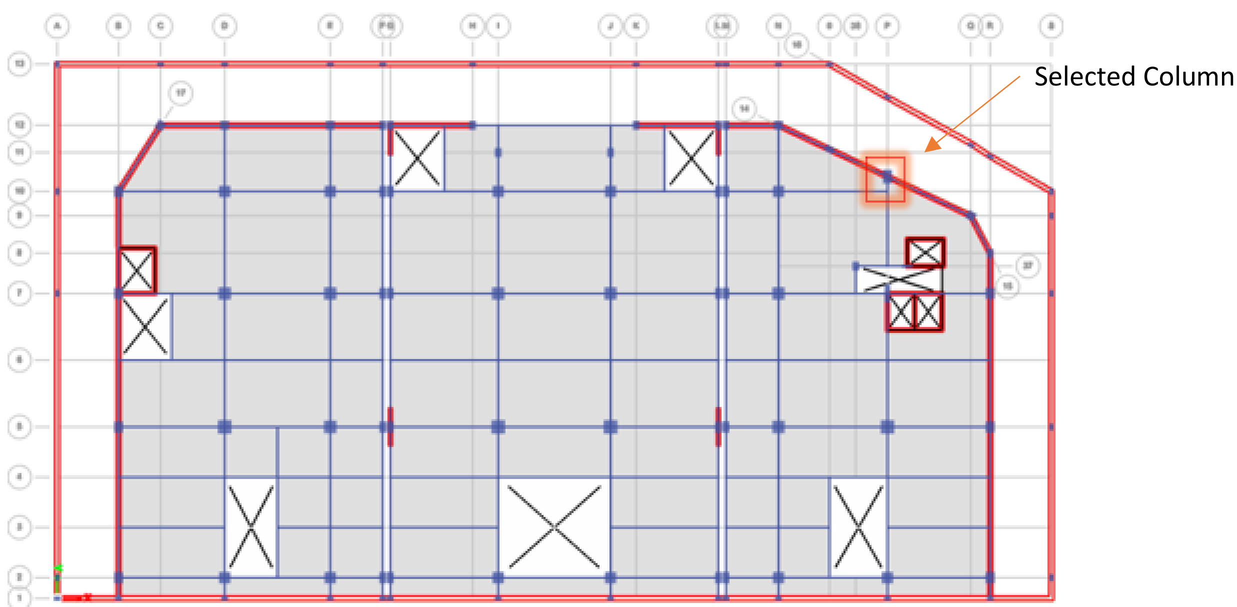

Figure 4-13: Typical Plan of 11 story building

The equivalent static force under ELF analysis is applied in the x-direction of building and the shear force of selective columns of each building in 2-2 direction and 3-3 direction are extracted and tabulated for each model variation. The tabulated values are also presented graphically to better understand the variation trends.

4.2.5.1 Local Shear in 2-2 Direction

Local shear in 2-2 direction under ELF loading for all the variations of all the buildings are calculated and presented in the following table. All the tabulated values are also presented graphically for better understanding the trends of results with the change in base stiffness. The following table shows the column shear in 2-2 direction for 4B

Table 4-14: Column shear in 2-2 direction for 4 story building

Column shear in 2-2 direction for 4B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	18.992	8.843	8.08	7.619	7.436	6.72	5.732
10.5	14.889	6.906	6.673	6.424	6.31	5.803	5
21	13.514	6.299	5.994	5.72	5.601	5.109	4.398
31.5	7.046	3.283	3.083	2.89	2.805	2.464	2.049
42	5.448	2.541	2.403	2.276	2.225	2.027	1.753
52.5	0	0	0	0	0	0	0

Like the above table of column shear in 4 story building, the results for 8 story and 11 story buildings are also tabulated below. The following table shows the column shear in 2-2 direction for 8B

