AN INVESTIGATION OF THE INERTIAL INTERACTION OF BUILDING STRUCTURES ON SHALLOW FOUNDATIONS WITH SIMPLIFIED SOIL-STRUCTURE INTERACTION ANALYSIS METHODS

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ABSTRACT

AN INVESTIGATION OF THE INERTIAL INTERACTION OF BUILDING STRUCTURES ON SHALLOW FOUNDATIONS WITH SIMPLIFIED SOIL-STRUCTURE INTERACTION ANALYSIS METHODS

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Seismic response of a structure is influenced by the inertial interaction between structure and deformable medium, on which the structure rests, due to flexibility and energy dissipation capability of the surrounding soil. The inertial interaction analyses can be performed by utilizing simplified soil-structure interaction (SSI) analyses methods. In literature, it is noted that varying soil conditions and foundation types can be modeled by using these SSI approaches with spring-dashpot couples having certain stiffness and damping.

In this study, the seismic response of superstructure obtained by using simplified SSI methods is compared with those of the fixed base systems. For this purpose, single and multi degree of freedom structural systems are modeled with both spring–dashpot couple and fixed base models. Each system is analyzed for varying structural and soil stiffness conditions under the excitation of three different seismic records. Next, the total base shear acting on the structural system and internal forces of load bearing members are investigated to observe the inertial interaction and foundation uplift effects on the superstructure. It is also aimed to examine the compatibility of the simplified SSI approaches utilized in the analyses.

It is concluded that the structural and soil stiffness parameters are the most influential parameters that affect seismic structural response. Structures become more sensitive to varying soil properties as the structural stiffness increases. On the other hand, decreasing soil stiffness also increases the sensitivity of the structure to the seismic excitation. Calculated values of total base shear and internal member forces revealed that the inertial interaction might be detrimental for the superstructure. Contrary to general belief, the fixed base approach does not always yield to the results, which are on the safe side. Considering the analysis results, it is concluded that SSI analysis is very useful for more precise and economical design for the seismic behavior.

Keywords: Soil-structure interaction, shallow foundations, simplified inertial interaction methods, foundation uplift

ÖZ

BASİTLEŞTİRİLMİŞ ZEMİN-YAPI ETKİLEŞİMİ ANALİZ YÖNTEMLERİ İLE SIĞ TEMELLER ÜZERİNE KURULU BİNA TÜRÜ YAPILARIN ATALET ETKİLEŞİMİ HAKKINDA BİR İNCELEME

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Bir yapının sismik tepki özellikleri, yapıyı çevreleyen zeminin esneklik ve enerji sönümleme kapasitesinden dolayı yapı ve yapının oturduğu deforme olabilen ortam arasındaki atalet etkileşiminden etkilenir. Atalet etkileşimi analizleri, basitleştirilmiş zemin-yapı etkileşimi analiz metodları kullanılarak gerçekleştirilebilir. Süregelen çalışmalarda, değişen zemin koşulları ve temel tiplerinin bu zemin yapı etkileşimi yaklaşımlarıyla, belirli rijitlik ve sönümleme kapasitesine sahip yay-amörtisör çiftleri kullanılarak modellenebileceğine dikkat çekilmiştir.

Bu çalışmada, üstyapıların zemin yapı etkileşimi metodları kullanılarak elde edilen sismik tepkisi sabit mesnetli sistemlerinkiyle karşılaştırılmıştır. Bu amaçla, tek ve çok serbestlik dereceli yapısal sistemler hem yay-amörtisör çiftleri hem de sabit mesnet sistemleri ile modellenmiştir. Her sistem değişen yapısal ve zemin rijitliği koşullarında üç farklı deprem kaydı altında analiz edilmiştir. Daha sonra, yapısal sistem üzerinde etkiyen toplam taban kesmesi ve yapısal elemanlarda oluşan içsel kuvvetler, atalet etkileşimi ve temel kalkmasının yapı üzerindeki etkilerini gözlemlemek üzere incelenmiştir. Ayrıca analizlerde kullanılan basitleştirilmiş zemin yapı etkileşimi analiz yaklaşımlarının uyumluluğunu incelemek amaçlanmıştır.

Sonuç olarak, yapısal ve zemin rijitlik değerleri yapının sismik davranışını etkileyen başlıca parametrelerdir. Yapısal rijitlik arttıkça, yapı değişen zemin özelliklerine karşı daha hassas bir hale gelmektedir. Diğer taraftan azalan zemin rijitliğide, yapının sismik itkilere olan hassasiyetini ayrıca artırmaktadır. Hesaplanan toplam taban kesmesi ve içsel kuvvet değerleri atalet etkileşimi analizlerinin yapı için hasar verici nitelikte olabileceğini ortaya çıkarmıştır. Genel inanışın aksine, sabit mesnet yaklaşımı her zaman güvenli tarafta kalan sonuçlar vermemektedir. Analiz sonuçları göz önünde bulundurulduğunda zemin yapı etkileşimi analizlerinin sismik etkilere karşı daha hassas ve ekonomik yapı tasarımı yapılması için çok faydalı olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Zemin-yapı etkileşimi, sığ temeller, basitleştirilmiş atalet etkileşimi yöntemleri, temel kalkması

To My Beloved Parents,

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LIST OF ABBREVIATIONS AND SYMBOLS

c	Damping coefficient
k	Stiffness
g_i	Storey dead loads
m	Mass
q_i	Storey live loads
r_1, r_2	Rotational degree of freedom
w_i	Storey weights
u	Displacement of lumped mass
u_1, u_2	Translational degree of freedom in horizontal direction
u_g	Horizontal support excitation
u_t	Total harmonic displacement
u_z	Vertical harmonic displacement
$\ddot{u}_z(t)$	Vertical harmonic acceleration
v_1, v_2	Translational degree of freedom in vertical direction
C_z	Dynamic dashpot constant
E_c	Elasticity modulus of concrete
F	Faulting type
G	Shear modulus
G_{tan}	Tangent shear modulus

G_{sec}	Secant shear modulus
K_z	Dynamic spring constant
K_{xx}, K_{yy}, K_{zz}	Rocking stiffness of foundation
$K_{x,y,z\ sur}$	Translational stiffness of foundation
Vs	Shear wave velocity
Mw	Moment magnitude
RFB	Joyner Boore distance
MDOF	Multi degree of freedom
SDOF	Single degree of freedom
MPSS	Multiple point spring system (Winkler Springs)
SPSS	Single point spring system (Gazetas' Springs)
ν	Poisson's ratio
ρ	Density
ω	Circular frequency
σ	Normal traction
v	Vertical displacement
K	Dynamic vertical impedance

CHAPTER 1

INTRODUCTION

1.1. General

With few exceptions, the structures are established on or in touch with ground. Since the deformable soil has significant effects on the overall seismic behavior of the structure, the interaction between the soil and the structure is to be taken into account. The way in which the superstructure resting on a deformable medium (soil) is influenced by the response of that medium is referred to as soil structure interaction (SSI).

There are different approaches to consider the effects of SSI on superstructures. One of the primary effects is to introduce soil stiffness to the system behavior. In other words flexible foundation behavior can be implemented into the system. During dynamic excitation, the forces will be transmitted from the superstructure to the soil. If the structure is resting on the deformable medium, these forces will produce a movement in foundation in contrast to a fixed-base structure. Displacements of the foundation affect the response of the structural system. The effects of deformable medium on the response of structural system are defined as inertial interaction. An important point is that, during the seismic excitation there will be deformations in the foundation soil even if the system has no mass. Because of that reason, movements of a rigid foundation on or embedded in deformable medium will be different from the free field deformations. This phenomenon is called kinematic interaction. In the general sense, kinematic interaction introduces the system a ground motion different from the free field acceleration. Effects of embedment and wave scattering are also taken into account in kinematic interaction.

Although the deformable soil has significant effects on the seismic behavior of the structure as discussed above, in practice, such effects are generally neglected in the design stage. While the influences due to SSI might be detrimental for the superstructure, there is a common belief that SSI has a beneficial effect on the seismic response of superstructure. In addition, many current design codes, such as Eurocode 8, NEHRP 1997, etc, state that SSI analysis can be neglected under certain circumstances.

SSI can be modeled by using various approaches, each having different modeling capability. Considering the features of the superstructure and foundation as well as the characteristics of foundation soils a proper method can be used. By utilizing numerical methods like finite element or finite difference, the soil can be modeled as continuum and the superstructure can be defined by suitable elements. Such approaches provide the designer with ability to perform rigorous nonlinear analysis through definition of a yield criterion for soil. However, this method is neither easy to apply nor efficient, particularly for the case of dynamic analysis. Accordingly, simplified approaches are often used in practice. Disc on surface of truncated semi-infinite translational or rotational cone models, discrete element model for cones or lumped parameter model consisting of springs and dashpots are widely used as simplified SSI analysis methods [2]. Despite the loss of precision, these simplified physical methods are capable of analyzing key aspects of the behavior such as the force-displacement relationship of system with reasonable effort, economy and accuracy.

In this study, the seismic response of SSI models consisting of springs and dashpots are compared with those of the fixed-base systems. Two different spring approaches are utilized; the first consists of rotational and translational (both vertical and horizontal) springs as well as the corresponding dashpots applied at the foundation level, the other, widely known as Winkler Springs [3] consists of only translational springs and dashpots but the vertical springs are numerous and are distributed beneath the foundation. Hence, these vertical springs provide both vertical and rotational stiffness at the foundation. It is to be noted that the Winkler Springs also have the advantage of modeling the uplift effects over the footing response. In this study, a series of parametric analyses are conducted to understand the effects of SSI on single degree of freedom (SDOF) systems (such as bridge piers and elevated storage tanks); and on multi degree of freedom (MDOF) systems (like ordinary building structures). The focus is on the comparison of the seismic behavior of the fixed-base structures and structures modeled by springs and dashpots to implement the SSI response.

1.2. Literature Review

The concept of interaction between the structure and soil has been studied for a few decades. The article published by Ehlers [5] on "The effect of soil flexibility on vibrating system" in 1942 is the pioneering study of SSI. Ehlers used translational truncated semi-infinite cone model to examine the vertical and horizontal motions of the foundation resting on homogenous halfspace. More than 30 years later, using spring-dashpot-mass model the rocking motion of the shallow foundations are examined by Meek [6] in 1974. Later, a different approach for simple SSI models is provided by Dobry and Gazetas [7]. Their approach consists of frequency-dependent foundation impedances and is applicable for any arbitrarily shaped rigid surface foundations. Although, this method was proposed for the machine foundations, Gazetas [8] simplified and generalized the formulations for practical use in 1991. Then in 1992, the function of semi-infinite cone model is expanded and formulized for homogeneous halfspace by Meek and Wolf [9]. Wolf also studied the modeling of response of a single pile in homogenous halfspace by generalizing the cone model [10]. In 1994, using double cones, embedded foundation in homogenous halfspace is modeled by Meek et. al. [11]. Stewart et.al. [12] made a comparison between the analytical methods and empirical formulations as a further study on the issue. The aim of that study was to compare the measured effects of SSI such as period lengthening and damping with the predictions of the analytical formulations [13].

Although SSI may have little effect on the dynamic response of many structures, it can have significant adverse effects as well. Depending on the circumstances, neglecting the effects of SSI might be conservative or unconservative and must be evaluated by a case study [4]. According to FEMA 440 [1], structural systems having lateral stiffener such as braced frames and structures that have shear walls, can be quite sensitive for base rotations and translations. In a study about analytical methods for SSI in buildings under seismic loads, it is emphasized that the effects of inertial interaction may be more important for foundations without large rigid base slabs or deep embedment [12].

Despite the fact that different mechanisms existing between the soil and the structure established on it have significant effects on dynamic response, whether such effects are beneficial or not on the seismic response depends on the circumstances. However, in some current design codes the SSI effects are presumed to have beneficial effects on the structural response. In Eurocode 8 [14], it is stated that; "For the majority of common building structures, the effects of SSI tend to be beneficial, since they reduce the bending moments and shear forces in the superstructure". A similar point of view is also adopted by NEHRP 97 [15]. On the other hand, some studies reveal that under certain circumstances SSI might be detrimental for the superstructure. Mylonakis and Gazetas [16] have shown that when the recorded motions are used instead of idealized design spectra specified by the codes, increased fundamental period and the damping due to SSI does not necessarily yield to beneficial results. Contrarily, depending on the characteristics of the seismic records and the structural attributes, SSI analysis may be detrimental.

Gazetas and Apostolou [17] have studied the foundation uplift which is another phenomenon involving SSI. To examine the effects of uplift, separation of the vibrating footing from supporting soil is considered instead of fully bonded contact between the foundation and soil. Gazetas et. al. found out that uplifting behavior of the foundation of relatively tall structures is affected by both soil flexibility and bearing capacity of the soil. On the other side, the studies show that initiation of the uplift is closely related with the fundamental period of the structure and the characteristics of the ground shaking.

There exist different approaches to assess the SSI effects. Current analysis procedures defined in FEMA 356 [18] propose mainly two simplified SSI methods to introduce the flexibility of foundation by considering soil stiffness. Both of the approaches in which the foundation soil behavior is represented by springs and dashpots are mainly based on inertial SSI. The first method that is developed by Gazetas [8] is applicable for any solid base slab. In this method, the shape of the foundation, type of soil profile and the embedment of the footing can be taken into account. The spring coefficients given in FEMA 356 [18] for rectangular foundations are adapted from those suggested by Gazetas [8]. A representative drawing for Gazetas' soil model of springs and dashpots is given in the Figure 1.2.1

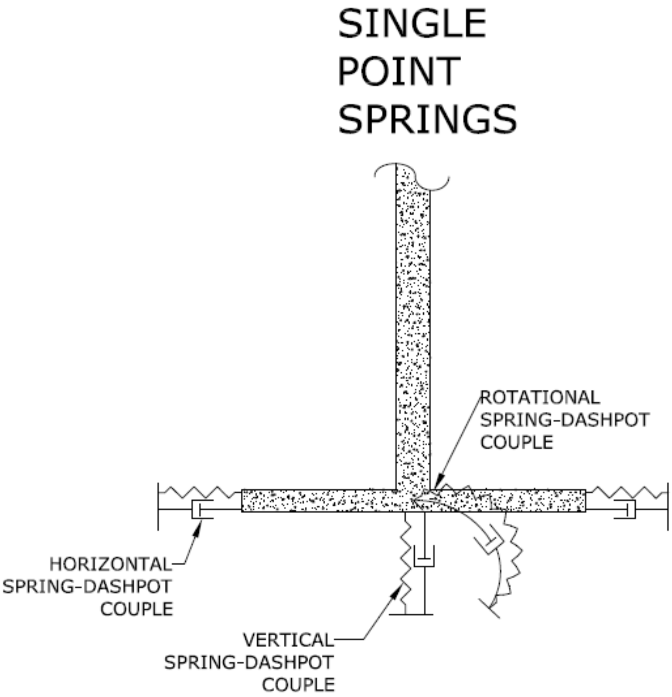


Figure 1.2-1 Gazetas's soil model of springs and dashpots

The other approach is the Winkler Springs Method. This method is applicable for shallow foundations as well as piles. The soil can easily be modeled to respond as linearly or non-linearly. This approach is also capable to model the foundation uplift behavior. In Figure 1.2.2 a representative drawing is given for a Winkler Springs model. When compared with the complete analysis of the soil and structural system by utilizing finite element method, Winkler Springs approach needs significantly less computational effort [3].

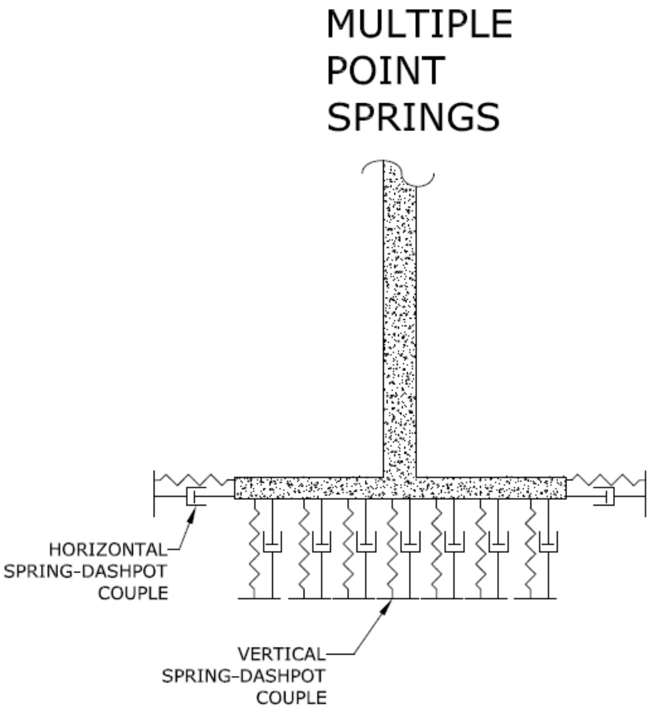


Figure 1.2-2 Winkler springs

In FEMA 440 [1], a general explanation about the simplified analysis methods is provided., the free field motion with 5% damping is suggested to be used as seismic demand for estimating the flexibility and strength of the springs conventionally in FEMA 440 [1]. On the other side, the stiffness coefficients defined in FEMA 356 [18] have been established on certain assumptions regarding soil strength, such that the foundation soil is presumed not to lose strength under seismic loading. It is also assumed that the soils have adequate ductility unless the stiffness and strength of the soil degraded considerably under cyclic loads.

In both of the simplified methods defined in FEMA 356 [18], the stiffness coefficients of the springs directly depend on soil shear modulus and Poisson’s ratio. Although soils under cyclic loading typically exhibit hysteretic behavior, the stiffness coefficients given in FEMA 356 are linear. The hysterical behavior can be approximated by using secant shear modulus of the hysteresis loop, instead of using tangent shear modulus [4]. A representative drawing for the stress-strain behavior of cyclically loaded soils is shown in Figure 1.2-3. The inclination of the loop given in that figure directly depends on the soil stiffness. The shear modulus of the specimen at any loading point can be defined by the tangent shear modulus, (G_{tan}). Since the tangent modulus varies through the loading process, secant shear modulus (G_{sec}) can be used as an average value of the loop. The secant shear modulus can be defined by the ratio of shear stress, ζ_c and shear strain, γ_c.

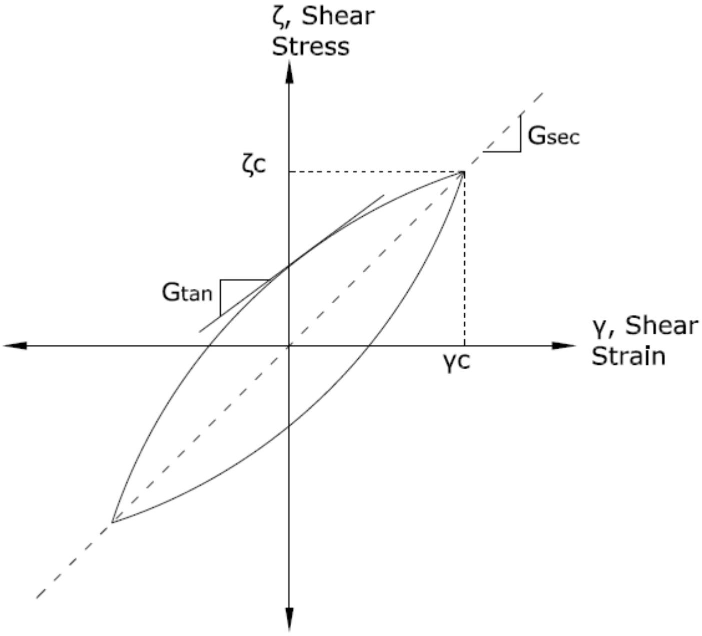


Figure 1.2-3 Tangent and secant shear moduli of cyclically loaded soils [4]

Such modeling of soil stiffness is known as equivalent linear model. In equivalent linear model, the damping ratio can be linearized as well. This model provides considerable computational efficiency in dynamic analysis and due to that reason, it is widely used.

1.3. Objective and Scope

The objective of this study is to provide an assessment of the effects of deformable foundation soils on the superstructure response under seismic loading conditions. This study aims to find out whether the ignored effects of SSI are beneficial or detrimental for the superstructure.

In order to be able to make a comparison between the general trend in design (fixed-base assumption) and that involving the SSI, both approaches are evaluated. In those analyses involving SSI, the inertial interaction mechanism is utilized by using the simplified methods defined in FEMA 356 [18]. The spring coefficients used the analyses are defined based on the equivalent linear model assumption. These analyses are performed for a set of parameters that are representative for a wide range of soil and structural stiffnesses. Time history analyses are employed in the dynamic solutions under seismic loading.

To examine the structural response, both single degree of freedom (SDOF) oscillator and frame systems are utilized. The foundation system is considered as composed of single footings resting on homogeneous elastic halfspace. A damping ratio of 5% is presumed for the structure. In addition, since the inertial interaction effects are more pronounced for the surficial foundations, no foundation embedment is taken into account.

Two different simplified spring models are employed to compare the response of inertial effects of SSI on superstructure resting on elastic halfspace with fixed-base system. These models are Gazetas' springs and Winkler springs models. In Winkler method, foundation uplift phenomenon is also examined.

The thesis is composed of five chapters. The object and scope of the study, and a brief literature survey are given in this chapter.

Chapter 2 presents the methodology of the performed analyses. The structural and foundation models and the analyses methods are explained, and the summary information about the used acceleration records is given in Chapter 2.

Chapter 3 presents the results of the analyses of parametric studies. For a given set of parameters, analyses are performed for three different foundation models and three different structure models with varying stiffnesses and three different time history records for different soil profiles.

Chapter 4 presents a discussion of the results given in Chapter 3 and conclusions of the study.

Finally, suggested future studies are given in Chapter 5.

CHAPTER 2

ANALYSIS METHODOLOGY

2.1. Introduction

In this chapter, modeling and analysis approaches that are utilized to examine the behavior of fixed based structure and the structure resting on deformable soil are explained. Particular types of modeling are utilized to examine the effects of SSI under different circumstances. Although there exist many possible simplified approaches to model the foundation, two of the proposed approaches that define the deformable medium as springs and dashpots are discussed in this section in detail. These widely used approaches suggested by FEMA 356 [18] are those proposed by Gazetas and the Winkler Springs procedures. In FEMA 356 [18], both of these procedures that simplify the SSI analysis are defined. The procedures introduce the inertial interaction effects of the SSI in an efficient and economical way. Definitions of the springs proposed by FEMA 356 [18] are based on the approach of equivalent linear model.

The foundation modeling approaches are applied on different superstructural systems to make a generalization of the structural response. Two different idealized structural systems are used in the analyses: first, simple SDOF systems and second, MDOF frame systems. By performing these analyses on different structural systems, it is intended to understand the effects of SSI on the general response of structural systems.

On the following pages, the modeling approaches for both the foundation and superstructure resting on it are defined in detail. Combining the different modeling approaches, the effects of SSI are examined for a wide range of varying soil and structural parameters. The basis of the assumptions and the analysis methods utilized in this study are also described in this chapter.

2.2. Modeling Approaches

2.2.1. Structural Modeling Approaches

Idealized structural systems are used to capture the general trends in the structural response as a function of various parameters. In the initial stage of the study, the parametric studies are performed utilizing a relatively simpler structural model. Accordingly, the structures are idealized with a lumped mass and a massless load bearing structural element (SDOF). In the latter stages of the study, the analyses performed for the simple structures are also applied on the frame systems (MDOF). Load bearing elements utilized in both of the structural systems are considered as linear elastic in the analyses. The idealized structural models utilized during the case studies are defined in this section.

2.2.1.1. Single Degree of Freedom Systems

At the outset, the response of structures such as elevated water tanks and bridge piers that can be idealized as a concentrated mass supported by a beam element are studied. A representative sketch for an elevated water tank and its idealization is given in Figure 2.2-1a.

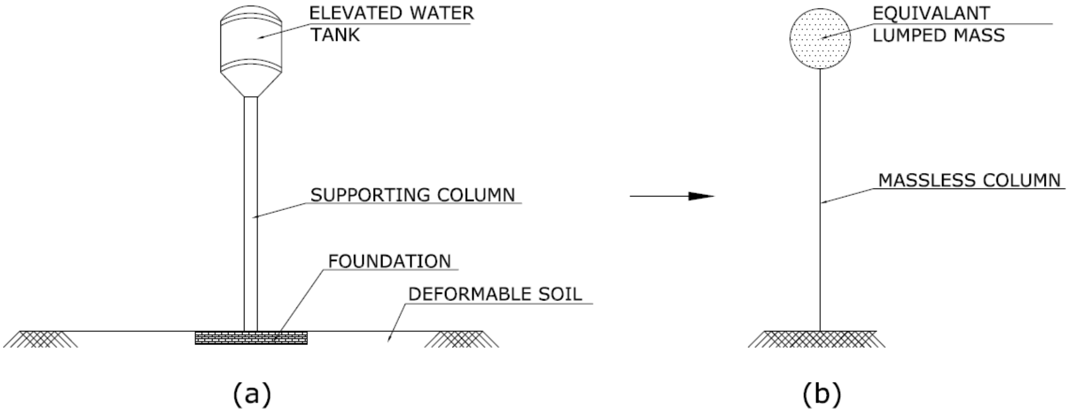


Figure 2.2-1 Elevated water tank (a) and its idealization (b)

When the tank is full, the mass of the water can be considered as lumped, and when compared with the water mass, the relatively light supporting column can be defined as massless as shown in Figure 2.2-1b.

As also presented in Figure 2.2-2, simply the system consists of a lumped mass (m), a massless axially rigid column having a lateral stiffness (k) and a damping (c). The response of the column is presumed to be elastic throughout the analyses under any loading condition.

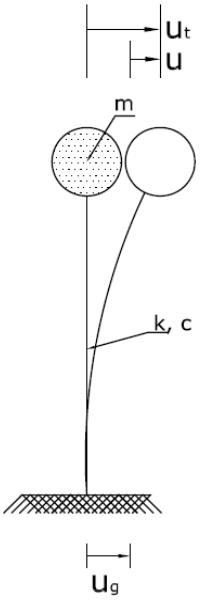


Figure 2.2-2 SDOF system behavior subjected to ground motion

2.2.1.2. Multi Degree of Freedom Systems

After examining the behavior of SDOF systems for both fixed based and based on deformable soil, the analyses are extended with the structures having finite number of degrees of freedom. Simple Multi Degree of Freedom (MDOF) systems are utilized in order to model typical building type frame structures. In Figure 2.2-3, a three-dimensional view of the structure used in the analyses is given.

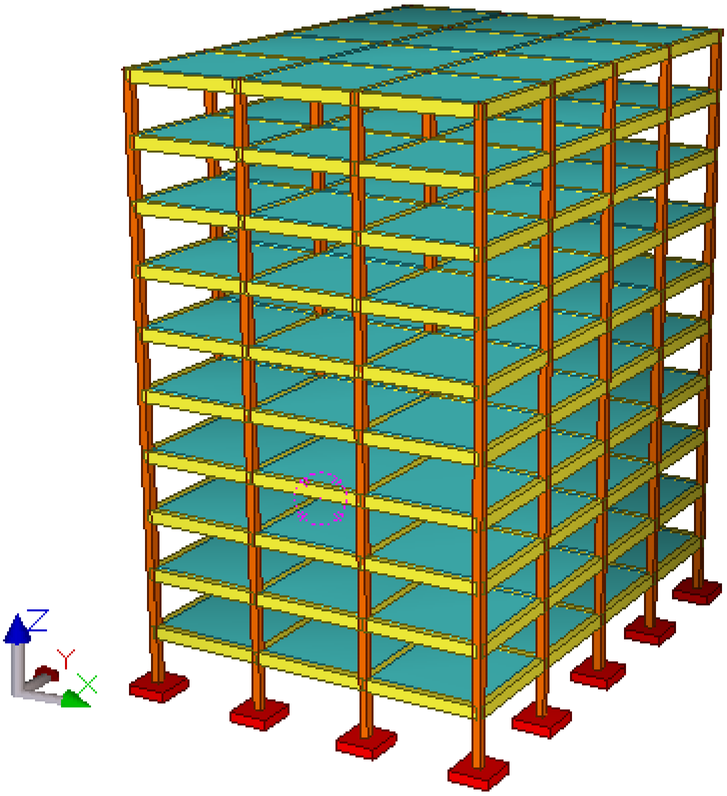


Figure 2.2-3 Three-dimensional view of the typical analyzed structure

Since most of the building type structures have a uniform shape both in floor plan along with the floor height, a typical building for any arbitrary axis length, storey height, and column and beam dimensions, as shown in Figure 2.2-4, is selected for the analyses. Analyses are performed in 2-dimensions.

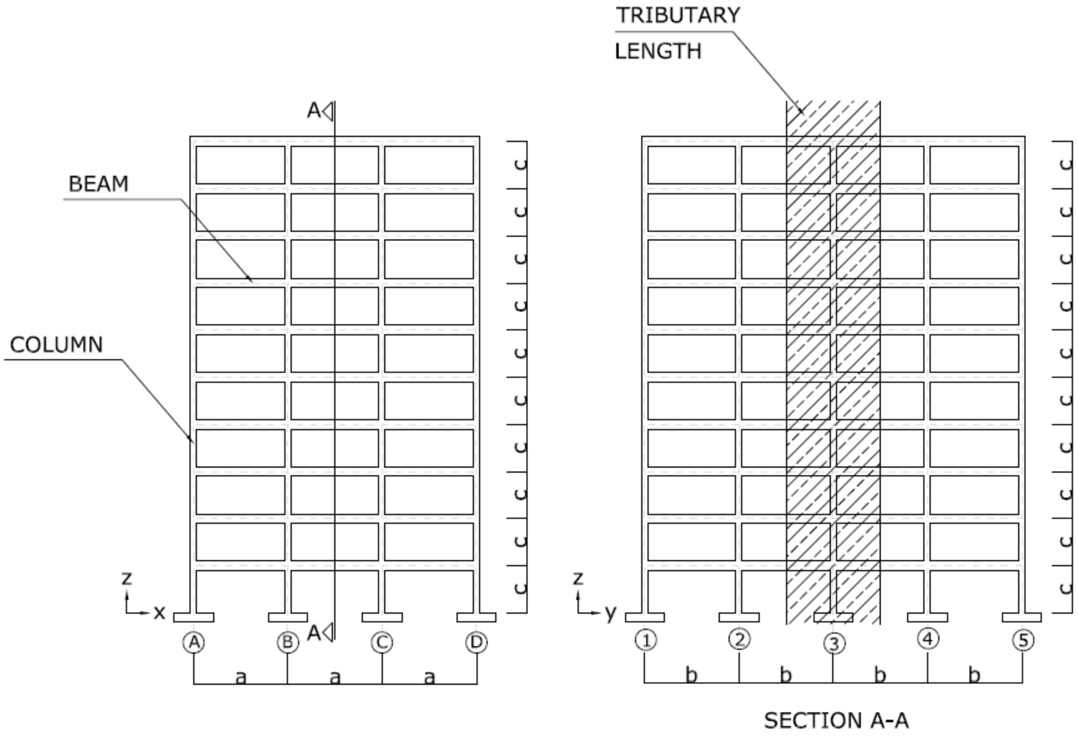


Figure 2.2-4 Sectional views of the building

The structure is modeled by frame elements having six degrees of freedom as shear frame system. In each end of the frame member, there exist one rotational and two translational degrees of freedom representing the axial load, shear load and bending moment as shown in Figure 2.2-5.

Figure 2.2-5 Degrees of freedom of a frame member

In the analyses, the distributed mass of the system throughout the building is considered to be concentrated at floor levels. This concentrated mass is applied on columns according to their tributary areas as lumped masses as shown in Figure 2.2-6.

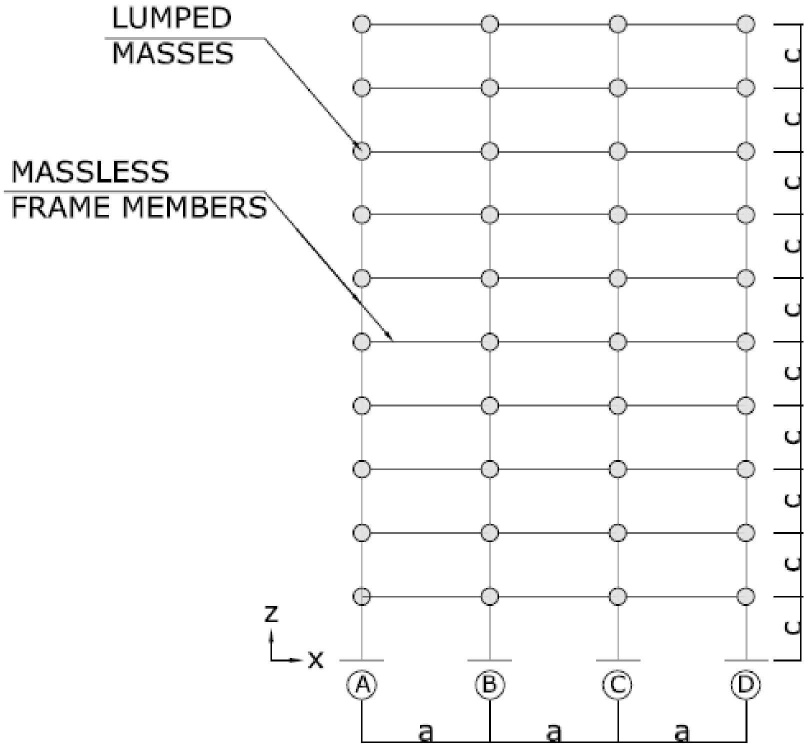


Figure 2.2-6 Idealized model of the building structure used in the analysis

2.2.2. Foundation Modeling Approaches

Depending on the flexibility of the soil on which the structure rests, foundations oscillate when the dynamic loads are applied. Diverse factors such as the characteristics of the underlying soils, attributes of the foundation and the structural system, nature of the dynamic loading affect the oscillation behavior of the foundation during seismic excitation. To make a comparison between the behavior of the fixed based structures and structures resting on deformable soil two different modeling approaches are used in the models. The two approaches known as Winkler Springs and that proposed by Gazetas take into account the stiffness properties of the soil-foundation system in terms of inertial interaction of the SSI. In the following sections these method are described in detail.

2.2.2.1. Fixed Base System

The most widely used and the simplest analysis approach for modeling the foundations of structures is fixed base assumption. In the fixed base analysis approach, the system is presumed to be resting on an infinitely stiff medium and besides incapable of uplift. A simplified model for fixed based structure is shown in Figure 2.2-7.

