DYNAMIC SOIL STRUCTURE INTERACTION –A CASE STUDY IN JORDAN

By
Huda Rida Al-Kasasbeh

SUPERVISOR
Dr. HASSAN SAFFARINI, Prof.

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Faculty of Graduate Studies
The University Of Jordan

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COMMITTEE DECISION

This Thesis (DYNAMIC SOIL STRUCTURE INTERACTION –A CASE STUDY IN JORDAN) was successfully defended and approved on April 4, 2007

Examination Committee	**Signature**
Dr. Hassan Saffarini, Chairman Prof. of Civil Engineering	....
Dr. Abdullah Assaad, Member Prof. of Civil Engineering	....
Dr. Anis S. Shatnawi, Member Assist. Prof. of Civil Engineering	Shatnawi........ Anis
Dr. Amjad Barghouthi , Member Assoc. Prof. of Civil Engineering (Arab Center of Engineering Studies)	....

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DEDICATION

This thesis is respectfully dedicated to my eyes who lightened my way; my parents, my brothers, my sisters, my beloved husband, teachers, and to all my friends, for their help, support and encouragement.

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By
Huda AL-Kasasbeh
Supervisor
Dr. Hassan Saffarini

ABSTRACT

This thesis addressed the concept of soil-structure interaction (SSI) applied to multi-story buildings. Structures are commonly simplified by assuming a fixed base and ignoring the effect of soil-structure interaction. However, the soil flexibility affects the dynamic characteristics of structures and influences their dynamic behavior. The intention in this work is to present an ongoing study, the aim of which is to evaluate the seismic response of the actual structure with emphasis on SSI. Three-dimensional models of four R/C buildings are investigated; including five-, ten-, and twenty-stories as well as the Jordan Gate tower of forty-two stories. These were analyzed using the finite element program SAP2000. The objective is to investigate the response of the structure to an earthquake-loading taking into account the SSI. A sensitivity study was carried out in which fundamental period, the structural horizontal displacements, and base shear for different types of soil were investigated. It was found that the soil flexibility increases the natural period, it was also concluded that the effect of soil structure interaction is more significant when the soil is softer than when it is stiffer.

INTRODUCTION

1.1 Introduction

It is a common practice in Jordan to neglect the effect of soil-structure interaction based on the somewhat questionable assumption, that the foundation medium is very stiff. In reality, the structure always interacts with the soil to some extent during earthquakes, imposing soil deformations that cause the motions of the structure soil interface to differ from those that would have been observed in the free field.

In the rigid foundation model, the energy received by the structure from the base during an earthquake can only be dissipated through internal damping mechanisms. In the case of flexible soils some energy is fed back to the base and radiated away giving rise to the so-called geometric damping (Ambrosini et al., 2000).

During the last quarter of the 20th century, the importance of dynamic soil-structure interaction for several structures founded on soft soils was well recognized. If not considered in the analysis, the accuracy in assessing structural safety in the face of earthquakes cannot be considered for adequately. For this reason, seismic soil-structure interaction analysis has become a major topic in earthquake engineering.

In this study, four reinforced concrete (R/C) buildings: five-story, ten-story, twenty-story, and forty two-story buildings were analyzed to investigate the effect of soil-structure interaction and to study the effect of different parameters on their behavior as they are subjected to earthquake excitation. Such behavior is compared with analyses carried out on these models while assuming rigid bases.

The forty two-story building used in the analysis is a true building which is currently under construction in Amman-Jordan and is expected to be the tallest in Jordan to date. This is one of the twin towers named the Jordan Gate as shown in Figure (1.1).

The numerical model simulates the entire structure as consisting of three media: soil, foundation, and superstructure, by using two finite element programs, namely Extended Three dimensional Analysis of Building Systems ETABS (ETABS,2005) and Structural Analysis Program SAP2000 (SAP2000,2004).

A three dimensional finite element model was created to study the structural behavior under static and dynamic conditions.

Figure (1.1) Jordan Gate twin towers

1.2 Objectives

The objectives of this study are:

1. To compare the seismic response of the multi-story R/C buildings while taking soil-structure interaction into account with the same buildings when soil-structure interaction is not considered.
2. To compare the static and dynamic structural behavior of the structure when SSI is being considered.
3. To investigate the behavior of the Jordan Gate as a case study for SSI.
4. To investigate the effect of the number of floors (low, moderate, and high-rise buildings).
5. To study the effect of soil type on the structural behavior.

1.3 Methodology

In this study linear analysis incorporating soil structure interaction of four R/C buildings was carried out. Static and dynamic analyses were carried out on five-story, ten-story, twenty-story and forty two-story buildings, the latter represent a Jordan Gate building.

The work performed in this thesis was carried out according to the following steps:

1. Literature review of work and studies related to the subject.
2. A representative layout of a reinforced concrete building was selected.
3. The architectural and structural design drawings of the Jordan Gate were reviewed.
4. Available modeling techniques in ETABS and SAP2000 programs were used for modeling the structures.
5. Three dimensional finite element models were performed. Two models were constructed for each building: the first model assumed rigid base and the second model considered soil-structure interaction.

6. A model with a rigid base was constructed using ETABS program and a model with soil was constructed using SAP2000 program. The soil-structure interaction model was constructed using a direct method (the structure and the soil are modeled directly).
7. Different types of soil were carried out
8. Linear analysis was made to compute the fundamental period, displacement response, and columns base shear.
9. The results were tabulated, presented graphically and thus analyzed.
10. Conclusions and recommendations were brought out.

BACKGROUND

2.1 Overview

Over the past decades, the dynamic soil-structure interaction has increasingly attracted the interest of researchers and engineers in the fields of structural dynamics, wave mechanics, and soil dynamics. The methods of investigation mainly consist of experimental studies and computational analysis. The methods of analysis are generally divided into two groups: analytical and numerical simulation. Analytical methods were popular in the past, before the common use of computer technology, although only simple problems could be solved. With the rapid progress in computer technology, numerical simulation has become widely used for the soil-structure interaction (Lu Xillin et al., 2005).

In spite of the importance of soil-structure interaction, there are no accepted guidelines to establish when the influence of the foundation flexibility may be expected to be significant. There is also little or no information in literature on the error that may result from either neglecting the consideration of this factor or using incorrect values for the soil or foundation parameters.

2.2 Literature review

A lot of research has been conducted on the subject of soil-structure interaction over the past two decades. Clough (1997) outlines the phenomenon and the basic approach for the incorporation of the interaction in the analysis of the soil and the structure

Nassim (1986) presented the behavior of buildings during earthquake ground motion, considering the soil-structure interaction. A computer program is used to handle the mathematical computations to perform the structural response analysis for earthquake excitations. Two example problems are presented; these were a 17-story building and water tank. These examples illustrate the complexities of the interaction phenomenon and show the effects of the soil parameters on the response of the structure.

Chen and Hsu (2004) investigated the effect of soil structure interaction on the dynamic response of a soil structure system by using a model of structure supported on elastic half space. The study derived the factor which represents the effect of soil structure interaction, so that the original soil structure interaction system was transformed into an equivalent fixed base.

Nakamura (2005) presented a practical method for estimating dynamic soil stiffness on surface of multi-layered soil. Their paper estimated the influence of layered soil in soil structure interaction analysis. Although a great number of investigations have been carried out on this subject, in this paper a simple and practical formula for estimating the horizontal dynamic stiffness of a rigid foundation on the surface of multi layered soil was proposed. In this method waves propagation using the concept of the cone model was used to calculate the response impulse function in the time domain which was then transformed to frequency domain.

Halabian (2001) presented a finite element formulation for the response analysis of TV-towers subjected to earthquake ground motion accounting for soil-structure interaction. The effects of foundation flexibility on the dynamic behavior of TV-towers were evaluated for two different types of foundation, shallow footing and deep foundation, and various soil profiles. A typical example for these towers is analyzed and the results for a range of soil dynamic parameters are presented.

The author used the direct stiffness approach in structural analysis; by modeling a significant part of the soil around the embedded structure and apply the free field motion at the fictitious soil-structure interface as shown in Figure (2.1).

The results of his research showed that, irrespective of the type of foundation and soil models, the soil-structure interaction increased the natural period of the structure. The foundation flexibility for the range of foundation properties reduced the base moment. It was also concluded that the effect of soil-structure interaction may have a large effect on the base shear of the tower and should be considered in the analysis, especially for the design of horizontal reinforcement.

The significant seismicity of Jordan (Armouti, 2004, Saffarini, 2000, Kublawi and Saffarini, 1999) made this study quite relevant, particularly in view of the surge in construction activities of tall buildings witnessed in Amman and other parts of the country.

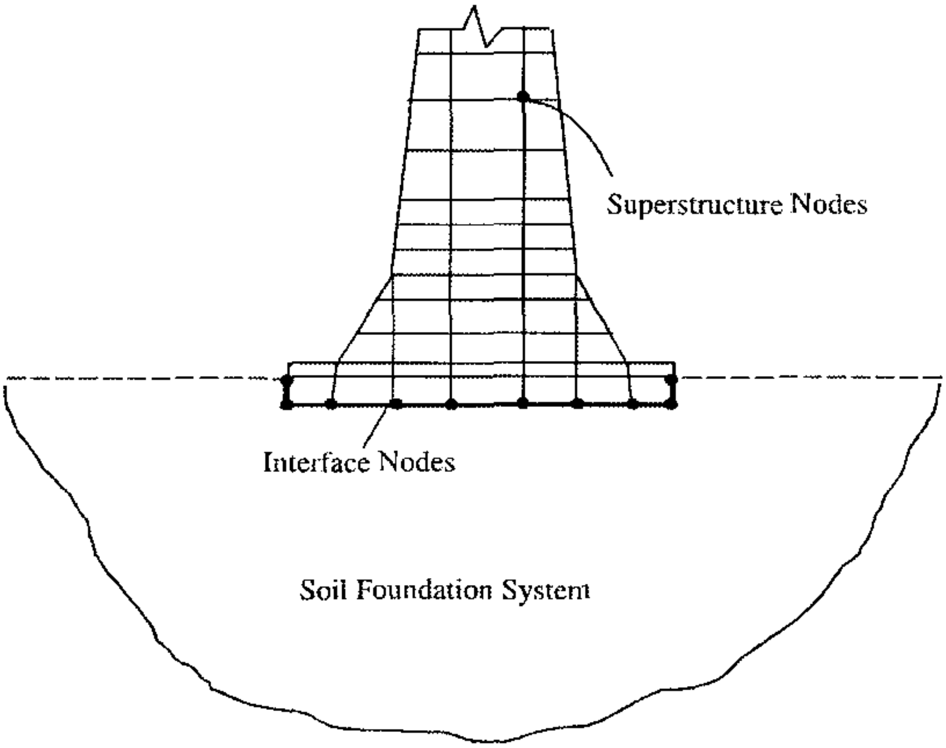

Figure (2.1) Soil-structure interaction system of Halabian TV towers

2.3 Finite Element Method

The finite element method (FEM) is a numerical method for solving problems of engineering and mathematical physics.

The process involves subdividing a complex system into a finite number of individual components of elements whose behavior is easily understood, and then rebuilding the original system from such components to study the whole system behavior. These elements connected at a finite number of joints are called "Nodes". The properties of the elements are formulated and combined to obtain the properties of the entire structure.

The equation of equilibrium for the entire structure is then obtained by combining the equilibrium equations for each element such that the continuity is ensured at each node. The necessary boundary conditions are then imposed and the equations of equilibrium are solved to obtain the required variables such as stress, temperature distribution or velocity flow depending on the application.

The finite element method is useful for problems with complicated geometries, loadings, and material properties where analytical solutions can not be obtained.

2.4 Soil Structure Interaction

The seismic excitation experienced by structures is a function of the earthquake source, travel path effects, local site effects, and soil structure interaction effects. The result of the first three of these factors is a free-field ground motion. Structural response to free-field motion is influenced by soil structure interaction.

Stewart et al., (1999) described two mechanisms of interaction which take place between the structure, foundation, and soil:

1- Inertial interaction: inertia developed in the structure due to its own vibrations gives rise to base shear and moment which in turn causes displacements of the foundation relative to the free-field.

   So there is an interaction between the mass of the structure and the soil deposit which is known as inertial interaction. The acceleration field induces inertial forces in the structure which are transmitted to the foundation. They modify additionally the dynamic behavior of the system. In general, two effects are observed: on one hand, the flexibility of the soil induces a reduction in the resonance frequencies of the total system; on the other hand, additional damping is included to the system because of the wave radiation to infinity.

2- Kinematic Interaction: the presence of stiff foundation elements on or in soil causes foundation motion to deviate from free-field motions as a result of ground motion incoherence, wave inclination, or foundation embedment. Kinematic effects are described by a frequency dependent transfer function relating the free-field motion to the motion that would occur on the base slab when structures were massless.

Most general purpose programs for the earthquake analysis of structures do not have the option of identifying the soil mass as a separate type of mass on which the earthquake forces do not act. Therefore, an approximation that has commonly been used is to neglect the mass of the soil completely in the analysis.

In this research we assume massless foundation, so there is no inertial interaction, and thus only the analysis of the soil foundation interaction is addressed.

Soil structure interaction analysis procedures include direct approaches in which the soil and structure are modeled together and analyzed in a single step and the substructure approache where the analysis is broken down into several steps (Clough, 1999).

2.4.1 Direct Approach:

To deal fully with soil structure interaction mechanism, the soil must be represented explicitly in the analytical model, and in principle it appears that this could be done by merely combining a layer of soil with the model of substructure; in fact some of the earliest attempts to deal with SSI treated the problem following this approach.

Unfortunately, this direct approach has the major deficiency that the bounded soil model does not allow vibration energy in the structure and soil to propagate away, and thus it ignores the effective damping mechanism. For this reason a bounded soil layer model should be used only in cases where the soil supporting the structure is underlain by a very stiff rock layer as shown in Figure (2.2).

If the soil is modeled as a finite element assemblage, a direct analysis may be performed for the combined soil-structure system.

One deficiency of this formulation is that the earthquake excitation is applied at the base of the soil layer, whereas the seismic input usually is expressed in terms of accelerograms recorded at the free-field soil surface.

2.4.2 Substructure Approach:

In a substructure analysis of SSI, the foundation and the structure are represented as two independent mathematical modules or substructures. The connection between them is provided by intersection forces of equal amplitude but acting in opposite direction on the two substructures. The total motions developed at the interface are the sum of the free–field motions at the interface of the soil without the added structure plus the additional motions resulting from the interaction. The dynamic equilibrium relationships for the interface degrees of freedom are written in terms of these motions and then are solved to determine the resulting displacements.

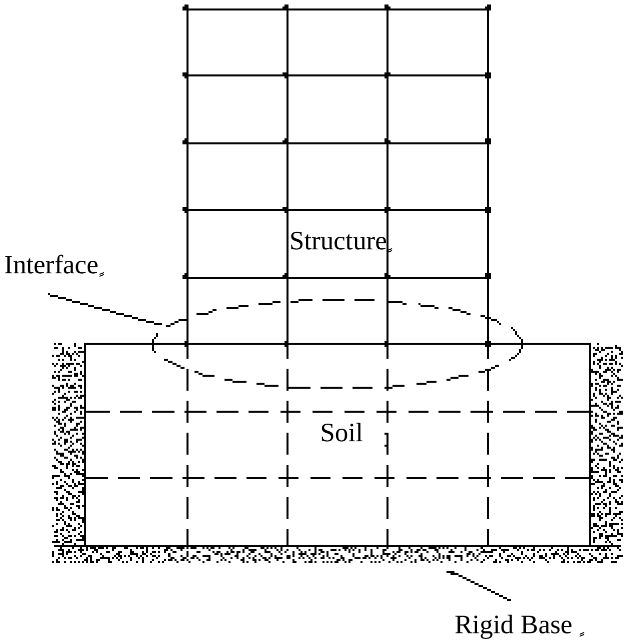

Figure (2.2) Structure is underlain by a very stiff rock layer

FINITE ELEMENT MODELING

3.1 Overview:

Numerical modeling for all cases of buildings and explanations of all necessary information needed to complete this model were discussed in this chapter. The numerical models were created by the SAP2000 finite element program which was then used to perform static and dynamic finite element analyses.