Table 4-15: Column shear in 2-2 for 8 story building

Column shear in 2-2 for 8B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	5.876	7.705	7.16	6.991	6.738	5.215	2.862
11	42.209	46.186	45.709	45.174	44.41	43.466	40.049
22	54.741	55.648	53.949	53.72	51.909	49.819	46.429
33	48.165	48.865	48.094	46.86	44.978	42.806	40.832
44	44.069	45.049	44.255	43	42.072	41.797	38.612
55	39.102	39.23	39.448	40.384	40.26	39.942	38.955
66	33.816	33.968	33.173	33.804	33.879	32.675	32.482
77	20.914	21.105	20.228	19.543	18.555	18.254	17.546
88	0	0	0	0	0	0	0

The following table shows the column shear in 2-2 direction for 11B

Table 4-16: Column shear in 2-2 for 11 story building

Column shear in 2-2 direction for 11B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	0.633	0.792	0.627	0.578	0.525	0.498	0.451
10.5	5.25	6.227	4.95	4.78	4.56	4.23	3.99
21	1.877	2.784	1.85	1.64	1.47	1.14	1.1
31.5	1.55	1.755	1.49	1.41	1.38	1.23	1.17
42	2.076	3.056	2.02	1.98	1.79	1.58	1.39
52.5	3.049	3.177	2.98	2.89	2.77	2.72	2.61
63	3.197	3.349	2.97	2.76	2.46	2.18	2.03
73.5	3.166	3.357	3.08	2.97	2.807	2.506	2.398
84	3.392	3.492	3.12	2.96	2.78	2.45	2.32
94.5	2.65	2.84	2.44	2.36	2.25	2.15	1.98
105	2.01	2.22	1.96	1.89	1.81	1.75	1.71
115.5	0	0	0	0	0	0	0

The graphical representation of tabulated values is given below.

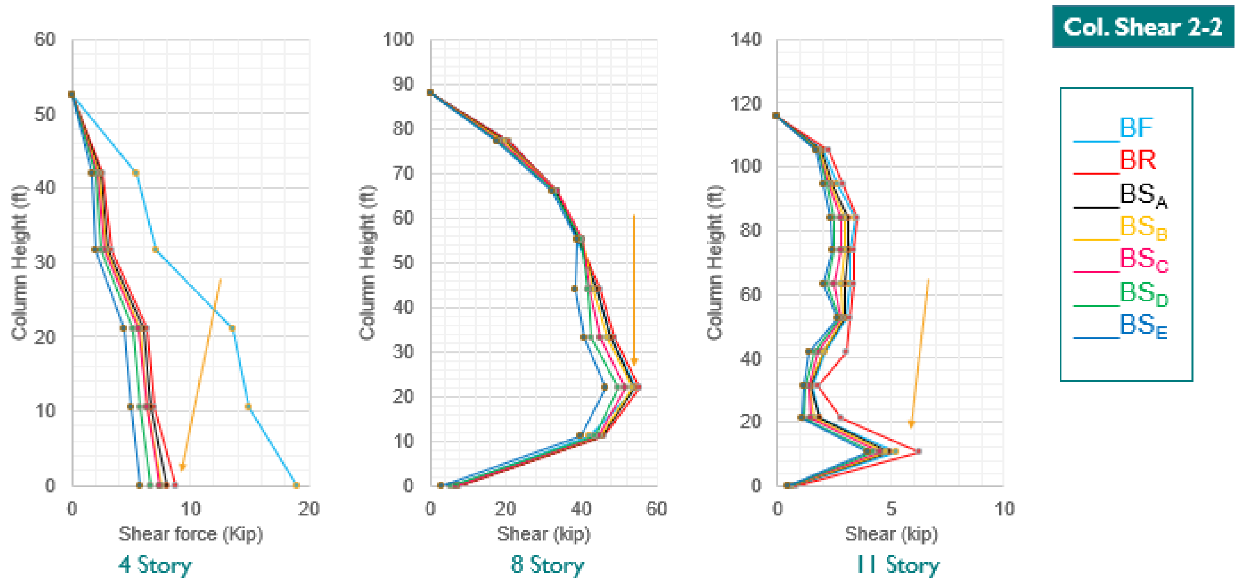

Figure 4-14: Column shear in 2-2 direction

Among all the models, maximum variation is observed in model BF, BR, and BS_E at the base and lower portion of the buildings. The column shear results for BF, BR, and BS_E along with the percentage of their variations are presented below for better visualization. Column Shear 2-2 values for BF, BR and BS_E are shown below.