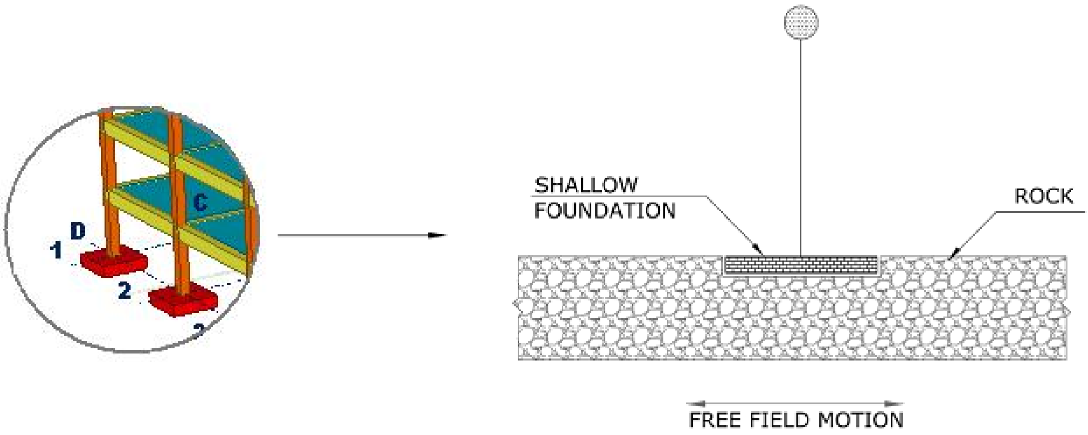


Figure 2.2-7 Fixed base modeling approach

Due to its simplicity and presuming the results produced remain on the safe side when compared to those methods that consider SSI, many current design codes recommend fixed base approach. Accordingly, the stiffness of the foundation system and the soil layer on which the foundation is situated are ignored in this approach. More recently, however, research shows that depending on the circumstances this approach does not always provide solutions on the safe side. Besides, the solutions can be uneconomical in many cases.

2.2.2.2. Single Point Springs System (Gazetas' Springs)

The spring-dashpot system proposed by Gazetas is mainly developed for the vibratory response of rigid foundations subjected to dynamic excitation generated by a machine. In general, rigid reinforced concrete blocks are used as foundation for most of the machine foundations. The dynamic response of these blocks stems from the deformation of the ground, and due to that reason, the system has six degrees of freedom and the foundation is treated as a rigid block in general as shown in Figure 2.2-8.

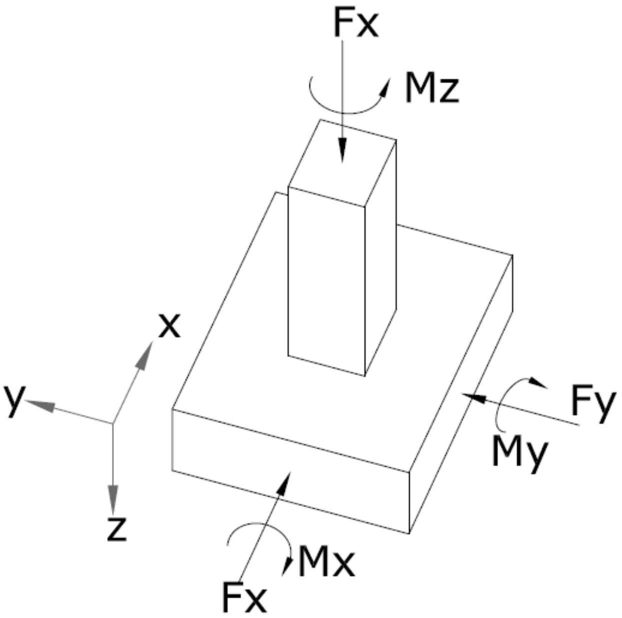


Figure 2.2-8 Degrees of freedoms of a rigid foundation block

Gazetas [8] developed a general method to obtain dynamic displacements and rotations due to steady state harmonic excitations for each of the 6 degrees of freedom. Since any non-harmonic excitation can be defined through superposition of a number of sinusoidal functions by the use of Fourier Transformation, utilizing harmonic excitations to characterize seismic load effects is a rational approach.

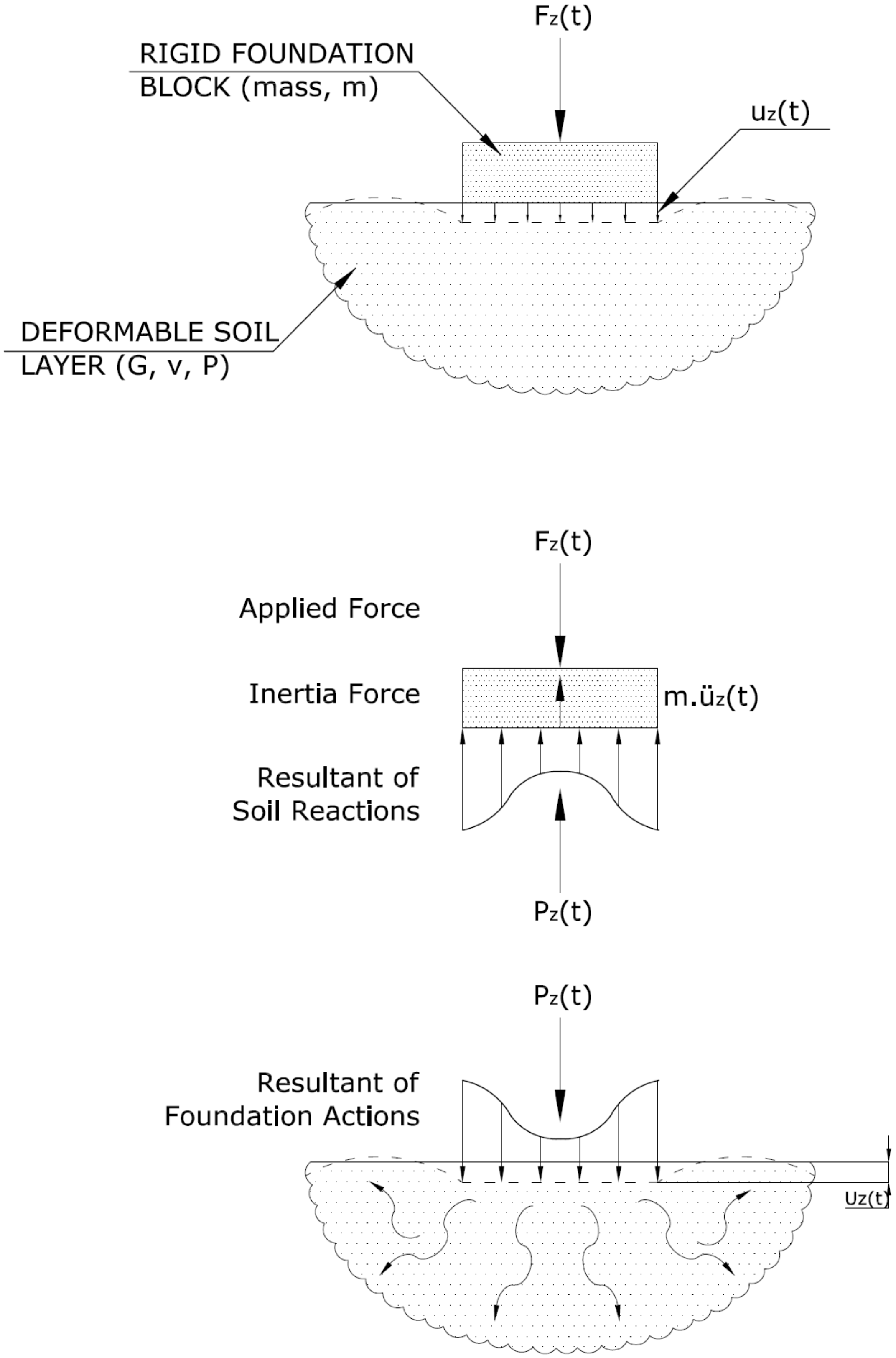


Figure 2.2-9 Force diagram of vertically vibrating foundation

The dynamic force equilibrium of the free body diagram given in Figure 2.2-9 can be written as follows;

$$P_z(t) + m\ddot{u}_z(t) = F_z(t) \qquad \text{(Eq. 2.2-1)}$$

$$P_z(t) = \kappa_z u_z(t) \qquad \text{(Eq. 2.2-2)}$$

Eq. 2.2-1 and Eq. 2.2-2 define the force equilibrium of the rigid foundation and the soil layer respectively. The "K" given in Eq. 2.2-2 represents the dynamic vertical impedance of the system. When these two equations are combined,

$$\kappa_z u_z(t) + m\ddot{u}_z(t) + F_z(t) = 0 \qquad \text{(Eq. 2.2-3)}$$

Eq. 2.2-3 is obtained. The only unknown parameter in the combined equation is the vertical dynamic impedance of the system. Utilizing theoretical and experimental results, Gazetas derived the dynamic impedance as;

$$\kappa_z = \bar{K}_z + i\omega C_z \qquad \text{(Eq. 2.2-4)}$$

In Eq. 2.2-4, K_z and C_z are the frequency dependant soil parameters related with the stiffness and damping properties of the system. Here, K_z refers to the dynamic stiffness and C_z is the damping coefficient of the medium. Since the response of the system to the harmonic excitation is needed, the impedance equation (Eq.2.2-4) is substituted into the dynamic force equilibrium equation (Eq.2.2-1) to obtain the equation of motion of the simple oscillator having mass (m), spring constant (K_z) and dashpot constant (C_z).

$$m\ddot{u}_z(t) + C_z\dot{u}_z(t) + K_z u_z(t) = F_z(t) \qquad \text{(Eq. 2.2-5)}$$

Finally, the amplitude of the vertical oscillation is derived as follows;

$$u_z = \left|\bar{u}_z\right| = \frac{F_z}{\sqrt{\left(K_z - m\omega^2\right) + \omega^2 C_z^2}} \qquad \text{(Eq. 2.2-6)}$$

The response of soil against a vertically oscillating foundation is defined by Eq. 2.2-6 containing frequency dependent spring stiffness and dashpot coefficients. For the other five degrees of freedom utilizing a similar approach the response of foundation can be generalized. However, since the response for each degree of freedom is dependent on excitation frequency, Gazetas re-derived the spring and dashpot coefficients for a particular excitation frequency and presented it for any solid base-mat shape resting on or embedded in homogeneous half-space [8].

Although the spring and dashpot coefficients for arbitrarily shapes of the base-mat on the surface of or embedded in the homogeneous half-space are presented in “Foundation Engineering Handbook, 1991” [8], since rectangular foundation shapes are mostly used in buildings the given coefficients are optimized for rectangular footings in FEMA 356 [18]. Orientation of the foundation for the given formulas is illustrated in the Figure 2.2-10. In this figure, G represents the shear modulus and v is the Poisson’s ratio of the deformable soil.

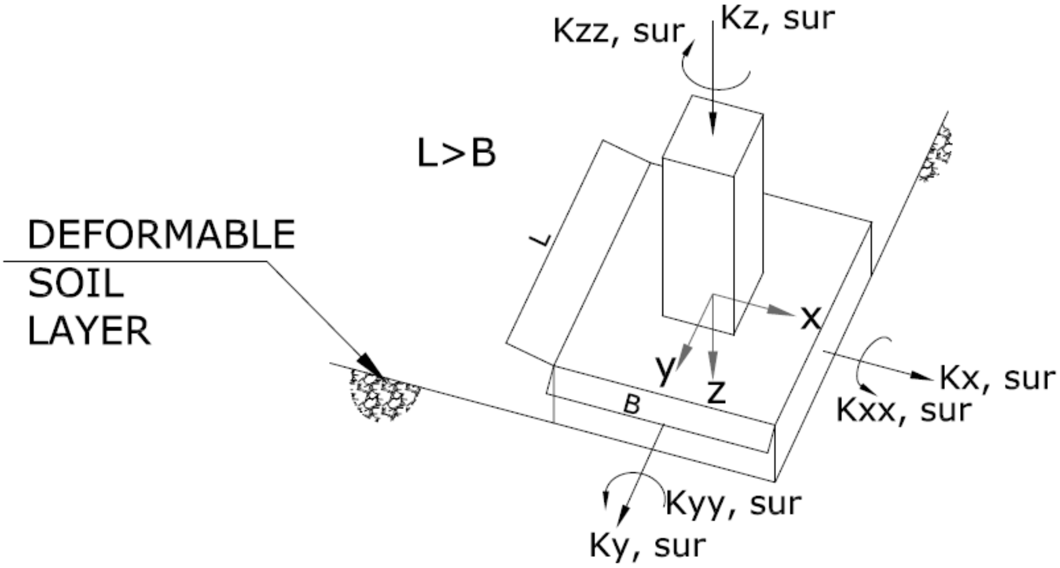


Figure 2.2-10 Foundation system orientation

The spring coefficient formulations given below for each degree of freedom are compatible with the orientation given in Figure 2.2-10.

Translation along x-axis

$$K_{x,sur} = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right] \tag{Eq. 2.2-7}$$

Translation along y-axis

$$K_{y,sur} = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 0.4\frac{L}{B} + 0.8\right] \tag{Eq. 2.2-8}$$

Translation along z-axis

$$K_{z,sur} = \frac{GB}{1-\nu}\left[1.55\left(\frac{L}{B}\right)^{0.75} + 0.8\right] \tag{Eq. 2.2-9}$$

Rocking about x-axis

$$K_{xx,sur} = \frac{GB^3}{1-\nu}\left[0.4\left(\frac{L}{B}\right) + 0.1\right] \tag{Eq. 2.2-10}$$

Rocking about y-axis

$$K_{yy,sur} = \frac{GB^3}{1-\nu}\left[0.47\left(\frac{L}{B}\right)^{2.4} + 0.034\right] \tag{Eq. 2.2-11}$$

Rocking about z-axis

$$K_{zz,sur} = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45} + 0.51\right] \tag{Eq. 2.2-12}$$

When the calculations are performed in two-dimensional space, the spring coefficients of translation along x and z-axes and rocking about y-axis are used.

2.2.2.3. Multiple Point Springs System (Winkler Springs)

Winkler spring-dashpot model is the other widely used approach capable of describing the behavior of rigid foundations subjected to combined vertical, horizontal and moment loading defined in FEMA 356 [18]. This modeling approach is based on the parameter of modulus of subgrade reaction.

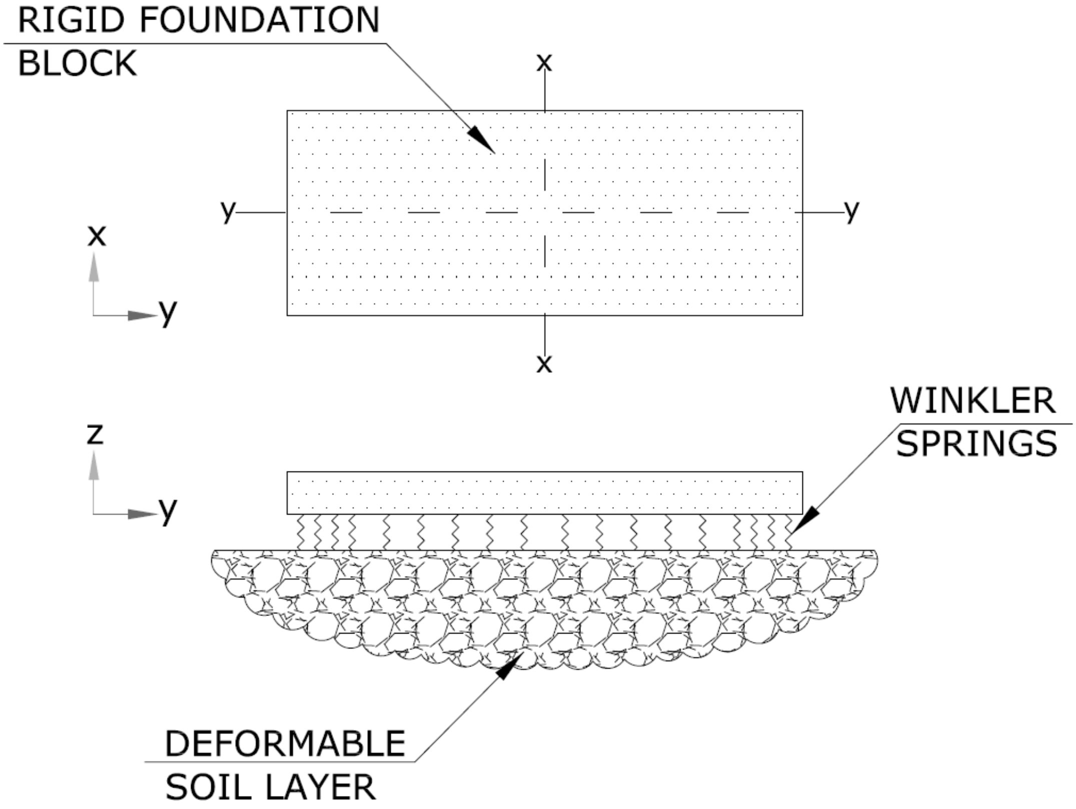


Figure 2.2-11 A representative modeling approach with Winkler Springs

In Figure 2.2-11, a representative drawing for the Winkler spring approach is shown. Considering the loading condition, the behavior of springs in terms of the relationship between normal traction, σ and vertical displacement, v can be defined as shown in Figure 2.2-12 [3]. If the system is subjected to pure vertical load, it is convenient to use the spring having the property represented in Figure 2.2-12a. However, since in general horizontal loads and bending moments also act on the foundation system, contact separation between foundation and soil can be introduced as shown in Figure 2.2-12b. Therefore, the Winkler springs utilized in the analyses are defined to be capable of simulating tension cut off during analyses according to the behavior illustrated in the Figure 2.2-12b.

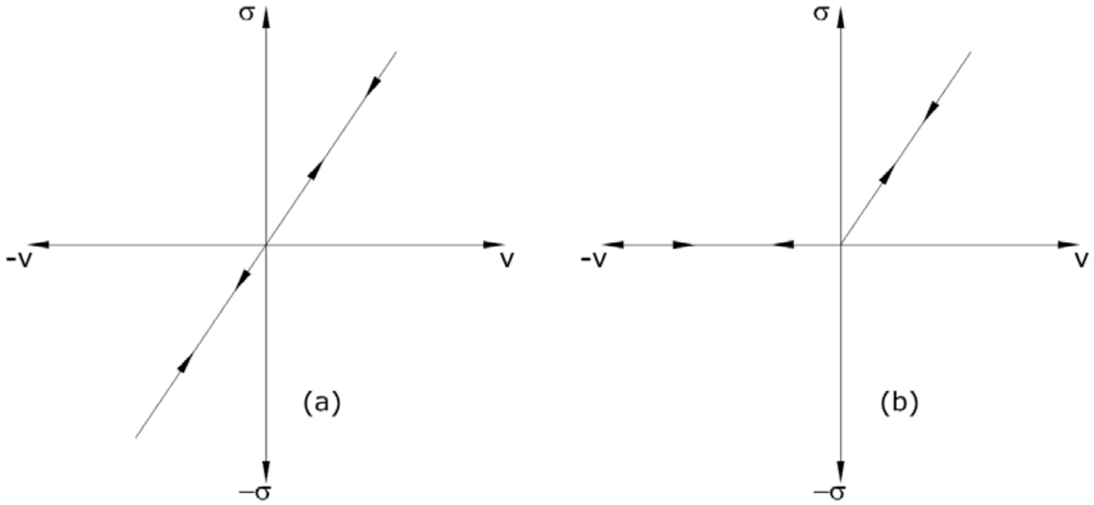


Figure 2.2-12 Alternative spring behavior models

In FEMA 356 [18], the distributed vertical stiffness of the springs is derived by dividing the total vertical stiffness of the foundation to the foundation area. On the other hand, using a similar approach, the rotational stiffnesses of the distributed springs are obtained by dividing the rotational stiffness of the foundation by the moment of inertia of the foundation. However, the soil response beneath the rigid foundation is not uniform. Accordingly, the vertical and rotational stiffnesses of the defined springs are variable.

The base-contact pressure distribution variation beneath a foundation is shown in Figure 2.2-13a and 2.2-13b for clayey and sandy soils, respectively. As a result, springs with different stiffnesses are used to model the soil response as shown in Figure 2.2-14.

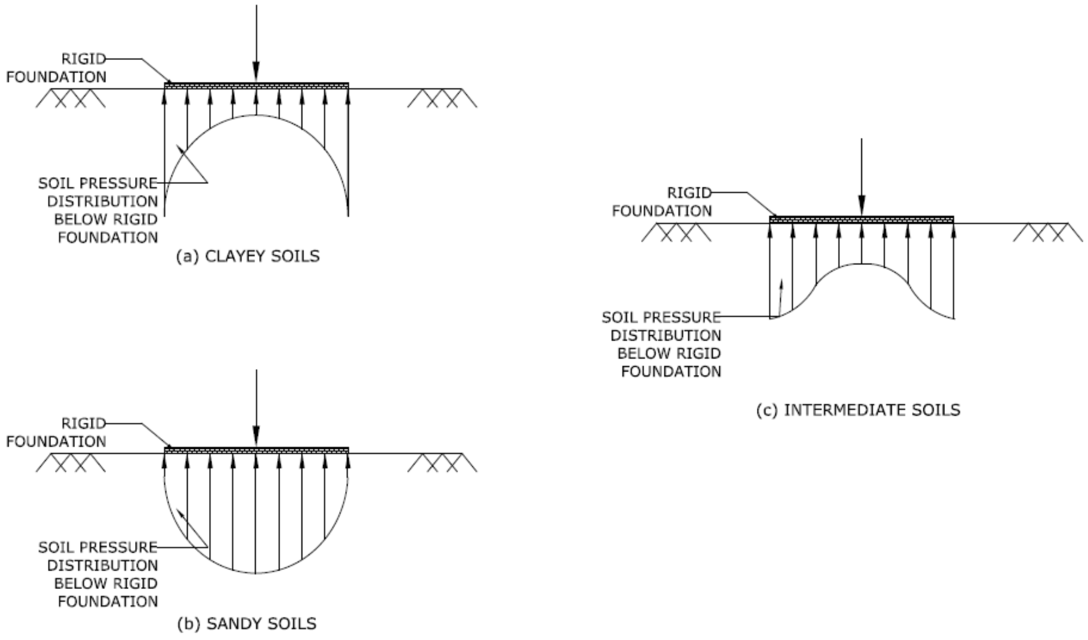


Figure 2.2-13 Soil behavior under vertical load below rigid smooth foundation

The vertical stiffness of the springs defined in FEMA 356 [18] is given below. The orientation of the identities expressed by the given formulas is presented in Figure 2.2-14.

Stiffness coefficient of the vertical spring located near the edge

$$k_{end} = \frac{6.83\,G}{1 - \nu} \qquad \text{(Eq. 2.2-13)}$$

Stiffness coefficient of the vertical spring located near the middle of foundation

$$k_{mid} = \frac{0,73\,G}{1 - \nu} \qquad \text{(Eq. 2.2-14)}$$

Where, G represents the Shear Modulus and ν is the Poisson’s ratio of the deformable soil.

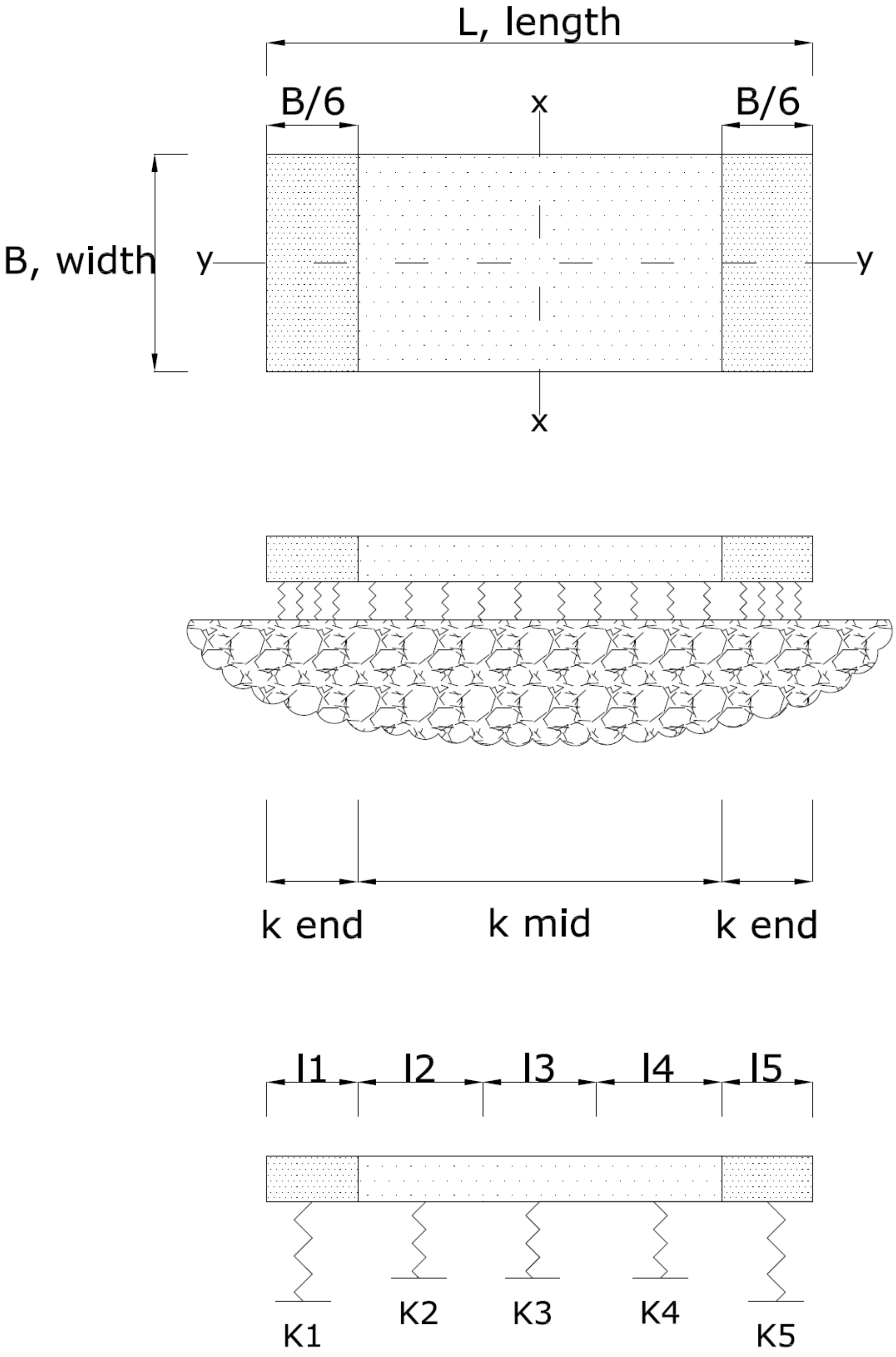


Figure 2.2-14 Winkler Springs representation

2.3. Methods of Analysis

2.3.1. Time History Analysis Records

It is well known that the deformable foundation medium elongates the fundamental period of the structural system. Due to that reason, if the idealized response spectra defined in current codes are used in the dynamic analyses, SSI results in a beneficial effect on most of the superstructures. However, there exists exceptions and hence the limitations are to be tested.

Three different synthetically generated time history records adopted from "Limitations on Point-Source Stochastic Simulations in terms of Ground-Motion Models" [24] used in the parametric studies. One selected sample record is representative of three different sites considering local site effects by the help of the software, ProShake [25]. During optimization, Monte Carlo Simulation Technique is performed for the selected depth of soil profile, thickness, dynamic properties and shear wave velocity of the layers. Moreover, fault type, fault distance and moment magnitude of the earthquake are also taken into account. The records are optimized for a strike-slip fault and closest distance from site to the vertical projection of the fault rupture (Joyner-Boore Distance) is selected as 17.3 km. The moment magnitude of the seismic excitation for each record is defined as 6.4. The site classifications and the shear wave velocity ranges for the records are as follows;

- For Rock Site : $760 \text{ m/s} < V_s \leq 1500 \text{ m/s}$
- For Dense Soil Site : $360 \text{ m/s} < V_s \leq 760 \text{ m/s}$
- For Soft Soil Site : $180 \text{ m/s} \leq Vs \leq 360 \text{ m/s}$

where V_s ranges for the given site classes are adopted from NEHRP [15].

The plots of the mentioned time-history records and the response spectrum for each record are shown in Figures 2.3-1 to 2.3-6.

PLOT OF TIME HISTORY RECORD REPRESENTATIVE OF SOFT SOIL SITE EFFECTS

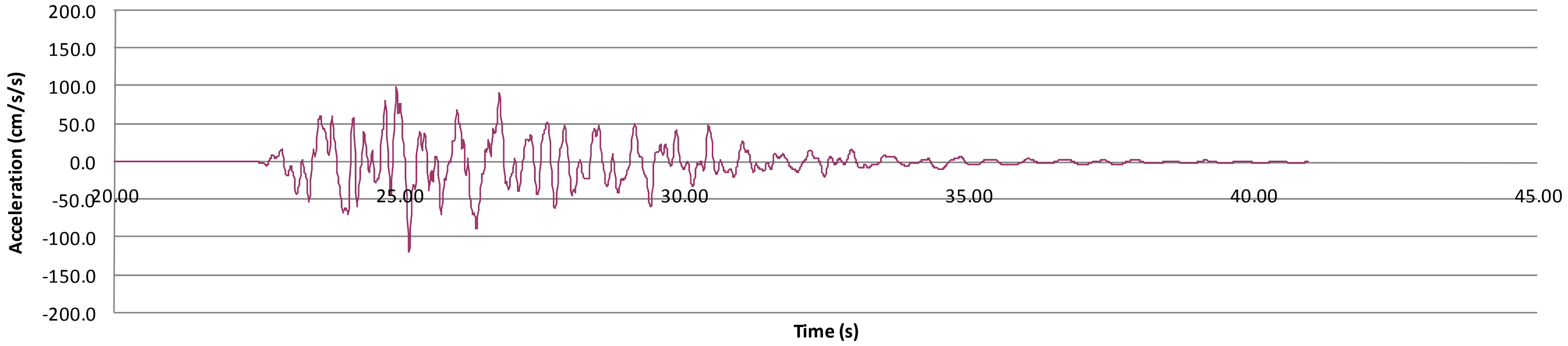


Figure 2.3-1 Plot of time history record representative of soft soil site effects

Shear Wave Velocity	Vs= 180 m/s ≤ Vs ≤ 360 m/s
Moment Magnitude	Mw=6.4
Faulting Type	F=Strike-Slip
Joyner-Boore Distance	RFB= 17.3 km

PLOT OF TIME HISTORY RECORD REPRESENTATIVE OF DENSE SOIL SITE EFFECTS

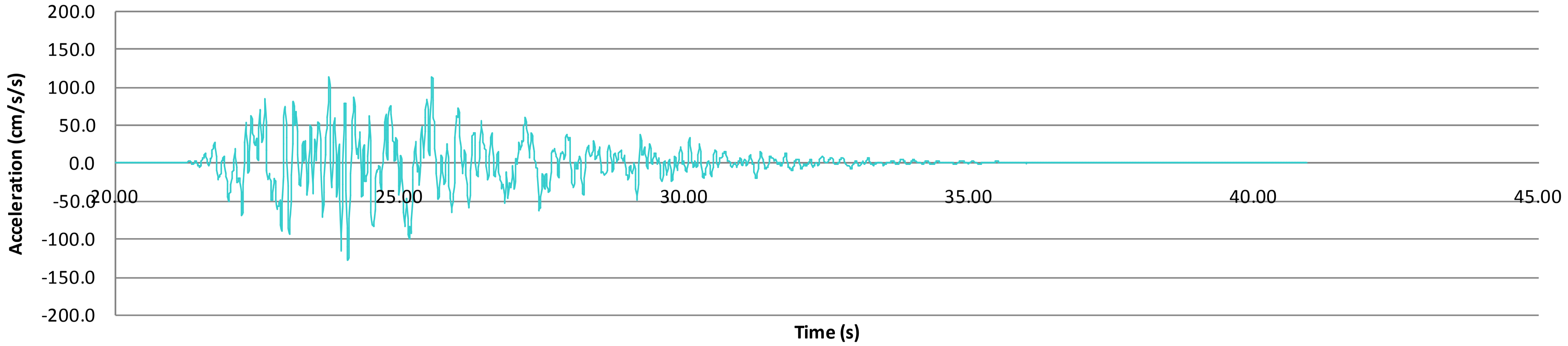


Figure 2.3-2 Plot of time history record representative of dense soil site effects

Shear Wave Velocity	Vs= 360 m/s < V_s ≤ 760 m/s
Moment Magnitude	Mw=6.4
Faulting Type	F=Strike-Slip
Joyner-Boore Distance	RFB= 17.3 km

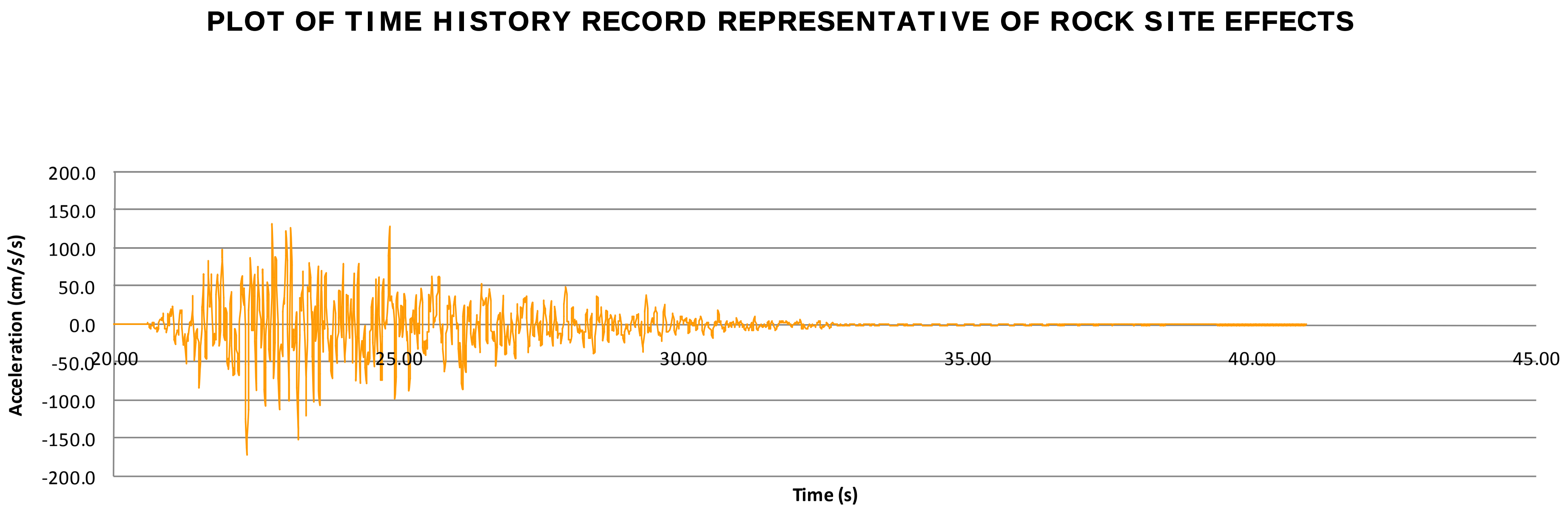


Figure 2.3-3 Plot of time history record representative of rock site effects

Shear Wave Velocity	Vs= 760 m/s < V_s ≤ 1500 m/s
Moment Magnitude	Mw=6.4
Faulting Type	F=Strike-Slip
Joyner-Boore Distance	RFB= 17.3 km