3.2 SAP2000 Finite Element Program:

In this study the static and dynamic analysis were performed by utilizing the finite element analysis program SAP2000.

The library of SAP2000 contains several types of elements: Three dimensional prismatic and non-prismatic frame elements (FRAME), three dimensional shell elements (SHELL), and three dimensional 8 node brick elements (SOLID) which are used to model the structure.

Each element used in the model can have any geometry defined by joint coordinates and any material properties defined by an assigned material property. Different types of elements can be used in the model in order to define the geometry or the continuity of the structure. There is no limitation for the number of joints, elements, material, loading and boundary conditions. The maximum size of model and number of equations depend solely on the capacity of computer.

3.2.1 Functions

Options are available to define functions to describe how load varies as a function of period or time. The functions are needed for certain types of analysis only; they are not used for static analysis. A function is a series of digitized abscissa-ordinate data pairs. Two types of functions are available:

- Response-spectrum functions: Pseudo-spectral acceleration vs. period for use in response-spectrum analysis.
- Time-history functions: Loading magnitude vs. time for use in time-history analysis.

3.2.2 Analysis Cases

An analysis case defines how loads are to be applied to the structure, and how the structural response is to be calculated. Many types of analysis cases are available. Most broadly, analyses are classified as linear or nonlinear, depending upon how the structure responds to the loading.

The results of linear analyses may be superposed, i.e., added together after analysis. The following types of linear analysis are available:

- **Static analysis:** The most common type of analysis. Loads are applied without dynamic effects.
- **Modal Analysis:** Calculation of dynamic modes of the structure by eigenvector or Ritz-vector method. Loads are not actually applied, although they can be used to generate Ritz vectors.

- **Response-Spectrum Analysis:** Statistical calculation of the response due to acceleration loads requires response-spectrum functions. In the response spectrum method, the modes of vibration determined from finite element modeling are amplitude weighted by a response spectrum method which relates the maximum acceleration induced in a single degree of freedom mechanical oscillator to the oscillator's natural period. A typical response spectrum curve is shown in Figure (3.1). Because the timing of the peaks of individual modal responses is not taken into account, and because peaks of all modes will not occur simultaneously, modal responses are not combined algebraically. Modal responses are combined using the SRSS (square root of sum of squares) or the CQC (complete quadratic combination) method.

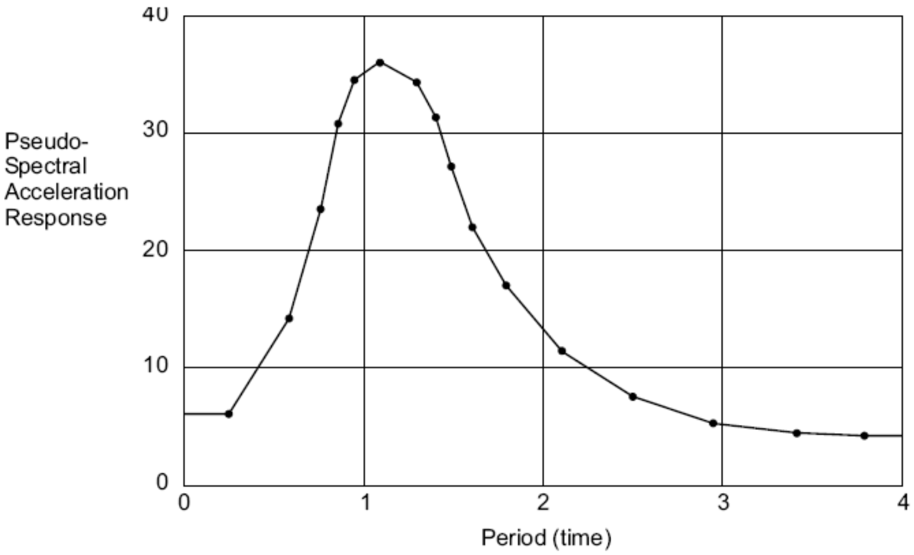

Figure (3.1) Typical Response Spectrum Curve

- **Time-History Analysis:** Time-varying loads are applied using time-history functions. The solution may be by modal superposition or direct integration methods. The time history method is a more rigorous solution technique. The response of each mode of vibration to a specific acceleration record is calculated at each point in time using the Duhamel integral. All modal responses are then added together algebraically for each time step throughout the earthquake event.

3.2.3 Analysis Results

Analysis results can be graphically displayed for any case that has been carried out. These displays include:

- Deformed shapes.
- Reactions and spring forces for joints.
- Force and moment diagrams for frames, cables, and links.
- Force and moment stress-resultant contour plots for shells.
- Stress contour plots for shells, planes, a solids, and solids.
- Influence-lines for displacements, reactions, spring forces, and frame/cable forces and moments.
- Virtual work plots for all object types.

Deformed shapes can be animated; animating the deformed shape sometimes helps to clarify the behavior of the structure.

3.3 Assumptions:

The analysis of a structure founded on soil deposits and subjected to dynamic loads was addressed. The excitation can be defined as applied dynamic forces or as seismic excitation. The loads are the known values in the system. The deformations of the system are the unknown. Simplification and assumptions are made in order to be able to solve the system with the help of numerical solution strategies.

The following assumptions were made:

3.3.1 Linear Elastic Behavior:

The response is assumed to behave linearly with the load. This restricts the approach to small displacement amplitudes and to linear material behavior.

3.3.2 Linear Behavior of Soil

The soil media is supposed to be one finite layer with linear elastic behavior.

3.3.3 Massless Foundation

Most structural analysis computer programs automatically apply the seismic loading to all masses degrees of freedom within the computer model and thus can not solve the SSI problem. This lack of capability has motivated the development of the massless foundation model. This allows the correct seismic forces to be applied to the structure; however the inertia forces within the foundations material are neglected.

3.3.4 Fixed Boundary Conditions

The most common analytical SSI models are based on the assumption that the soil domain may be represented by an elastic half space, and dashpots may be used to represent the transmitting boundary conditions (Wolf, 1989). These boundary conditions are required to model both radiations damping of the foundation motion as waves propagate outward into the infinite domain, and to prevent reflection back into the foundation from any artificially introduced finite domain.

By fixing all degrees of freedom on the domain boundaries, any radiation of energy away from the structure is made impossible. Waves are fully reflected and resonance frequencies can appear that don't exist in reality.

If the soil volume is large and modal damping exists, then a finite soil media with fixed boundaries can produce converged results; as the soil model becomes larger, the energy dissipation due to normal modal damping within the massive soil is significantly larger than the effects of radiation damping for transient earthquake type of loading (Mullen, 2003).

3.4 Analysis Procedure

Three dimensional finite element analyses are adaptable for more representative results than two dimensional analyses. A 3D model for the building has been developed using SAP2000. The slabs were modeled as shell elements, the columns were modeled as frame elements, foundation was modeled as thick plate element, and soil was modeled as solid elements.

In this study, linear analysis of soil structure interaction of four buildings was carried out. The four buildings are: five, ten, twenty and forty two story (Jordan Gate). Each analysis was carried out several times; once assuming a rigid base while other cases involved soil-structure interaction with various soil properties. Static and dynamic analyses were performed for comparative purposes.

3.4.1 Rigid Base Modeling

Representative reinforced concrete buildings layout have been selected for the three buildings; five, ten, and twenty-story were modeled using ETABS program. Sizing of members in these buildings was utilized in accordance with the American Concrete Institute (ACI) code.

3.4.1.1 Five-Story Building

The first model was a five-story building. Its floor area is 400 square meters; the slab is 200mm flat slab for all stories; the height of each story is 3m; walls are 300mm in thickness; exterior columns are 350mm x 350mm and interior columns are 450mm x 450mm as shown in Figures (3.2) and (3.3).

3.4.1.2 Ten-Story Building

The second model was a ten-story building. Its floor area is 400 square meters; the slab is 200mm flat slab for all stories; the height of each story is 3m; walls and columns are shown in Table (3.1), plan and 3D model are shown in Figures (3.4) and (3.5).

3.4.1.3 Twenty-Story Building

The third model was a twenty-story building. Its floor area is 400 square meters; the slab is 200mm flat slab for all stories; the height of each story is 3m; walls and columns are shown in Table (3.2), plan and 3D model are shown in Figures (3.6) and (3.7).

3.4.1.4 Jordan Gate Tower

A model of a mega project, the Jordan Gate was generated; the architectural and structural design drawings were obtained from Consolidated Consultants (C.C.) Company in Amman. The project has a large floor plate area at its podium and is the tallest building planned in Amman. It comprises two towers. Each tower has a floor area of 1500 square meters and rises forty two stories high; the height of each story is 4m, as shown in Figures (3.8) and (3.9).

Table (3.1) walls and columns dimensions for the 10-story building

	walls	columns	
Stories		exterior	interior
1 - 5	500mm	450mmx450mm	700mmx700mm
6 -10	300mm	350mmx350mm	450mmx450mm

Table (3.2) walls and columns dimensions for the 20-story building

	walls	columns	
Stories		exterior	interior
1 - 10	700mm	600mmx600mm	1200mmx1200mm
11 - 15	400mm	450mmx450mm	700mmx700mm
16 - 20	300mm	350mmx350mm	450mmx450mm