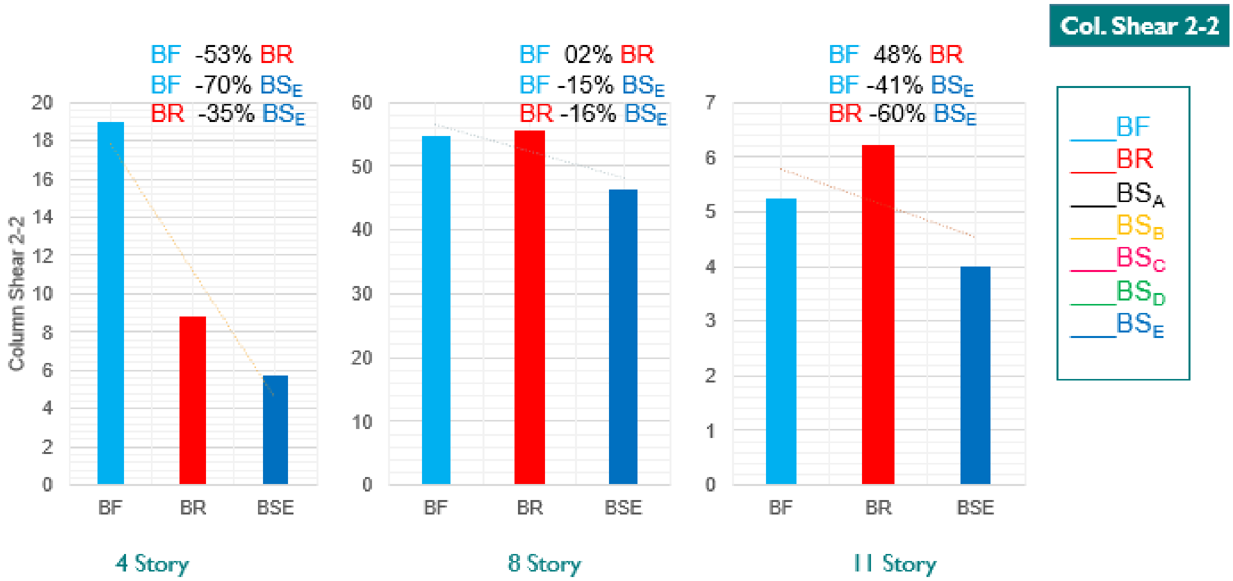

Figure 4-15: Column shear in 2-2 direction comparison of BF, BR and BSA

If we look at the variation from BF to BR a maximum of 53% decrease is observed in the case of 4 story building. The variation of BF to BR for 8 story and 11 story building is 2% and 48% respectively which is the same as the Global response. This shows that foundation modeling reduces column shear of the low-rise building by increasing its stiffness at the base. The effect of increased stiffness at the base in terms of column shear is negligible in the case 8 story building but it becomes prominent as we further increase the height of the buildings.

By introducing soil springs at the base of raft footing, the column shear of 4 story building is decreased 35% for BS_E. The effect of soil modeling is comparatively low in the case of 8 story building. There is a 16% decrease for 8 story, and it becomes prominent as we increase the height further. 60% decrease is observed in the case of 11 story building. For column shear results, the maximum change is observed in the case of 4 story building for foundation modeling and in 11 story for soil modeling. It shows that soil modeling affects the Base Shear results of all the buildings. This variation is also affected by building geometry and the relative stiffness of the building and its base. That is why the 8 and 11 story buildings have variations in their behavior.