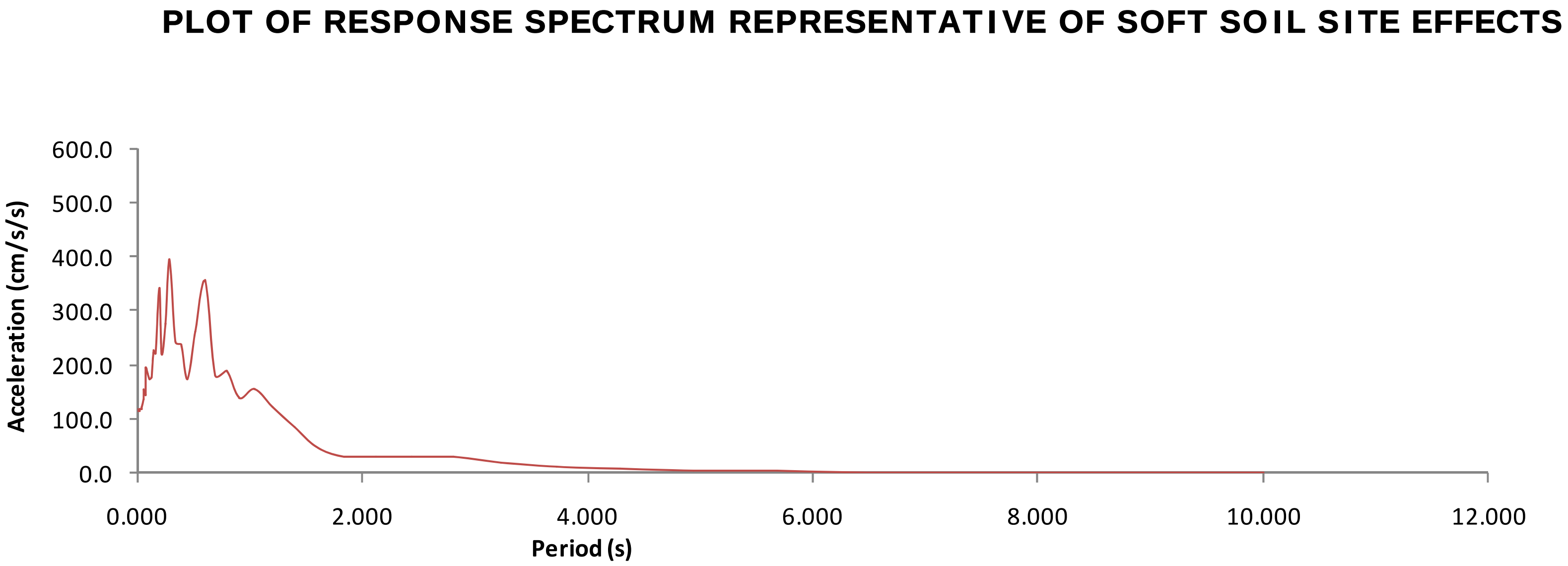


Figure 2.3-4 Plot of response spectrum representative of soft soil site effects

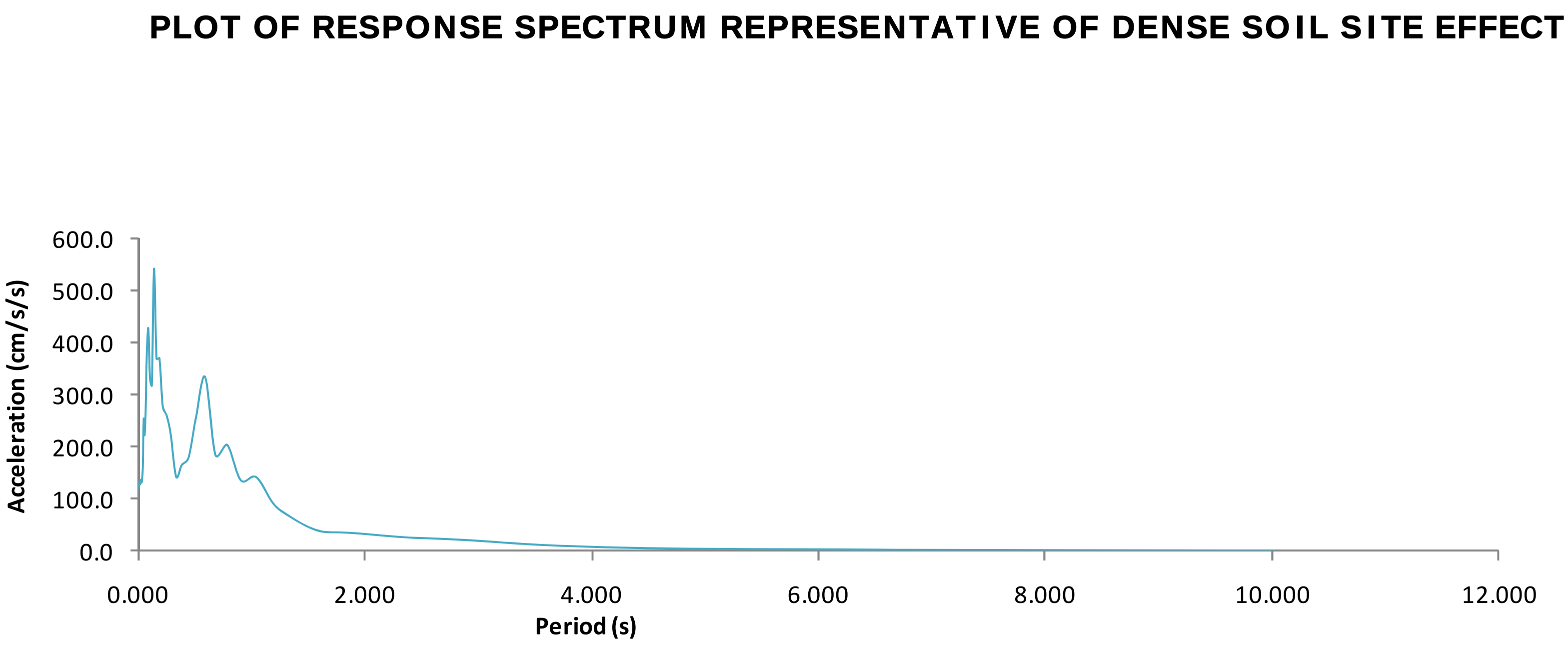


Figure 2.3-5 Plot of response spectrum representative of dense soil site effects

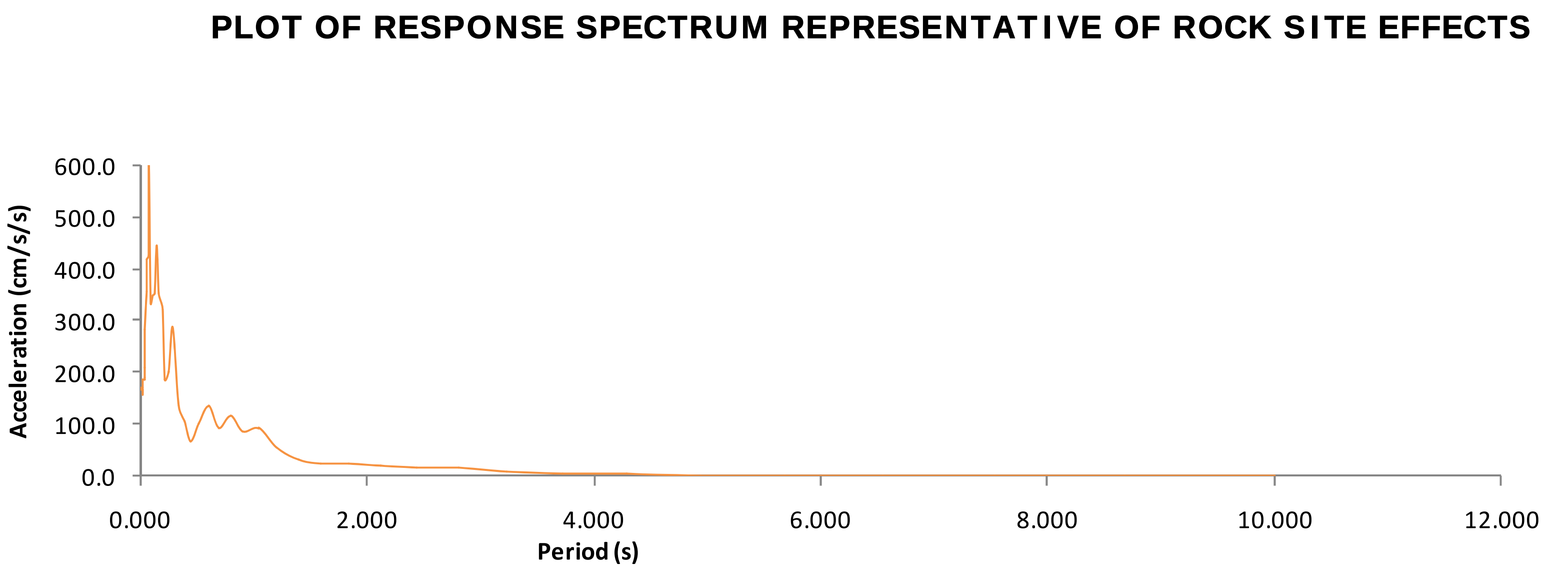


Figure 2.3-6 Plot of response spectrum representative of rock site effects

2.3.2. Utilized Finite Element Program – SAP2000

All the cases are analyzed in accordance with the conditions defined in Chapter 2 utilizing the Structural Analysis Program, SAP2000 [19]. In this section, software capabilities in terms of the structural members definitions and the solution methodology of the non-linear time history analyses are explained.

Structural members are defined as non-prismatic frame elements sensitive to axial, shearing and bending deformations. The stiffness matrix of any element associated with other elements can directly be calculated by the use of displacement method. A representative drawing for an arbitrary frame element is given in Figure 2.3-7. In fact, the frame element is composed of a number of non-prismatic frames each of which has axial, shear and bending properties independently [20].

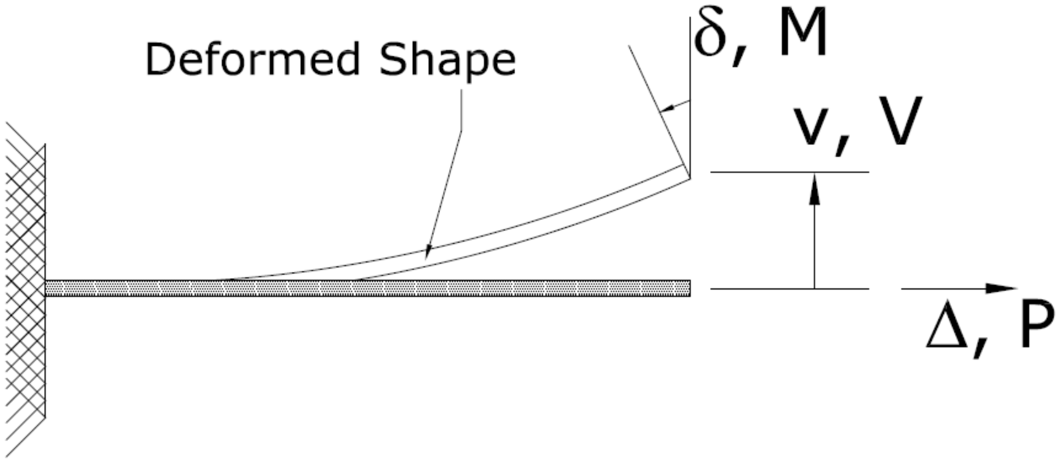


Figure 2.3-7 Arbitrary frame element

The axial displacement Δ, vertical displacement v, the end rotation δ and the axial load P, vertical load V, and the end moment M are defined as the relative displacements and corresponding forces in Figure 2.3-7.

On the other side, it is possible to assign springs that have rotational or translational stiffness properties, for each of the six degrees of freedom. Each spring may consist of different sub elements such as spring and dashpot as shown in Figure 2.3-8. Moreover, the analysis software lets the user to define linear or nonlinear Force-Displacement behavior of the springs as represented in the Figure 2.2-12. Furthermore, non-linear time history analyses are solved numerically by pre-defined direct integration method proposed by Newmark [21].

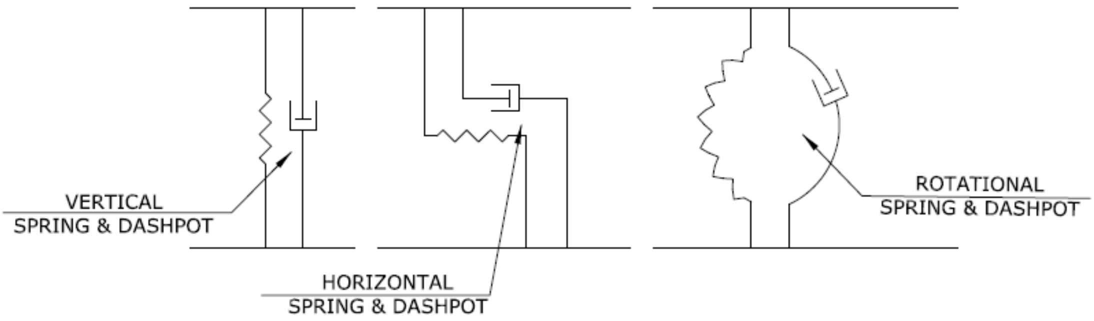


Figure 2.3-8 Translational and rotational spring-dashpot systems

CHAPTER 3

PARAMETRIC STUDIES

3.1. Introduction

The theoretical approaches regarding analysis of dynamic response given in Chapter II are applied on different combinations of structural and foundation systems. The purpose is to understand the response of the structure modeled with deformable medium underlying it. To be able to obtain results in a broad perspective, three different structural systems (i.e., one SDOF system and two MDOF systems) are combined with three different foundation-modeling approaches (i.e., fixed base system and two simplified SSI modeling approaches). The two simplified foundation modeling approaches defined in FEMA 356 [18] known as Gazetas springs and Winkler springs are also compared to examine the modeling capabilities of each method.

In this chapter, dimensions and material properties of the analyzed structural systems, soil stiffness parameters and details of the models are presented. Parametric variations are arranged in the analyses so as to single out the effect of a specific variation in the sub- or super-structural parameter on the dynamic response. At the outset, the dimensions and material properties of the structural elements of the models are described. Then, varying soil stiffness parameters and spring constants of both simplified modeling approaches are defined, and, modeling assumptions and combined analyses models are explained in detail.

3.2.Structural Systems

3.2.1. SDOF Systems

The simplest structural model used is a SDOF system. Bridge piers, elevated water tanks and even more complicated structures can simply be modeled as a SDOF system. As shown in Figure 3.2-1, the structural system is composed of two members as load bearing column and foundation. To be able to model the structure as a SDOF system, the lateral stiffness is represented by the stiffness of the massless column and the structural mass is presumed to be concentrated at a particular height above the foundation. The foundation is defined by relatively rigid frame elements when compared to the load-bearing column.

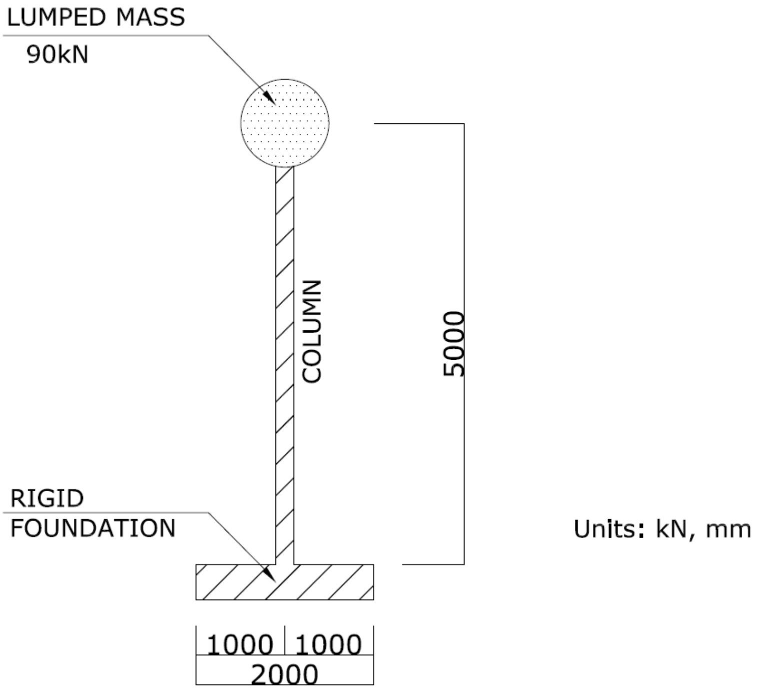


Figure 3.2-1 Typical single degree of freedom system

In the analyses, the height of the concentrated mass is selected as 5m. The foundation is considered as square single footing having dimensions of 2m by 2m. Figure 3.2-1 represents a typical SDOF system used in the analyses.

To analyze structures having different vibration periods, the structural stiffness is changed gradually keeping the mass constant in the analyses. The system properties of the models used in the analyses are presented in Table 3.2-1.

Table 3.2-1 SDOF system model properties

Model	Elasticity Modulus of Concrete, Ec (Mpa)	Lumped Mass (kN)	Dimensions of the Load Bearing Column (cm/cm)	Lateral Stiffness of the Load Bearing Column (kN/m)
SDOF System 1	30	90	55/55	5490,4
SDOF System 2	30	90	50/50	3750,0
SDOF System 3	30	90	45/45	2460,4
SDOF System 4	30	90	40/40	1536,0
SDOF System 5	30	90	35/35	900,4
SDOF System 6	30	90	30/30	486,0
SDOF System 7	30	90	25/25	234,4

3.2.2. MDOF Systems

MDOF systems are analyzed so as to make a comparison and investigate the influence of simplification to a SDOF system on the response. For this purpose, two different MDOF building structures, having identical plans but different storey numbers (four-storey and ten-storey) are analyzed

Four-Storey Building

A structure having a uniform floor plan in both x and y directions and a typical floor height is selected for the analyses. Floor plans of all stories are rectangular in shape and having dimensions of 24.0 m by 18.0m. Three-dimensional view of the structure is given in Figure 3.2-2. The analyses are performed in 2-dimensions on the idealized frame, which is shown in Figure 3.2-3.

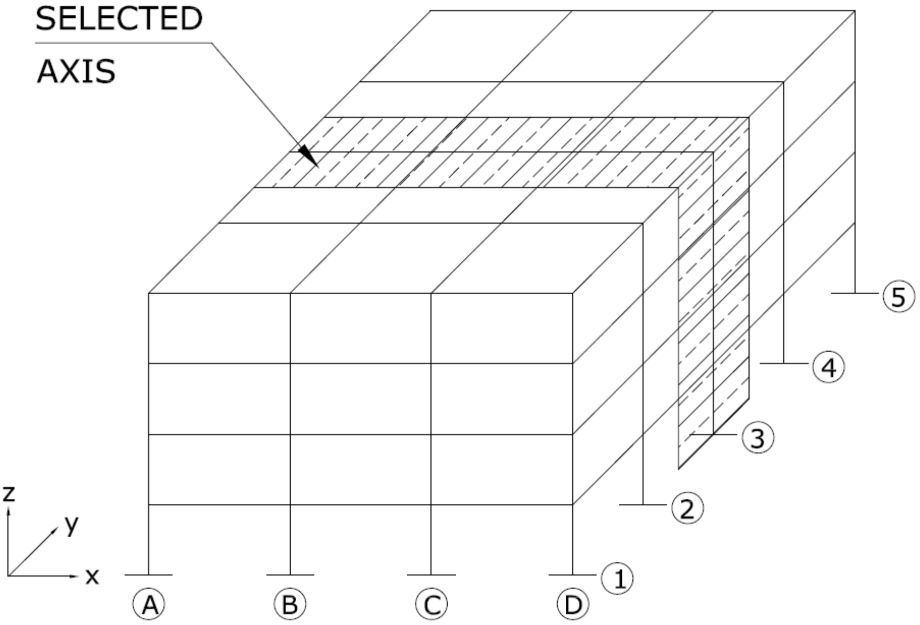


Figure 3.2-2 Three-dimensional view of the four-storey building structure

Since the frame members are defined as massless, the mass of these structural members and other design loads such as live loads and additional dead loads proposed by TS498 [22] are assigned as lumped mass on the analysis model. In TS498 for regular buildings 2.0 kN/m^2 live load (q) is suggested to be considered as design load. Moreover, 1.5 kN/m^2 dead load (g) is considered as design dead load. According to the tributary width of the selected axis, the design loads are applied as uniform line load as shown in Figure 3.2-4.

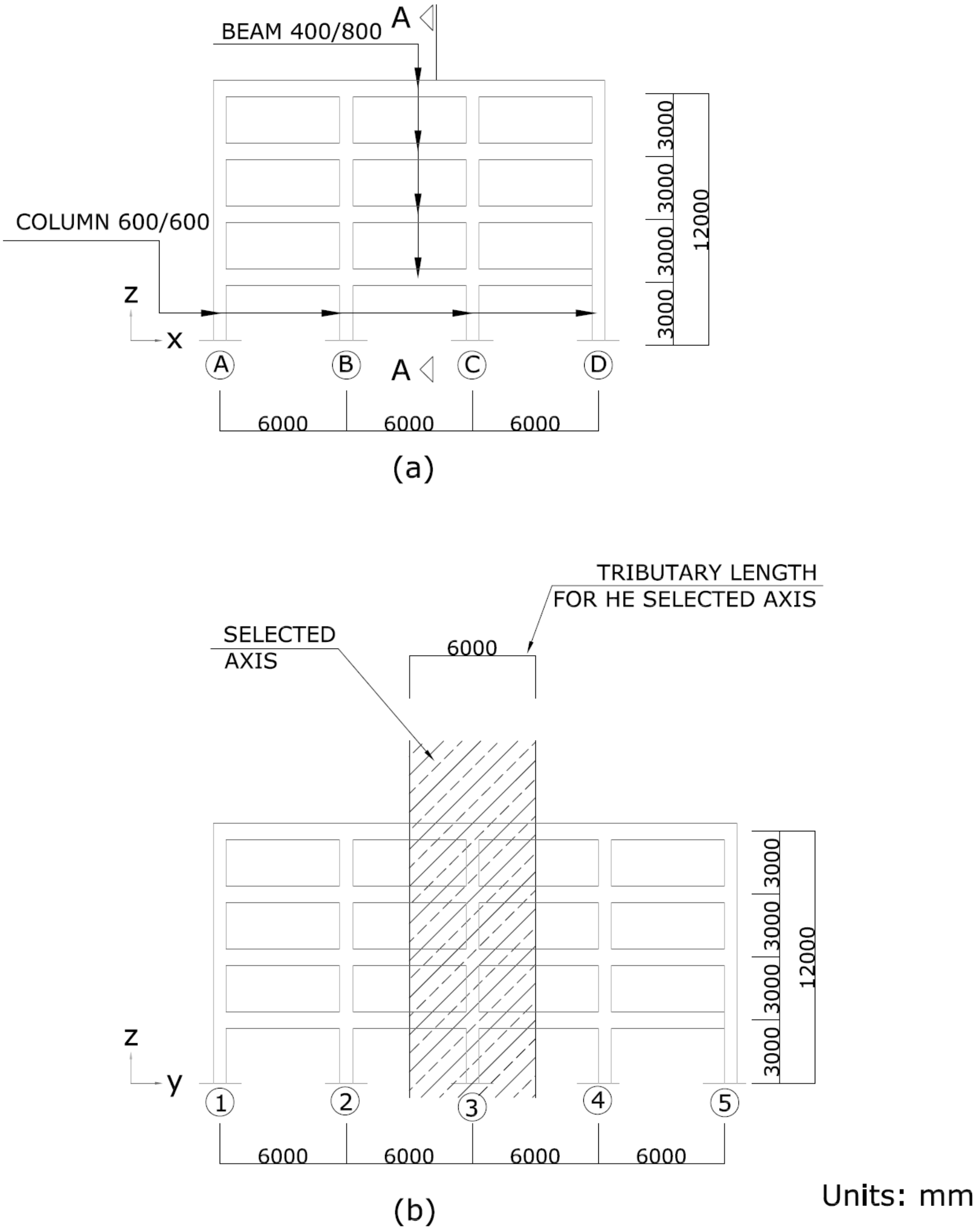


Figure 3.2-3 (a) Selected axis of the four-storey building for analyses (b) A-A section view

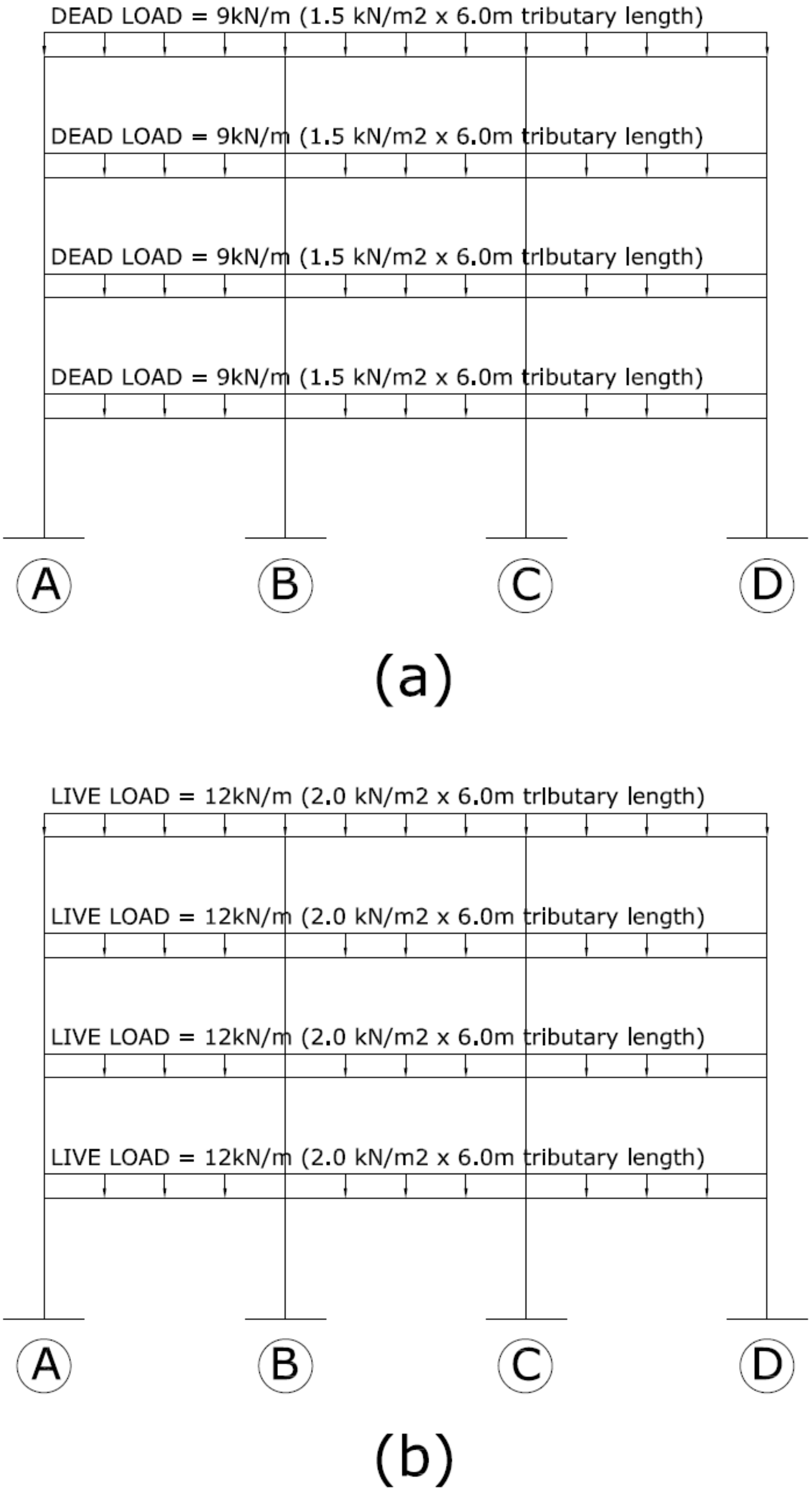


Figure 3.2-4 Design loads for four-storey building (a) dead load (b) live load

The seismic load, which is composed of the self-weight of the columns, beams and the slabs, is calculated in accordance with the Specification for Structures to be Built in Disaster Areas (SSBDA) [23]. Accordingly, the storey weights (w_i) are calculated as recommended as specified in the following equation.

$$w_i = g_i + n.q_i \qquad \text{(Eq. 3.2-1)}$$

where the coefficient n is called the live load participation ratio, and for regular building structures a value of 0.3 is recommended in SSBDA [23]. The seismic load assigned as lumped mass on joints is calculated by considering the tributary area of the slabs corresponding to the analyzed frame. The lumped mass distribution scheme of the analyzed frame of 4-storey building thus calculated is given in Figure 3.2-5.

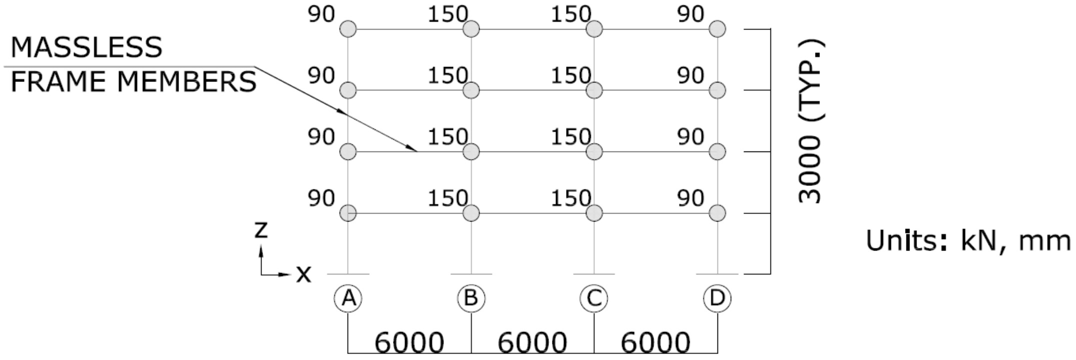


Figure 3.2-5 Mass distribution for four-storey frame

Ten-Storey Building

The same floor plan defined for the four-storey building is also used for the ten-storey building. The distance between axes, the floor height and the dimensions of the structural members are kept as the same. The only difference between these two structures is the number of stories. The three-dimensional view of the ten-storey structure and the analyzed frame are respectively shown in Figures 3.2-6 and 3.2-7.