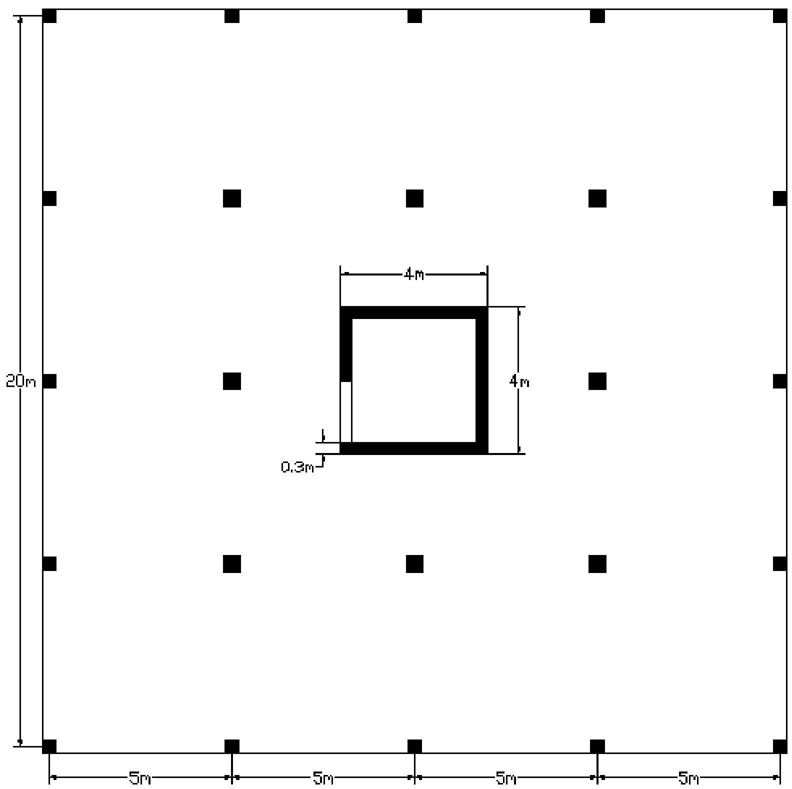

Figure (3.2) Plan of first story for the 5-story R/C building

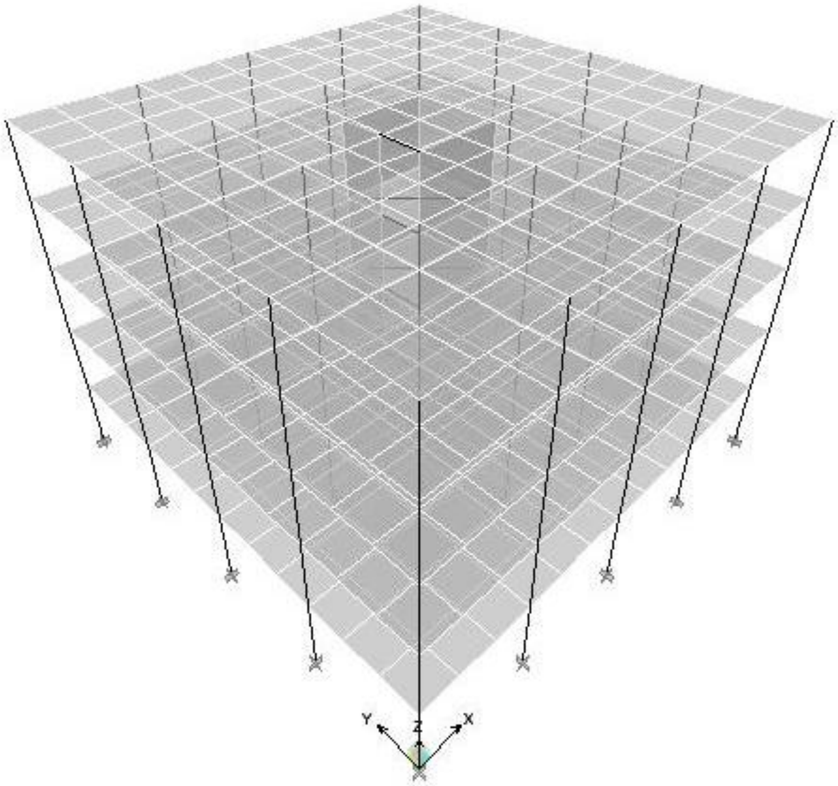

Figure (3.3) 3D rigid base model of 5-story R/C building

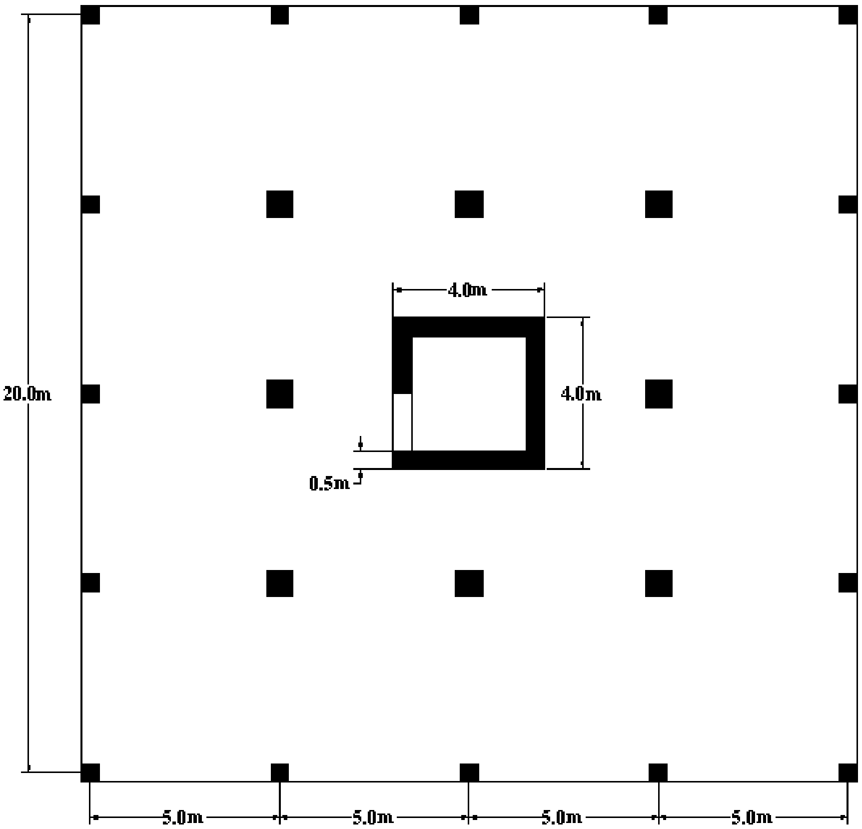

Figure (3.4) Plan of first story for the 10-story R/C building

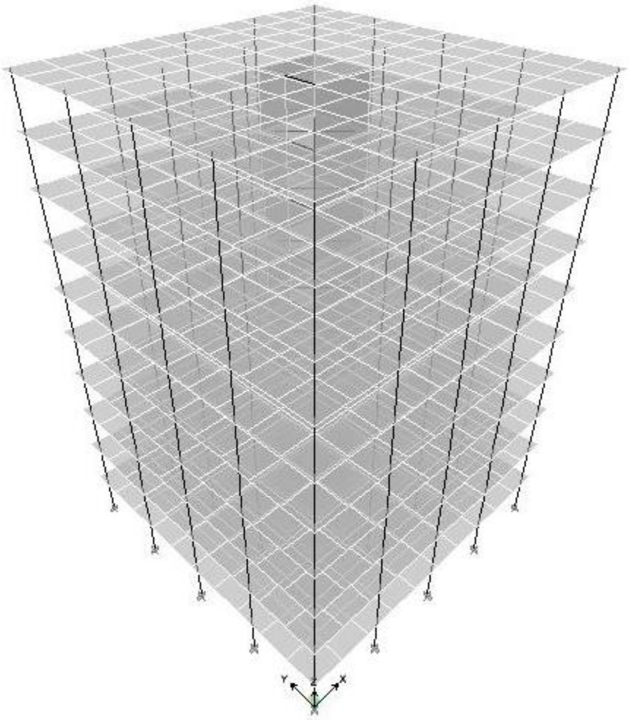

Figure (3.5) 3D rigid base model of 10-story R/C building

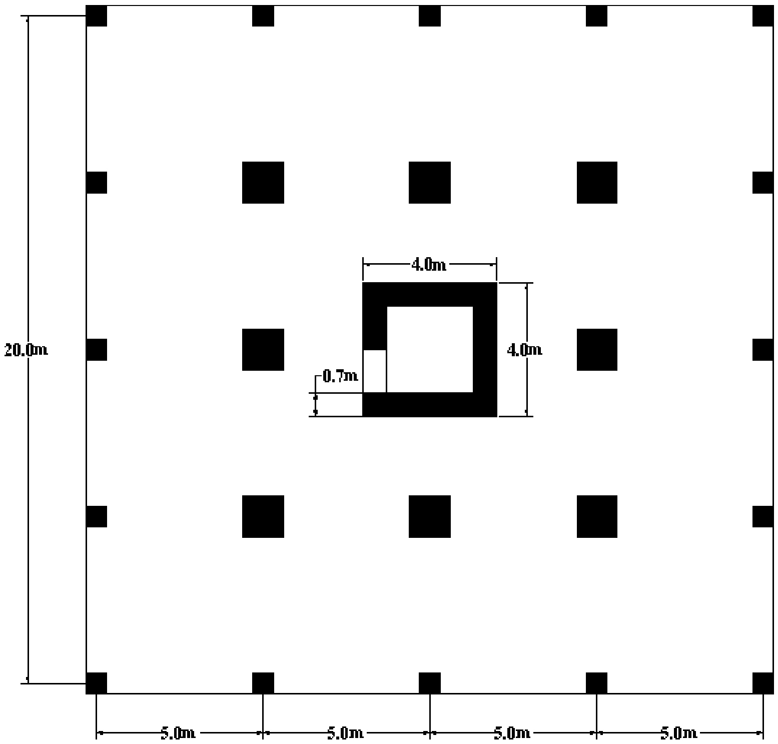

Figure (3.6) Plan of first story for the 20-story R/C building

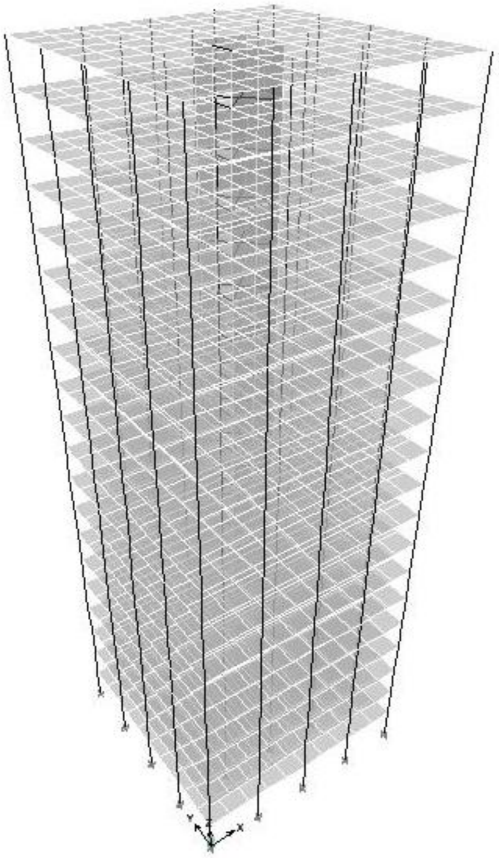

Figure (3.7) 3D rigid base model of 20-story R/C building

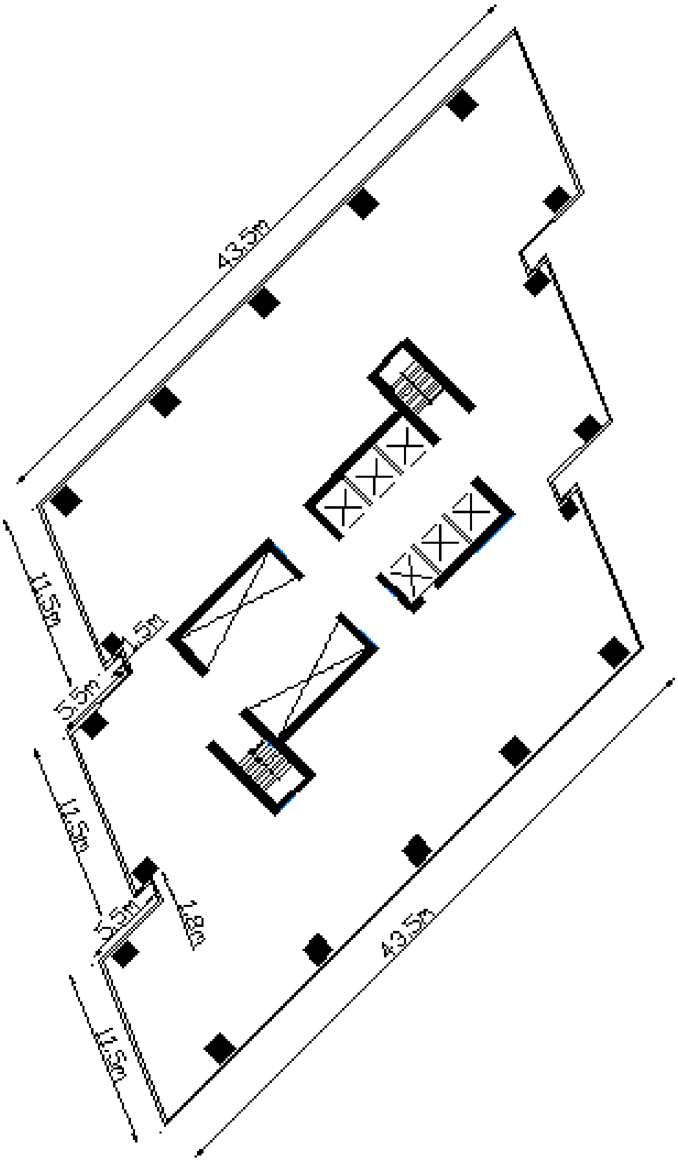

Figure (3.8) Plan outlines of Jordan Gate tower

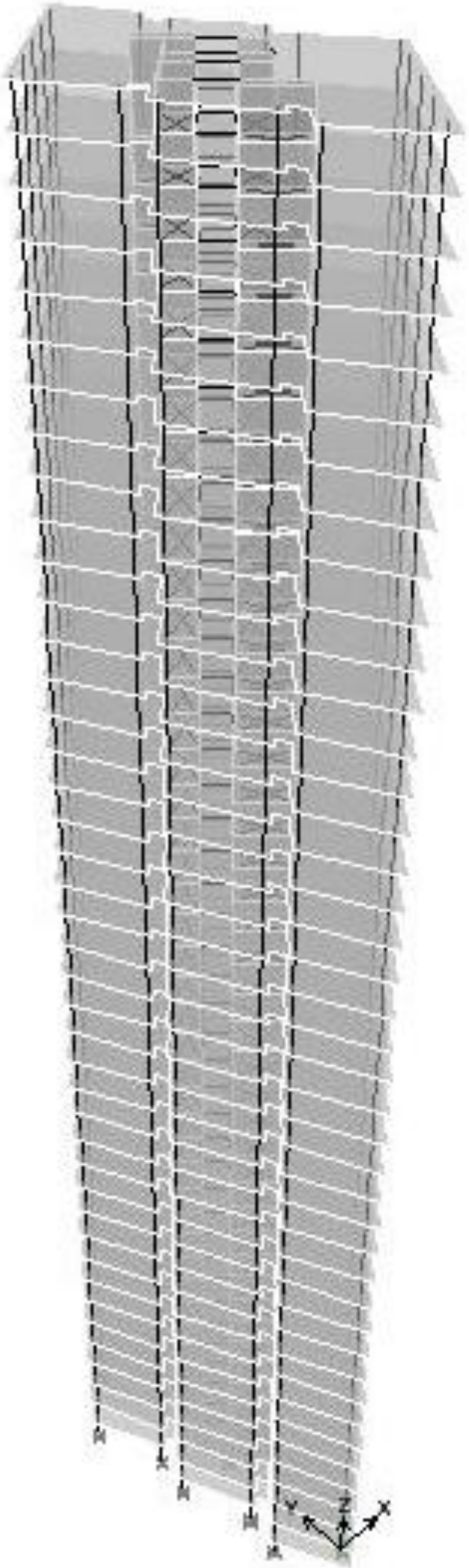

Figure (3.9) 3D rigid base model of Jordan Gate tower

3.4.2 Soil Structure Interaction Modeling

SAP2000 program was used for modeling the soil and the foundations; the raft foundation was modeled as a thick plate and the soil media was modeled as solid elements.

3.4.2.1 Types of Elements

The structure was modeled using 3D isoperimetric elements; soil was modeled using two types of elements; the linear 8-noded isoperimetric hexahedron (brick) elements with 6 DOF per node, and the linear 6-noded elements with 6 DOF per node, as shown in Figure (3.10).

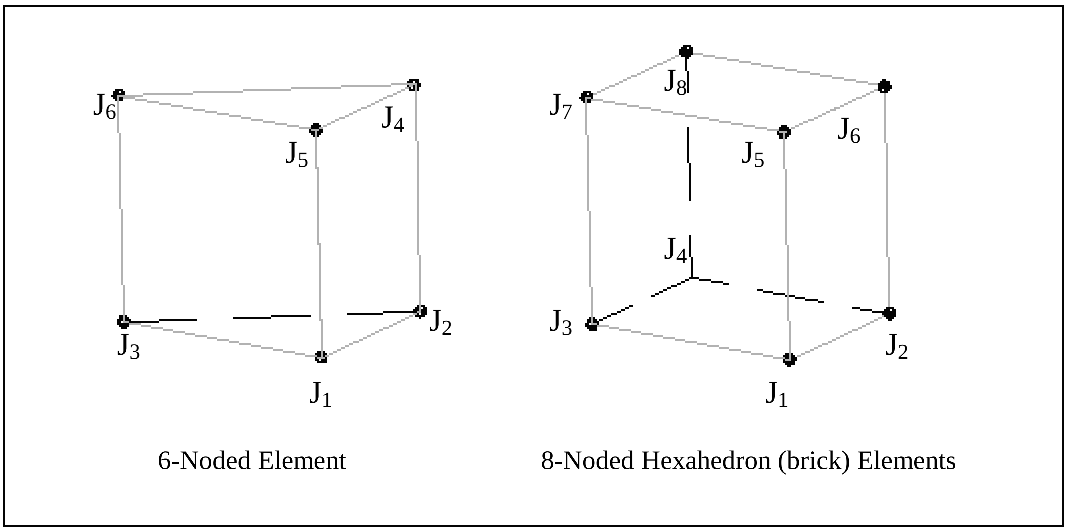

Figure (3.10) Types of finite elements used for soil modeling

3.4.2.2 Meshing

Structural elements (slabs, walls, and columns) were meshed automatically by SAP2000, but the foundation and the soil were meshed manually, element by element for the three R/C buildings and for the Jordan Gate tower; to make sure that each end of the base columns was connected to the node at the raft foundation, as shown in Figures (3.11) and (3.12).

3.4.2.2.1 Meshing Size

Raft foundation and the soil were meshed into small elements; these elements were meshed to satisfy the compatibility between nodes. Each node at the end of the column was connected to the node in the raft foundation. A random size of elements was chosen, and the response of the structure was obtained, then the mesh size was reduced until a relatively constant response of the structure was reached. The largest size of element that was used in the actual study was 2x2m.The responses that were used to check the meshing size are the period of the structure, and the lateral displacement at the top of the structure using static equivalent method and the period of the structure as shown in Figures (3.13) and (3.14). The accuracy of the solution can be enhanced marginally by using smaller elements, but in this case the capacity of available computer would not permit such fine meshing.