4.2.5.2 Local Shear in 3-3 Direction

Local shear in 3-3 direction under ELF loading for all the variations of all the buildings are calculated and presented in the following table. All the tabulated values are also presented graphically for better understanding the trends of results with the change in base stiffness. The following table shows the column shear 3-3 for 4B

Table 4-17: Column shear in 3-3 direction for 4 story building

Column shear in 3-3 direction for 4B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	1.009	0.486	0.715	0.903	0.969	1.153	1.182
10.5	0.588	0.316	0.358	0.423	0.453	0.598	0.671
21	0.602	0.374	0.445	0.524	0.557	0.68	0.768
31.5	0.434	0.202	0.272	0.354	0.389	0.528	0.628
42	0.024	0.007	0.0079	0.0165	0.0204	0.0354	0.0465
52.5	0	0	0	0	0	0	0

Like the above table of column shear in 4 story building, the results for 8 story and 11 story buildings are also tabulated below. The following table shows the column shear 3-3 for 8B

Table 4-18: Column shear in 3-3 for 8 story building

Column Shear in 3-3 direction for 8B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	9.194	10.38	10.374	10.645	10.898	13.111	18.32
11	99.543	99.63	103.671	109.332	111.305	119.914	135.06
22	8.87	9.03	9.024	9.21	9.148	8.854	7.858
33	19.617	19.87	20.33	21.108	21.299	21.993	22.936
44	19.098	19.174	19.613	20.444	20.615	21.247	22.051
55	16.749	16.794	17.166	17.987	18.144	18.759	19.578
66	15.01	15.045	15.423	16.277	16.433	17.059	17.857
77	13.748	13.791	14.169	14.948	15.141	15.89	16.879
88	0	0	0	0	0	0	0

The following table shows the column shear in 3-3 direction for 11B

Table 4-19: Column shear in 3-3 direction for 11 story building

Column Shear in 3-3 direction for 11B (kip)							
Story	BF	BR	BS_A	BS_B	BS_C	BS_D	BS_E
0	2.278	3.464	3.548	3.729	3.982	4.195	5.404
10.5	7.549	8.636	9.677	10.338	10.83	11.92	12.055
21	11.53	12.374	12.528	12.714	12.85	13.35	13.68
31.5	10.384	10.637	11.097	11.875	12.066	12.76	13.703
42	9.101	9.177	9.616	10.447	10.618	11.25	12.054
52.5	8.998	9.043	9.415	10.236	10.393	11.008	11.82
63	9.055	9.09	9.468	10.322	10.478	11.104	11.902
73.5	8.564	8.607	8.985	9.764	9.957	10.706	11.695
84	8.389	8.49	8.99	9.54	9.91	10.52	11.6
94.5	6.33	6.74	6.95	7.12	7.87	8.13	8.41
105	4.59	4.931	5.14	5.46	5.95	6.24	6.54
115.5	0	0	0	0	0	0	0

The graphical representation of tabulated values is given below.