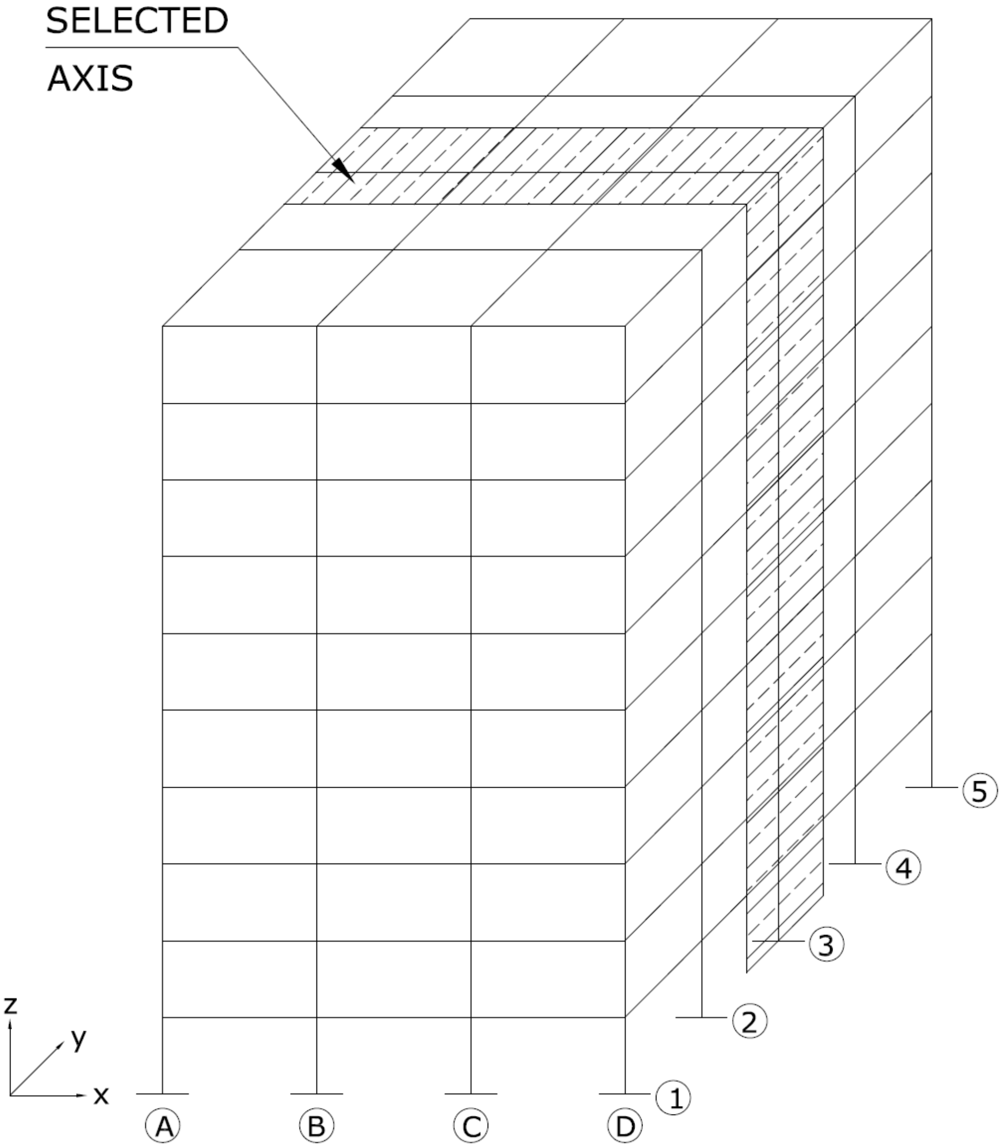
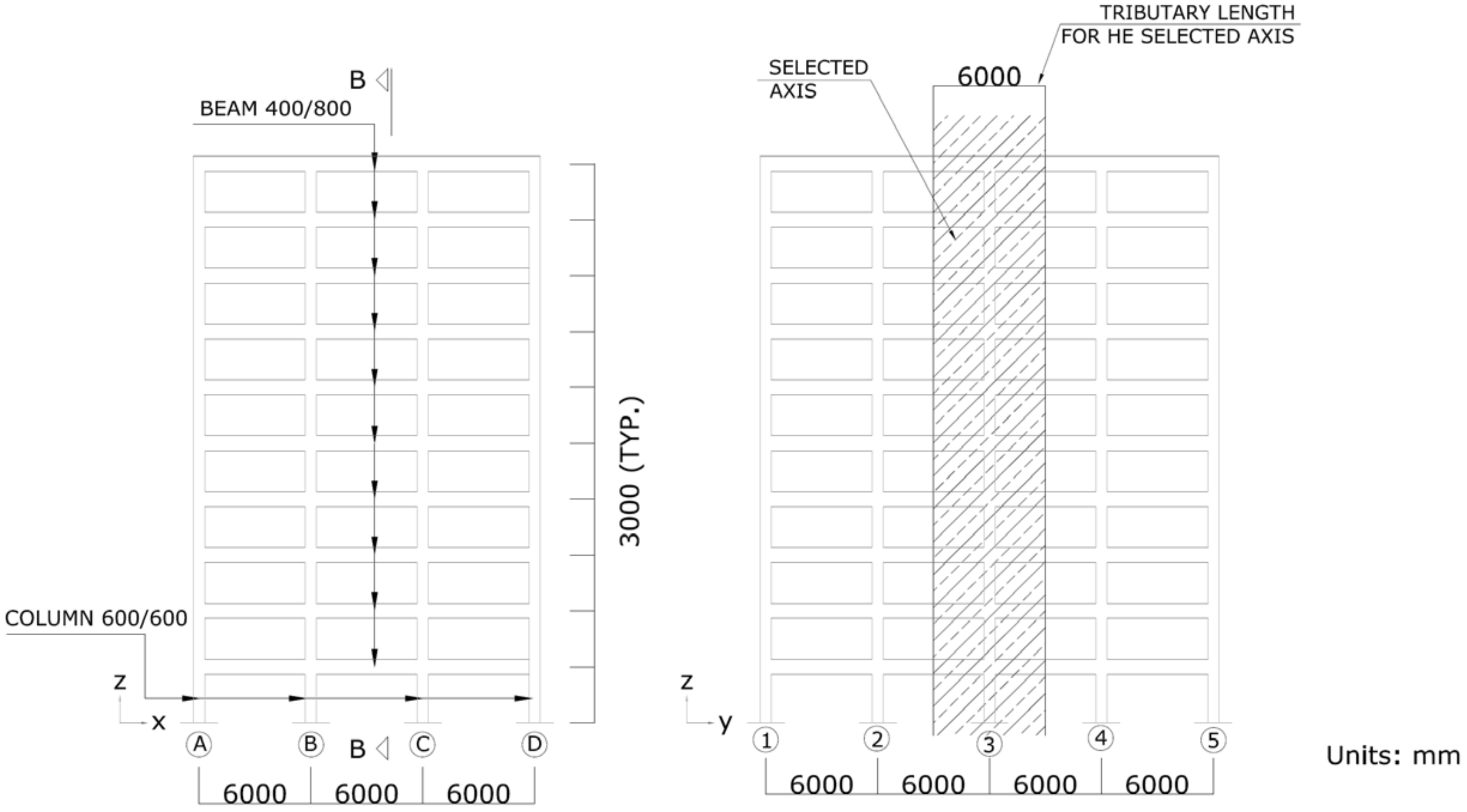


Figure 3.2-6 Three-dimensional view of the ten-storey building



(a) (b)

Figure 3.2-7 (a) Analyzed frame of the ten-storey building (b) B-B section view

Definition of the design loads and the procedure used for defining the lumped masses for the structural system are not different from the procedure defined for the four-storey structure. The design loads acting on the ten-storey building and the corresponding mass distribution for the structure are given in Figures 3.2-8 and 3.2-9, respectively.

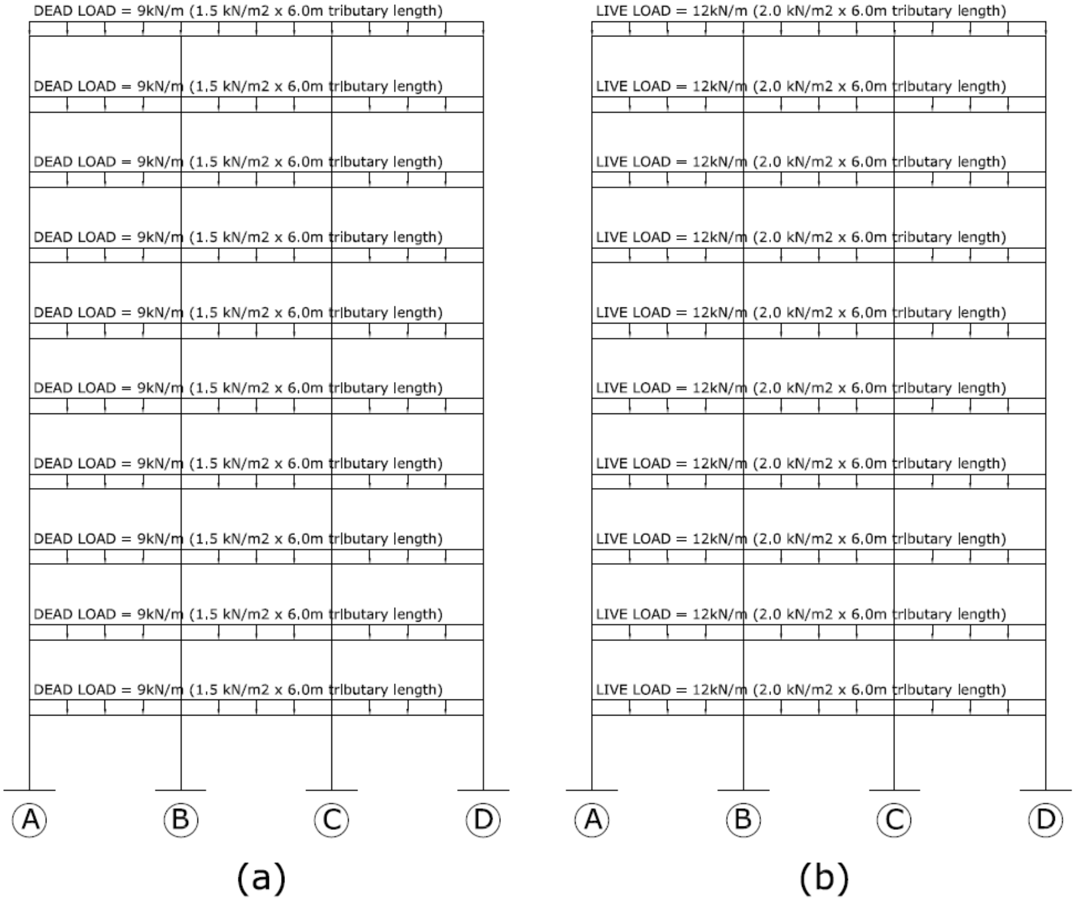


Figure 3.2-8 Design loads for ten-storey building (a) dead loads (b) live loads

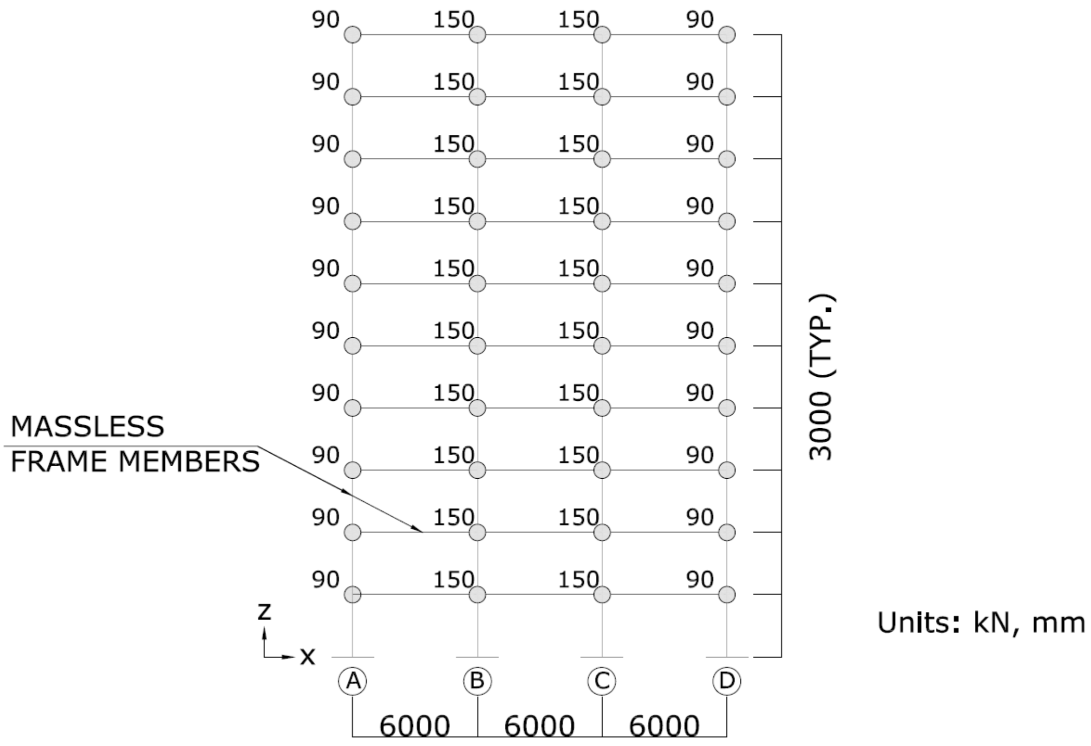


Figure 3.2-9 Mass distribution for ten-storey building

3.3. Foundation Systems

Three different foundation modeling approaches, namely the fixed base, single point spring and multiple point spring systems are utilized in the analyses. It is intended to understand the behavior of the systems composed of different foundation modeling approaches. The modeling assumptions of each method are explained in this section.

3.3.1. Fixed Base Systems

Each structural system defined in Section 3.2 is analyzed by assuming the structure is fixed at the base. The ultimate aim is to observe through comparison to the results of other model cases, whether it is reasonable to assume in practice that this approach always provides results on the safe side.

In the fixed base approach, columns transferring the loads to the ground are fixed at the foundation level, as shown in Figure 3.3-1. The foundation medium is intrinsically presumed to be infinitely rigid in this case.

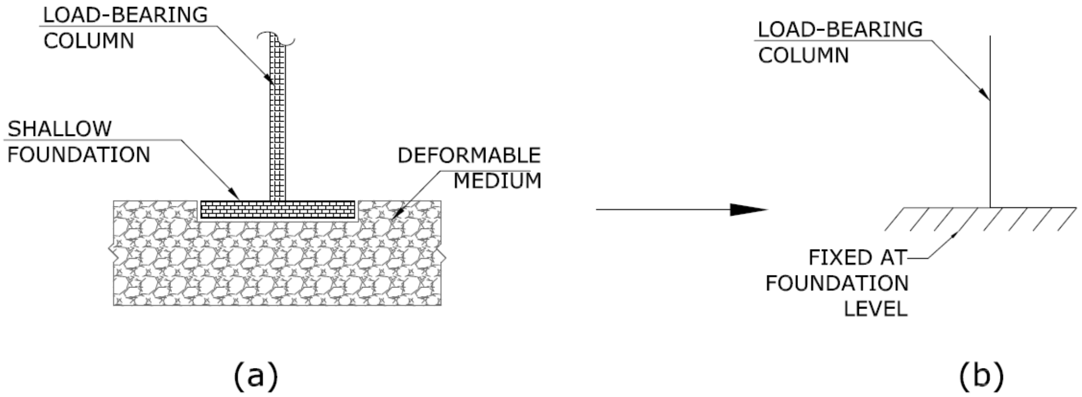


Figure 3.3-1 (a) Actual foundation system (b) Fixed base modeling approach

3.3.2. Single Point Springs Systems

The approach also known as Gazetas' springs, is composed of a series of springs and dashpots assigned to the foundations of the columns connecting to the ground. Since the structural analyses are conducted in two-dimensions, the spring and dashpot couples are provided so as to respond for two translational (vertical and horizontal directions) and one rotational degrees of freedom, as shown in Figure 3.3-2.

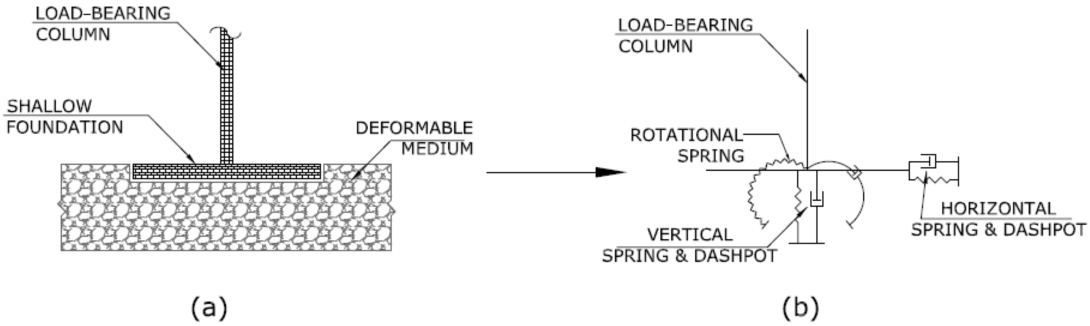


Figure 3.3-2 (a) Actual foundation system (b) Single point springs system

While calculating the coefficients of the spring stiffness, parameters related with both the geometrical properties of the foundation system and the deformable medium are taken into account. For the dashpots, 5% damping is defined as the equivalent-damping ratio in the analyses. The calculated soil shear modulus values, spring stiffnesses and dashpot damping coefficients used in the analyses are presented in Table 3.3.1.

Table 3.3-1 Spring stiffnesses and dashpot damping coefficients (Gazetas'Springs)

Structural System	Foundation Width (m)	Foundation Length (m)	Soil Shear Modulus (Mpa)	Site Classification	Horizontal Spring Stiffness (kN/m)	Vertical Spring Stiffness (kN/m)	Rotational Spring Stiffness (kN.m/m)	Horizontal Dashpot Damping Coefficient (%)	Vertical Dashpot Damping Coefficient (%)	Rotational Dashpot Damping Coefficient (%)
SDOF	2	2	5	Soft Site	27059	33571	28800	5	5	5
SDOF	2	2	10	Soft Site	54118	67143	57600	5	5	5
SDOF	2	2	20	Soft Site	108235	134286	115200	5	5	5
SDOF	2	2	40	Medium Stiff Site	216471	268571	230400	5	5	5
SDOF	2	2	60	Medium Stiff Site	324706	402857	345600	5	5	5
SDOF	2	2	80	Stiff Site	432941	537143	460800	5	5	5
SDOF	2	2	100	Stiff Site	541176	671429	576000	5	5	5

Structural System	Foundation Width (m)	Foundation Length (m)	Soil Shear Modulus (Mpa)	Site Classification	Horizontal Spring Stiffness (kN/m)	Vertical Spring Stiffness (kN/m)	Rotational Spring Stiffness (kN.m/m)	Horizontal Dashpot Damping Coefficient (%)	Vertical Dashpot Damping Coefficient (%)	Rotational Dashpot Damping Coefficient (%)
MDOF	3	3	5	Soft Site	40588	50357	97200	5	5	5
MDOF	3	3	10	Soft Site	81176	100714	194400	5	5	5
MDOF	3	3	20	Soft Site	162353	201429	388800	5	5	5
MDOF	3	3	40	Medium Stiff Site	324706	402857	777600	5	5	5
MDOF	3	3	60	Medium Stiff Site	487059	604286	1166400	5	5	5
MDOF	3	3	80	Stiff Site	649412	805714	1555200	5	5	5
MDOF	3	3	100	Stiff Site	811765	1007143	1944000	5	5	5

3.3.3. Multiple Point Springs Systems

In this foundation modeling approach, contrary to the other approaches the springs are assigned to the rigid foundation slab underlying the whole structure instead of the individual columns. A series of vertical springs attached beneath the foundation slab provide both vertical and rotational stiffness to the system. The model used in the studies is presented in Figure 3.3-3. In the figure, each spring shown represents spring dashpot couple.

Spring stiffness coefficients are calculated according to the procedure defined in Section 2-2. Dimensions of the foundation and properties of the deformable medium are taken into account during the calculations. The dashpot-damping coefficient is defined as 5%. In order to introduce varying foundation stiffnesses to the superstructure, varying spring stiffnesses are utilized in the analyses. In table 3.3.1, the soil shear moduli, spring stiffnesses and dashpot damping coefficients calculated accordingly are presented.

Table 3.3-2 Spring stiffnesses and dashpot damping coefficients (Winkler Springs)

Structural System	Foundation Width (m)	Foundation Length (m)	Soil Shear Modulus (Mpa)	Site Classification	Vertical Edge Spring Stiffness (kN/m)	Vertical Middle Spring Stiffness (kN/m)	Vertical, Edge and Middle Dashpot Damping Coefficient (%)
SDOF	2	2	5	Soft Site	7318	1825	5
SDOF	2	2	10	Soft Site	14636	3650	5
SDOF	2	2	20	Soft Site	29271	7300	5
SDOF	2	2	40	Medium Stiff Site	58543	14600	5
SDOF	2	2	60	Medium Stiff Site	87814	21900	5
SDOF	2	2	80	Stiff Site	117086	29200	5
SDOF	2	2	100	Stiff Site	146357	36500	5

Structural System	Foundation Width (m)	Foundation Length (m)	Soil Shear Modulus (Mpa)	Site Classification	Vertical Edge Spring Stiffness (kN/m)	Vertical Middle Spring Stiffness (kN/m)	Vertical Edge Dashpot Damping Coefficient (%)
MDOF	3	3	5	Soft Site	24393	2086	5
MDOF	3	3	10	Soft Site	48786	4171	5
MDOF	3	3	20	Soft Site	97571	8343	5
MDOF	3	3	40	Medium Stiff Site	195143	16686	5
MDOF	3	3	60	Medium Stiff Site	292714	25029	5
MDOF	3	3	80	Stiff Site	390286	33371	5
MDOF	3	3	100	Stiff Site	487857	41714	5

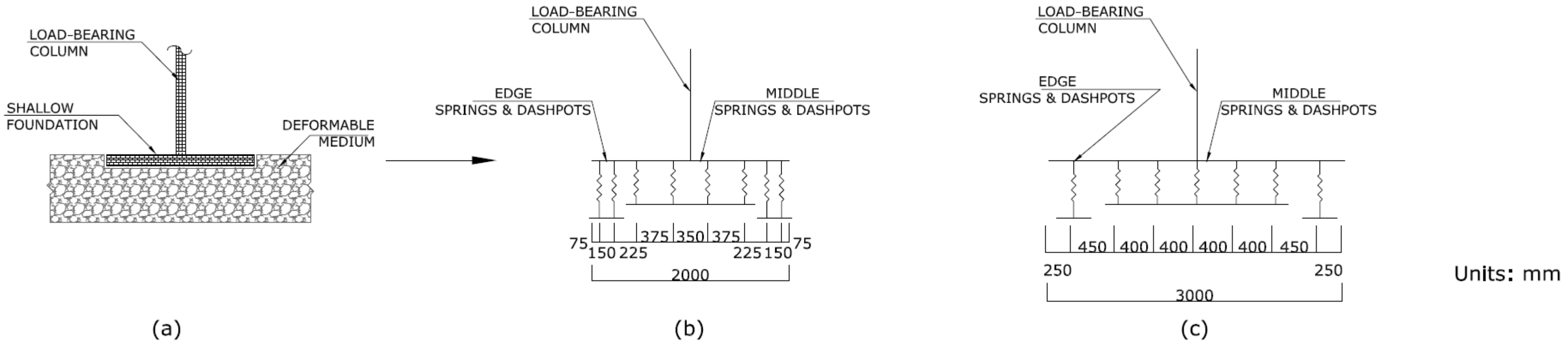


Figure 3.3-3 (a) Actual foundation system (b) Multiple point springs system arrangement for SDOF structures (c) Multiple point springs system arrangement for MDOF structures

3.4. Analyses of Systems

A series of analyses are performed in order to ascertain the effects of the presumed models on the structural response. The analyses consist of a combination of the three different structural systems, three different foundation systems and three different earthquake records. In addition, the parameters that affect the response of the system are systematically changed in the analyses. For the case studies, about 200 different analysis runs are performed.

In table 3.4-1, structural and foundation features as well as the deformable medium properties of each model analyzed are tabulated. In the analyses, the methodology defined in Chapter 2 is followed considering the parameters defined in Chapter 3.

Table 3.4-1 Analysis models used in parametric studies

	Structural System Properties				Foundation System Properties				Seismic Excitation		
Model ID	Structural System	Load-Bearing Column Dimenions (cm/cm) (for SDOF)	Lateral Stiffness of the Load Bearing Column (kN/m) (for SDOF)	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Poisson's Ratio	Soil Shear Modulus (Mpa)	Site Classification	For Soft Soil	For Medium Stiff Soil	For Stiff Soil
Model 1	SDOF	40/40	1536,0	-	Fixed Base	-	-		+	+	+
Model 2	SDOF	40/40	1536,0	-	SPSS	0,3	5	Soft Site	+	+	+
Model 3	SDOF	40/40	1536,0	-	SPSS	0,3	10	Soft Site	+	+	+
Model 4	SDOF	40/40	1536,0	-	SPSS	0,3	20	Soft Site	+	+	+
Model 5	SDOF	40/40	1536,0	-	SPSS	0,3	40	Medium Stiff Site	+	+	+
Model 6	SDOF	40/40	1536,0	-	SPSS	0,3	60	Medium Stiff Site	+	+	+
Model 7	SDOF	40/40	1536,0	-	SPSS	0,3	80	Stiff Site	+	+	+
Model 8	SDOF	40/40	1536,0	-	SPSS	0,3	100	Stiff Site	+	+	+
Model 9	SDOF	40/40	1536,0	-	MPSS	0,3	5	Soft Site	+	+	+
Model 10	SDOF	40/40	1536,0	-	MPSS	0,3	10	Soft Site	+	+	+
Model 11	SDOF	40/40	1536,0	-	MPSS	0,3	20	Soft Site	+	+	+
Model 12	SDOF	40/40	1536,0	-	MPSS	0,3	40	Medium Stiff Site	+	+	+
Model 13	SDOF	40/40	1536,0	-	MPSS	0,3	60	Medium Stiff Site	+	+	+
Model 14	SDOF	40/40	1536,0	-	MPSS	0,3	80	Stiff Site	+	+	+
Model 15	SDOF	40/40	1536,0	-	MPSS	0,3	100	Stiff Site	+	+	+
Model 16	SDOF	55/55	5490,4	-	Fixed Base	-	-	-	+	+	+
Model 17	SDOF	50/50	3750,0	-	Fixed Base	-	-	-	+	+	+
Model 18	SDOF	45/45	2460,4	-	Fixed Base	-	-	-	+	+	+
Model 1	SDOF	40/40	1536,0	-	Fixed Base	-	-	-	+	+	+
Model 19	SDOF	35/35	900,4	-	Fixed Base	-	-	-	+	+	+
Model 20	SDOF	30/30	486,0	-	Fixed Base	-	-	-	+	+	+
Model 21	SDOF	25/25	234,4	-	Fixed Base	-	-	-	+	+	+

Table 3.4-2 continued

	Structural System Properties				Foundation System Properties				Seismic Excitation		
Model ID	Structural System	Load-Bearing Column Dimenions cm/cm (for SDOF)	Lateral Stiffness of the Load Bearing Column (kN/m) (for SDOF)	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Poisson's Ratio	Soil Shear Modulus (Mpa)	Site Classification	For Soft Soil	For Medium Stiff Soil	For Stiff Soil
Model 22	SDOF	55/55	5490.4	-	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 23	SDOF	50/50	3750.0	-	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 24	SDOF	45/45	2460.4	-	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 25	SDOF	40/40	1536.0	-	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 26	SDOF	35/35	900.4	-	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 27	SDOF	30/30	486.0	-	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 28	SDOF	25/25	234.4	-	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 29	SDOF	55/55	5490.4	-	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 30	SDOF	50/50	3750.0	-	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 31	SDOF	45/45	2460.4	-	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 32	SDOF	40/40	1536.0	-	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 33	SDOF	35/35	900.4	-	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 34	SDOF	30/30	486.0	-	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 35	SDOF	25/25	234.4	-	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 36	MDOF	-	-	4	Fixed Base	-	-	-	+	+	+
Model 37	MDOF	-	-	4	SPSS	0.3	5	Soft Site	+	+	+
Model 38	MDOF	-	-	4	SPSS	0.3	10	Soft Site	+	+	+
Model 39	MDOF	-	-	4	SPSS	0.3	20	Soft Site	+	+	+
Model 40	MDOF	-	-	4	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 41	MDOF	-	-	4	SPSS	0.3	60	Medium Stiff Site	+	+	+
Model 42	MDOF	-	-	4	SPSS	0.3	80	Stiff Site	+	+	+
Model 43	MDOF	-	-	4	SPSS	0.3	100	Stiff Site	+	+	+
Model 44	MDOF	-	-	4	MPSS	0.3	5	Soft Site	+	+	+
Model 45	MDOF	-	-	4	MPSS	0.3	10	Soft Site	+	+	+
Model 46	MDOF	-	-	4	MPSS	0.3	20	Soft Site	+	+	+
Model 47	MDOF	-	-	4	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 48	MDOF	-	-	4	MPSS	0.3	60	Medium Stiff Site	+	+	+
Model 49	MDOF	-	-	4	MPSS	0.3	80	Stiff Site	+	+	+
Model 50	MDOF	-	-	4	MPSS	0.3	100	Stiff Site	+	+	+
Model 51	MDOF	-	-	10	Fixed Base	-	-	-	+	+	+
Model 52	MDOF	-	-	10	SPSS	0.3	5	Soft Site	+	+	+
Model 53	MDOF	-	-	10	SPSS	0.3	10	Soft Site	+	+	+
Model 54	MDOF	-	-	10	SPSS	0.3	20	Soft Site	+	+	+
Model 55	MDOF	-	-	10	SPSS	0.3	40	Medium Stiff Site	+	+	+
Model 56	MDOF	-	-	10	SPSS	0.3	60	Medium Stiff Site	+	+	+
Model 57	MDOF	-	-	10	SPSS	0.3	80	Stiff Site	+	+	+
Model 58	MDOF	-	-	10	SPSS	0.3	100	Stiff Site	+	+	+
Model 59	MDOF	-	-	10	MPSS	0.3	5	Soft Site	+	+	+
Model 60	MDOF	-	-	10	MPSS	0.3	10	Soft Site	+	+	+
Model 61	MDOF	-	-	10	MPSS	0.3	20	Soft Site	+	+	+
Model 62	MDOF	-	-	10	MPSS	0.3	40	Medium Stiff Site	+	+	+
Model 63	MDOF	-	-	10	MPSS	0.3	60	Medium Stiff Site	+	+	+
Model 64	MDOF	-	-	10	MPSS	0.3	80	Stiff Site	+	+	+
Model 65	MDOF	-	-	10	MPSS	0.3	100	Stiff Site	+	+	+

SDOF: Single Degree of Freedom System

MDOF: Multi Degree of Freedom System

SPSS: Single Point Spring System

MPSS: Multiple Point Spring System

CHAPTER 4

INTERPRETATION OF RESULTS AND DISCUSSION

4.1. Introduction

Series of analyses are already carried out utilizing two basic simplified SSI approaches for the cases defined. In this section, results of the analyses are presented, interpreted and discussed. The analyses results are interpreted on the basis of total base shear acting over the structure and compared between SDOF and MDOF systems. The internal member forces of MDOF systems are extensively examined. Change in bending moments, axial and shear forces on load bearing structural members for each analysis case are investigated to observe the structural response as closely as possible. The effect of foundation uplift on the seismic behavior of the structure is also investigated.

4.2.Examination of SDOF Systems

In order to examine the seismic response of SDOF systems in a systematic way the structural stiffness and soil shear modulus are changed in turn, keeping one of the two parameters constant each time.

4.2.1. Results of SDOF Systems Analyses with Different Soil Shear Modulus

For the analyses, a load-bearing column having 1.536kN/m lateral stiffness (cross-sectional dimensions of 40cm by 40cm) is selected. To investigate the effects of varying soil stiffness on the response, soil shear modulus is changed within a range of 5MPa to 100MPa in the analyses. According to the model numbers defined in Chapter 3, the fundamental system periods and maximum total base shear acting on the structure are tabulated in Table 4.2-1.

Table 4.2-1 Analyses results of SDOF systems with constant structural stiffness

Model ID	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	System Period (s)	Total Base Shear Under Dynamic Loads (kN)	Total Base Shear Under Dynamic Loads (kN)	Total Base Shear Under Dynamic Loads (kN)
					Seismic Excitation Representative of Soft Soil Site Effects	Seismic Excitation Representative of Dense Soil Site Effects	Seismic Excitation Representative of Rock SiteEffects
Model 1	Fixed Base	-	-	1,67592	14,5	44,5	35,8
Model 2	SPSS	5	Soft Site	1,72323	14,7	39,9	36,6
Model 3	SPSS	10	Soft Site	1,73486	14,8	39,0	36,8
Model 4	SPSS	20	Soft Site	1,75056	15,0	37,4	36,8
Model 5	SPSS	40	Medium Stiff Site	1,79184	15,2	34,6	37,4
Model 6	SPSS	60	Medium Stiff Site	1,90069	23,3	35,9	36,3
Model 7	SPSS	80	Stiff Site	2,10155	31,4	34,8	32,1
Model 8	SPSS	100	Stiff Site	2,45445	17,0	35,5	29,3
Model 9	MPSS	5	Soft Site	1,73758	14,8	32,8	27,6
Model 10	MPSS	10	Soft Site	1,75223	15,0	29,4	25,9
Model 11	MPSS	20	Soft Site	1,77639	15,1	30,3	29,4
Model 12	MPSS	40	Medium Stiff Site	1,82374	17,6	28,1	27,2
Model 13	MPSS	60	Medium Stiff Site	1,95894	21,1	28,7	24,5
Model 14	MPSS	80	Stiff Site	2,20459	20,9	26,9	23,3
Model 15	MPSS	100	Stiff Site	2,62789	15,3	23,5	21,5

Variation of the fundamental system period is presented in Figure 4.2-1. Here, the two main trends related with the modeling approaches can be observed. First, the system periods obtained from the analyses of both simplified spring-dashpot systems are very close to each other for similar type of soil conditions. As it was stated in Chapter 2, the vertical spring stiffnesses of both SPSS and MPSS are derived from the total vertical and rotational stiffness of the foundation system in a similar way. On the other hand, since the system periods are obtained by utilizing linear-modal analyses, tension cut-off that can be defined for MPSS is not taken into account in the analyses. Accordingly, identical system periods are calculated.

The second outcome that can be inferred from Figure 4.2-1 is related with the range of shear modulus. When the system periods of three modeling approaches (namely the fixed base system, SPSS and MPSS) are investigated, it can be seen that for stiff sites system periods converge to same value. Hence, the system tends to behave like a fixed base system, as would be expected, and the impact of SSI on the fundamental system period of the system diminishes.