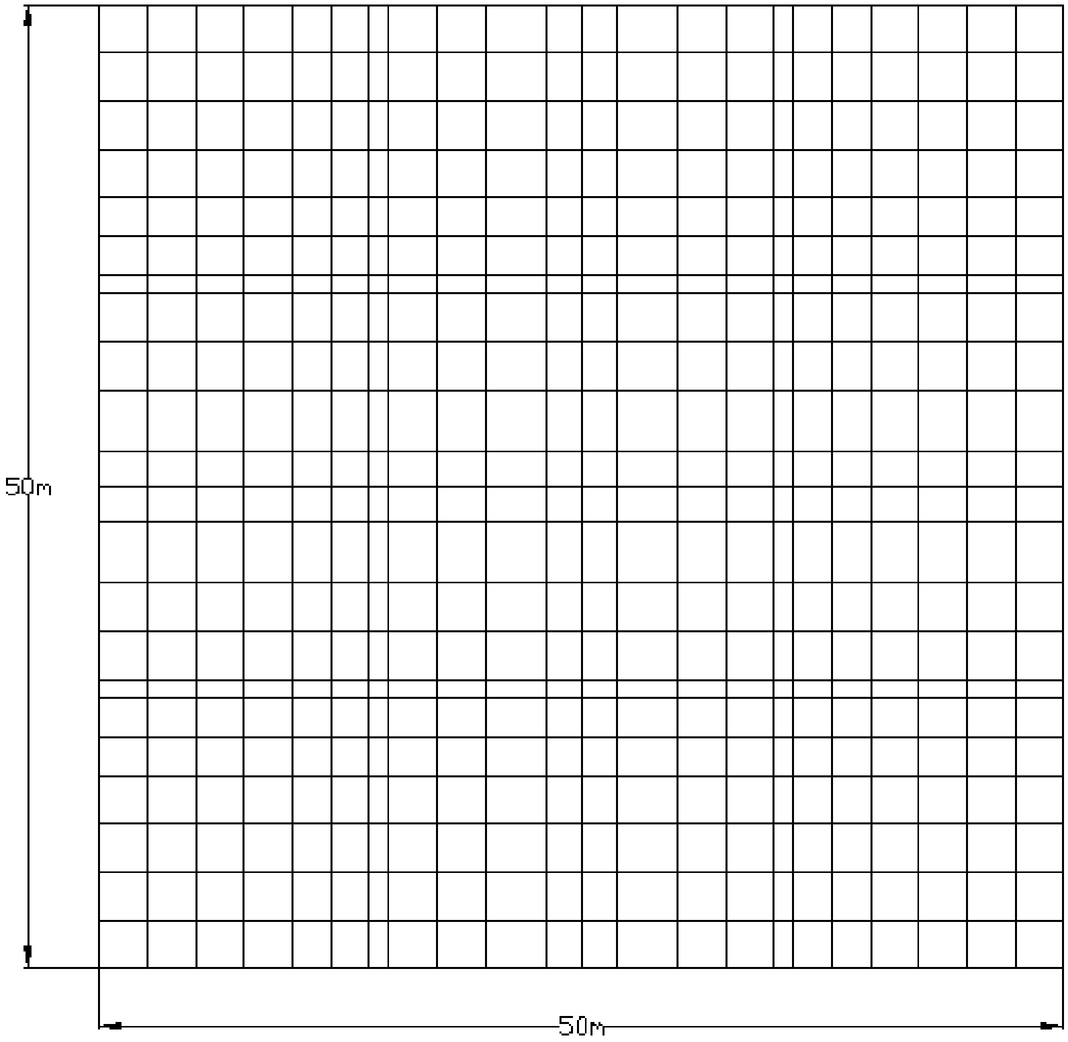

Figure (3.11) Plan of meshing soil for 5-, 10-, and 20-story R/C building

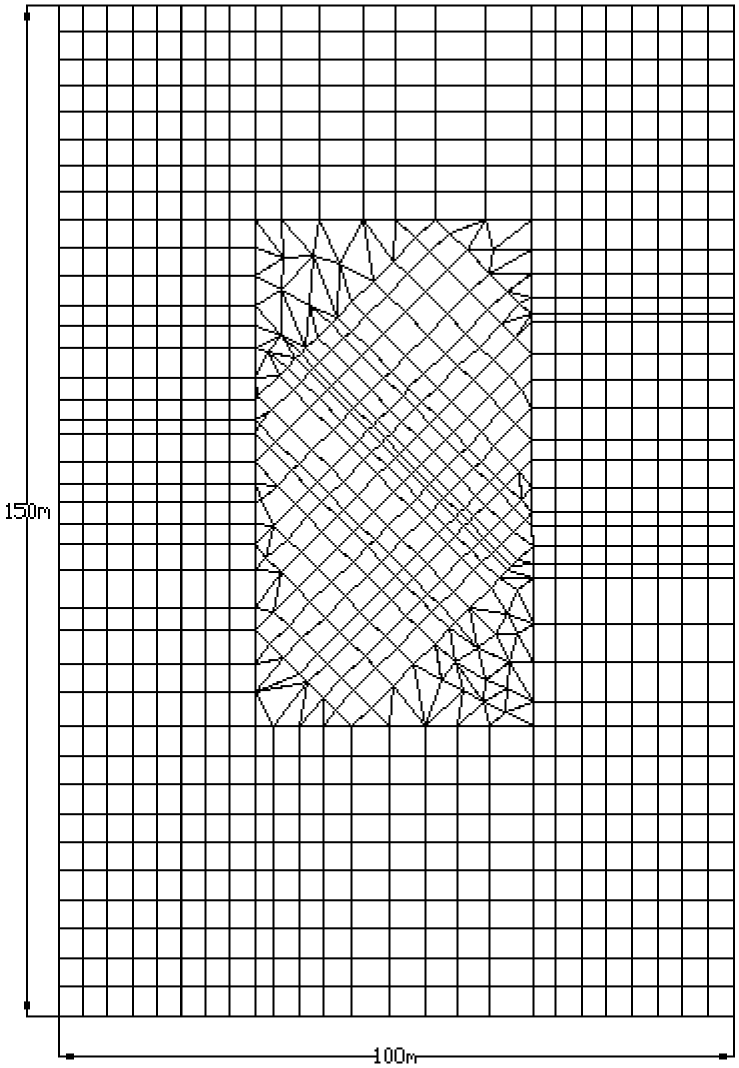

Figure (3.12) Plan of meshing soil for Jordan Gate tower

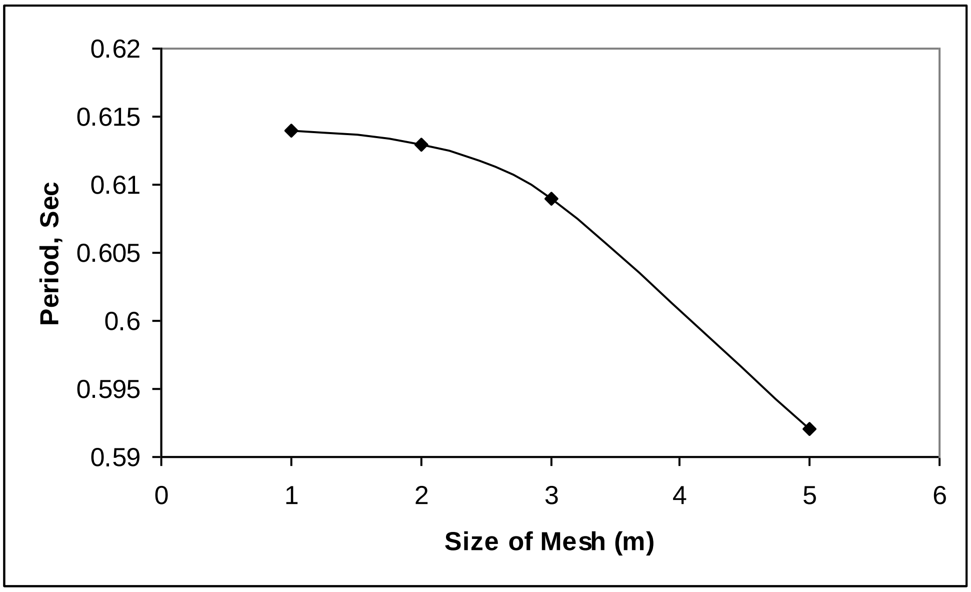

Figure (3.13) Period of structure vs. size of mesh of 5-story R/C building with Es=30MPa.

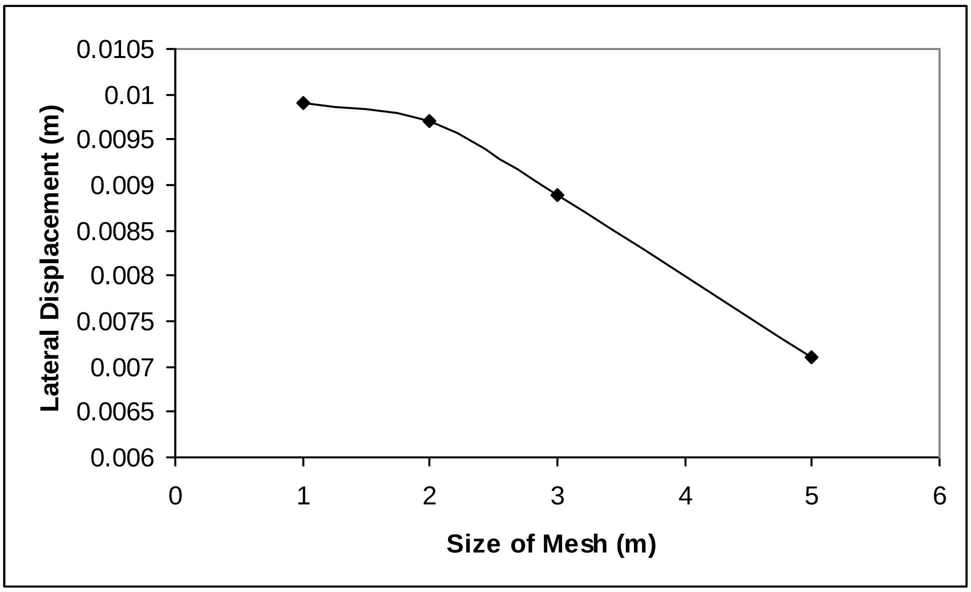

Figure (3.14) Lateral displacement vs. size of mesh of 5-story R/C building using equivalent static method with Es=30MPa.

3.4.2.3 Soil Properties

The effect of soil type was represented by considering five types of soil with different moduli of elasticity, (Bowles, 1997) as shown in Table (3.3), (Bowles, 1997).

Table (3.3) Values of Es for selected soils

Es	30MPa	100MPa	500MPa	1000MPa	5000MPa
Soil type	Medium clay	Hard clay	Glacial till (dense)	Glacial till (very dense)	shale

3.4.2.4 Boundary Conditions

In this work a fixed boundary conditions was assumed for all directions of soil as shown in Figure (3.15).

3.4.2.5 Soil Model Dimensions

Because fixed boundaries were chosen the soil dimension was chosen to be sufficiently large to justify this assumption. Material damping was introduced into soil (solid elements) to limit the propagation of the reflected waves and thus to permit ignoring the influence of the radiation of the half space into the structure.

At the beginning a random dimension of soil was chosen, and the response of the structure was obtained, then the dimension was increased until a relatively constant response of the structure was reached. The period of the structure, and the lateral displacement at the top of the structure using static equivalent method and period of the structure as shown in Figures (3.16) and (3.19) were used to check the influence of the soil model dimensions.

The selected soil dimensions for the five-story, ten-story, and twenty-story were 50mx50mx50m, and for the Jordan Gate tower were150mx100mx50m.

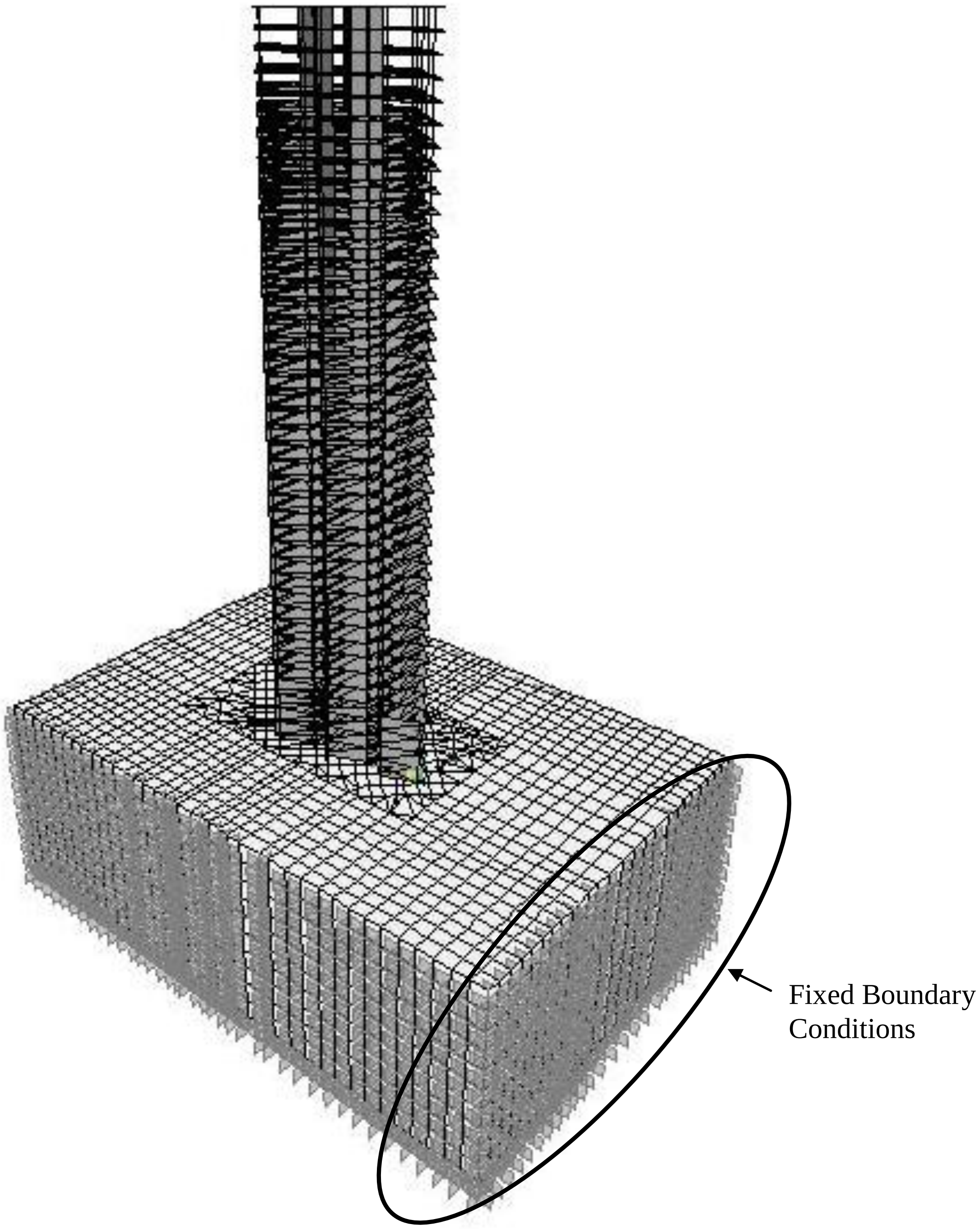

Figure (3.15) Boundary Conditions of Soil

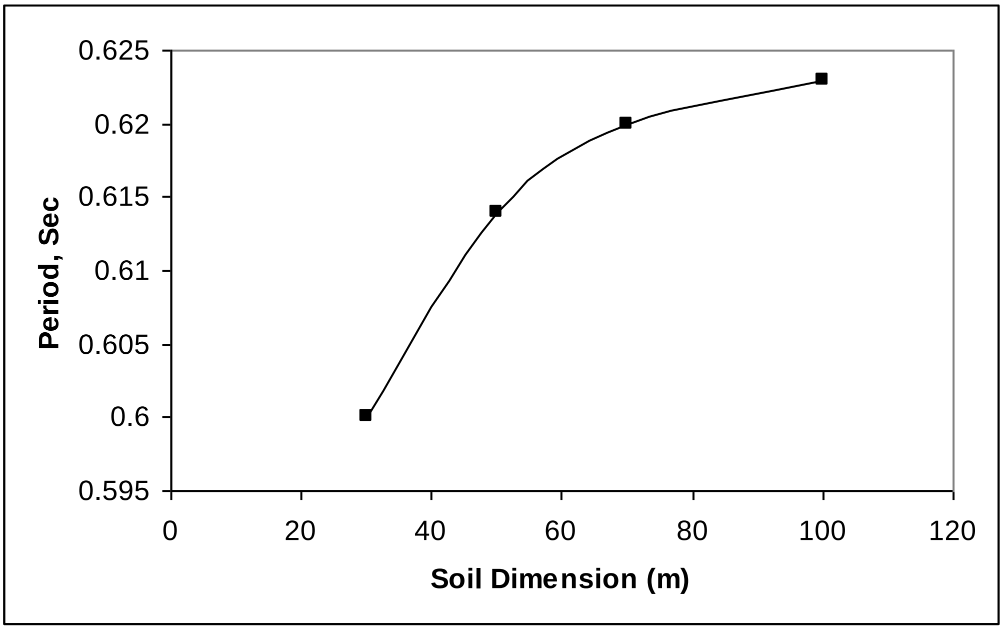

Figure (3.16) Period of structures vs. soil dimension of 5-story R/C building with Es=30MPa.