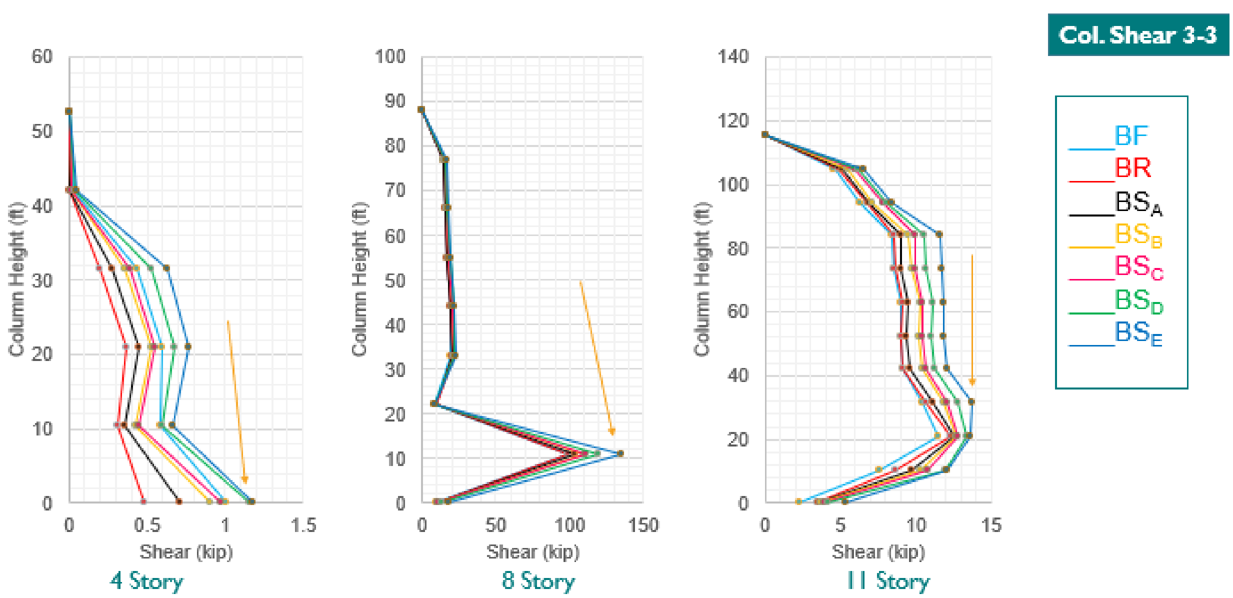

Figure 4-16: Shear force comparison of 3-3 direction

Among all the models, maximum variation is observed in model BF, BR, and BS_E at the base and lower portion of the buildings. The column shear results for BF, BR, and BS_E along with the percentage of their variations are presented below for better visualization. Column Shear 3-3 values for BF, BR and BS_E are shown below.

Figure 4-17: Column shear in 3-3 direction comparison of BF, BR and BSA

If we look at the variation from BF to BR a maximum of 28% decrease is observed in the case of 4 story building. The variation of BF to BR for 8 story and 11 story building is less than 1% that is almost the same as the Global response. This shows that foundation modeling reduces column shear of the low-rise building by increasing its stiffness at the base. The effect of increased stiffness at the base in terms of column shear is negligible in the case of mid-rise buildings.

By introducing soil springs at the base of raft footing, the column shear of 4 story building is increased 105% for BS_E. The effect of soil modeling is comparatively low in the case of 8 story and 11 story building that is 36% and 32% respectively. This trend is opposite to the trend of column shear in the 2-2 direction because the lateral force of ELF is applied perpendicular to the 3-3 axis of the column. In this case, the maximum variation is observed in the case of 4 story building, showing the highest effect of soil modeling on low rise buildings.

4.3 – Summary

Comparison of response parameters obtained by considering current design practices to the results obtained by considering base flexibility and SSI effects will be drawn. The result obtained by ELF analysis of building models with fixed base condition were tabulated. The ELF analysis was also performed with similar parameters and seismic response parameters for models with footing and soil springs were also extracted and compared with results of fixed base condition. This comparison helped in understanding the influence of SSI on typical structures of Pakistan because of local soil and site conditions. A set of recommendations is developed based on the obtained results.

Chapter – 05

Conclusions and Recommendations

5.1 Conclusions

A comparative analysis of typical buildings of Pakistan is performed by considering SSI effects due to all five soil types presented by the Building Code of Pakistan (BCP). Soft soil S_E displayed the maximum variation among all the soil types. Based on the results of the comparative analysis, the following conclusions are drawn.

- The seismic responses (displacements, inter-story drifts, shear forces and overturning moments) of low-rise buildings can be significantly affected by the foundation modeling and inertial soil-structure interaction as compared to mid-rise buildings.
- The modeling of the actual foundation (raft footing) with the superstructure can result in a considerable reduction in base shear values for low-rise buildings (when compared with the fixed based condition).
- In general, the effect of soil-structure interaction on seismic responses is more prominent for flexible soil conditions. The highest difference (compared to fixed support condition) is observed for S_E soil type. This observation is in line with several previous studies
- The natural time periods, lateral displacements and story drifts increased up to 24%, 21% and 52% respectively for 4 story building resting in S_E soil type (as compared with the fixed based condition).
- The overall results show that a significant reduction in all seismic demands can be obtained by including the actual foundation geometry and soil stiffness in the analysis model of RC low-rise buildings.

Base on the analysis of all the obtained results, it is concluded that SSI increases the seismic demands for low rise buildings constructed on S_E Soil Type. The SSI effect should be considered for such cases. The influence of SSI can be ignored for buildings above 10-story heights as this approach is more conservative. There was a considerable effect of soil modeling on the shear demands of all the buildings. The major difference was observed in mid-rise buildings. The trend of shear variation was the same for Global and Local response of buildings.