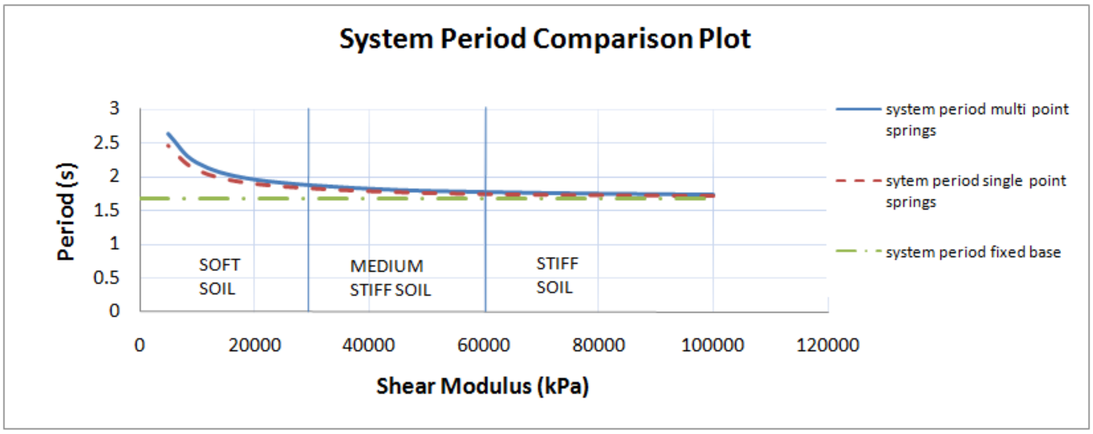
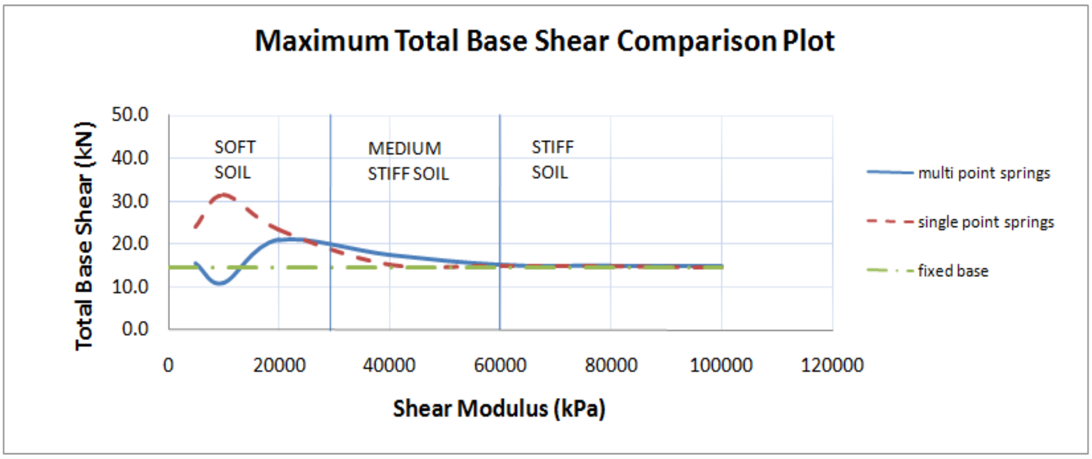
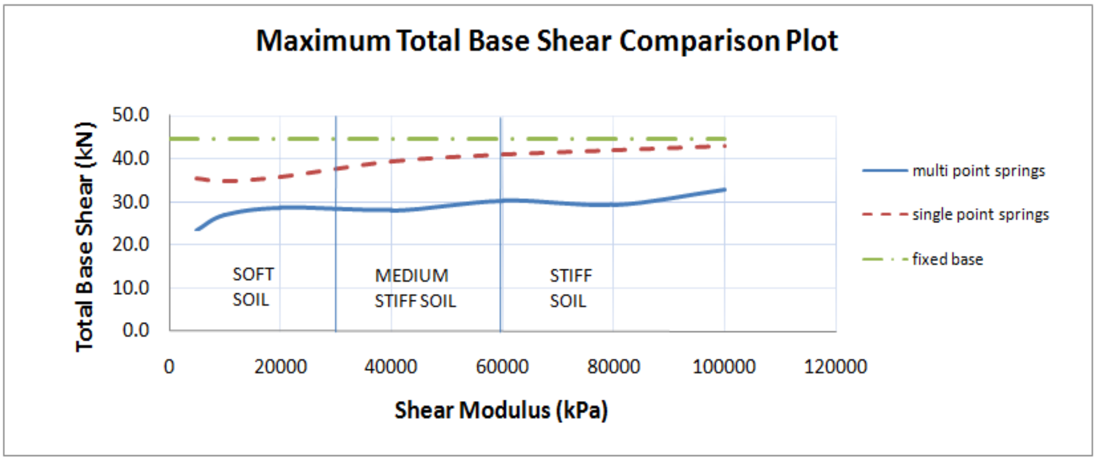


Figure 4.2-1 Variation of system period for SDOF systems with constant structural stiffness

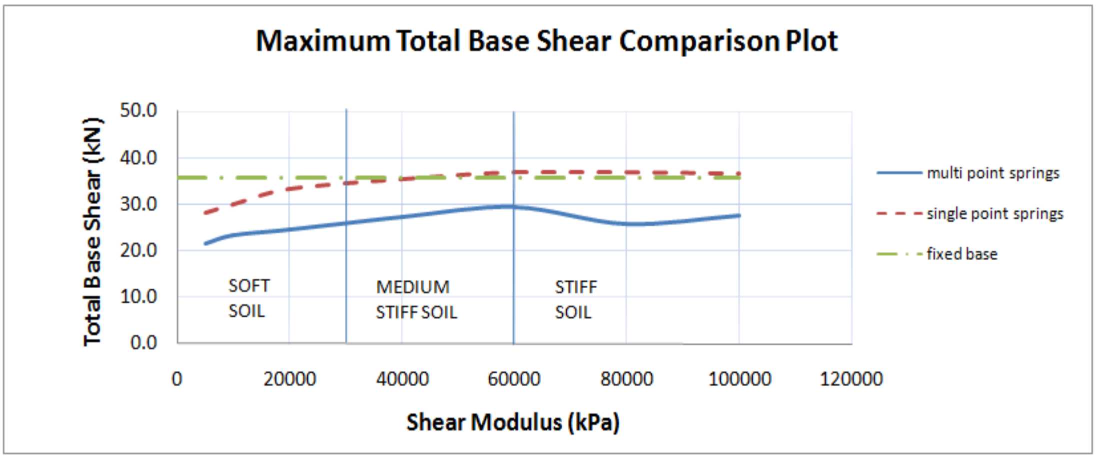
Variations of the maximum total base shear for the SDOF system having constant structural stiffness are plotted in Figure 4.2-2 for the earthquake input representative of three different site effects (i.e., for soft soil site, dense soil site and rock site). Moreover, maximum average drifts (drift between the base and the top of the structure including the contribution from base rotations) of the SDOF systems with varying soil shear modulus for each earthquake input are presented and compared in Appendix B.



(a)



(b)



(c)

Figure 4.2-2 Maximum total base shear comparison plots of SDOF system with constant structural stiffness and for seismic excitation representative of a) soft soil site b) dense soil site c) rock site

The plots in Figure 4.2-2 show that the maximum total base shear acting on the systems does not only change with the varying soil shear modulus, but it can also be significantly dependent on the characteristics of the earthquake record.

Contrary to the generally held idea that the SSI effects are always beneficial, in Figure 4.2-2 (a) the maximum base shear of SPSS exceeds even that of the fixed base model. This shows that higher total base shear values can result in reality compared to the simplified fixed base system depending on the circumstances consisting of the foundation soil stiffness, structural attributes and characteristics of the earthquake record.

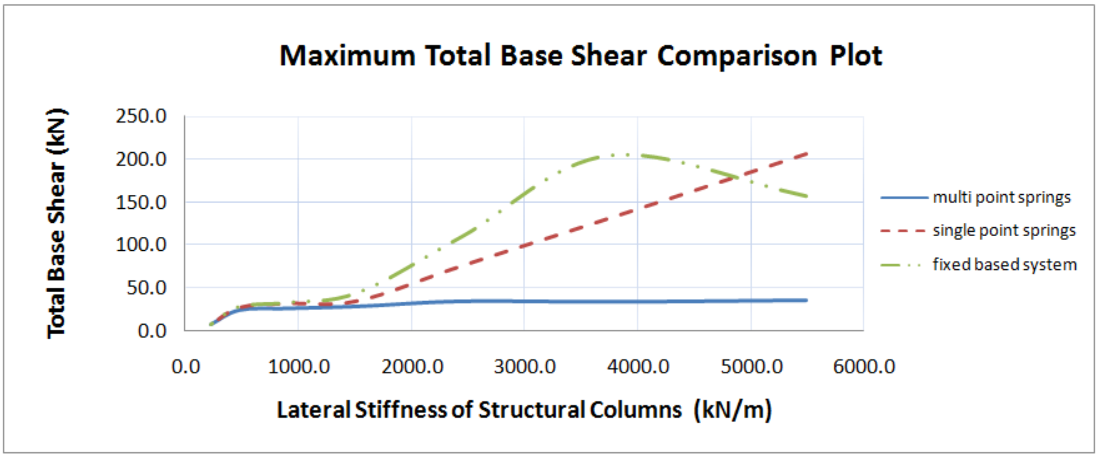
4.2.2. Results of SDOF Systems Analyses with Different Structural Stiffnesses

For this series of analyses, shear modulus value is selected as 40 MPa for the foundation soil. To investigate the effect structural stiffness on the response, varying column dimensions are utilized in the models. In accordance with the analysis cases defined in Chapter 3, the maximum total base shear values are presented in Table 4.2-2.

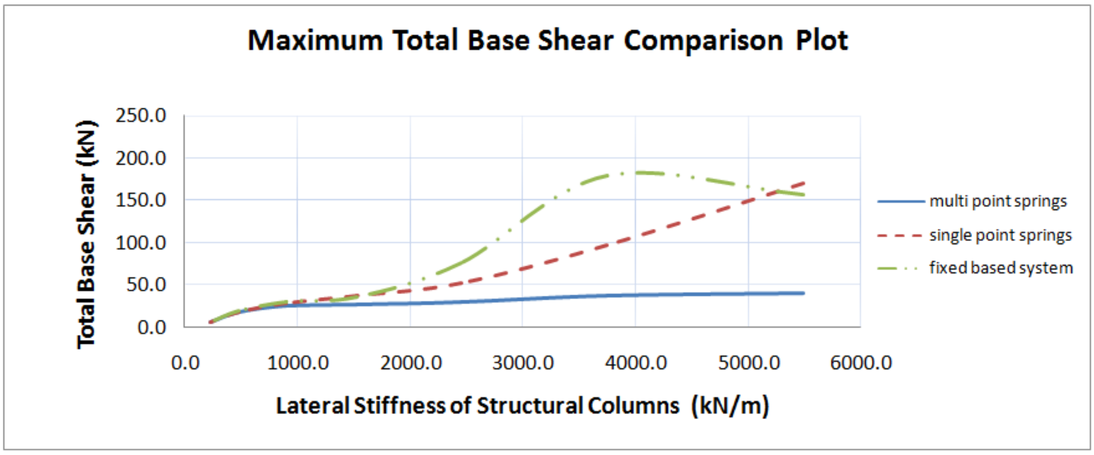
Table 4.2-2 Analyses results of SDOF systems with constant soil shear modulus

Model ID	Foundation Modeling Approach	Load-Bearing Column Dimenions (cm/cm)	Lateral Stiffness of the Load Bearing Column (kN/m)	System Period (s)	Total Base Shear Under Dynamic Loads (kN)	Total Base Shear Under Dynamic Loads (kN)	Total Base Shear Under Dynamic Loads (kN)
					Seismic Excitation Representative of Soft Soil Site Effects	Seismic Excitation Representative of Dense Soil Site Effects	Seismic Excitation Representative of Rock Site Effects
Model 16	Fixed Base	55/55	5490,4	0,888247	157,4	157,1	104,8
Model 17	Fixed Base	50/50	3750,0	1,073973	204,8	179,3	121,8
Model 18	Fixed Base	45/45	2460,4	1,324991	110,7	76,4	43,8
Model 1	Fixed Base	40/40	1536,0	1,675922	44,5	35,8	24,5
Model 19	Fixed Base	35/35	900,4	2,187782	32,7	30,1	20,9
Model 20	Fixed Base	30/30	486,0	2,976425	28,1	19,4	13,6
Model 21	Fixed Base	25/25	234,4	4,284359	7,2	5,3	3,5
Model 22	SPSS	55/55	5490,4	1,091312	205,6	169,3	110,1
Model 23	SPSS	50/50	3750,0	1,247156	130,6	96,4	51,4
Model 24	SPSS	45/45	2460,4	1,468871	75,7	52,3	27,0
Model 25	SPSS	40/40	1536,0	1,791841	34,6	37,4	25,9
Model 26	SPSS	35/35	900,4	2,277799	31,4	28,4	22,4
Model 27	SPSS	30/30	486,0	3,042204	26,7	18,0	12,5
Model 28	SPSS	25/25	234,4	4,331018	7,0	5,1	3,4
Model 29	MPSS	55/55	5490,4	1,142933	35,2	40,5	31,4
Model 30	MPSS	50/50	3750,0	1,292567	33,4	37,4	31,5
Model 31	MPSS	45/45	2460,4	1,507619	34,0	29,8	22,6
Model 32	MPSS	40/40	1536,0	1,82374	28,1	27,2	21,3
Model 33	MPSS	35/35	900,4	2,302977	25,7	25,0	20,6
Model 34	MPSS	30/30	486,0	3,062094	23,7	17,5	12,1
Model 35	MPSS	25/25	234,4	4,344312	6,9	5,1	3,4

Plots of variation of the maximum total base shear as a function of the structural stiffness for the SDOF system are given in Figure 4.2-3, for the seismic excitation representative of soft soil site, dense soil and rock.



(a)



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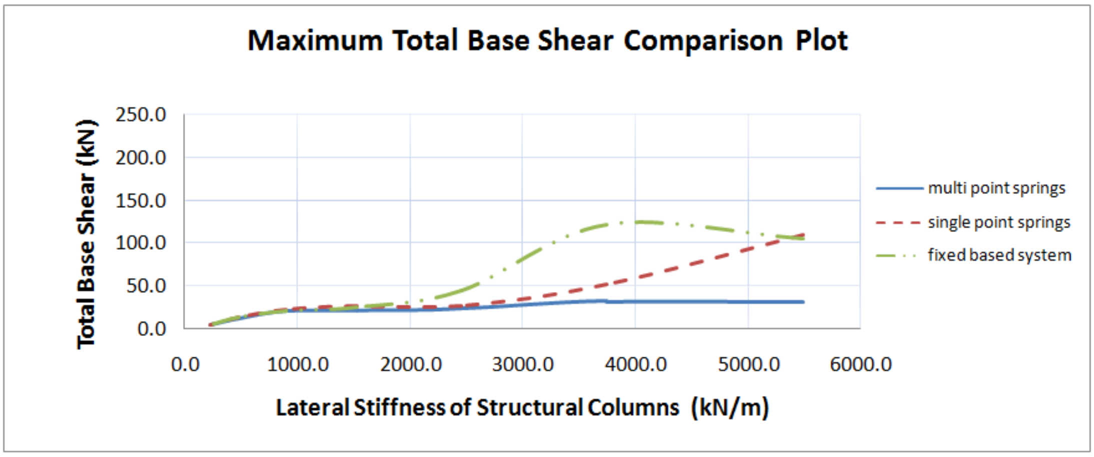
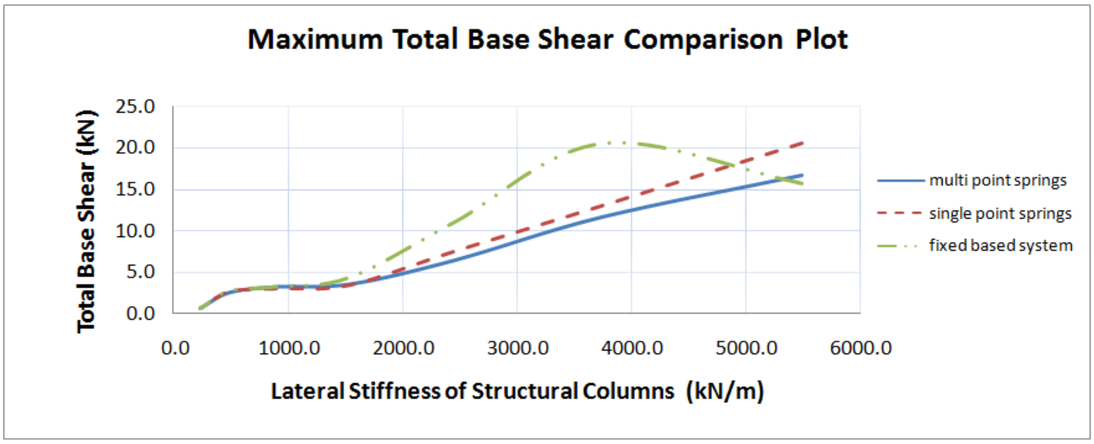


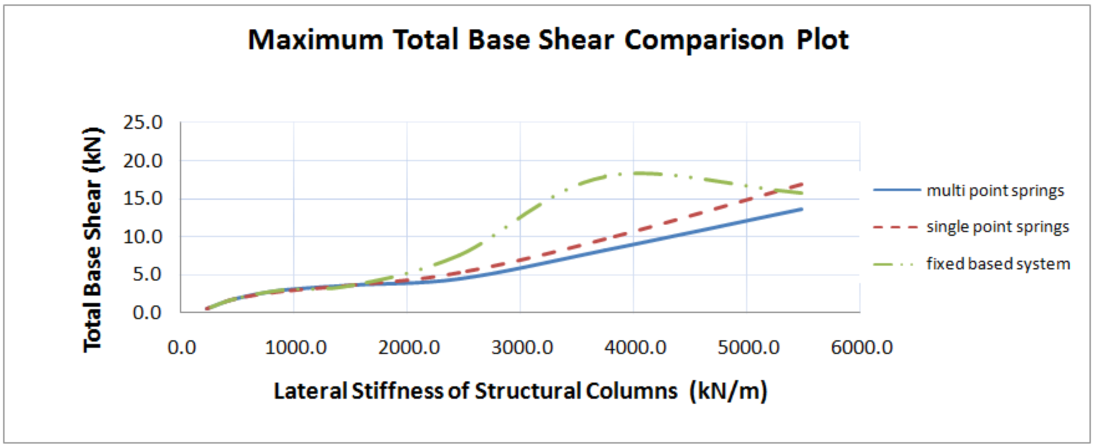
(c)

Figure 4.2-3 Maximum total base shear comparison plots of SDOF system with constant foundation soil stiffness and for seismic excitation representative of a) soft soil site b) dense soil site c) rock site

From the plots given in Figure 4.2-3, it is clearly seen that higher structural stiffness results in increased base shear in all of the sites, and for the models including SSI effects, base shear again exceeds that of the fixed based. With increasing structural flexibility, all models converge and the base shear is reduced as would be expected. In other words, as the structural flexibility increases, SSI effects on superstructure decreases. Due to that reason for the lower structural stiffness same results are obtained in all models. The other striking observation is the difference between SPPS and MPSS, which is more emphasized particularly for higher structural stiffness. This difference is due to the foundation uplift, which can be implemented only in MPSS. Accordingly, due to the fact that the effect of uplift phenomenon, which greatly reduced the seismic response, are neglected in fixed base and SPSS models, the results can be overly conservative. Since when the uplift phenomenon is observed, the stiffness of the foundation decreases step by step. In order to confirm that the differences between the results of MPSS and that of other two models are indeed due to the uplift, the applied seismic acceleration is scaled to prevent uplift and analyses were performed. The plot of the maximum total base shear values obtained from the analyses results are presented in Figure 4.2-4.



(a)



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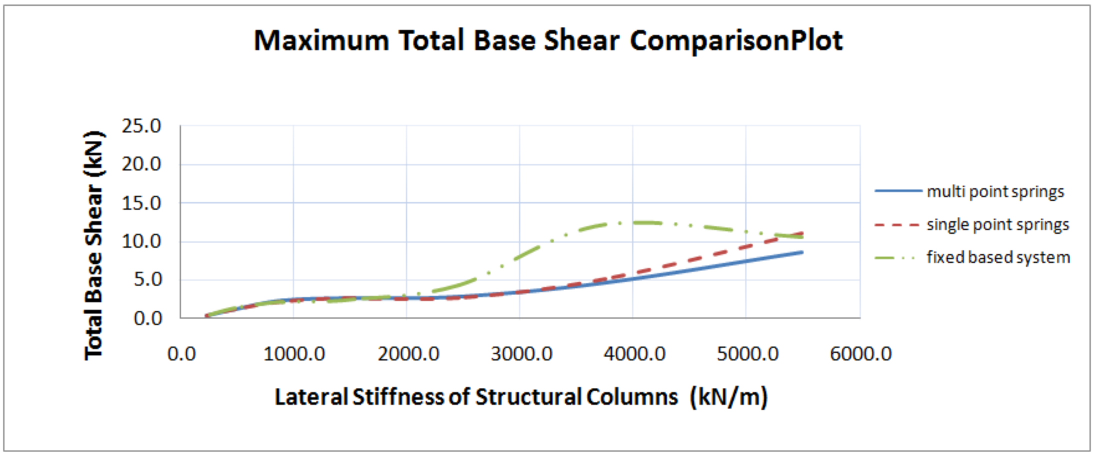


(c)

Figure 4.2-4 Comparison of maximum total base shear for the case of scaled seismic excitation representative of a) soft soil site b) dense soil site c) rock site

4.3.Examination of MDOF Systems

Response of MDOF systems are examined in this section. The effects of structural geometry and stiffness properties of the foundation soils on structural behavior are presented. The analyses results are evaluated in terms of both maximum total base shear and maximum internal member forces.

4.3.1. Results of Four-Storey Building Analyses with Different Soil Shear Modulus

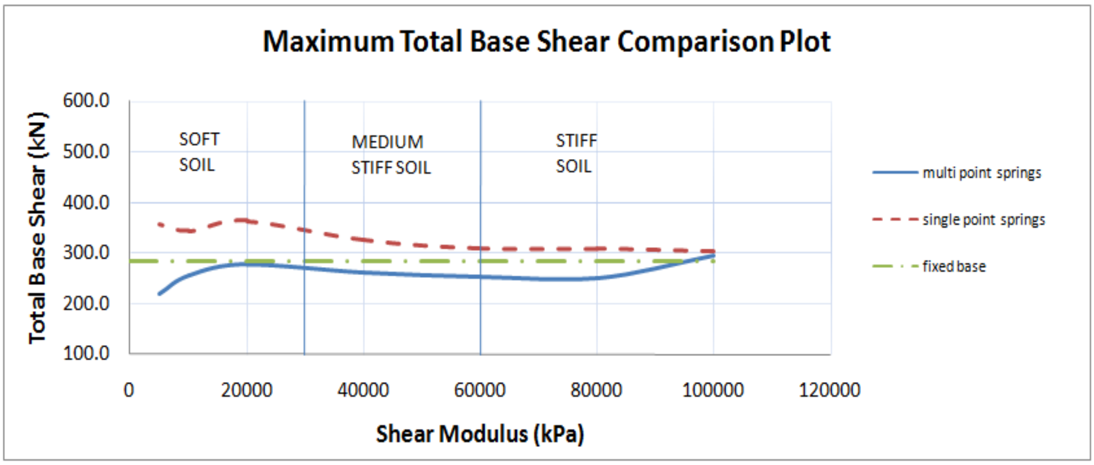
4.3.1.1. Comparison of the Maximum Total Base Shear

The shear modulus values of soil were varied within a range of 5MPa to 100MPa. Resulting maximum total base shear values are presented in Table 4.3-1 in accordance with the analysis cases defined Chapter 3.

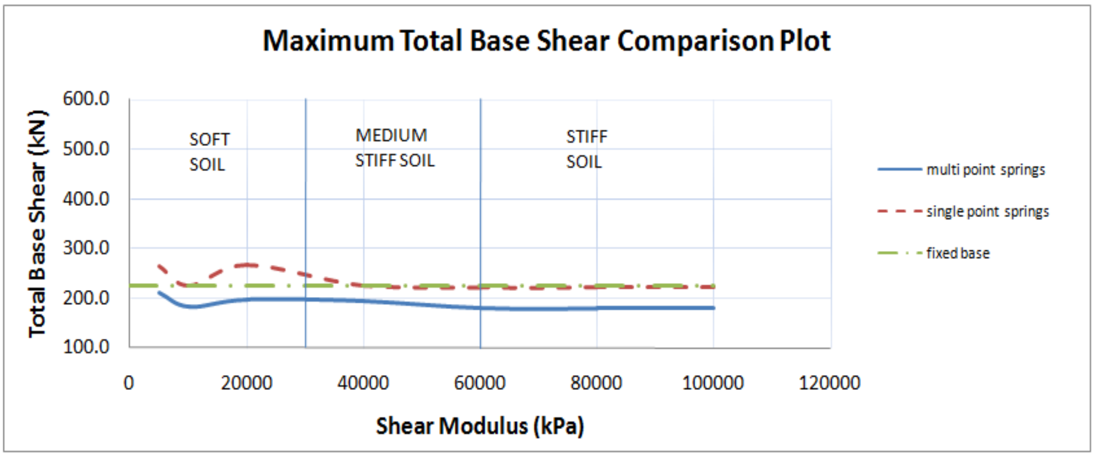
Table 4.3-1 Analyses results for four-storey structure with varying soil shear modulus

Model ID	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	System Period (s)	Total Base Shear Under Dynamic Loads (kN)	Total Base Shear Under Dynamic Loads (kN)	Total Base Shear Under Dynamic Loads (kN)
					Seismic Excitation Representative of Soft Soil Site Effects	Seismic Excitation Representative of Dense Soil Site Effects	Seismic Excitation Representative of Rock Site Effects
Model 36	Fixed Base	-	-	0,275299	284,0	224,0	152,0
Model 37	SPSS	5	Soft Site	0,451587	356,0	265,0	200,0
Model 38	SPSS	10	Soft Site	0,37563	314,0	224,0	217,0
Model 39	SPSS	20	Soft Site	0,329989	364,0	266,0	211,0
Model 40	SPSS	40	Medium Stiff Site	0,304115	325,0	226,0	155,0
Model 41	SPSS	60	Medium Stiff Site	0,294889	314,0	221,0	154,0
Model 42	SPSS	80	Stiff Site	0,290143	309,0	221,0	145,0
Model 43	SPSS	100	Stiff Site	0,28725	305,0	223,0	138,0
Model 44	MPSS	5	Soft Site	0,448482	220,0	212,0	169,0
Model 45	MPSS	10	Soft Site	0,376417	257,0	183,0	166,0
Model 46	MPSS	20	Soft Site	0,331925	277,0	197,0	133,0
Model 47	MPSS	40	Medium Stiff Site	0,305999	262,0	194,0	156,0
Model 48	MPSS	60	Medium Stiff Site	0,296601	254,0	180,0	144,0
Model 49	MPSS	80	Stiff Site	0,291734	251,0	179,0	131,0
Model 50	MPSS	100	Stiff Site	0,288756	294,0	179,0	123,0

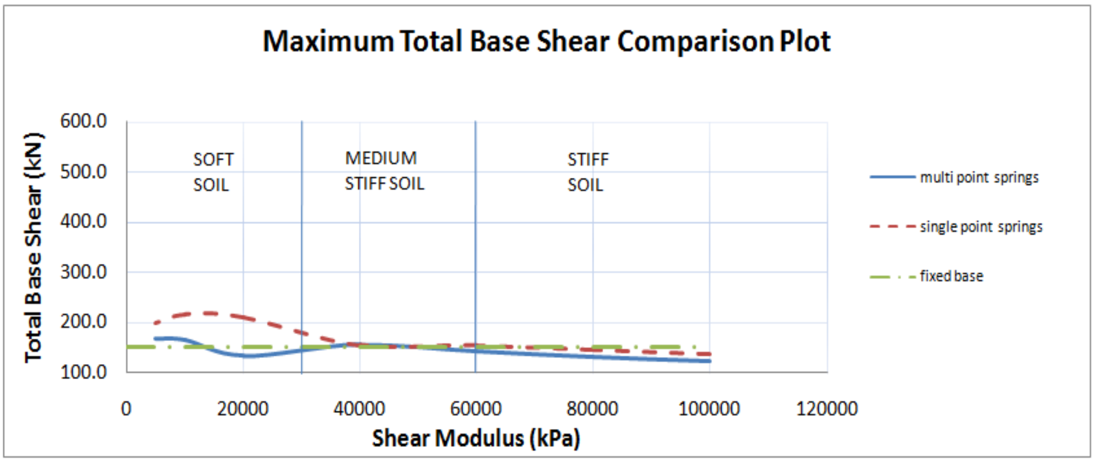
The plots of maximum total base shear values of four-storey structure models are presented in Figure 4.3-1, for three different time-history record representative of varying local site effects.



(a)



(b)



(c)

Figure 4.3-1 Maximum total base shear comparison plots of the four-storey building structure for seismic excitation representative of a) soft soil site b) dense soil site c) rock site

Two main ideas can be inferred from the plots given in Figure 4.3-1. Initially, the structure seems more sensitive to the SSI for the lower values of soil shear modulus. When the total base shear values are examined, the results obtained from both SSI modeling methods approach to the results of fixed base system for rock. However, for the lower values of soil shear modulus, consideration of SSI may lead to higher total base shear when compared with the fixed base system. When the maximum average drifts of four-storey building, presented in Appendix B are examined, it is seen that this conclusion is also valid for structural drifts. This observation again confirms that the fixed base modeling does not always yield results that are on the safe side.

Also, it is to be noted from Figure 4.3-1 that quite similar response is observed between SPSS and MPSS, and the differences can be attributed to the foundation uplift.

4.3.1.2. Comparison of the Internal Forces in the Structural Members

Maximum total base shear acting on the system is a representative parameter for the overall structural behavior. However, the internal member forces are essential in the structural design. Accordingly, one internal and one external column and beam are selected for monitoring maximum member effects as shown in Figure 4.3-2. Maximum axial force, shear force and moment obtained from different foundation modeling approaches for these selected members are compared.

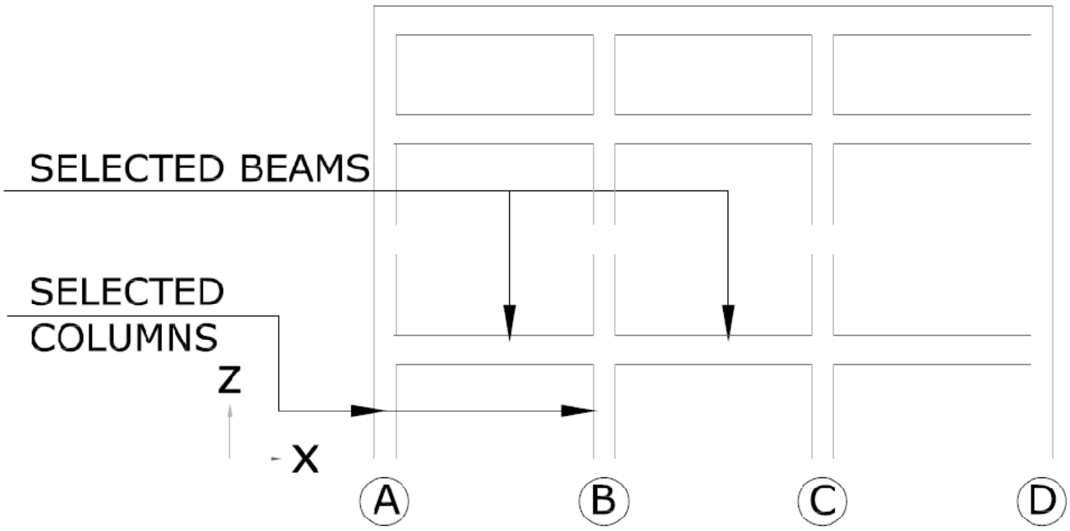
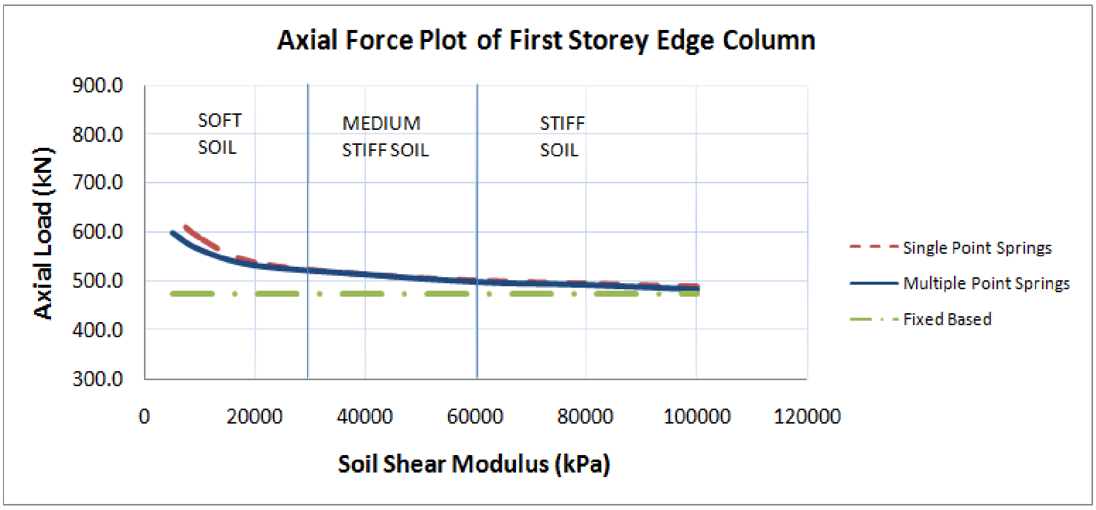


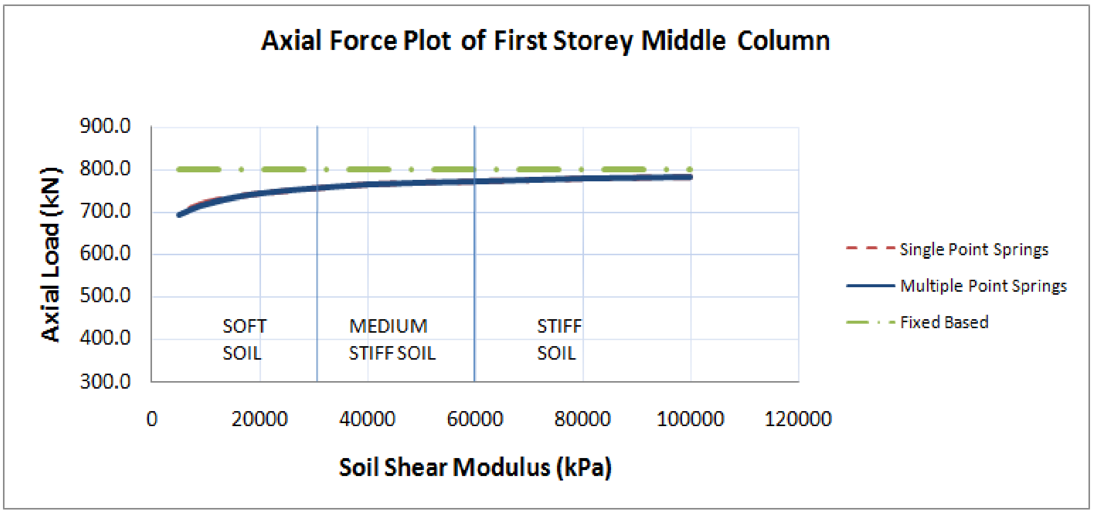
Figure 4.3-2 Selected structural members for monitoring

Maximum internal forces obtained from the analyses of the four-storey structure are tabulated for each earthquake record representative of soft soil site, dense soil site and rock site in Appendix A, Table A.1-1. As it can be observed from the table, the structure exhibits a very similar behavior for all three seismic excitations. Due to that reason, the maximum axial force, shear force and moment acting on the selected members are given here in the form of plots for the seismic excitation representative of dense soil effects only for each foundation modeling approach. The maximum values are given as plot couples to be able to make a visual comparison between the external and internal members.

In Figure 4.3-3, variation of the maximum axial force for the first storey internal and external columns is presented. It is seen that for the greater values of the soil shear modulus all three foundation modeling approaches converge to the same result. Also, the superstructure is very sensitive to SSI for the lower values of the soil shear modulus. The edge columns are subject to higher axial forces compared to that obtained from the fixed base approach for soft soils. On the other side, the fixed base approach yields higher axial forces on the internal columns.