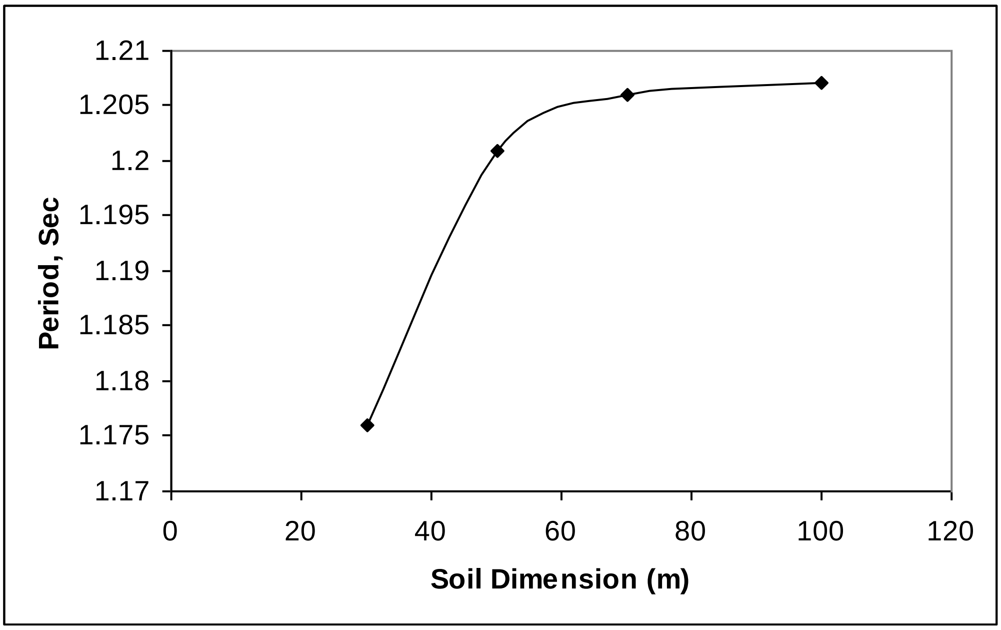

Figure (3.17) Period of structures vs. soil dimension of 10-story R/C building with Es=30MPa

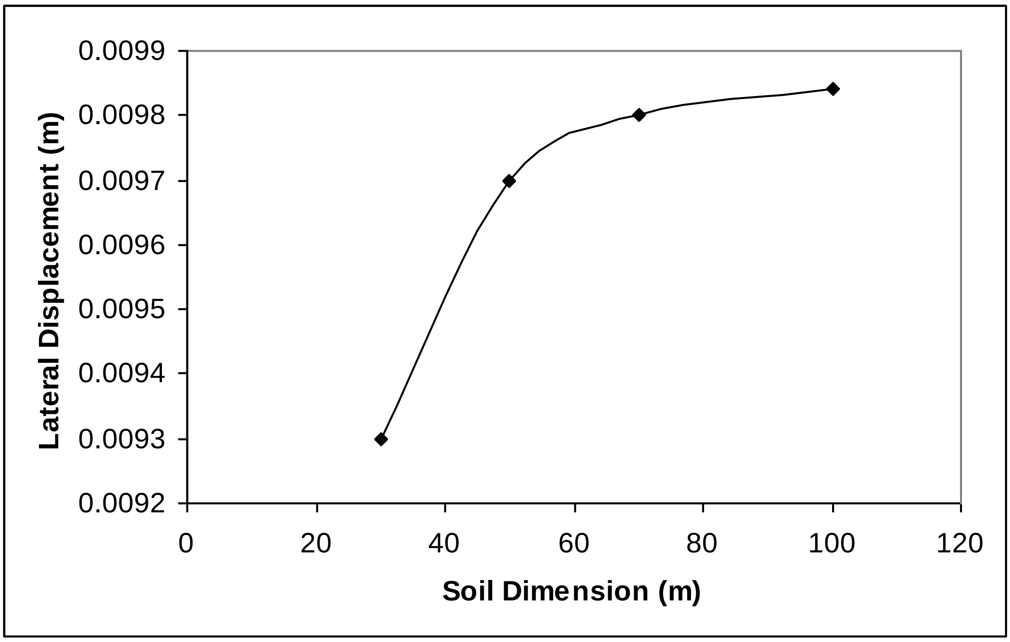

Figure (3.18) Lateral displacement vs. soil dimension of 5-story R/C building using equivalent static method with Es=30MPa.

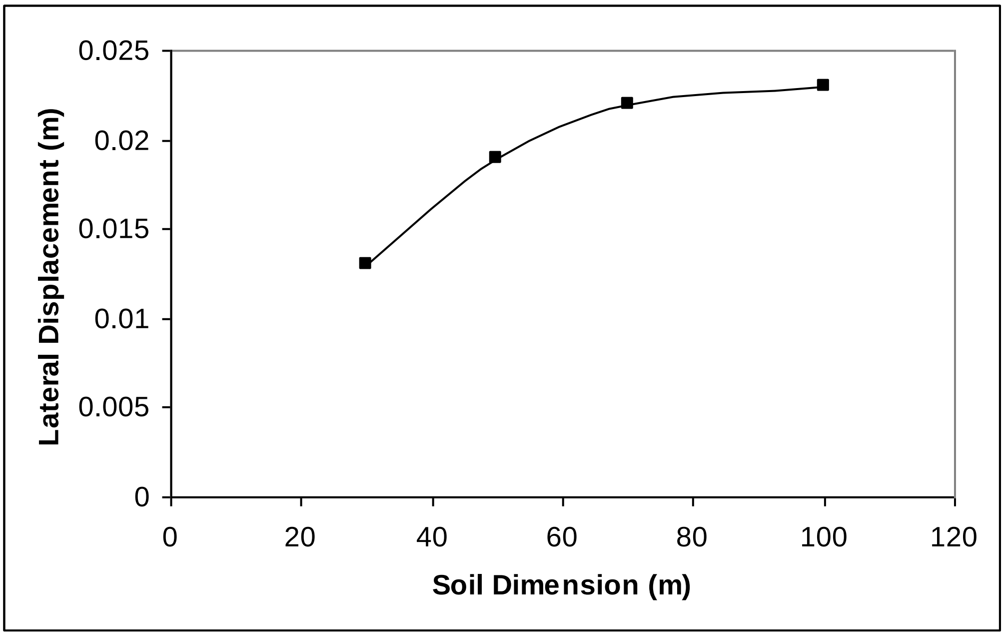

Figure (3.19) Lateral displacement vs. Soil dimension of 10-story R/C building using equivalent static method with Es=30MPa.

3.4.2.6 Soil Structure Interface

One of the most important problems in this kind of analysis is the soil structure interface; in our models, soil structure interface was modeled by the finite element method directly without gap elements; the raft foundation was modeled as a thick plate element, this plate was meshed to small elements, then the soil was modeled directly under the plate and meshed to small solid elements; each node of the plate elements is connected to the node at the top surface of the solid elements to satisfy the compatibility requirements.

3.4.2.7 Soil Structure Interaction Models

Evaluating the interaction of soil structure system subjected to a seismic load is an important step in any dynamic analysis.

Soil structure interaction models for five-story building, ten-story building, twenty-story building and for the forty two-story tower (Jordan Gate) are shown in Figures (3.20) to (3.23).