5.2 Recommendations

A set of recommendations is presented below.

- There is a need for special guidelines in the Building Code of Pakistan for incorporation of SSI effect for low-rise buildings constructed on S_E Soil Type.
- Further research should be carried out for Buildings with multiple basements and/or constructed on pile foundations to understand the embedment effect of soil conditions of Pakistan.
- Kinematic Interaction Effects are ignored in this research work. This research work should be expanded by studying the Kinematic Interaction Effects of soil on typical low to mid-rise buildings of Pakistan.

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Appendices

Appendix A: An Example for the Calculation of Soil Springs Properties

The following example elaborates on the calculation of soil spring properties.

The following two equations will be used in this example.

$$r_Z = \frac{\sqrt{LB}}{\pi} \text{ ----------------------- (i)}$$

$$K_Z = \frac{4G\Upsilon\mathbf{Z}}{(1-\mu)} \text{ --------------------(ii)}$$

Let's take a building with 40ft x 61ft (12.2m x 18.6m) raft footing resting on S_A soil type.

Length of footing = L = 12.2m

Width of footing = B = 18.6m

Using Equation (i), we get

Equivalent Radius = Υ_Z = 8.5m

Also,

Shear Wave Velocity = V_{s30} = 1600 m/s

Density of Soil = ρ = 4.5 KN/m^3

Shear Modulus of Soil = G = 7095 KN/m^2

Poisson Ratio = μ = 0.4

Using Equation (ii), we get

Modulus of Subgrade Reaction = K = 7095 $KN/m/m^2$

Modulus of Subgrade Reaction was assigned to Area Springs that were assigned under the Raft Footing by using 1 x 1 meshing.

Appendix B: Summary of Soil Properties of Case Study Buildings

Summary of Soil Properties of Case Study Buildings is shown here in the form of the following tables.

Table B-1: Soil properties for 4 story building

Summary of Soil Properties for 4B					
Soil Types	S_A	S_B	S_C	S_D	S_E
L	12.2	12.2	12.2	12.2	12.2
B	18.6	18.6	18.6	18.6	18.6
Υ_Z	8.498875	8.498875	8.498875	8.498875	8.498875
V_{s30}	1600	1125	500	225	150
ρ	4.434251	1.884709	2.85423	1.630989	0.570846
G	7094.801	2120.298	1427.115	366.9725	85.62691
μ	0.4	0.4	0.4	0.4	0.4
K	401985.5	120134.3	80859.16	20792.36	4851.55

Similar to the above table, all the calculations are repeated for 8 story building. Modulus of Subgrade Reaction (K) for all five soil types under consideration is calculated using dimensions of raft footing of 8 story building. Calculated values are shown in the following table.

Table B-2: Soil properties for 8 story building

Summary of Soil Properties for 8B					
Soil Types	S_A	S_B	S_C	S_D	S_E
L	20.3	20.3	20.3	20.3	20.3
B	56.2	56.2	56.2	56.2	56.2
Υ_Z	19.05642	19.05642	19.05642	19.05642	19.05642
V_{s30}	1600	1125	500	225	150
ρ	4.434251	1.884709	2.85423	1.630989	0.570846
G	7094.801	2120.298	1427.115	366.9725	85.62691
μ	0.4	0.4	0.4	0.4	0.4
K	901343.3	269368.6	181304.7	46621.2	10878.28

Summary of Soil Properties for 11 story building for all five soil types under consideration is given in the following table.

Table B-3: Soil properties for 11 story building

Summary of Soil Properties for 11B					
Soil Types	S_A	S_B	S_C	S_D	S_E
L	66.75	66.75	66.75	66.75	66.75
B	53	53	53	53	53
Υ_Z	33.55743	33.55743	33.55743	33.55743	33.55743
V_{s30}	1600	1125	500	225	150
ρ	4.434251	1.884709	2.85423	1.630989	0.570846
G	7094.801	2120.298	1427.115	366.9725	85.62691
μ	0.4	0.4	0.4	0.4	0.4
K	1587222	474345	319268.7	82097.68	19156.12