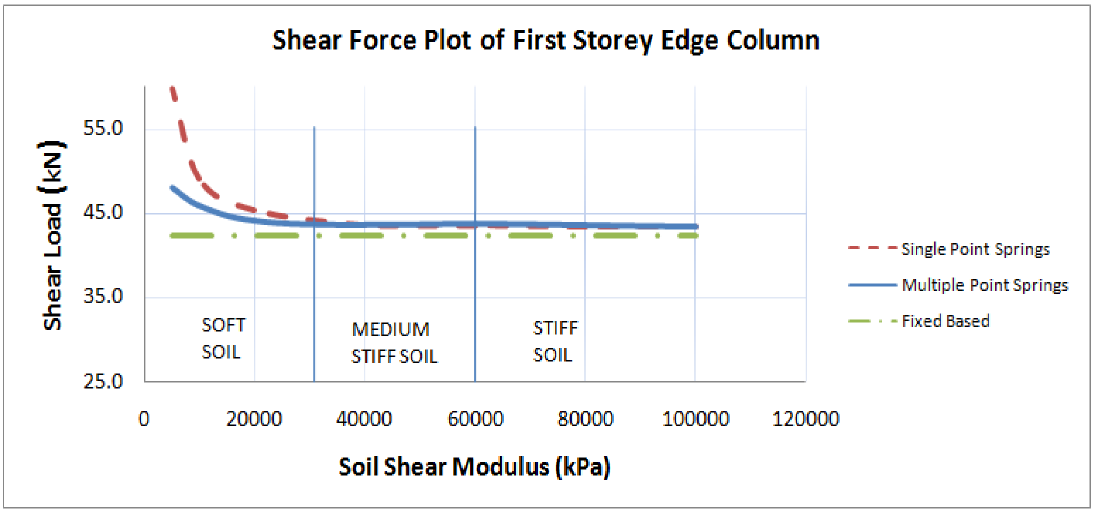
(a)



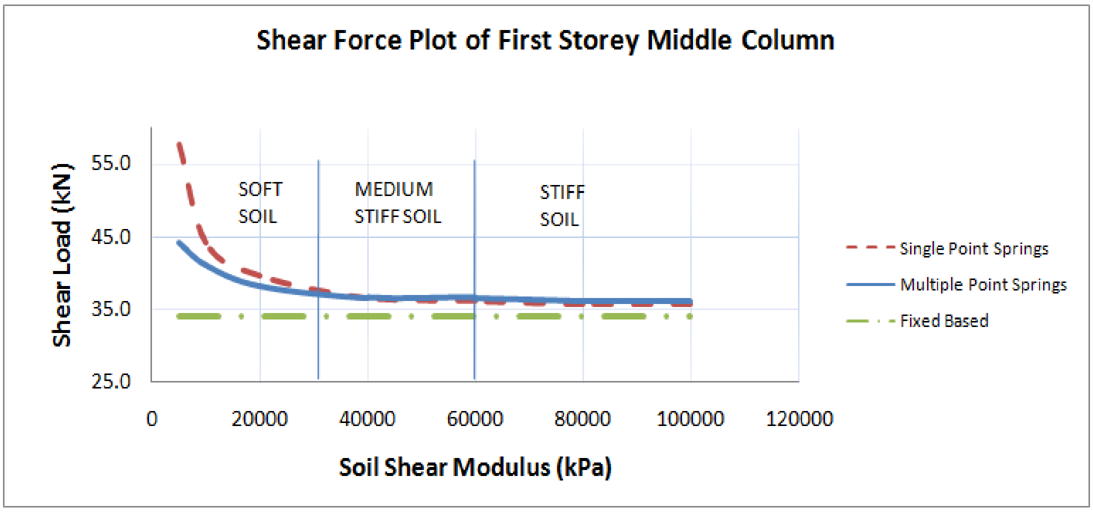
(b)

Figure 4.3-3 Axial force plot for seismic excitation representative of dense soil site a) edge column b) middle column

A similar trend is observed regarding the variation of maximum shear force given in Figure 4.3-4. That is, SSI effects are pronounced for lower values of shear modulus and convergence is observed with increasing soil stiffness. Also, it is observed that a consideration of SSI can yield much greater shear forces in structural members when compared with the results of the fixed base assumption. Although the maximum total base shear acting on the superstructure obtained from the fixed base approach is generally greater than the shear force obtained from the approaches that consider SSI, the situation can be reversed when evaluated on the basis of individual structural members.



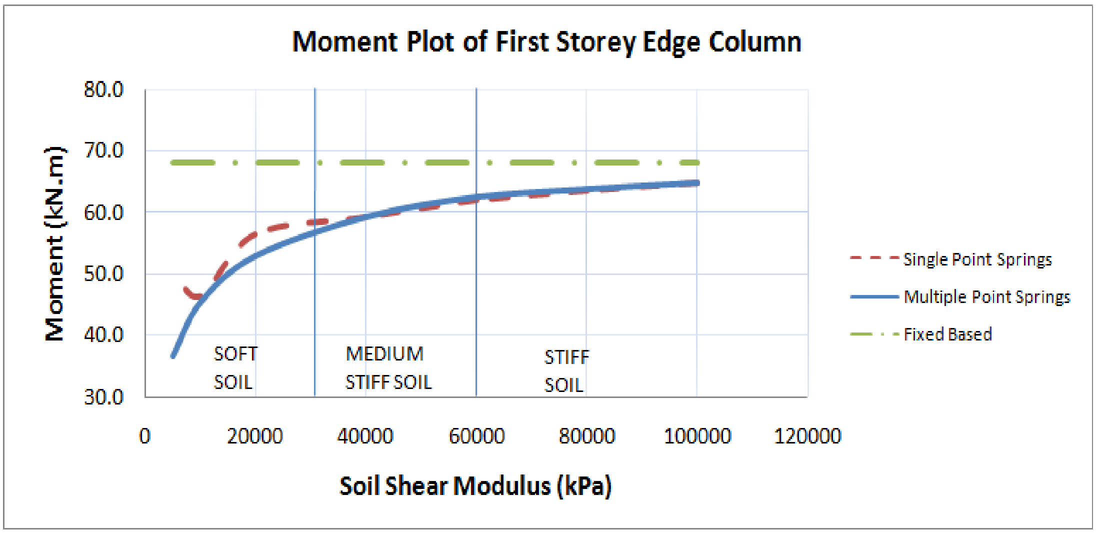
(a)



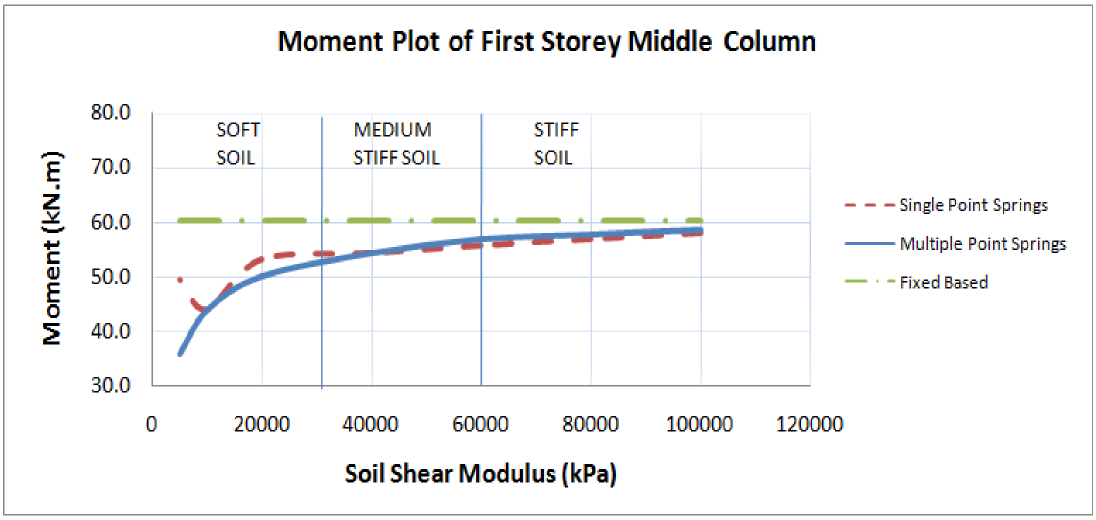
(b)

Figure 4.3-4 Shear force plot for seismic excitation representative of dense soil site a) edge column b) middle column

Variation of the maximum moments given in Figure 4.3-5 reveals that flexural capacity demand for the selected columns decreases when the foundation system is modeled with the deformable medium. Since inclusion of SSI provides flexibility to the foundations, this reduction with respect to the fixed base approach is understandable. In this case, if the actual flexural demand on columns is less than that of obtained by the fixed base approach, more economical structural systems can be designed by considering SSI.



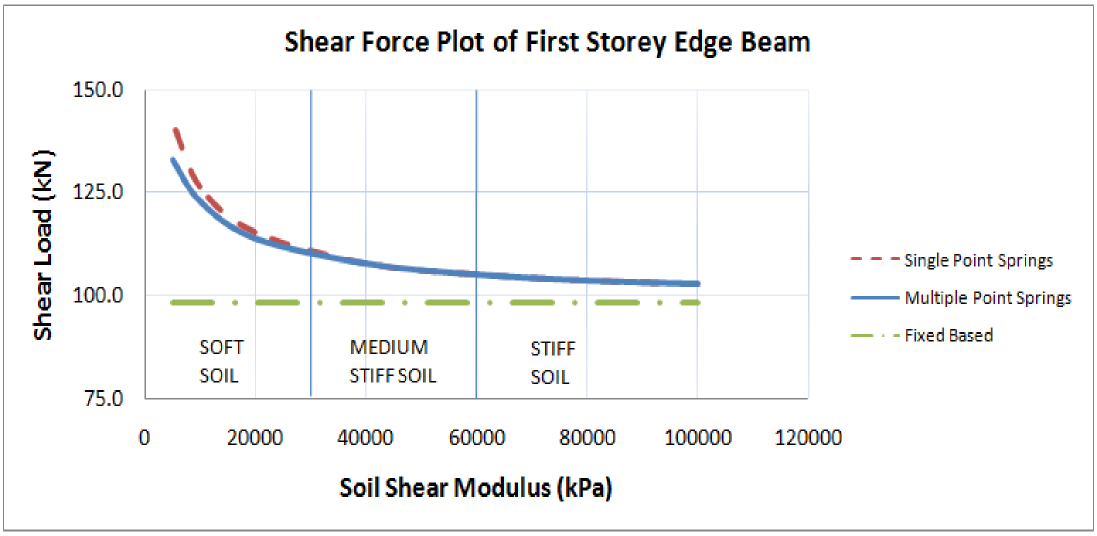
(a)



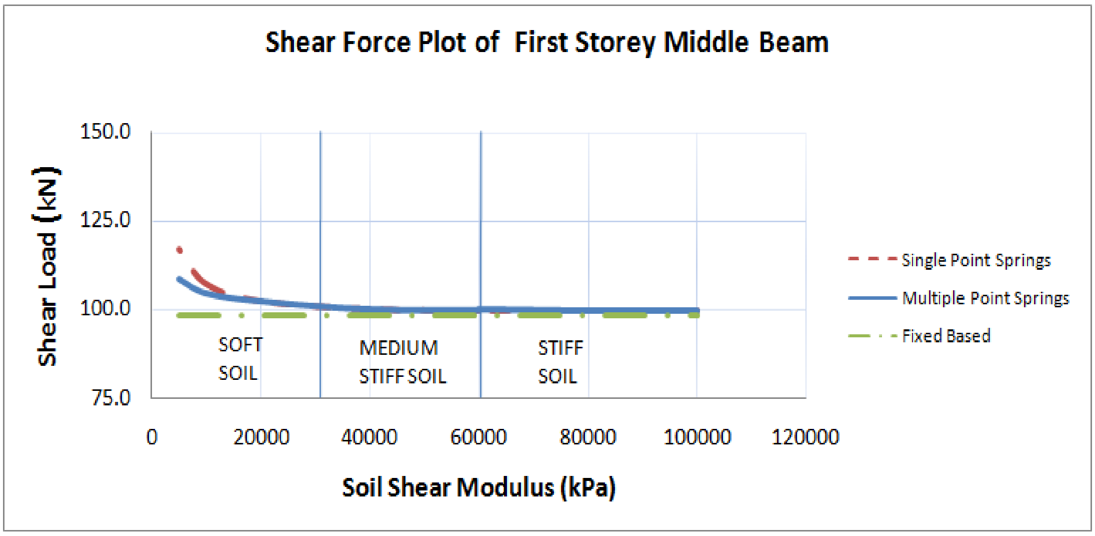
(b)

Figure 4.3-5 Moment plot for seismic excitation representative of dense soil site a) edge column b) middle column

Similar to the behavior observed for the columns, SSI approaches result in higher shear forces on the beams compared to those calculated using the fixed base approach as shown in Figure 4.3-6. Therefore, if structural design is performed according to the results of fixed base approach, the designed members are likely to be subjected to higher shear forces under seismic conditions.



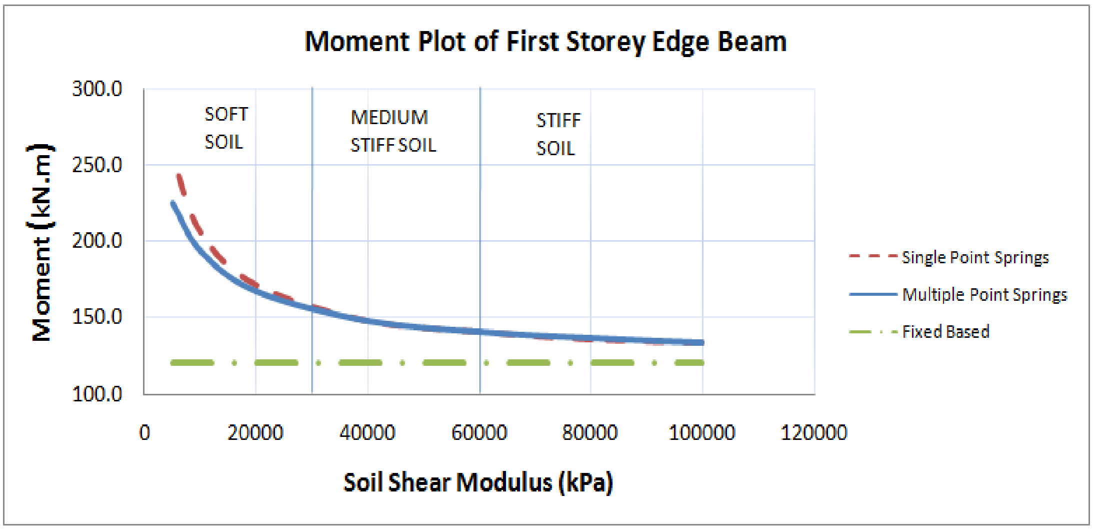
(a)



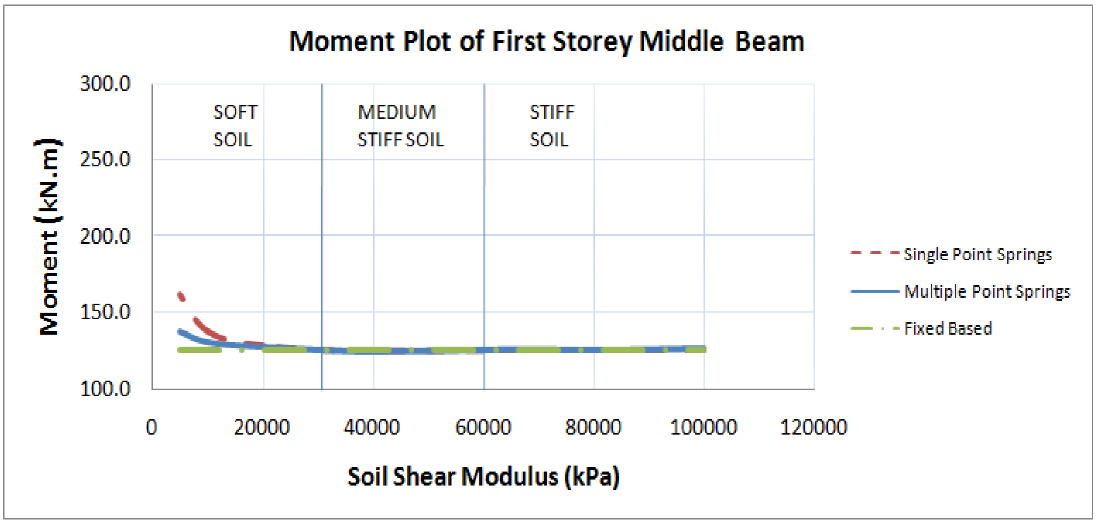
(b)

Figure 4.3-6 Shear force plot for seismic excitation representative of dense soil site a) edge beam b) middle beam

In contrast to the behavior observed in the columns regarding variation of the maximum moment, especially the edge beams were subject to relatively much higher bending moments when SSI is considered (See Figure 4.3-7). In the models considering SSI, since the first floor columns are not fixed at the base, the moment effects under horizontal loads are transmitted to the beam column connections and this leads to the increase of moment demand in the beams.



(a)



(b)

Figure 4.3-7 Moment plot for seismic excitation representative of dense soil site a) edge beam b) middle beam

There are two important points that can be inferred from the plots given for the selected structural members. First, the characteristics of the load variations obtained through consideration of SSI are generally quite close to each other. This is due to the fact that no uplift is observed at all during the analyses for all three time history records. The second conclusion is related with the comparison of the results of fixed base approach and simplified SSI approaches. When the plots are examined, it is seen that for the soft soil, the effect of SSI is more pronounced and often on the unsafe side.

4.3.2. Results of a Ten-Storey-Building Analyses with Different Soil Shear Modulus

Since the analyses results of ten-storey building structure are quite parallel to the results of four-storey structure given in Section 4.3.1, these results are given in Appendix A in a similar way. Moreover, maximum average drifts of the ten-storey building for different soil shear moduli are presented and compared in Appendix B.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Introduction

The main objective of this study is to investigate the effects of deformable foundation soil on the seismic response of superstructures. It is intended to investigate whether the generally ignored effects of SSI in design are always beneficial as widely believed, or can be detrimental as well for the superstructure.

To make a comparison between the general design trends based on the fixed base assumption and the approaches that consider SSI, different models are utilized for the analyses. In the models that consider SSI, the inertial interaction mechanism is introduced into the system by two simplified approaches defined in FEMA 356 [18]; namely "Gazetas" and "Winkler" springs approaches. Spring stiffnesses for each simplified SSI approach are ascertained according to the equivalent linear model assumption. Three different structural systems including SDOF and MDOF and three different foundation-modeling approaches are combined to obtain the trends in a broad perspective.

To make inferences related to the seismic behavior of the superstructure, evaluations are based on the maximum total base shear acting over the structure average structural drifts and the maximum shear and axial forces as well as the moments acting over the structural elements. To be able to make generalizations about the structural behavior, three time history records representative of soft, medium stiff and stiff sites are utilized in the analyses. Moreover, the effect of uplift phenomenon, which can be modeled using Winkler springs, on the seismic response is investigated. By this means, the compatibility of the two simplified SSI approaches defined in FEMA 356 [18] is examined.

5.2. Conclusions

Based on the parametric studies, the conclusions reached depend on the assumptions and limitations, which are already discussed in the previous chapters of this study. Considering the limitations involved, the following conclusions are drawn for approximate inertial interaction analyses:

- One of the major parameters that affect seismic structural response is the stiffness of the structure. In general, the structures become more sensitive to changing foundation soil properties as the structural stiffness increases. In other words, independent of the characteristics of the seismic records utilized, fixed base and SSI approaches yield the same results as the flexibility of the structure increases. Accordingly, for the rigid structural systems, the exact seismic behavior can only be figured out by considering SSI. In addition, structures which are more flexible are observed to have the tendency to undergo to smaller total base shear.

- Decreasing soil shear modulus also increases the sensitivity of the structures to soil structure interaction as would be expected. As the shear modulus of the foundation soil increases, the structural response approaches to that of the fixed base system response.

- Both simplified SSI approaches (Gazetas and Winkler Springs approach) yield comparable results for the cases in which no foundation uplift is involved throughout the seismic excitation. In the case of occurrence of foundation uplift, the system becomes more flexible and total base shear is reduced considerably. Due to that reason, analyses performed with Winkler Spring approach is more advantageous when compared to Gazetas' Springs in terms of total cost.

- When the variation of element forces of the first storey columns and beams is examined, it is clearly seen that models in which SSI is considered may result in greater loads when compared to the fixed base approach especially for the lower values of the soil shear modulus. This conclusion is supported even in the cases in which higher total base shear values are acquired by fixed base analyses. In other words, there exist certain circumstances (especially for the lower values of the soil shear modulus) where consideration of SSI yields exceedingly higher base shear or element forces or moments for the superstructure. Owing to this reason, contrary to general belief, the fixed base approach does not always yield results that are on the safe side.

  On the other hand, SSI analyses affirm that shear or flexural capacity demand on structural members are generally not as high as the demand of the fixed base approach. As a result, consideration of SSI can lead to more realistic, hence more economical and safer designs provided that the properties of the soil on which the structure rests are well defined.

5.3. Recommendations

The following items are recommended for the future studies:

- The effectiveness of the simplified SSI approaches used in this study can be examined by rigorous numerical methods in which the soil is modeled as continuum and utilizing a proper yield criterion for the soil.
- Three-dimensional models could be utilized for results that are more precise.

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APPENDIX A

A.1. Results of Internal Forces in the Structural Members of a Four-Storey-Building

Maximum internal forces obtained from the analyses of the four-storey structure are given in Table A.1-1 for each earthquake record representative of the effects of rock site, dense soil site and soft soil site.

Table A.1-1 Internal forces in the structural members for the seismic excitation representative of soft soil site

Model ID	G, Shear Modulus (MPa)	Site Classification	Foundation Modeling Approach	First Story Edge Column (kN/kN.m)			First Story Middle Column (kN/kN.m)			First Story Edge Beam (kN/kN.m)		First Story Middle Beam (kN/kN.m)	
				Axial Force	Shear Force	Moment	Axial Force	Shear Force	Moment	Shear Force	Moment	Shear Force	Moment
Model 36	-	-	Fixed Based	478.9	44.4	72.5	800.7	36.9	65.1	99.8	125.1	100.0	129.4
Model 37	5	Soft Site	SPSS	638.1	56.8	52.2	698.1	53.1	52.1	142.5	256.1	116.4	160.6
Model 38	10	Soft Site	SPSS	600.5	58.6	69.1	717.7	56.3	67.6	132.6	225.0	113.2	155.9
Model 39	20	Soft Site	SPSS	557.3	53.6	74.6	740.9	50.0	72.7	120.4	187.4	107.3	142.9
Model 40	40	Medium Stiff Site	SPSS	520.1	46.9	66.8	762.0	40.5	63.5	110.0	155.3	102.2	130.9
Model 41	60	Medium Stiff Site	SPSS	505.6	46.6	68.7	771.0	40.1	63.1	107.2	147.1	101.7	131.0
Model 42	80	Stiff Site	SPSS	500.2	46.3	69.9	776.9	39.6	64.0	105.6	142.4	101.4	130.9
Model 43	100	Stiff Site	SPSS	496.3	46.1	70.7	780.9	39.2	64.6	104.6	139.4	101.2	130.7
Model 44	5	Soft Site	MPSS	609.0	49.4	38.9	692.8	45.6	37.8	134.6	230.1	109.9	142.3
Model 45	10	Soft Site	MPSS	574.4	49.6	51.2	717.9	46.0	50.0	126.0	203.9	107.7	140.4
Model 46	20	Soft Site	MPSS	540.7	46.1	56.9	742.3	41.8	55.1	116.0	173.5	104.1	134.1
Model 47	40	Medium Stiff Site	MPSS	520.1	46.9	66.8	762.0	40.5	63.5	109.9	155.3	102.2	130.9
Model 48	60	Medium Stiff Site	MPSS	503.3	45.8	66.7	770.9	39.4	61.7	106.6	145.5	101.4	130.3
Model 49	80	Stiff Site	MPSS	498.2	45.6	68.1	777.1	39.0	62.7	105.2	141.3	101.1	130.2
Model 50	100	Stiff Site	MPSS	495.0	45.4	69.9	781.0	38.7	63.3	104.3	138.6	101.0	130.1

Table A.1-2 Internal forces in the structural members for the seismic excitation representative of dense soil site

Model ID	G, Shear Modulus (MPa)	Site Classification	Foundation Modeling Approach	First Story Edge Column (kN/kN.m)			First Story Middle Column (kN/kN.m)			First Story Edge Beam (kN/kN.m)		First Story Middle Beam (kN/kN.m)	
				Axial Force	Shear Force	Moment	Axial Force	Shear Force	Moment	Shear Force	Moment	Shear Force	Moment
Model 36	-	-	Fixed Based	474.4	42.3	68.2	800.4	34.1	60.2	98.3	120.4	98.8	125.6
Model 37	5	Soft Site	SPSS	635.2	59.7	51.0	695.0	57.8	49.6	142.3	255.0	116.8	161.9
Model 38	10	Soft Site	SPSS	589.1	49.1	46.4	720.2	44.2	44.0	126.6	205.9	106.9	137.2
Model 39	20	Soft Site	SPSS	539.6	45.4	56.6	740.1	39.6	53.1	115.3	170.9	102.4	128.1
Model 40	40	Medium Stiff Site	SPSS	514.6	43.6	59.4	761.8	36.6	54.3	107.8	148.3	100.1	124.8
Model 41	60	Medium Stiff Site	SPSS	501.3	43.5	62.0	770.9	36.1	55.9	105.1	140.6	99.7	125.0
Model 42	80	Stiff Site	SPSS	494.5	43.4	63.7	777.0	35.7	57.0	103.6	136.1	99.5	125.2
Model 43	100	Stiff Site	SPSS	490.3	43.4	64.9	780.3	35.7	58.1	102.8	133.6	99.5	125.7
Model 44	5	Soft Site	MPSS	600.8	47.9	36.7	690.5	44.1	35.9	133.2	225.3	108.4	137.8
Model 45	10	Soft Site	MPSS	564.6	45.8	45.4	715.9	41.0	43.7	123.0	194.0	104.5	130.9
Model 46	20	Soft Site	MPSS	533.8	44.0	53.0	741.4	38.2	50.0	114.1	167.3	102.1	127.8
Model 47	40	Medium Stiff Site	MPSS	514.6	43.6	59.4	761.8	36.6	54.3	107.8	148.3	100.1	124.8
Model 48	60	Medium Stiff Site	MPSS	498.5	43.7	62.5	770.9	36.6	56.9	105.1	140.4	99.9	125.9
Model 49	80	Stiff Site	MPSS	493.4	43.5	63.9	777.0	36.2	57.9	103.7	136.3	99.7	125.9
Model 50	100	Stiff Site	MPSS	484.0	43.4	64.8	780.9	36.0	58.5	102.8	133.7	99.6	126.0

Table A.1-3 Internal forces in the structural members for the seismic excitation representative of rock site

Model ID	G, Shear Modulus (MPa)	Site Classification	Foundation Modeling Approach	First Story Edge Column (kN/kN.m)			First Story Middle Column (kN/kN.m)			First Story Edge Beam (kN/kN.m)		First Story Middle Beam (kN/kN.m)	
				Axial Force	Shear Force	Moment	Axial Force	Shear Force	Moment	Shear Force	Moment	Shear Force	Moment
Model 36	-	-	Fixed Based	469.4	37.0	58.1	798.8	27.5	48.8	95.7	112.0	96.6	119.0
Model 37	5	Soft Site	SPSS	595.6	35.7	24.4	684.1	30.2	24.2	125.9	200.7	100.6	113.2
Model 38	10	Soft Site	SPSS	565.3	42.1	44.3	710.6	35.9	42.1	121.4	188.8	102.7	124.4
Model 39	20	Soft Site	SPSS	533.6	40.2	46.7	741.2	32.9	41.9	112.0	160.2	99.4	119.1
Model 40	40	Medium Stiff Site	SPSS	512.0	41.0	55.5	761.1	33.4	49.4	106.7	144.8	99.5	122.8
Model 41	60	Medium Stiff Site	SPSS	501.6	40.0	56.6	770.2	31.8	50.1	103.4	135.0	98.4	121.0
Model 42	80	Stiff Site	SPSS	491.8	40.0	58.1	775.7	31.8	51.1	102.1	131.2	98.4	121.8
Model 43	100	Stiff Site	SPSS	487.2	39.4	58.3	779.7	31.1	51.0	100.9	127.6	98.0	121.1
Model 44	5	Soft Site	MPSS	581.8	32.2	19.3	686.6	26.6	19.2	122.5	189.7	98.2	107.1
Model 45	10	Soft Site	MPSS	551.1	37.8	33.5	714.3	30.8	31.0	117.1	174.9	98.6	113.2
Model 46	20	Soft Site	MPSS	526.9	40.1	46.4	740.7	33.1	42.5	111.4	158.7	99.5	120.1
Model 47	40	Medium Stiff Site	MPSS	512.0	41.0	55.5	761.1	33.4	49.4	106.7	144.8	99.5	122.8
Model 48	60	Medium Stiff Site	MPSS	494.4	38.1	52.8	770.5	30.1	46.9	102.4	131.7	97.7	119.2
Model 49	80	Stiff Site	MPSS	489.2	38.1	54.4	776.4	29.9	47.9	101.1	127.8	97.5	119.3
Model 50	100	Stiff Site	MPSS	486.1	38.3	55.7	780.2	29.9	48.7	100.3	125.7	97.5	119.6

A.2. Results of a Ten-Storey Building with Different Soil Shear Modulus

The analyses results of a ten-storey building for both maximum total base shear values and structural member internal forces are presented in this section.

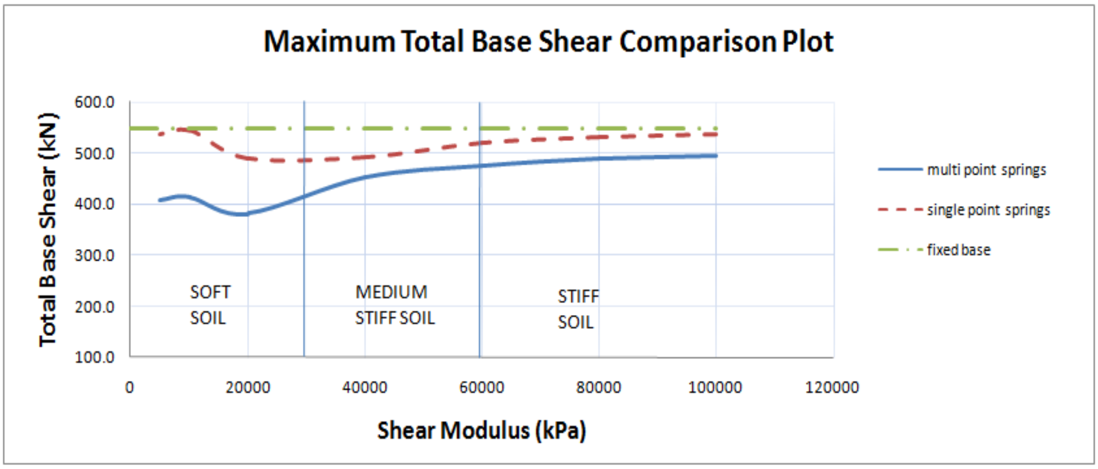
A.2.1 Comparison of the Maximum Total Base Shear

The shear modulus values of soil were varied within a range of 5MPa to 100MPa. Resulting maximum total base shear values are presented in Table A.2-1 in accordance with the analysis cases defined Chapter 3.

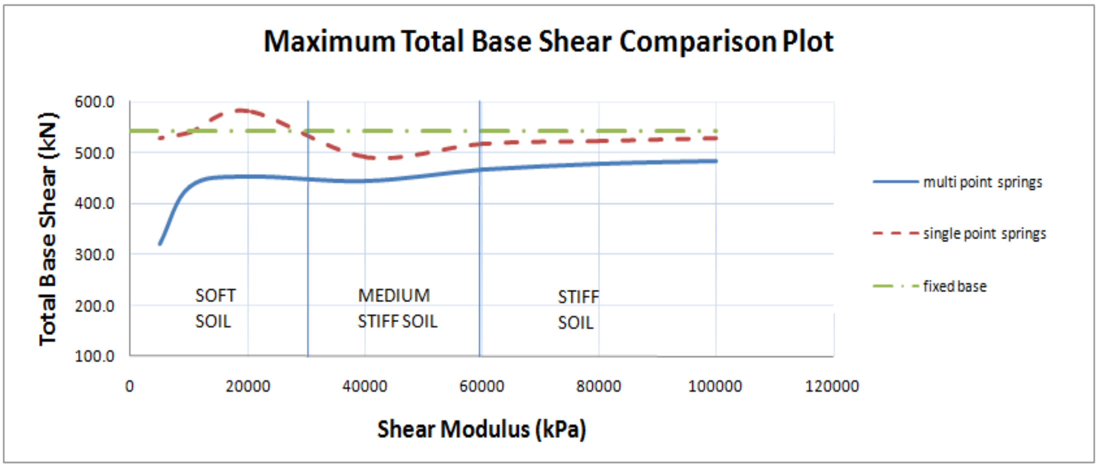
Table A.2-1 Analyses results for ten-storey structure with varying soil shear modulus

Model ID	**Foundation Modeling Approach**	**Soil Shear Modulus (Mpa)**	**Site Classification**	**System Period (s)**	**Total Base Shear Under Dynamic Loads (kN)**	**Total Base Shear Under Dynamic Loads (kN)**	**Total Base Shear Under Dynamic Loads (kN)**
					Seismic Excitation Representative of Soft Soil Site Effects	**Seismic Excitation Representative of Dense Soil Site Effects**	**Seismic Excitation Representative of Rock Site Effects**
Model 51	Fixed Base	-	-	0,709508	548,0	543,0	286,0
Model 52	SPSS	5	Soft Site	1,157631	536,0	527,0	291,0
Model 53	SPSS	10	Soft Site	0,960584	544,0	541,0	327,0
Model 54	SPSS	20	Soft Site	0,845016	490,0	582,0	359,0
Model 55	SPSS	40	Medium Stiff Site	0,780726	492,0	491,0	281,0
Model 56	SPSS	60	Medium Stiff Site	0,757969	519,0	518,0	285,0
Model 57	SPSS	80	Stiff Site	0,746275	530,0	523,0	289,0
Model 58	SPSS	100	Stiff Site	0,739142	536,0	527,0	291,0
Model 59	MPSS	5	Soft Site	1,122723	408,0	320,0	268,0
Model 60	MPSS	10	Soft Site	0,942831	414,0	432,0	311,0
Model 61	MPSS	20	Soft Site	0,837083	381,0	452,0	261,0
Model 62	MPSS	40	Medium Stiff Site	0,777957	453,0	445,0	243,0
Model 63	MPSS	60	Medium Stiff Site	0,756965	476,0	466,0	259,0
Model 64	MPSS	80	Stiff Site	0,74615	488,0	479,0	270,0
Model 65	MPSS	100	Stiff Site	0,739556	495,0	484,0	263,0

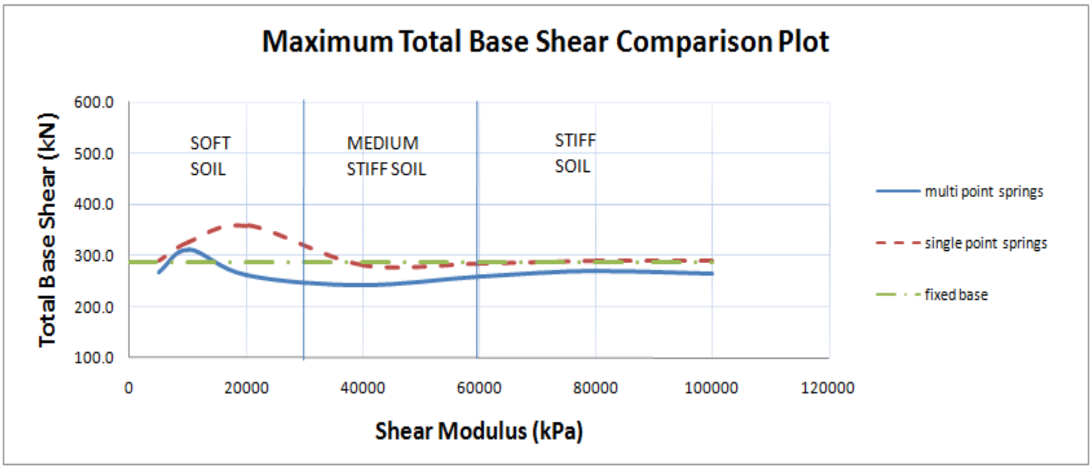
The plots of maximum total base shear values of ten-storey structure models are presented in Figure A.2-1, for three different conditions of site stiffness.