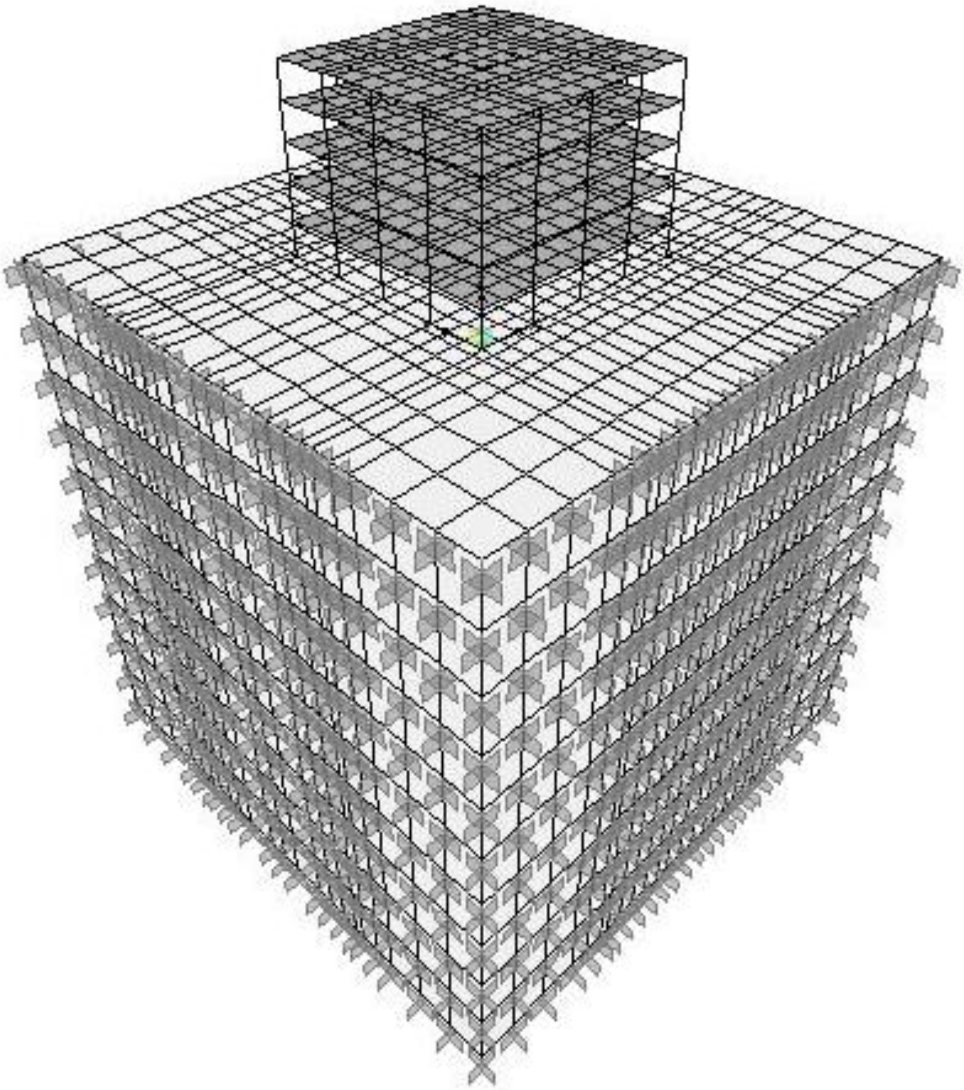

Figure (3.20) Soil-structure interaction model of 5-story R/C building

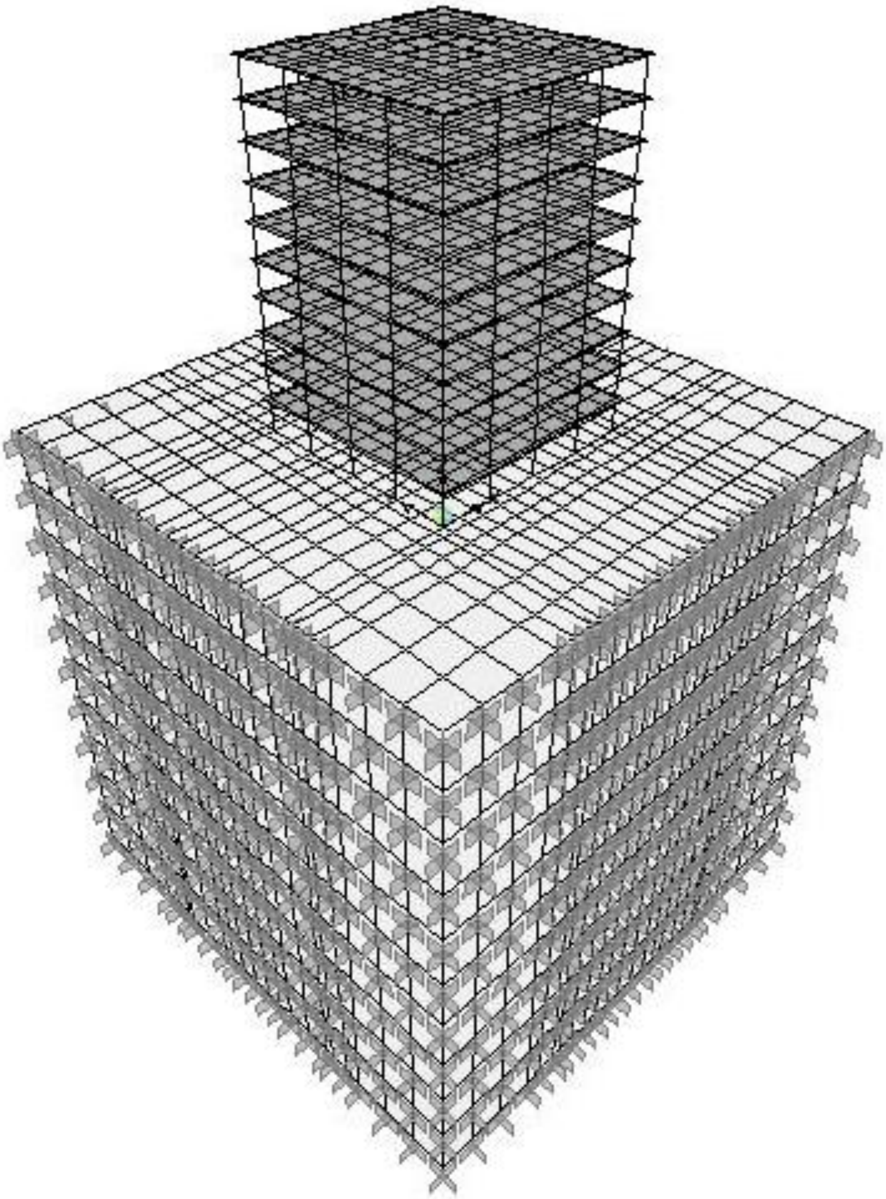

Figure (3.21) Soil-structure interaction model of 10-story R/C building

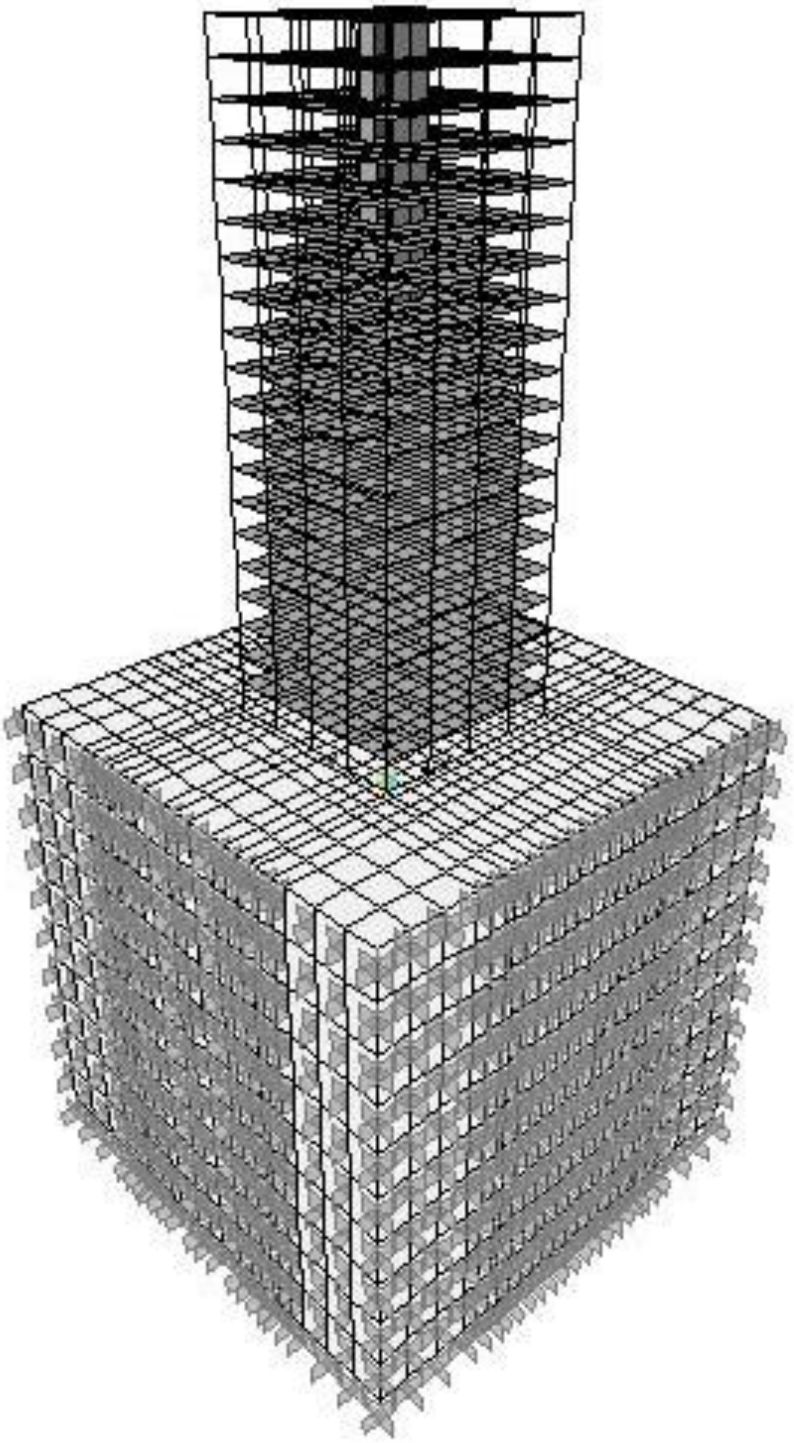

Figure (3.22) Soil-structure interaction model of 20-story R/C building

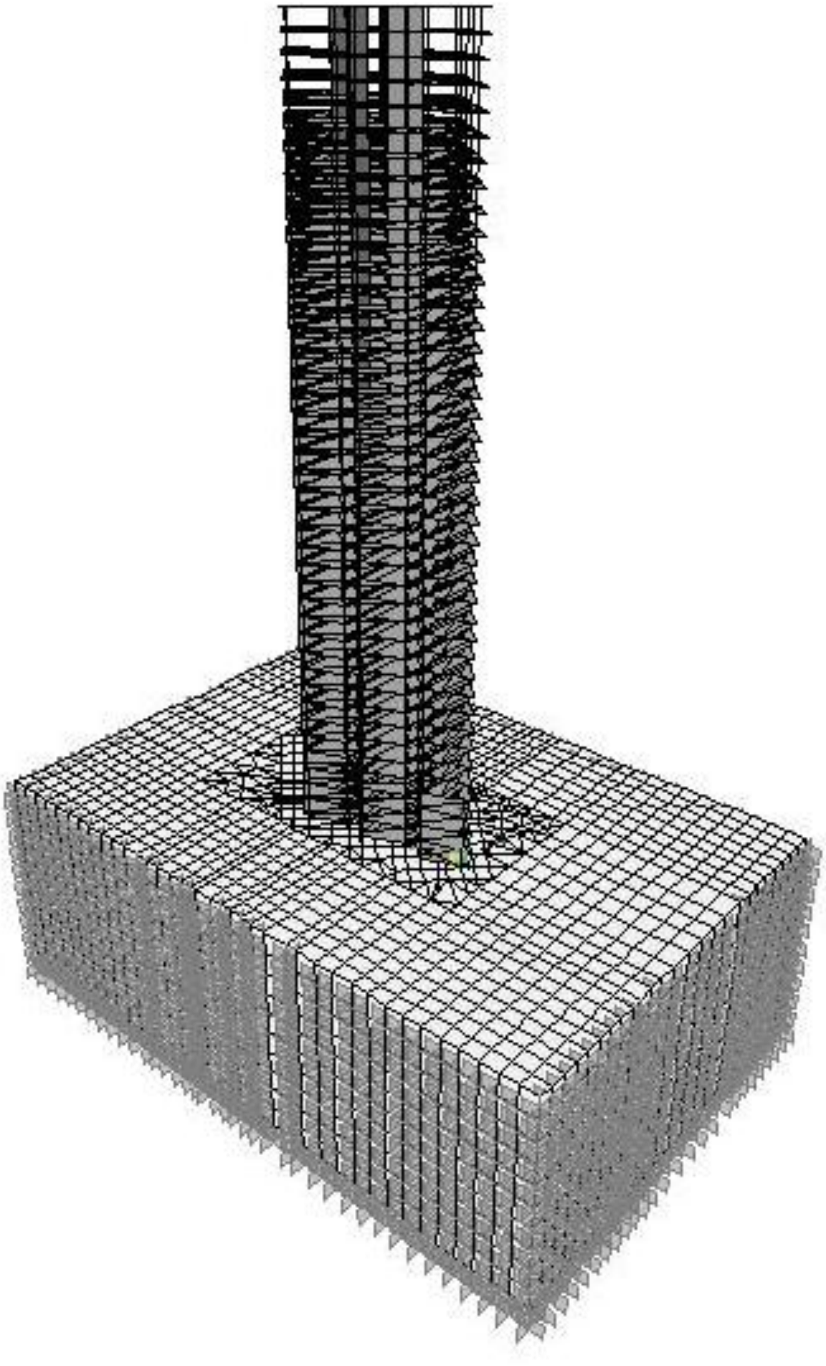

Figure (3.23) Soil-structure interaction model of Jordan Gate tower

STATIC AND DYNAMIC ANALYSIS RESULTS

4.1 Introduction

To understand the behavior of structure under seismic loading, static and dynamic analysis must be done for the structure. In this chapter static and dynamic analysis has been performed for three regular multi-story concrete buildings and the Jordan Gate tower.

4.2 Natural Period of Vibration

Dynamic response analysis is typically performed using finite element modal analysis. Modal analysis is used to determine the vibration modes of a structure. These modes are used to understand the behavior of the structure. The major modes of vibration are calculated, and the response of the structure to the earthquake is expressed as a combination of individual modal responses.

In this study, the natural period of vibration was calculated for all rigid base models and SSI models as shown in Figures (4.1) and (4.2) with using different types of soil.

It was found that considering SSI in analysis increases the period of the system. The period however decreases with the increase of stiffness of soil from soft to rock.

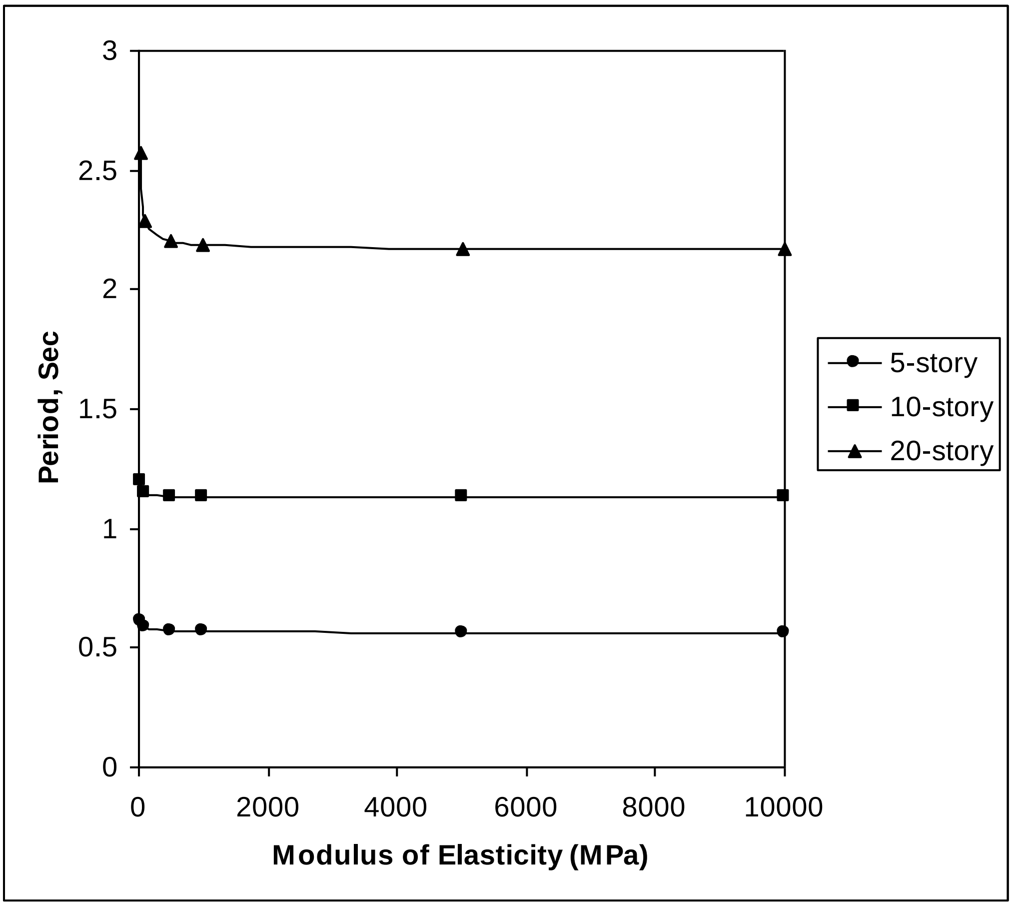

Figure (4.1) Natural period vs. modulus of elasticity of soil

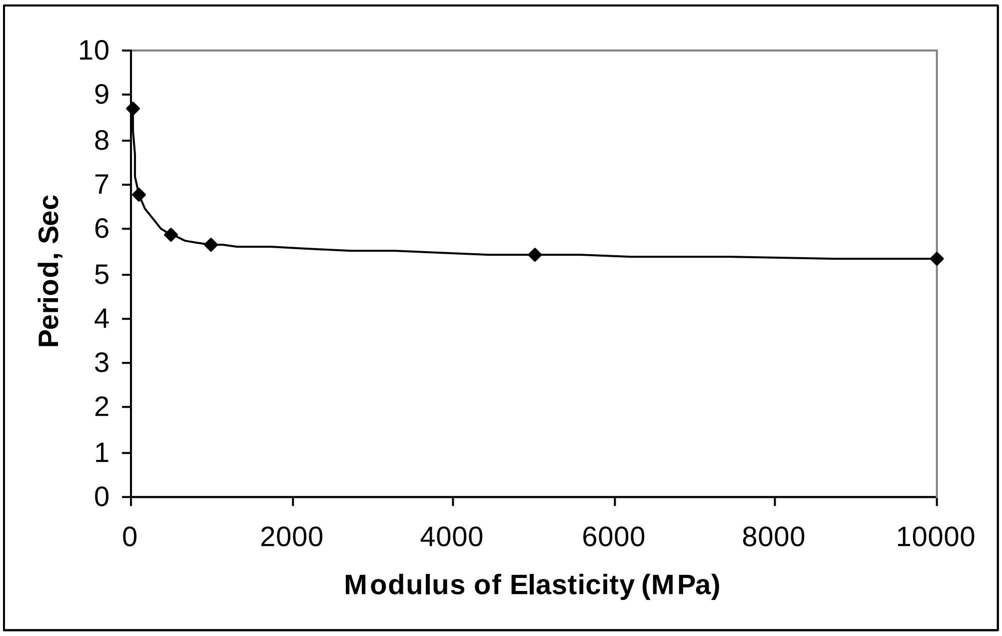

Figure (4.2) Natural period vs. modulus of elasticity of soil for Jordan Gate Towe

4.3 Equivalent Static Analysis

The linear static analysis of a structure involves the solution of the system of linear equations represented by:

$$K\ u = r$$

Where ***K*** is the stiffness matrix, ***r*** is the vector of applied loads, and ***u*** is the vector of resulting displacements.

Earthquake loads in this case are represented by static loads. Earthquake load parameters and coefficients were based on the 1997 Uniform Building Code (UBC, 1997) in global x direction.

The static lateral force procedure may be used, as described in the Uniform Building Code (UBC1997) for the following structures:

1. All structures, regular or irregular, in Seismic Zone 1.
2. Regular structures with height equal to or less than 73m.
3. Irregular structures not more than five stories with total height less or equal to 20m.

4.3.1 Equivalent Static Analysis Results

Two responses were obtained to represent the effect of SSI; lateral displacements and base shear forces using equivalent static method. Analysis results were plotted for different types of soil and different building heights.

4.3.1.1 Lateral Displacements

Lateral displacements at the top of the structure were calculated. The relation between the soil type and the lateral displacement for buildings, of different heights was established.

Figures (4.3) and (4.4) show that lateral displacement is highest when the soil type is soft, and it decreases when the soil type goes from soft soil to rock.

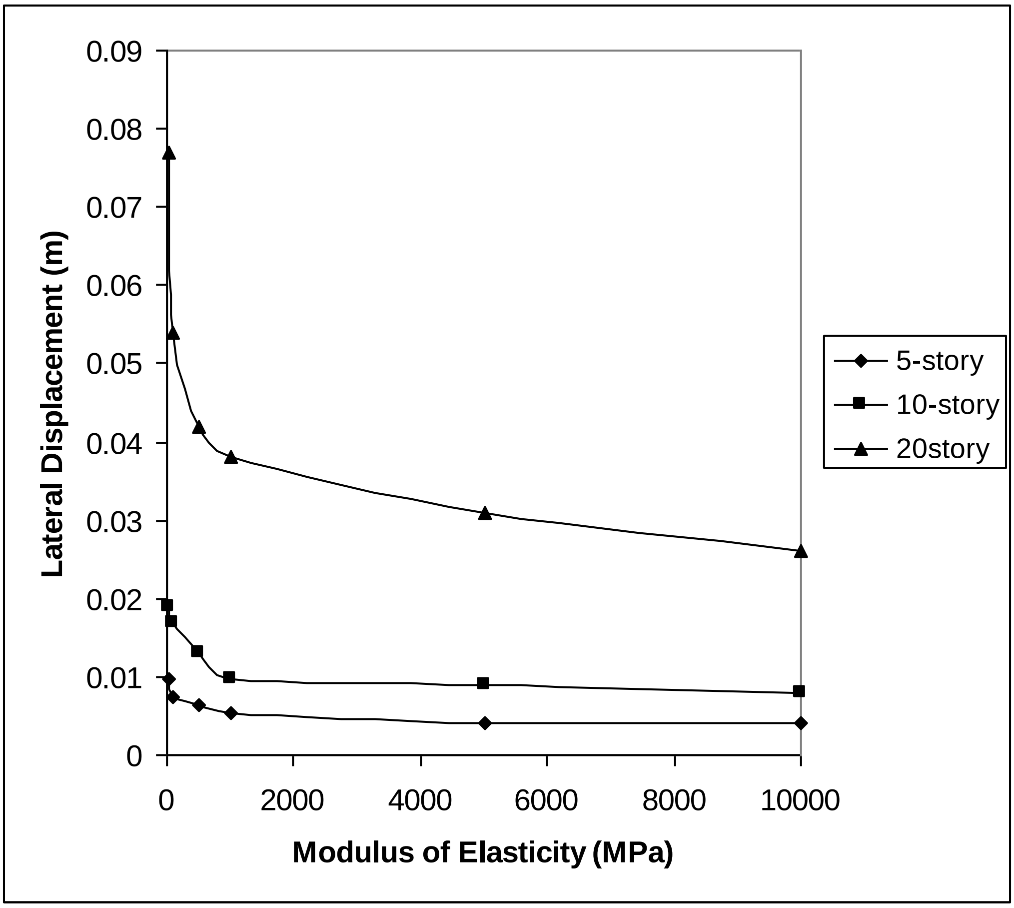

Figure (4.3) Lateral displacement vs. modulus of elasticity of soil using equivalent static method

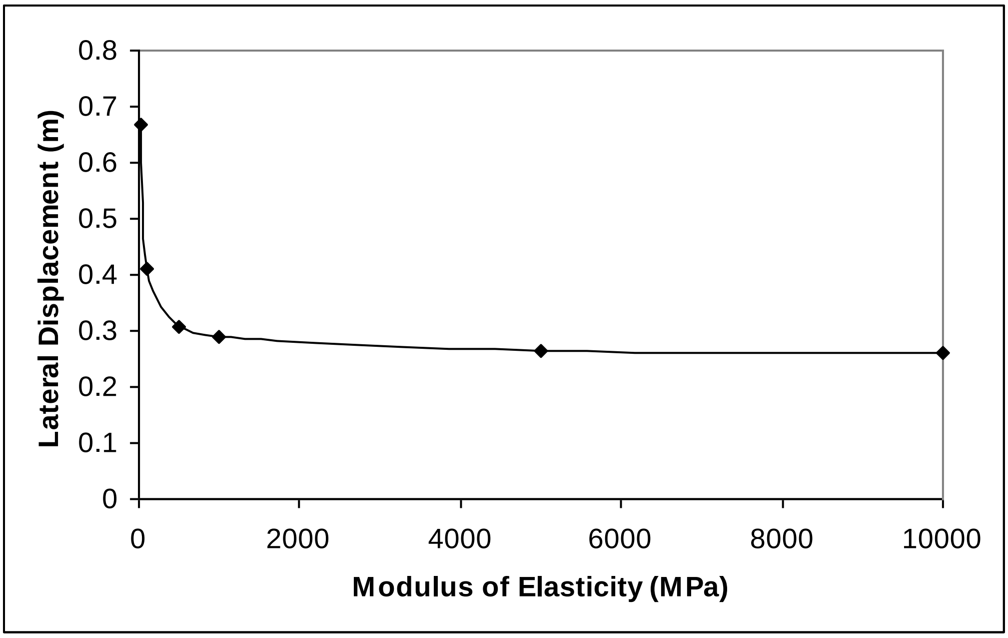

Figure (4.4) Lateral displacement vs. modulus of elasticity of soil of Jordan Gate tower using equivalent static method

4.3.1.2 Base Shear Forces

In this research the base shear forces of all columns in first story for all three buildings and Jordan Gate tower were calculated. Ratios of base shear (V_2) in x –direction to the summation of base shear of all columns ($V_2/\sum V_2$) were calculated for each column in first story for all buildings and for all soil types. Layout of columns for three R/C buildings and Jordan Gate tower are shown in Figures (4.5) and (4.6).