(a)



(b)



(c)

Figure A.2-1 Maximum total base shear comparison plots for ten story building structure the seismic excitation representative of a) soft soil site b) dense soil site c) rock site

Similar to the results of four-storey building, the structure seems more sensitive to the SSI for the lower values of soil shear modulus. The results obtained from both SSI modeling methods approach to the results of fixed base system for rock site. However, for soft soils, consideration of SSI may lead to higher total base shear when compared with the fixed base system.

A.2.2 Comparison of the Internal Forces in the Structural Members

The internal member forces are essential in the structural design. Accordingly, one internal and one external column and beam are selected for monitoring maximum member effects as shown in Figure A.2-2. Maximum axial force, shear force and moment obtained from different foundation modeling approaches for these selected members are compared.

Maximum internal forces obtained from the analyses of the ten-storey structure are presented in Table A.2-2 for each earthquake record representative of the effects of rock site, dense soil site and soft soil site.

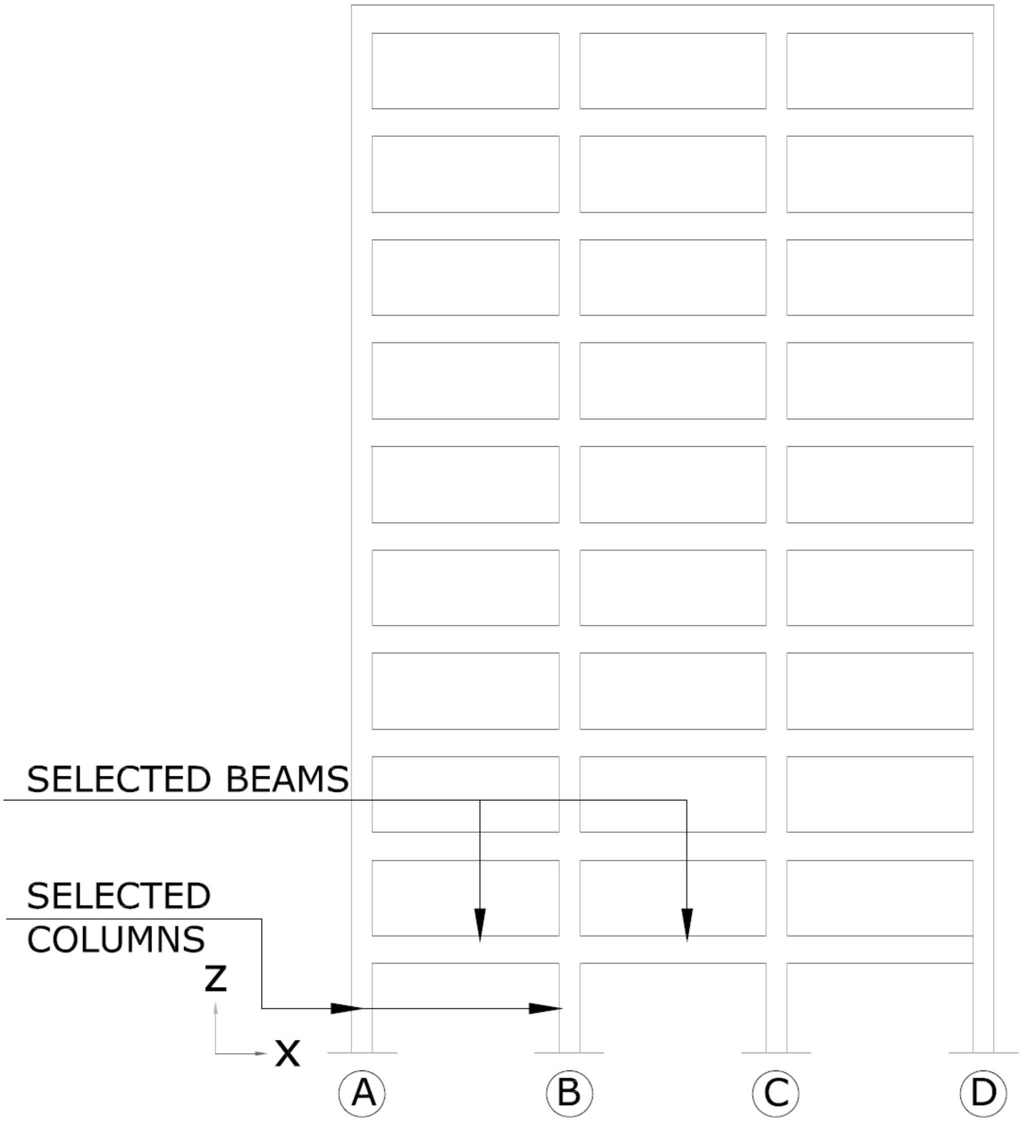


Figure A.2-2 Selected structural members used in the comparison study

Table A.2-2 Internal forces in the structural members for the seismic excitation representative of soft soil site

Model ID	**G, Shear Modulus (MPa)**	**Site Classification**	**Foundation Modeling Approach**	**First Story Edge Column (kN/kN.m)**			**First Story Middle Column (kN/kN.m)**			**First Story Edge Beam (kN/kN.m)**		**First Story Middle Beam (kN/kN.m)**	
				Axial Force	**Shear Force**	**Moment**	**Axial Force**	**Shear Force**	**Moment**	**Shear Force**	**Moment**	**Shear Force**	**Moment**
Model 51	-	-	Fixed Based	1642.0	109.5	209.7	1887.0	123.6	223.0	150.0	284.0	142.4	255.7
Model 52	5	Soft Site	SPSS	1952.8	141.7	177.3	1744.3	151.5	173.6	204.4	458.5	175.6	336.3
Model 53	10	Soft Site	SPSS	1876.2	109.7	165.8	1765.3	117.0	165.3	173.4	358.1	152.6	271.1
Model 54	20	Soft Site	SPSS	1779.7	107.2	175.6	1794.6	114.7	176.4	163.1	325.2	146.2	255.8
Model 55	40	Medium Stiff Site	SPSS	1773.7	120.4	214.1	1838.1	133.6	221.7	166.2	336.2	153.3	280.9
Model 56	60	Medium Stiff Site	SPSS	1750.1	120.1	218.8	1851.2	134.6	229.0	163.5	327.7	152	278.9
Model 57	80	Stiff Site	SPSS	1713.5	118.8	219.1	1853.1	133.7	230.6	161.2	320.5	150.5	275.6
Model 58	100	Stiff Site	SPSS	1718.0	117.6	218.5	1862.5	132.6	230.1	159.6	315.3	149.3	272.8
Model 59	5	Soft Site	MPSS	1788.4	111.4	122.4	1704.1	117.8	120.4	185.1	395.1	156.2	278.9
Model 60	10	Soft Site	MPSS	1761.0	109.7	127.1	1743.6	117.0	126.2	164.9	329.8	141.3	237.7
Model 61	20	Soft Site	MPSS	1735.0	103.4	160.6	1788.5	111.1	162.8	162.4	323	144.9	252.7
Model 62	40	Medium Stiff Site	MPSS	1728.2	111.9	191.4	1830.6	123.5	198.0	161.7	321.6	148.3	266.6
Model 63	60	Medium Stiff Site	MPSS	1713.2	113.1	200.1	1846.8	125.9	208.8	159.7	315.5	148	267.3
Model 64	80	Stiff Site	MPSS	1702.0	113.1	203.6	1855.3	126.5	213.5	158.2	310.7	147.3	266.5
Model 65	100	Stiff Site	MPSS	1693.8	112.9	205.0	1860.7	126.5	216.0	157.1	307.2	146.8	265.5

Table A.2-3 Internal forces in the structural members for the seismic excitation representative of dense soil site

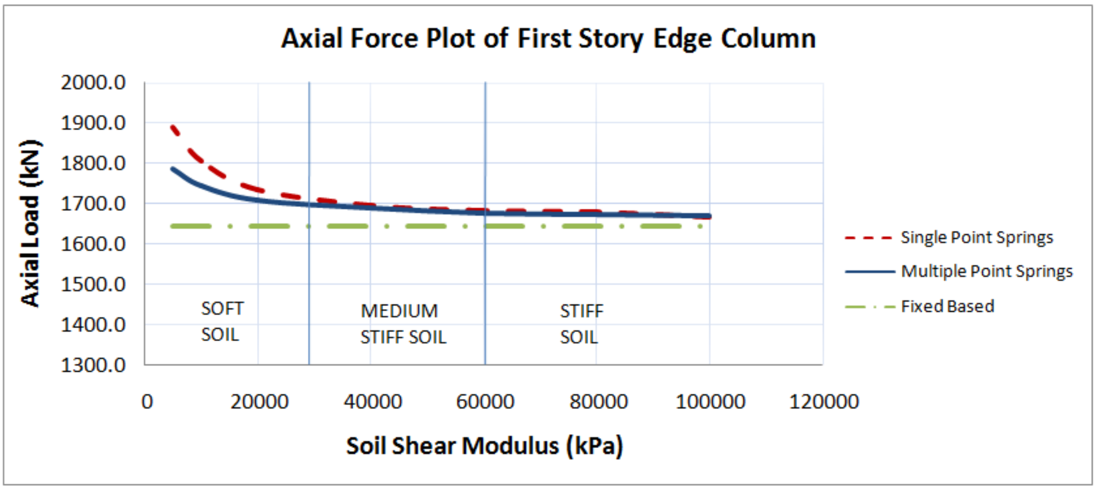
Model ID	G, Shear Modulus (MPa)	Site Classification	Support Conditions	First Story Edge Column (kN / kN.m)			First Story Middle Column (kN / kN.m)			First Story Edge Beam (kN / kN.m)		First Story Middle Beam (kN / kN.m)	
				Axial Force	Shear Force	Moment	Axial Force	Shear Force	Moment	Shear Force	Moment	Shear Force	Moment
Model 51	-	-	Fixed Based	1643.4	103.3	211.5	1885.8	124.7	225.1	150.6	286.9	142.9	257.4
Model 52	5	Soft Site	SPSS	1890.0	162.5	132.5	1696.0	162.3	130.2	178.3	402.3	160.3	280.6
Model 53	10	Soft Site	SPSS	1805.1	135.4	150.5	1753.4	135.2	149.7	168.8	362.8	152.2	254.9
Model 54	20	Soft Site	SPSS	1735.3	119.5	175.9	1786.7	120.9	178.6	164.1	345.2	146.7	257.4
Model 55	40	Medium Stiff Site	SPSS	1695.9	114.2	200.3	1836.7	130.4	216.0	164.4	330.4	151.5	275.7
Model 56	60	Medium Stiff Site	SPSS	1683.9	112.7	216.9	1851.1	133.1	226.7	162.6	324.9	151.2	276.7
Model 57	80	Stiff Site	SPSS	1680.3	111.0	218.0	1858.3	132.7	229.2	160.7	318.8	150.1	274.4
Model 58	100	Stiff Site	SPSS	1666.2	110.8	217.9	1863.1	132.1	229.9	159.3	314.3	149.1	272.2
Model 59	5	Soft Site	MPSS	1787.8	133.6	82.9	1684.3	145.3	82.2	161.9	348.1	150.8	271.6
Model 60	10	Soft Site	MPSS	1744.3	125.8	116.9	1739.0	125.4	116.4	159.8	327.9	143	245.1
Model 61	20	Soft Site	MPSS	1708.1	115.2	153.0	1782.8	116.9	154.5	159.5	313.5	141.7	243.1
Model 62	40	Medium Stiff Site	MPSS	1690.3	111.0	187.8	1828.4	120.2	191.1	160.5	317.7	147	262.7
Model 63	60	Medium Stiff Site	MPSS	1675.6	108.1	198.1	1845.5	121.7	206.6	159.1	313.5	147.3	265.3
Model 64	80	Stiff Site	MPSS	1671.7	105.5	202.4	1854.5	125.7	212.2	157.8	309.6	147	265.3
Model 65	100	Stiff Site	MPSS	1669.0	105.5	204.6	1869.1	126.0	215.1	156.9	306.5	146.6	264.8

Table A.2-4 Internal forces in the structural members for the seismic excitation representative of rock site

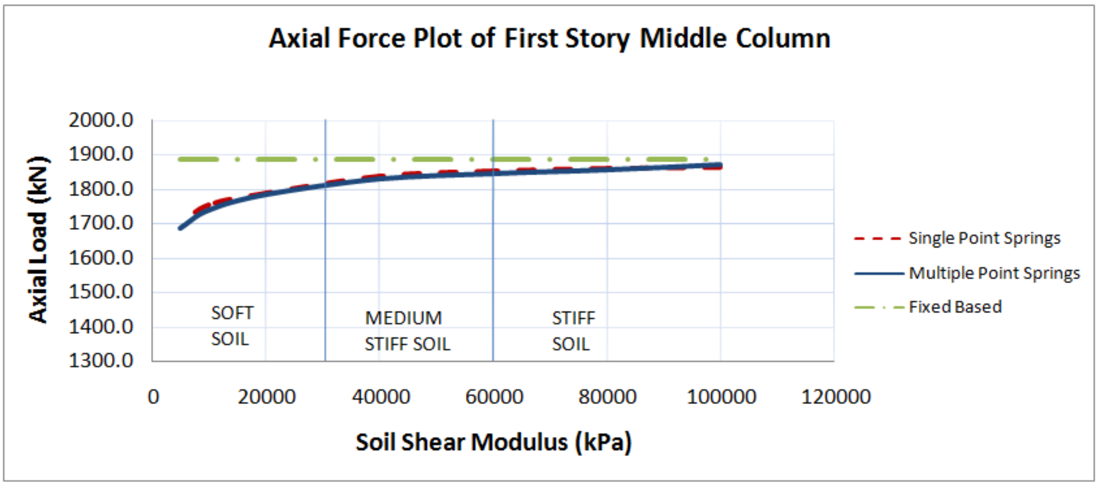
Model ID	G, Shear Modulus (MPa)	Site Classification	Support Conditions	First Story Edge Column (kN/kN.m)			First Story Middle Column (kN/kN.m)			First Story Edge Beam (kN/kN.m)		First Story Middle Beam (kN/kN.m)	
				Axial Force	Shear Force	Moment	Axial Force	Shear Force	Moment	Shear Force	Moment	Shear Force	Moment
Model 51	-	-	Fixed Based	1404.5	61.8	108.9	1884.8	59.9	106.8	114.5	171.7	111.5	163.2
Model 52	5	Soft Site	SPSS	1698.4	74.6	89.3	1669.0	75.1	88.5	156.5	300.7	127.4	191.7
Model 53	10	Soft Site	SPSS	1663.1	77.7	102.5	1706.9	78.1	101.1	151.0	283.6	126.7	193.2
Model 54	20	Soft Site	SPSS	1574.1	70.9	103.0	1749.3	69.0	101.7	138.6	244.8	119.0	174.4
Model 55	40	Medium Stiff Site	SPSS	1544.2	67.1	220.8	1797.9	66.2	104.5	130.6	220.8	117.7	174.1
Model 56	60	Medium Stiff Site	SPSS	1512.1	67.2	110.1	1818.5	66.5	108.9	127.6	211.7	117.0	174.0
Model 57	80	Stiff Site	SPSS	1490.8	66.2	110.6	1830.7	65.3	109.4	125.2	204.3	116.0	172.3
Model 58	100	Stiff Site	SPSS	1476.5	65.3	110.4	1839.2	64.3	109.1	123.5	199.0	115.3	170.8
Model 59	5	Soft Site	MPSS	1630.9	60.6	55.3	1657.3	57.8	54.7	146.5	267.7	117.6	162.9
Model 60	10	Soft Site	MPSS	1597.9	77.7	77.7	1701.5	78.1	76.4	142.9	257.3	119.0	170.8
Model 61	20	Soft Site	MPSS	1549.1	62.8	86.5	1751.9	61.5	85.7	133.9	229.7	115.8	165.5
Model 62	40	Medium Stiff Site	MPSS	1513.3	63.2	97.2	1799.6	61.4	95.4	127.5	210.7	114.9	166.5
Model 63	60	Medium Stiff Site	MPSS	1490.4	63.9	102.6	1821.1	62.3	100.9	125.2	203.9	114.9	168.2
Model 64	80	Stiff Site	MPSS	1475.4	63.4	104.0	1833.4	61.9	102.4	123.3	198.4	114.5	168.0
Model 65	100	Stiff Site	MPSS	1464.8	62.7	104.2	1841.5	61.2	102.7	121.9	194.1	114.1	167.3

It can be observed from the table that the structure exhibits a very similar behavior for all three seismic excitations. Because of that reason, the maximum axial force, shear force and moment acting on the selected members are given here in the form of plots for the seismic excitation representative of dense soil site only for each foundation modeling approach. The maximum values are given as plot couples to be able to make a visual comparison between the external and internal members.

In Figure A.2-3, variation of the maximum axial force for the first storey internal and external columns is presented. It is seen that for the greater values of the soil shear modulus all three foundation modeling approaches converge to the same result. Also, the superstructure is very sensitive to SSI for the soft soils. The edge columns are subject to higher axial forces compared to that obtained from the fixed base approach for the lower values of shear modulus. On the other side, the fixed base approach yields higher axial forces on the internal columns.



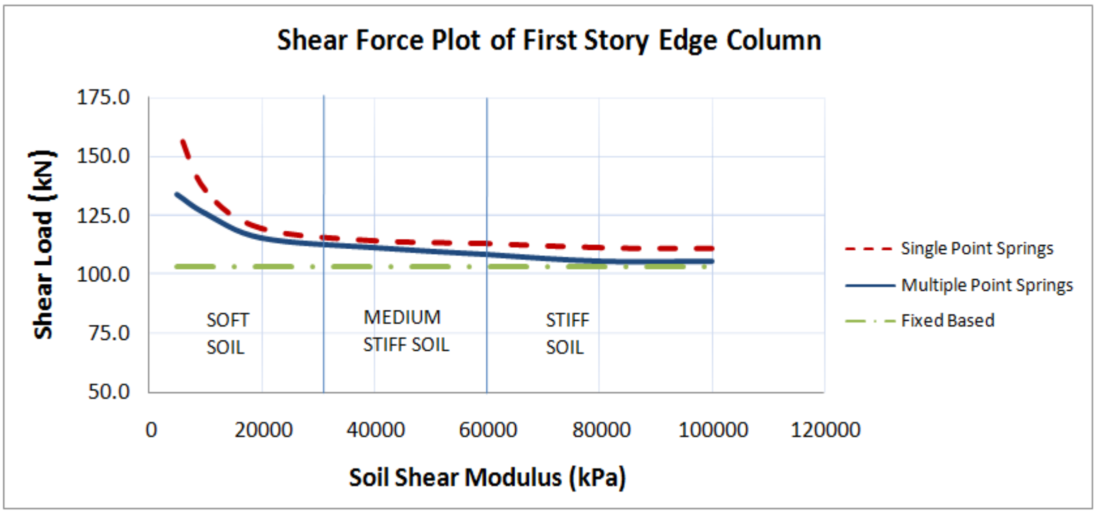
(a)



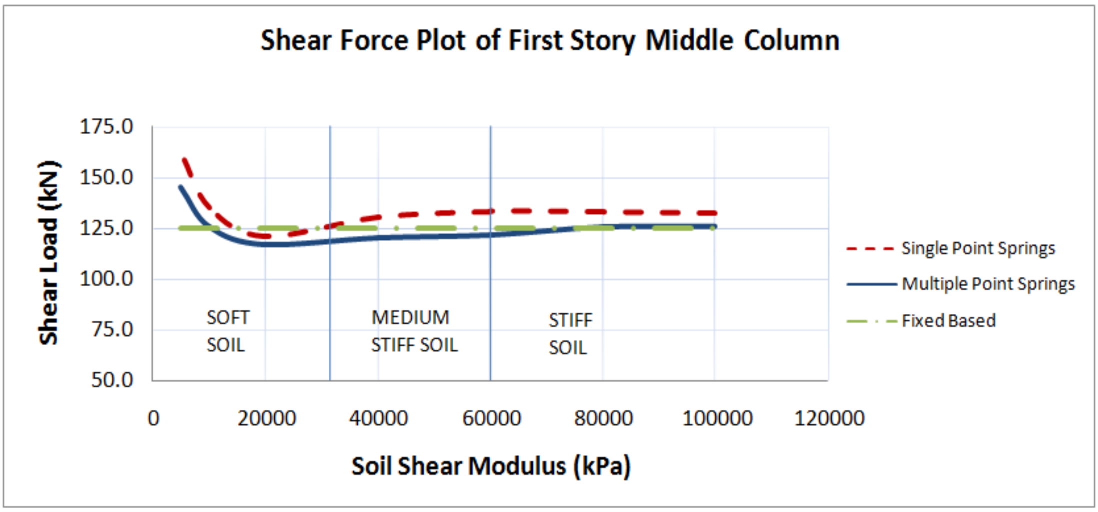
(b)

Figure A.2-3 Axial force plot for the seismic excitation representative of dense soil site a) edge column b) middle column

A similar trend is observed regarding the variation of maximum shear force given in Figure A.2-4. That is, SSI effects are pronounced for lower values of shear modulus and convergence is observed with increasing soil stiffness. In addition, it is observed that a consideration of SSI can yield much greater shear forces in structural members when compared with the results of the fixed base assumption. Although the maximum total base shear acting on the superstructure obtained from the fixed base approach is generally greater than the shear force obtained from the approaches that consider SSI, the situation can be reversed when evaluated on the basis of individual structural members.



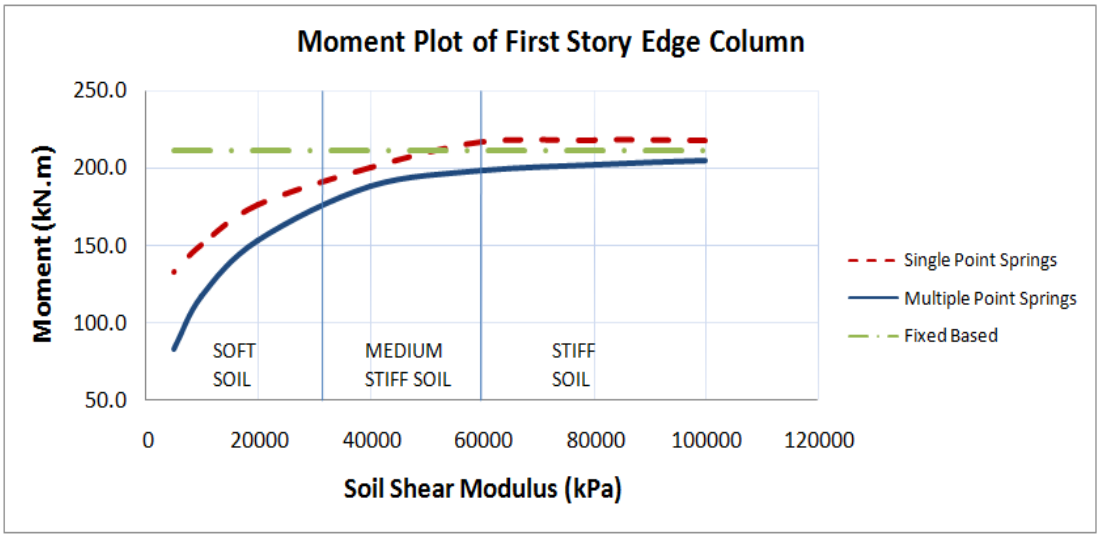
(a)



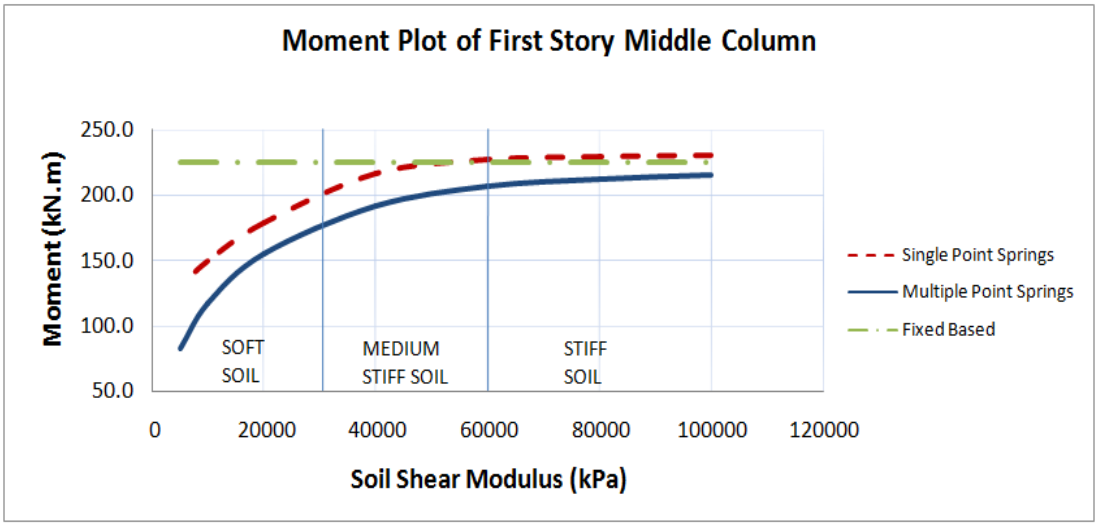
(b)

Figure A.2-4 Shear force plot for the seismic excitation representative of dense soil site a) edge column b) middle column

Variation of the moment plots given in Figure A.2-5 reveal that flexural capacity demand for the selected columns decreases when the foundation system is modeled with the deformable medium. Since inclusion of SSI provides flexibility to the foundations, this reduction with respect to the fixed base approach is understandable. In this case, if the actual flexural demand on columns is less than that of obtained by the fixed base approach, more economical structural systems can be designed by considering SSI.



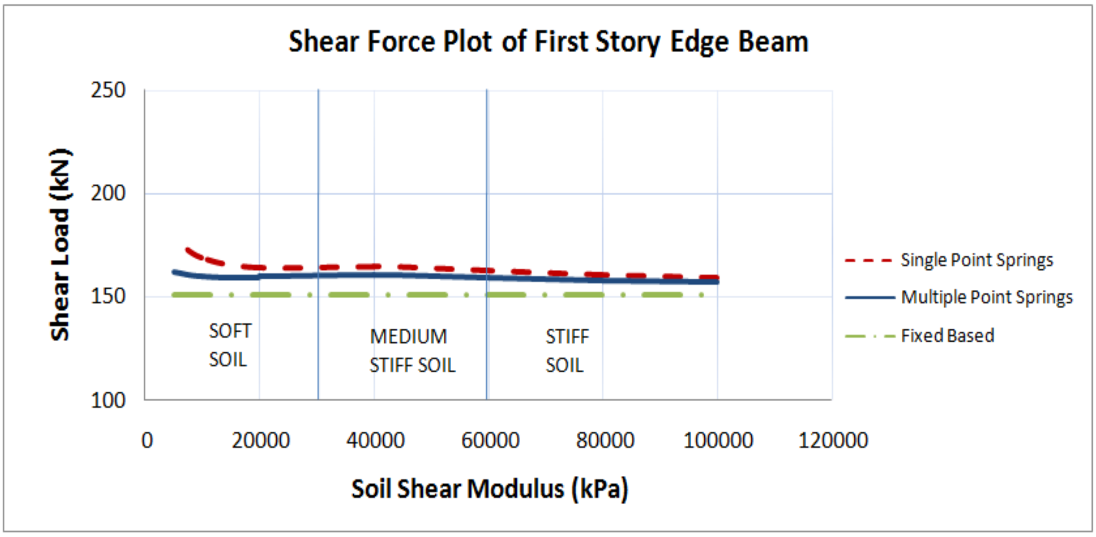
(a)



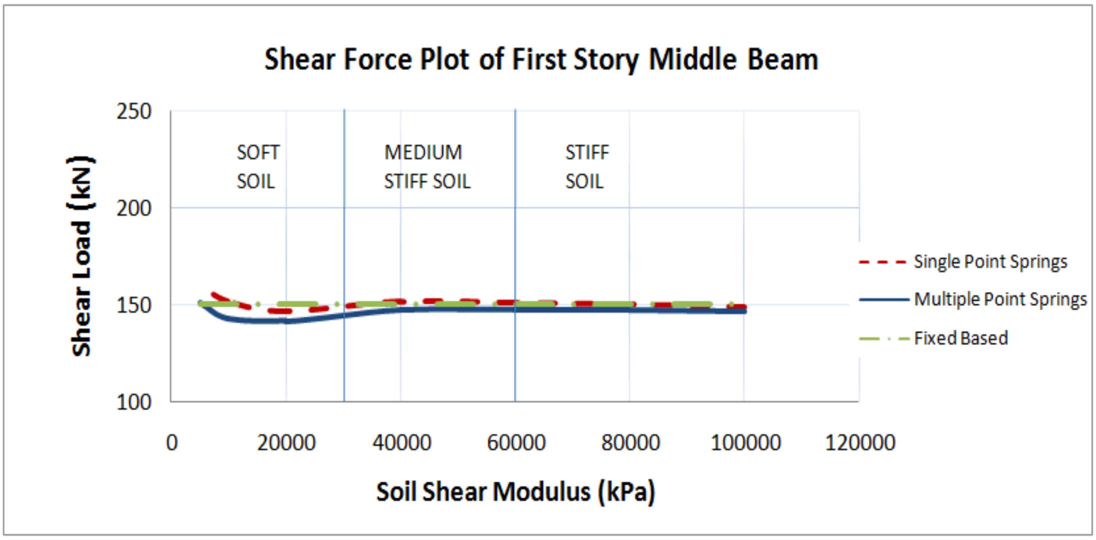
(b)

Figure A.2-5 Moment plot for the seismic excitation representative of dense soil site a) edge column b) middle column

Similar to the behavior observed for the columns, SSI approaches result in higher shear forces on the beams compared to those calculated using the fixed base approach as shown in Figure A-2.6. Therefore, if structural design is performed according to the results of fixed base approach, the designed members are likely to be subjected to higher shear forces under seismic conditions.



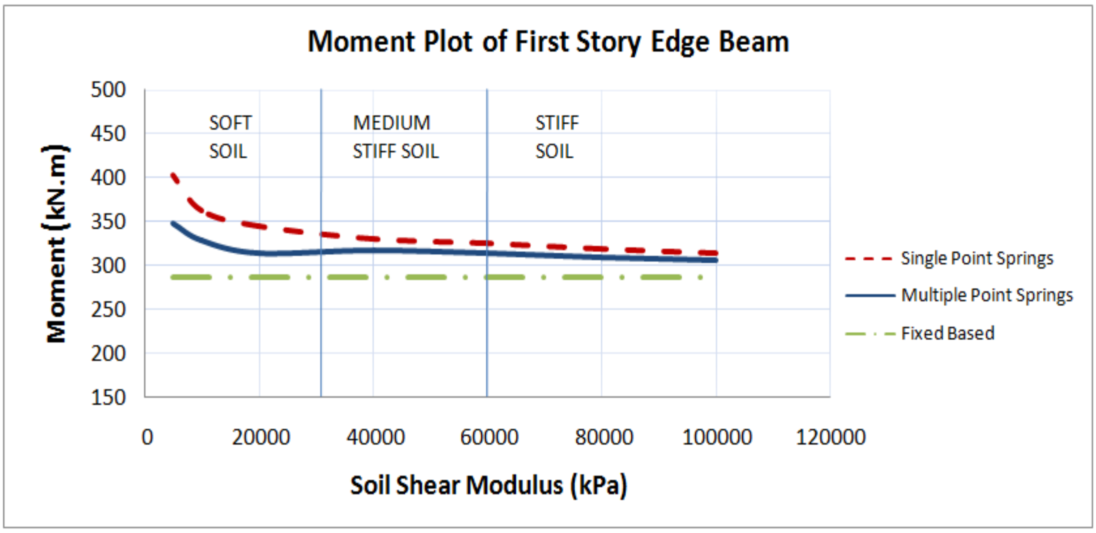
(a)



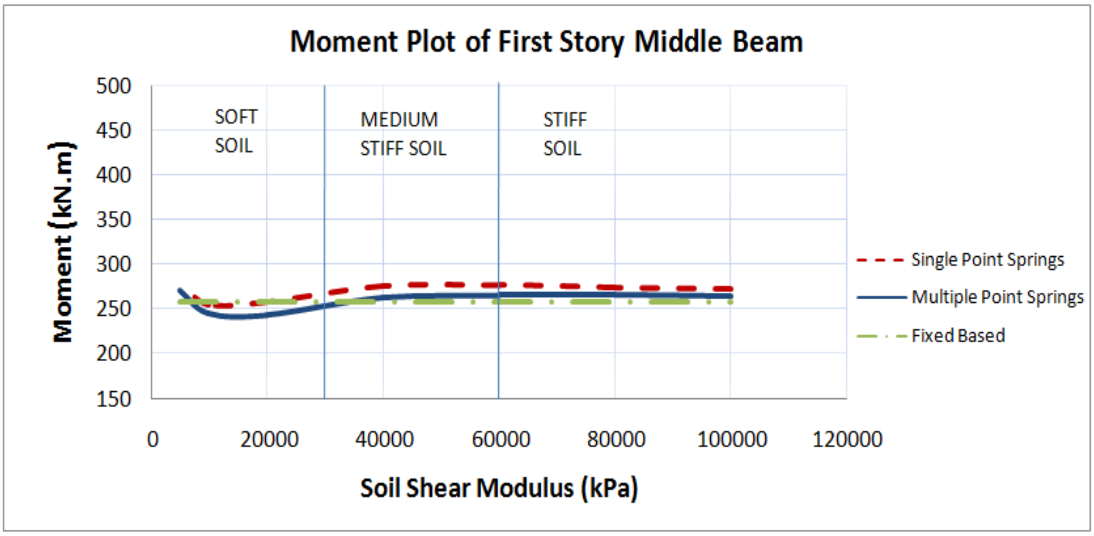
(b)

Figure A.2-6 Shear force plot for the seismic excitation representative of dense soil site a) edge beam b) middle beam

In contrast to the behavior observed in the columns regarding variation of the maximum moment, especially the edge beams were subject to relatively much higher bending moments when SSI is considered (See Figure A.2-7). In the models considering SSI, since the first floor columns are not fixed at the base, the moment effects under horizontal loads are transmitted to the beam column connections and this leads to the increase of moment demand in the beams.