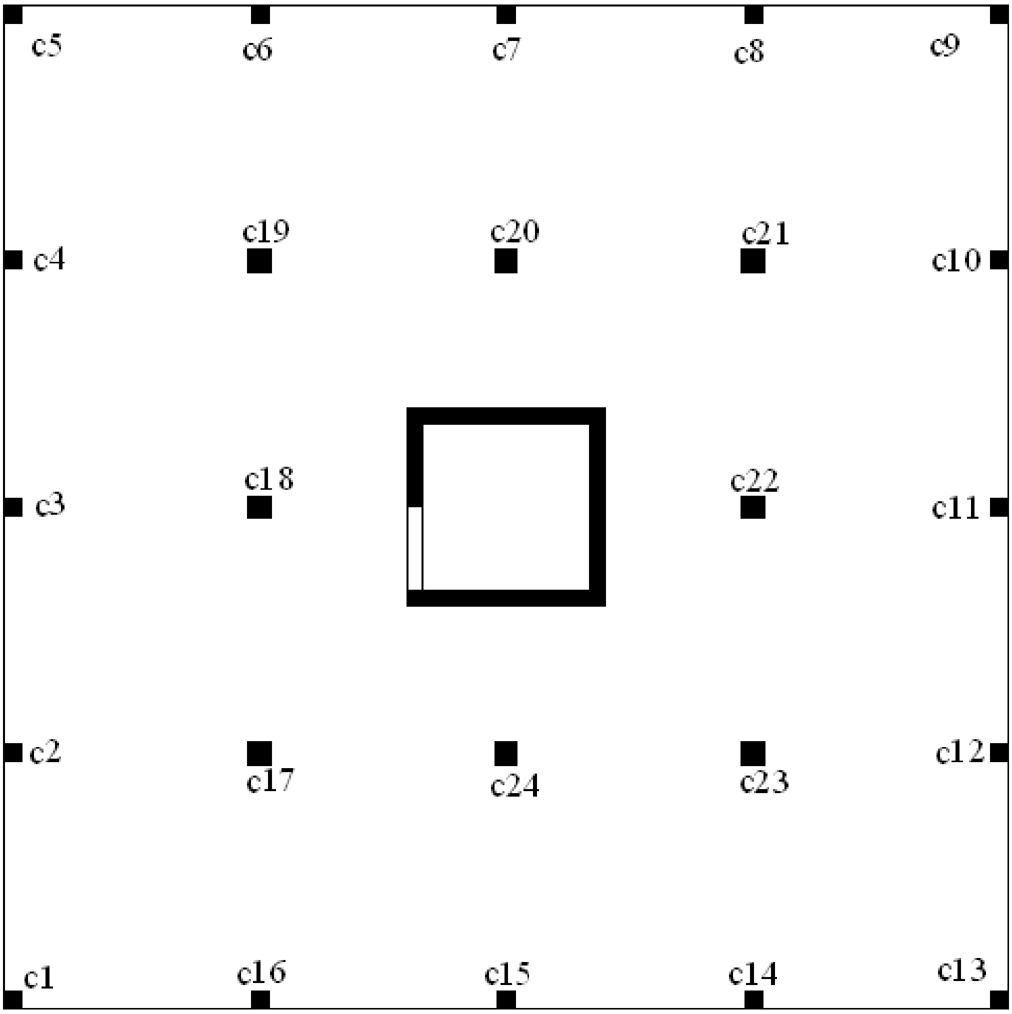

Figure (4.5) Layout of columns in 5-, 10-, and 20-story R/C buildings

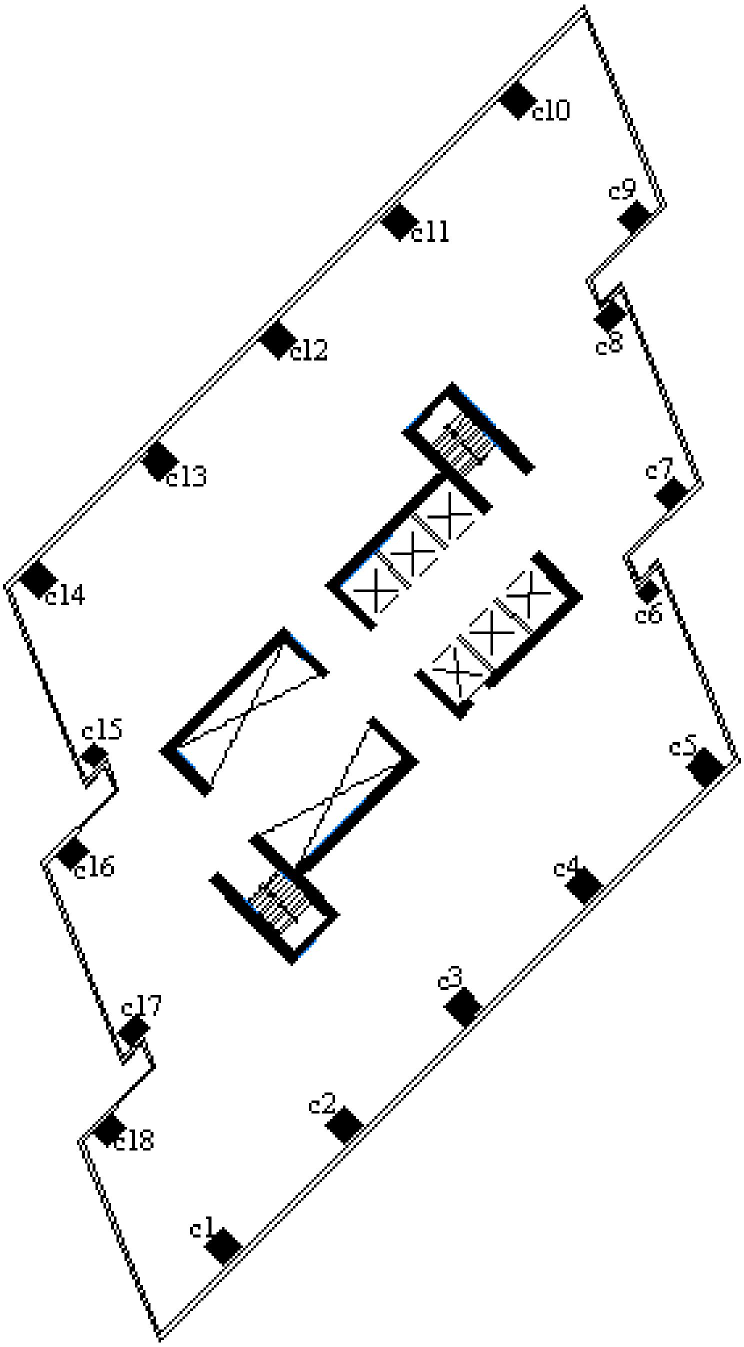

Figure (4.6) Layout of columns in Jordan Gate tower

Ratio of column base shear ($V_2/\sum V_2$) for different types of soil was calculated to study the effect of SSI on the distribution of base shear among columns.

Figures (4.7) to (4.10) show that the value of share of each column of the total base shear ($V_2/\sum V_2$) shows a lot of fluctuation in soft soils but becomes stable in stiff soils. This change varies from one column to another; most of the external columns have a relatively higher ratio in soft soil than in stiff soil, the reverse is true for internal columns as shown in Figures (4.11) to (4.18).

In other words external columns tend to attract more of the base shear when the soil is soft than they would if the soil is stiff. Naturally if SSI is ignored this behavior can not be depicted.

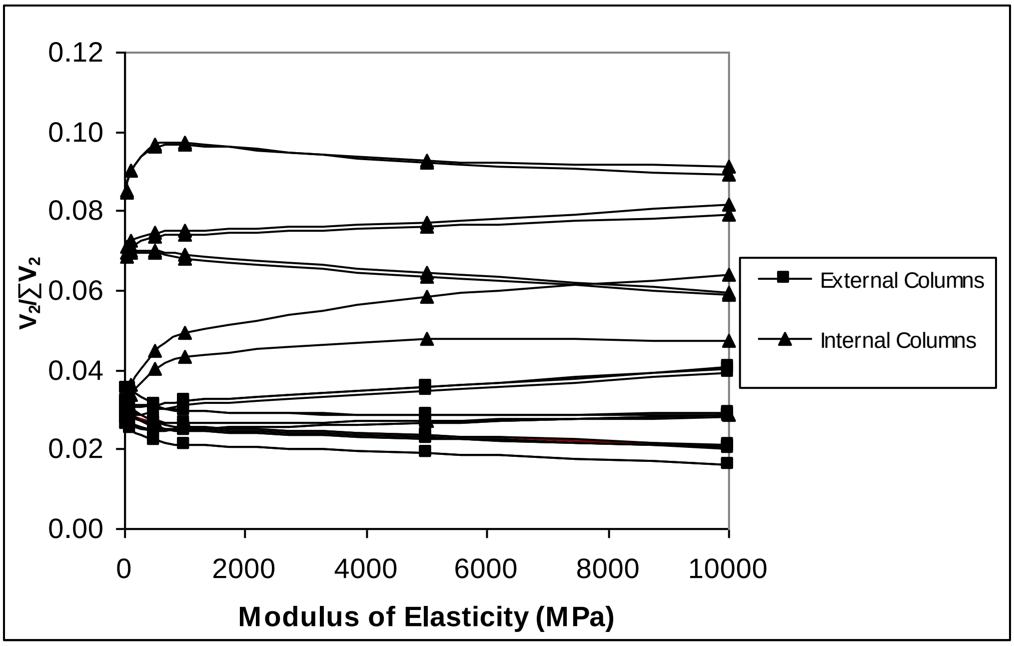

Figure (4.7) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of 5-story R/C building using equivalent static method.

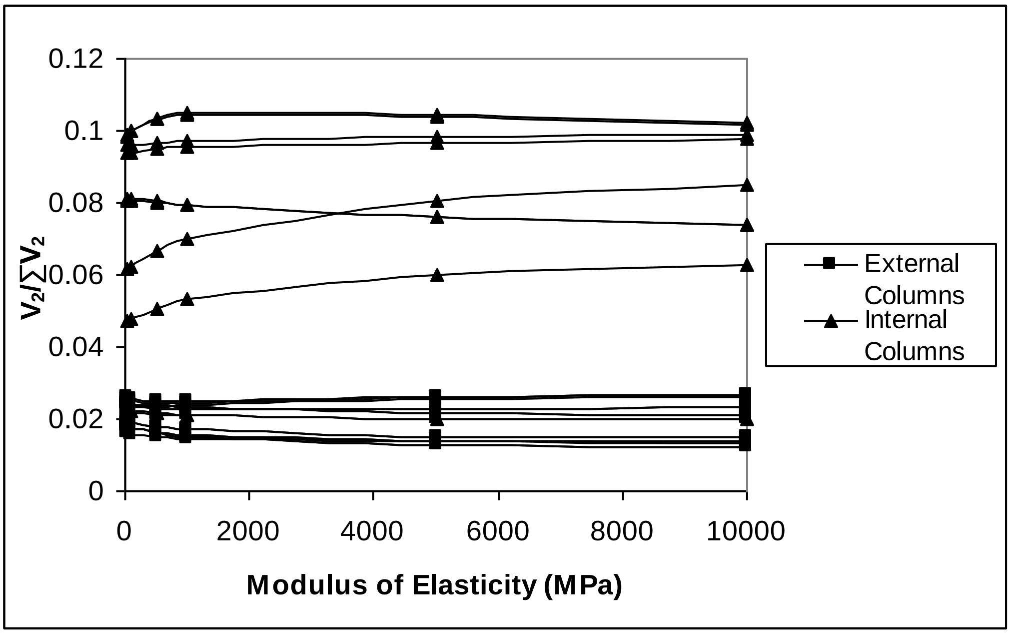

Figure (4.8) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of 10-story R/C building using equivalent static method.

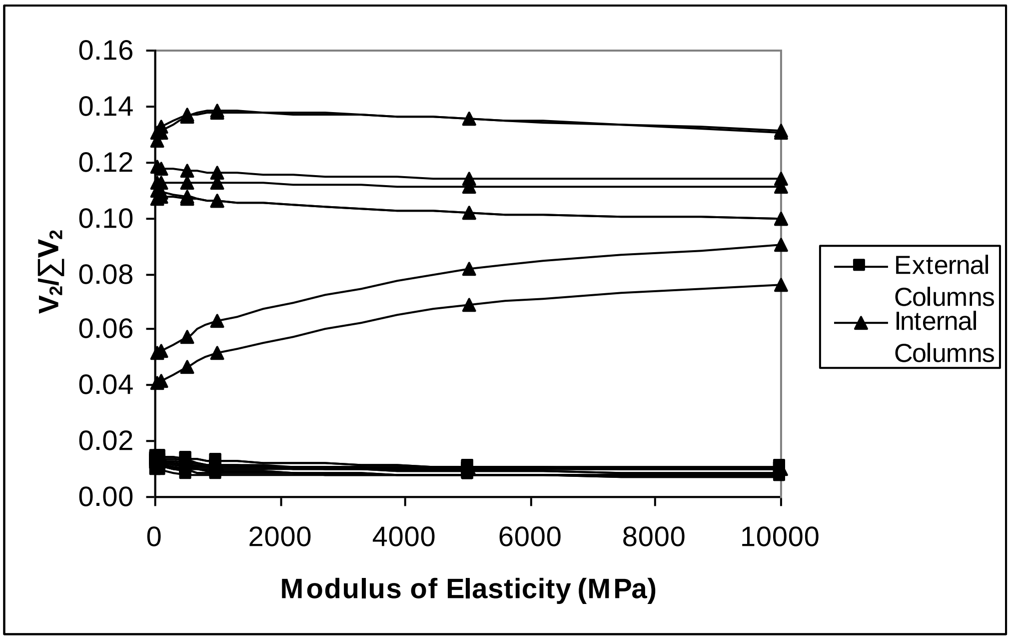

Figure (4.9) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of 20-story R/C building using equivalent static method

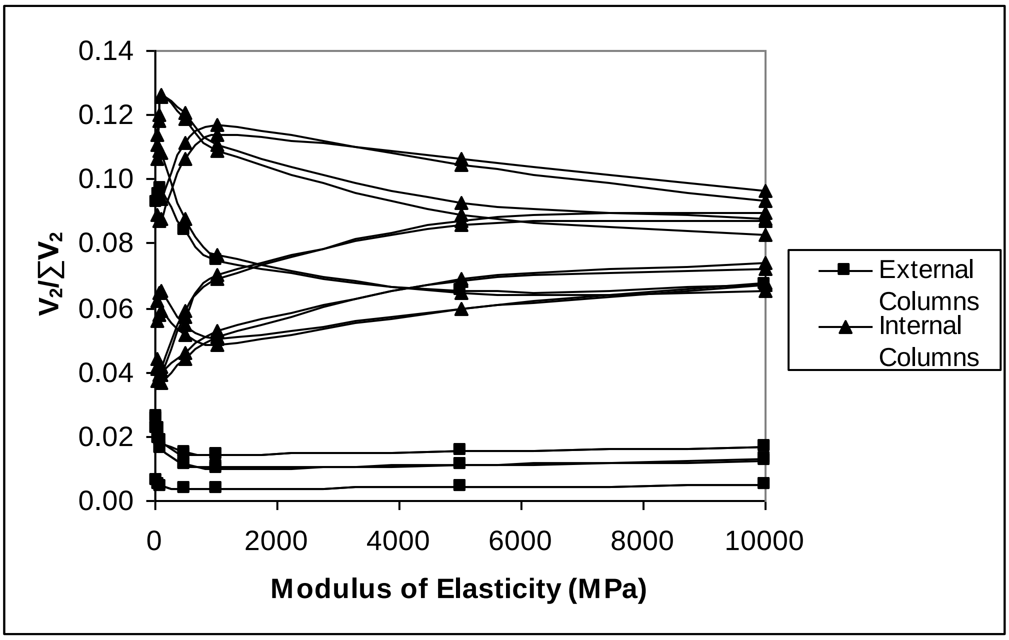

Figure (4.10) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of Jordan Gate tower using equivalent static method