(a)



(b)

Figure A.2-7 Moment plot for the seismic excitation representative of dense soil site a) edge beam b) middle beam

APPENDIX B

B.1. Maximum Average Drifts of the SDOF System with Varying Soil Shear Modulus

The average drifts of the SDOF system with varying soil shear modulus are calculated for each time step of input motions. Then the maximum values are selected and presented in Tables B.1-1, B.1-2 and B.1-3 for each earthquake record that represents the effects of rock site, dense soil site and soft soil sites. The results are also presented in the form of plots in Figure B.1-1.

Table B.1-1 Maximum average drifts of the SDOF system with varying soil shear modulus for the seismic excitation representative of soft soil site

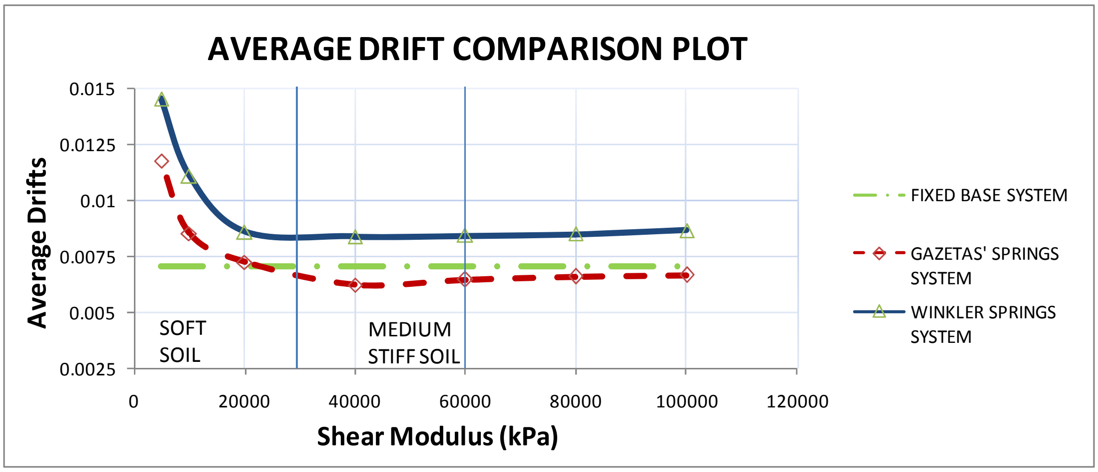
	Structural System Properties			Foundation System Properties			
Model ID	Structural System	Load-Bearing Column Dimenions (cm/cm) (for SDOF)	Lateral Stiffness of the Load Bearing Column (kN/m) (for SDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	Maximum Average Drifts
Model 1	SDOF	40/40	1536,0	Fixed Base	-	-	0,0070296
Model 2	SDOF	40/40	1536,0	SPSS	5	Soft Site	0,0066532
Model 3	SDOF	40/40	1536,0	SPSS	10	Soft Site	0,006584
Model 4	SDOF	40/40	1536,0	SPSS	20	Soft Site	0,0064624
Model 5	SDOF	40/40	1536,0	SPSS	40	Medium Stiff Site	0,0062186
Model 6	SDOF	40/40	1536,0	SPSS	60	Medium Stiff Site	0,007236
Model 7	SDOF	40/40	1536,0	SPSS	80	Stiff Site	0,0085346
Model 8	SDOF	40/40	1536,0	SPSS	100	Stiff Site	0,0117736
Model 9	SDOF	40/40	1536,0	MPSS	5	Soft Site	0,0086392
Model 10	SDOF	40/40	1536,0	MPSS	10	Soft Site	0,0085018
Model 11	SDOF	40/40	1536,0	MPSS	20	Soft Site	0,0084264
Model 12	SDOF	40/40	1536,0	MPSS	40	Medium Stiff Site	0,008394
Model 13	SDOF	40/40	1536,0	MPSS	60	Medium Stiff Site	0,0085924
Model 14	SDOF	40/40	1536,0	MPSS	80	Stiff Site	0,0110902
Model 15	SDOF	40/40	1536,0	MPSS	100	Stiff Site	0,0145198

Table B.1-2 Maximum average drifts of the SDOF system with varying soil shear modulus for the seismic excitation representative of dense soil site

	Structural System Properties			Foundation System Properties			
Model ID	Structural System	Load-Bearing Column Dimenions (cm/cm) (for SDOF)	Lateral Stiffness of the Load Bearing Column (kN/m) (for SDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	Maximum Average Drifts
Model 1	SDOF	40/40	1536,0	Fixed Base	-	-	0,0056632
Model 2	SDOF	40/40	1536,0	SPSS	5	Soft Site	0,0060968
Model 3	SDOF	40/40	1536,0	SPSS	10	Soft Site	0,0062112
Model 4	SDOF	40/40	1536,0	SPSS	20	Soft Site	0,0063538
Model 5	SDOF	40/40	1536,0	SPSS	40	Medium Stiff Site	0,006718
Model 6	SDOF	40/40	1536,0	SPSS	60	Medium Stiff Site	0,0073058
Model 7	SDOF	40/40	1536,0	SPSS	80	Stiff Site	0,0078642
Model 8	SDOF	40/40	1536,0	SPSS	100	Stiff Site	0,0097086
Model 9	SDOF	40/40	1536,0	MPSS	5	Soft Site	0,0071098
Model 10	SDOF	40/40	1536,0	MPSS	10	Soft Site	0,0071062
Model 11	SDOF	40/40	1536,0	MPSS	20	Soft Site	0,0072056
Model 12	SDOF	40/40	1536,0	MPSS	40	Medium Stiff Site	0,0074214
Model 13	SDOF	40/40	1536,0	MPSS	60	Medium Stiff Site	0,007994
Model 14	SDOF	40/40	1536,0	MPSS	80	Stiff Site	0,0088954
Model 15	SDOF	40/40	1536,0	MPSS	100	Stiff Site	0,0096416

Table B.1-3 Maximum average drifts of the SDOF system with varying soil shear modulus for the seismic excitation representative of rock site

	Structural System Properties			Foundation System Properties			
Model ID	Structural System	Load-Bearing Column Dimenions (cm/cm) (for SDOF)	Lateral Stiffness of the Load Bearing Column (kN/m) (for SDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	Maximum Average Drifts
Model 1	SDOF	40/40	1536,0	Fixed Base	-	-	0,0038584
Model 2	SDOF	40/40	1536,0	SPSS	5	Soft Site	0,0042192
Model 3	SDOF	40/40	1536,0	SPSS	10	Soft Site	0,0042758
Model 4	SDOF	40/40	1536,0	SPSS	20	Soft Site	0,0044158
Model 5	SDOF	40/40	1536,0	SPSS	40	Medium Stiff Site	0,004659
Model 6	SDOF	40/40	1536,0	SPSS	60	Medium Stiff Site	0,0049612
Model 7	SDOF	40/40	1536,0	SPSS	80	Stiff Site	0,0054518
Model 8	SDOF	40/40	1536,0	SPSS	100	Stiff Site	0,0072818
Model 9	SDOF	40/40	1536,0	MPSS	5	Soft Site	0,0046318
Model 10	SDOF	40/40	1536,0	MPSS	10	Soft Site	0,0047198
Model 11	SDOF	40/40	1536,0	MPSS	20	Soft Site	0,0048142
Model 12	SDOF	40/40	1536,0	MPSS	40	Medium Stiff Site	0,0049226
Model 13	SDOF	40/40	1536,0	MPSS	60	Medium Stiff Site	0,0050832
Model 14	SDOF	40/40	1536,0	MPSS	80	Stiff Site	0,0060968
Model 15	SDOF	40/40	1536,0	MPSS	100	Stiff Site	0,007448



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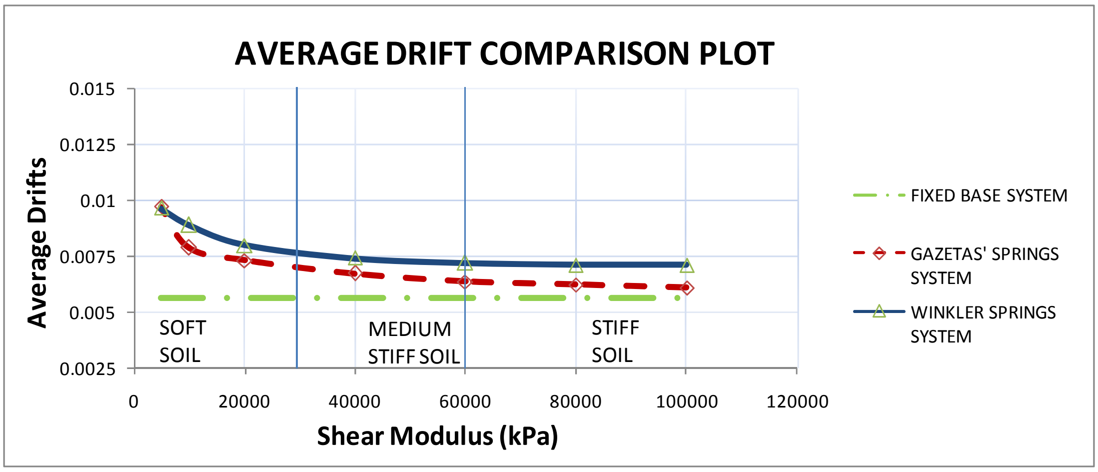

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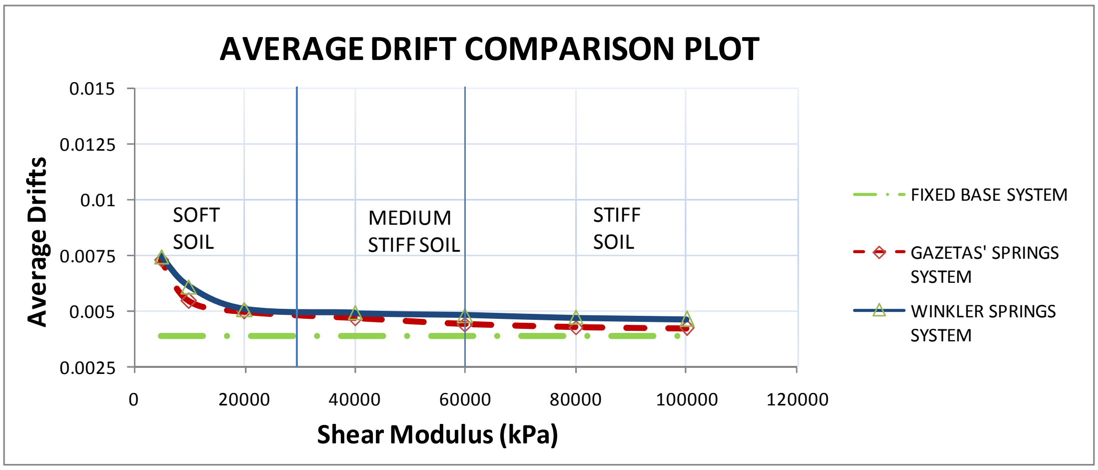


(c)

Figure B.1-1 Maximum average drift comparison plots of SDOF system with varying soil shear modulus for the seismic excitation representative of a) soft soil site b) dense soil site c) rock site

B.2. Maximum Average Drifts of the Four-Storey Building

The average drifts of the four-storey building are calculated for each time step of input motions. Then the maximum values are selected and presented in Tables B.2-1, B.2-2 and B.2-3 for each earthquake record that represents the effects of rock site, dense soil site and soft soil sites. The results are also presented in the form of plots in Figure B.2-1.

Table B.2-1 Maximum average drifts of the four-storey building for the seismic excitation representative of soft soil site

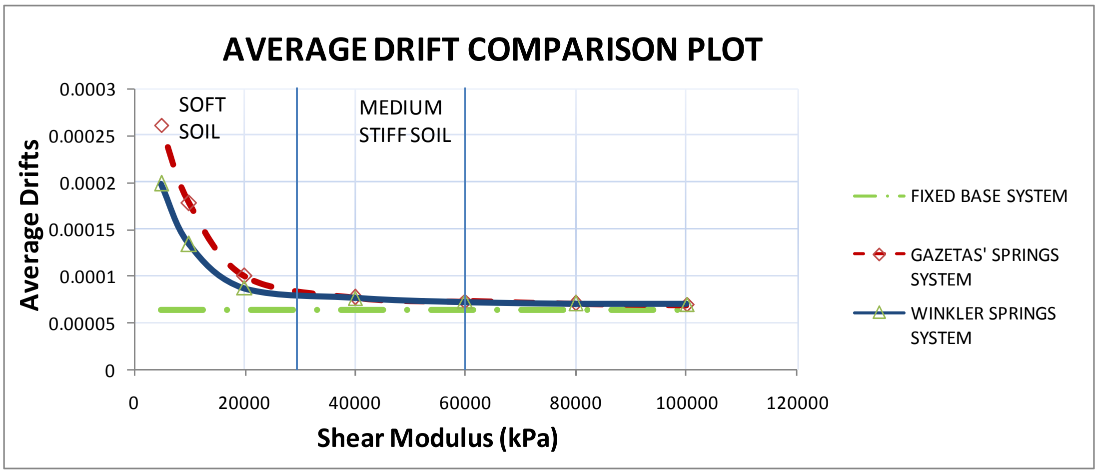
	Structural System Properties		Foundation System Properties			Maximum Average Drifts
Model ID	Structural System	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	
Model 36	MDOF	4	Fixed Base	-	-	6,42667E-05
Model 37	MDOF	4	SPSS	5	Soft Site	6,95333E-05
Model 38	MDOF	4	SPSS	10	Soft Site	7,08333E-05
Model 39	MDOF	4	SPSS	20	Soft Site	7,30667E-05
Model 40	MDOF	4	SPSS	40	Medium Stiff Site	7,71333E-05
Model 41	MDOF	4	SPSS	60	Medium Stiff Site	9,97667E-05
Model 42	MDOF	4	SPSS	80	Stiff Site	0,0001778
Model 43	MDOF	4	SPSS	100	Stiff Site	0,0002605
Model 44	MDOF	4	MPSS	5	Soft Site	0,0000696
Model 45	MDOF	4	MPSS	10	Soft Site	7,07667E-05
Model 46	MDOF	4	MPSS	20	Soft Site	7,27667E-05
Model 47	MDOF	4	MPSS	40	Medium Stiff Site	0,0000766
Model 48	MDOF	4	MPSS	60	Medium Stiff Site	8,72333E-05
Model 49	MDOF	4	MPSS	80	Stiff Site	0,0001337
Model 50	MDOF	4	MPSS	100	Stiff Site	0,0001988

Table B.2-2 Maximum average drifts of the four-storey building for the seismic excitation representative of dense soil site

	Structural System Properties		Foundation System Properties			
Model ID	Structural System	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	Maximum Average Drifts
Model 36	MDOF	4	Fixed Base	-	-	0,0000614
Model 37	MDOF	4	SPSS	5	Soft Site	6,61333E-05
Model 38	MDOF	4	SPSS	10	Soft Site	0,0000673
Model 39	MDOF	4	SPSS	20	Soft Site	6,90333E-05
Model 40	MDOF	4	SPSS	40	Medium Stiff Site	0,0000724
Model 41	MDOF	4	SPSS	60	Medium Stiff Site	0,0000815
Model 42	MDOF	4	SPSS	80	Stiff Site	0,000117433
Model 43	MDOF	4	SPSS	100	Stiff Site	0,000203667
Model 44	MDOF	4	MPSS	5	Soft Site	6,56667E-05
Model 45	MDOF	4	MPSS	10	Soft Site	6,65667E-05
Model 46	MDOF	4	MPSS	20	Soft Site	6,81333E-05
Model 47	MDOF	4	MPSS	40	Medium Stiff Site	7,07667E-05
Model 48	MDOF	4	MPSS	60	Medium Stiff Site	0,0000774
Model 49	MDOF	4	MPSS	80	Stiff Site	9,89333E-05
Model 50	MDOF	4	MPSS	100	Stiff Site	0,000142967

Table B.2-3 Maximum average drifts of the four-storey building for the seismic excitation representative of rock site

	Structural System Properties		Foundation System Properties			
Model ID	Structural System	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	Maximum Average Drifts
Model 36	MDOF	4	Fixed Base	-	-	0,0000457
Model 37	MDOF	4	SPSS	5	Soft Site	5,21667E-05
Model 38	MDOF	4	SPSS	10	Soft Site	0,0000537
Model 39	MDOF	4	SPSS	20	Soft Site	5,64667E-05
Model 40	MDOF	4	SPSS	40	Medium Stiff Site	6,30333E-05
Model 41	MDOF	4	SPSS	60	Medium Stiff Site	9,04333E-05
Model 42	MDOF	4	SPSS	80	Stiff Site	0,0001104
Model 43	MDOF	4	SPSS	100	Stiff Site	0,000106267
Model 44	MDOF	4	MPSS	5	Soft Site	5,05667E-05
Model 45	MDOF	4	MPSS	10	Soft Site	0,0000512
Model 46	MDOF	4	MPSS	20	Soft Site	5,26667E-05
Model 47	MDOF	4	MPSS	40	Medium Stiff Site	5,66333E-05
Model 48	MDOF	4	MPSS	60	Medium Stiff Site	7,16333E-05
Model 49	MDOF	4	MPSS	80	Stiff Site	7,41333E-05
Model 50	MDOF	4	MPSS	100	Stiff Site	8,87333E-05



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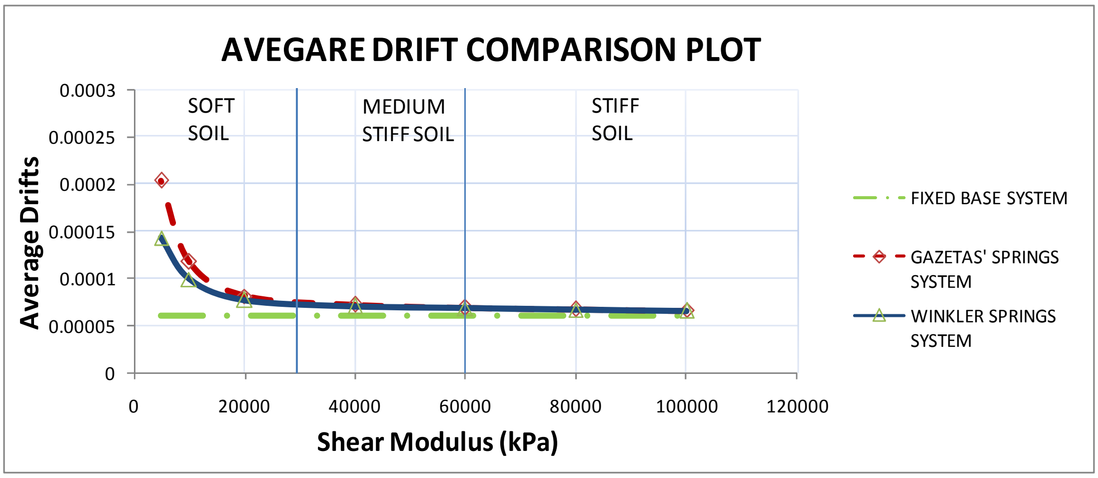

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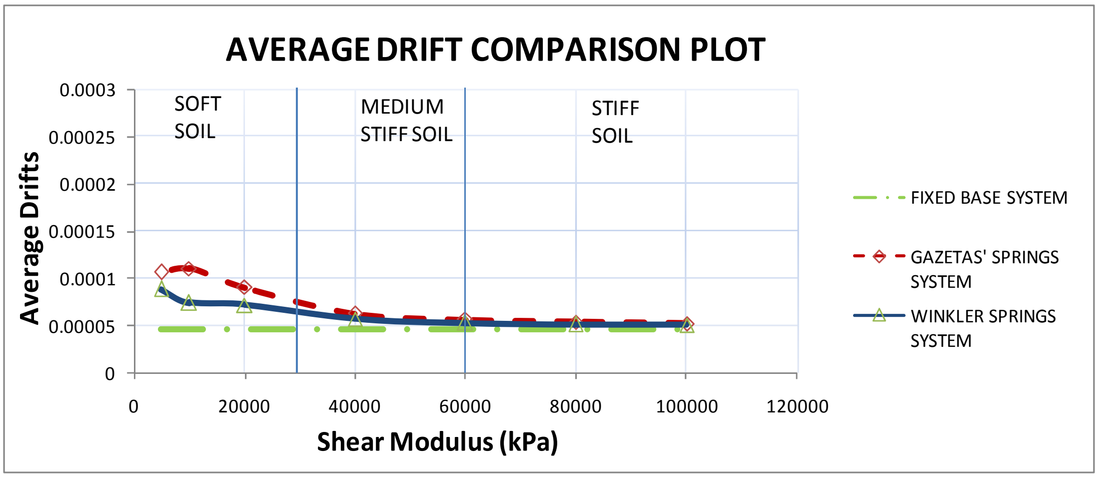


(c)

Figure B.2-1 Maximum average drift comparison plots of four-storey building for the seismic excitation representative of a) soft soil site b) dense soil site c) rock site

B.3. Maximum Average Drifts of the Ten-Storey Building

The average drifts of the ten-storey building are calculated for each time step of input motions. Then the maximum values are selected and presented in Tables B.2-1, B.2-2 and B.2-3 for each earthquake record that represents the effects of rock site, dense soil site and soft soil sites. The results are also presented in the form of plots in Figure B.3-1.

Table B.3-1 Maximum average drifts of the ten-storey building for the seismic excitation representative of soft soil site

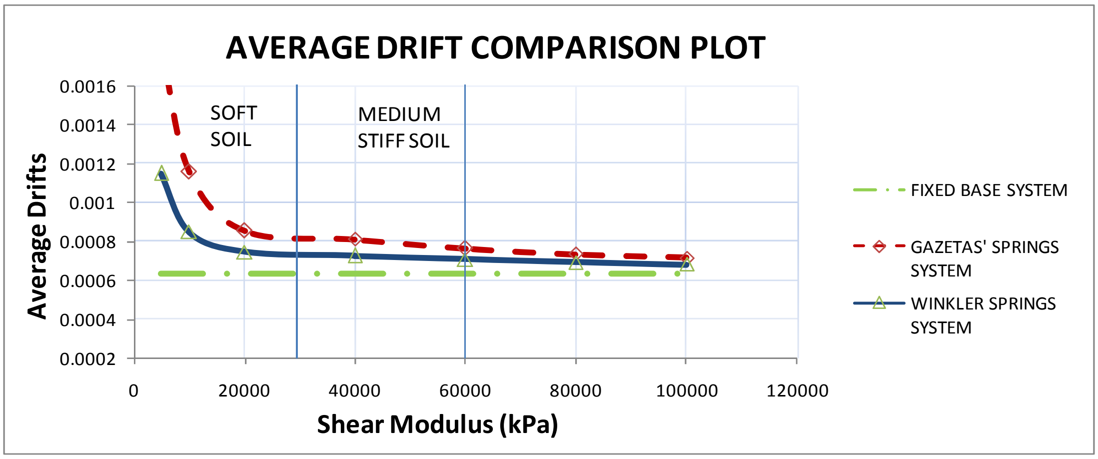
	Structural System Properties		Foundation System Properties			Maximum Average Drifts
Model ID	Structural System	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	
Model 51	MDOF	10	Fixed Base	-	-	0,000630767
Model 52	MDOF	10	SPSS	5	Soft Site	0,0007165
Model 53	MDOF	10	SPSS	10	Soft Site	0,0007353
Model 54	MDOF	10	SPSS	20	Soft Site	0,000764267
Model 55	MDOF	10	SPSS	40	Medium Stiff Site	0,0008115
Model 56	MDOF	10	SPSS	60	Medium Stiff Site	0,0008535
Model 57	MDOF	10	SPSS	80	Stiff Site	0,0011563
Model 58	MDOF	10	SPSS	100	Stiff Site	0,001816233
Model 59	MDOF	10	MPSS	5	Soft Site	0,0006833
Model 60	MDOF	10	MPSS	10	Soft Site	0,000692767
Model 61	MDOF	10	MPSS	20	Soft Site	0,000706533
Model 62	MDOF	10	MPSS	40	Medium Stiff Site	0,000727133
Model 63	MDOF	10	MPSS	60	Medium Stiff Site	0,000745533
Model 64	MDOF	10	MPSS	80	Stiff Site	0,000849333
Model 65	MDOF	10	MPSS	100	Stiff Site	0,001148267

Table B.3-2 Maximum average drifts of the ten-storey building for the seismic excitation representative of dense soil site

	Structural System Properties		Foundation System Properties			
Model ID	Structural System	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	Maximum Average Drifts
Model 51	MDOF	10	Fixed Base	-	-	0,000632667
Model 52	MDOF	10	SPSS	5	Soft Site	0,000710433
Model 53	MDOF	10	SPSS	10	Soft Site	0,000727
Model 54	MDOF	10	SPSS	20	Soft Site	0,0007514
Model 55	MDOF	10	SPSS	40	Medium Stiff Site	0,000786767
Model 56	MDOF	10	SPSS	60	Medium Stiff Site	0,000799333
Model 57	MDOF	10	SPSS	80	Stiff Site	0,0010565
Model 58	MDOF	10	SPSS	100	Stiff Site	0,001438033
Model 59	MDOF	10	MPSS	5	Soft Site	0,000676033
Model 60	MDOF	10	MPSS	10	Soft Site	0,0006831
Model 61	MDOF	10	MPSS	20	Soft Site	0,0006928
Model 62	MDOF	10	MPSS	40	Medium Stiff Site	0,000704533
Model 63	MDOF	10	MPSS	60	Medium Stiff Site	0,0006938
Model 64	MDOF	10	MPSS	80	Stiff Site	0,000812567
Model 65	MDOF	10	MPSS	100	Stiff Site	0,000899633

Table B.3-3 Maximum average drifts of the ten-storey building for the seismic excitation representative of rock site

	Structural System Properties		Foundation System Properties			
Model ID	Structural System	Storey Number (for MDOF)	Foundation Modeling Approach	Soil Shear Modulus (Mpa)	Site Classification	Maximum Average Drifts
Model 51	MDOF	10	Fixed Base	-	-	0,000296667
Model 52	MDOF	10	SPSS	5	Soft Site	0,000343733
Model 53	MDOF	10	SPSS	10	Soft Site	0,000354433
Model 54	MDOF	10	SPSS	20	Soft Site	0,0003713
Model 55	MDOF	10	SPSS	40	Medium Stiff Site	0,0003992
Model 56	MDOF	10	SPSS	60	Medium Stiff Site	0,000480267
Model 57	MDOF	10	SPSS	80	Stiff Site	0,0006427
Model 58	MDOF	10	SPSS	100	Stiff Site	0,000856433
Model 59	MDOF	10	MPSS	5	Soft Site	0,0003285
Model 60	MDOF	10	MPSS	10	Soft Site	0,000334967
Model 61	MDOF	10	MPSS	20	Soft Site	0,000343833
Model 62	MDOF	10	MPSS	40	Medium Stiff Site	0,0003566
Model 63	MDOF	10	MPSS	60	Medium Stiff Site	0,000399767
Model 64	MDOF	10	MPSS	80	Stiff Site	0,000455267
Model 65	MDOF	10	MPSS	100	Stiff Site	0,000593467



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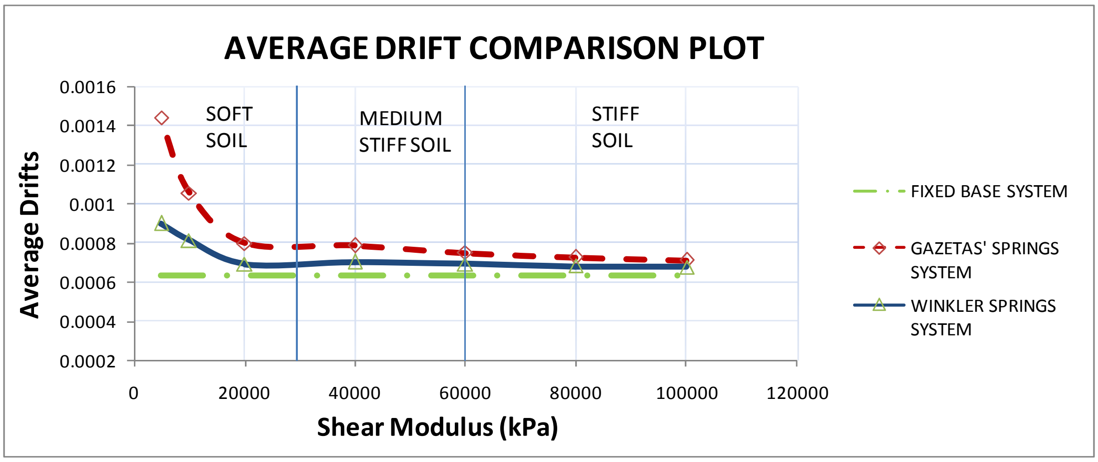

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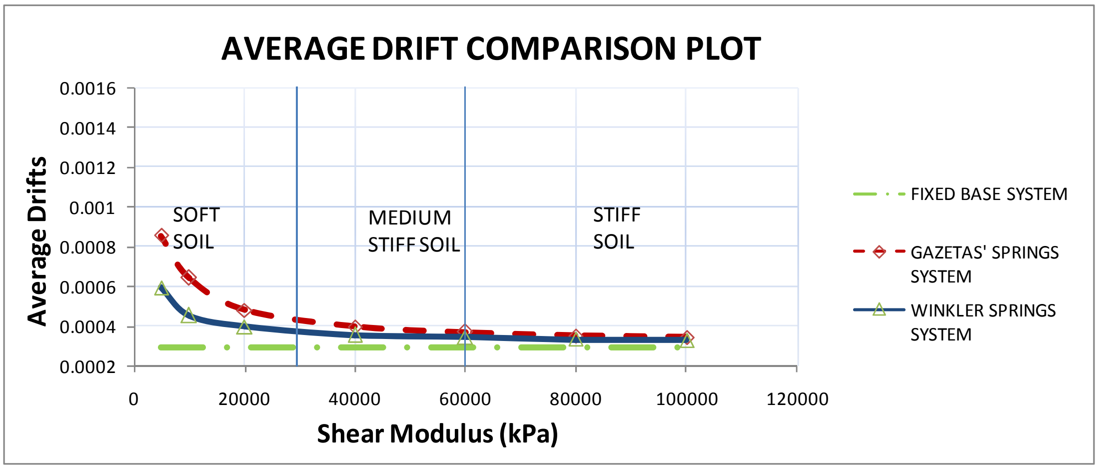

(c)

Figure B.3-1 Maximum average drift comparison plots of ten-storey building for the seismic excitation representative of a) soft soil site b) dense soil site c) rock site

B.4. Interpretation of Results and Conclusions

Structural drift is one of the key parameters that reflect the seismic response of the superstructure. Due to that reason, maximum average structural drifts are presented and compared in the previous sections.

A striking result is observed in all plots. When the given plots are examined, a similar trend is observed for both SDOF and MDOF systems in terms of seismic response of the structure. Especially for soft soils, higher structural drifts are obtained when the inertial interaction between the foundation and superstructure is considered. In contrast to fixed base system, additional displacements due to foundation rotation is observed in SSI analyses. Because of that reason, the total tip deflections in SSI analyses increases as shown in Figure B.4-1. In other words, the conclusions stated for the total base shears are also valid for structural drifts.

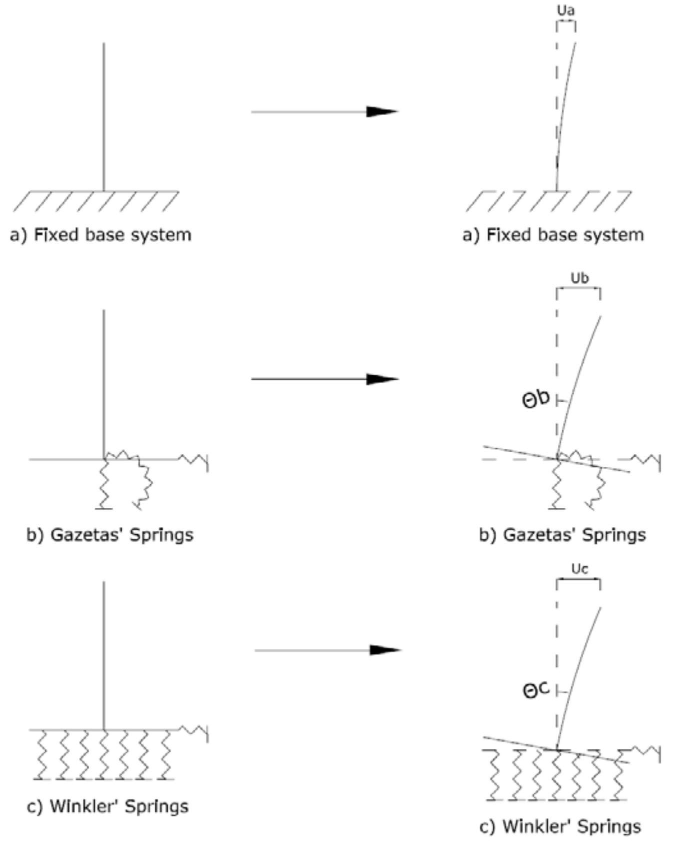

Figure B.4-1 Tip Displacements for a) fixed base system b) Gazetas' springs c) Winkler springs