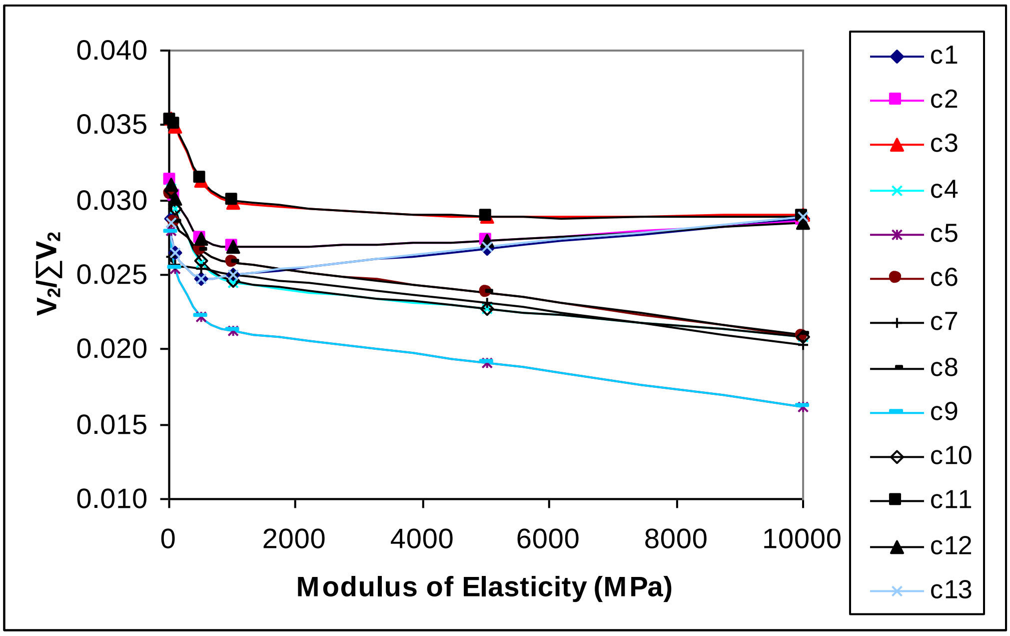

Figure (4.11) Base shear ratio for some external columns vs. modulus of elasticity of soil of 5-story R/C building using equivalent static method

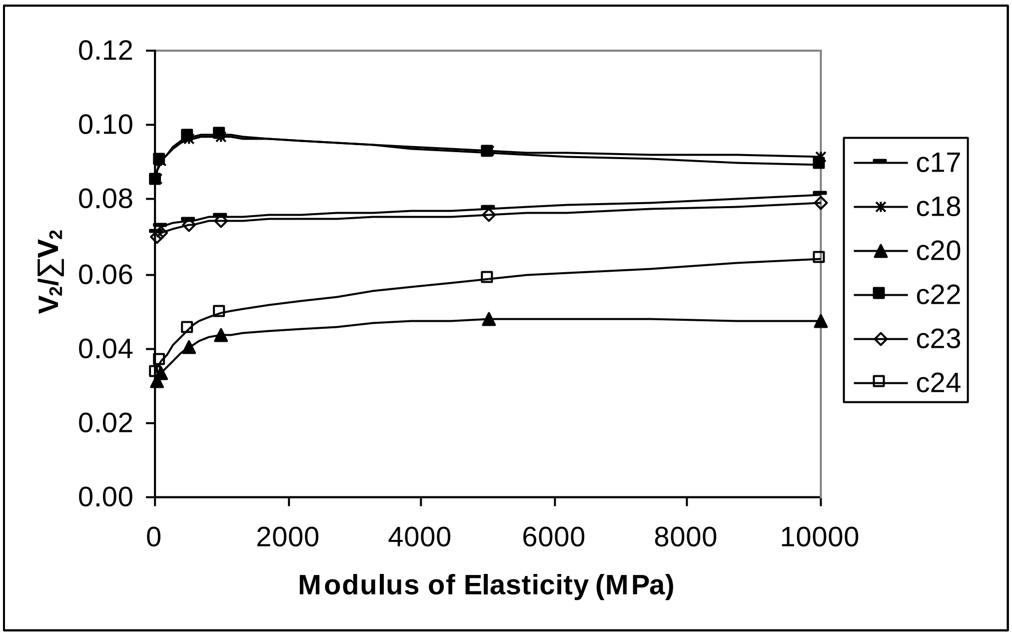

Figure (4.12) Base shear ratio for some internal columns vs. modulus of elasticity of soil of 5-story R/C building using equivalent static method

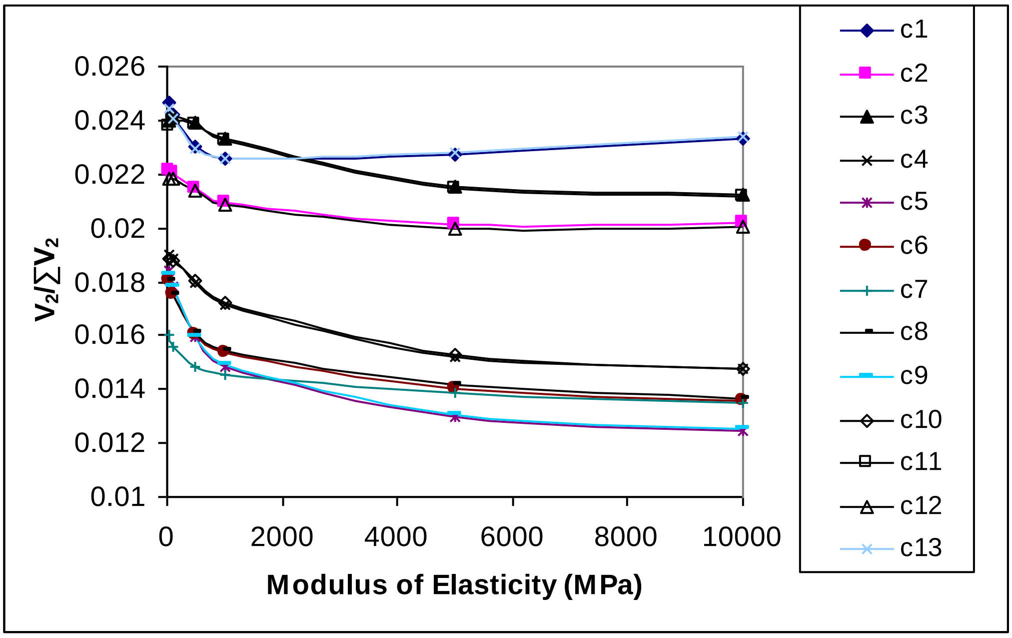

Figure (4.13) Base shear ratio for some external columns vs. modulus of elasticity of soil of 10-story R/C building using equivalent static method

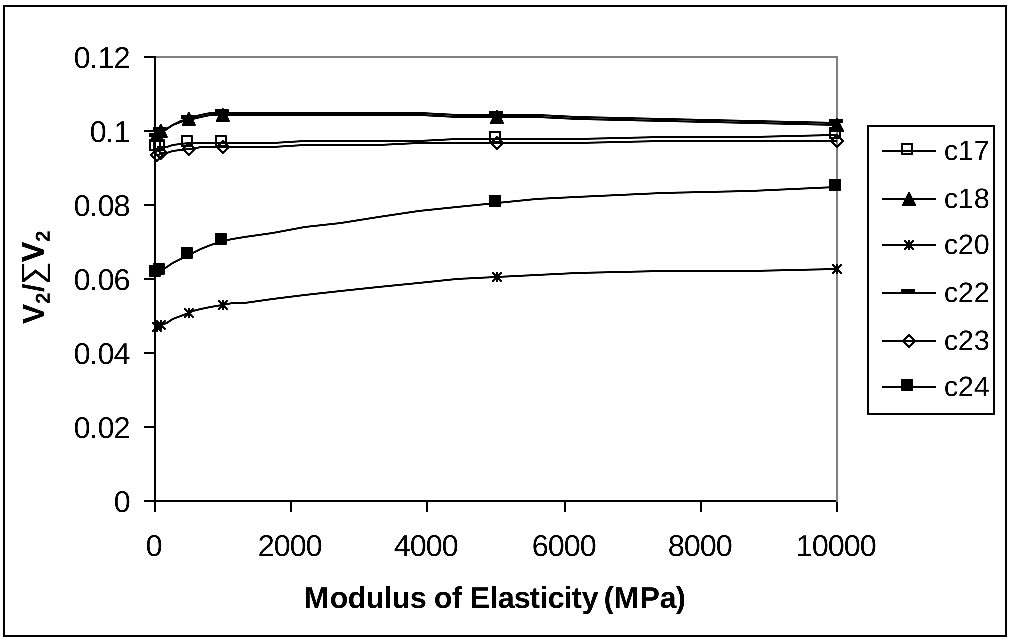

Figure (4.14) Base shear ratio for some internal columns vs. modulus of elasticity of soil of 10-story R/C building using equivalent static method

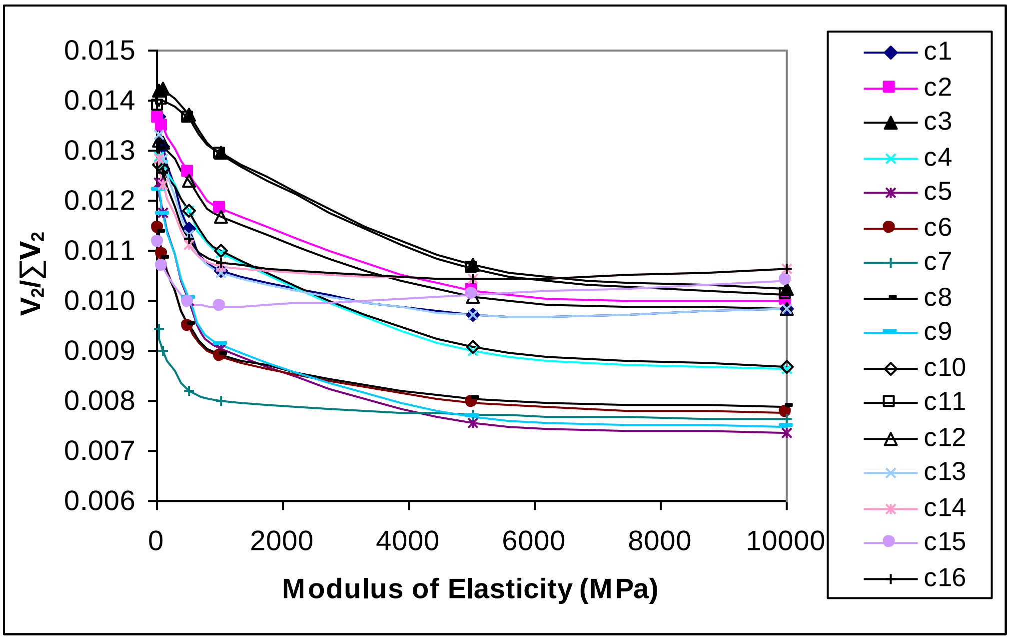

Figure (4.15) Base shear ratio for all external columns vs. modulus of elasticity of soil of 20-story R/C building using equivalent static method

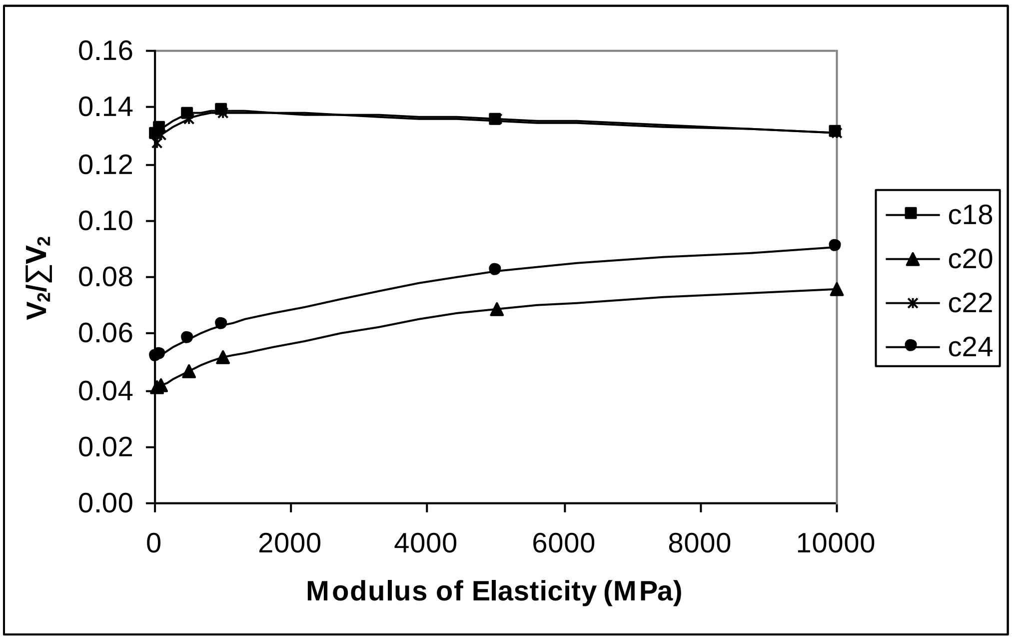

Figure (4.16) Base shear ratio for some internal columns vs. modulus of elasticity of soil of 20-story R/C building using equivalent static method

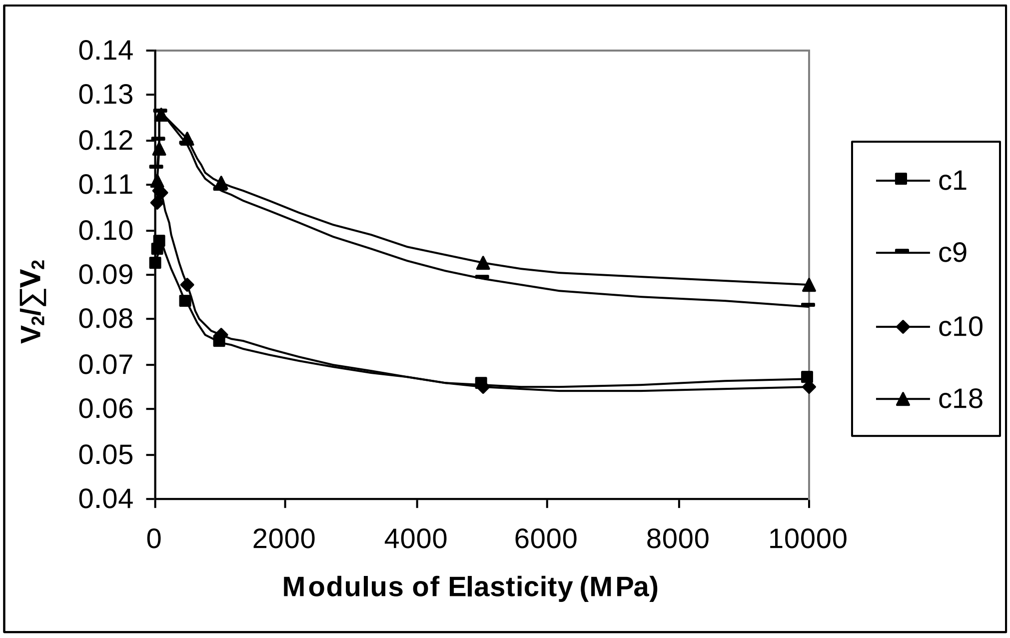

Figure (4.17) Base shear ratio for some columns vs. modulus of elasticity of soil of Jordan Gate tower using equivalent static method

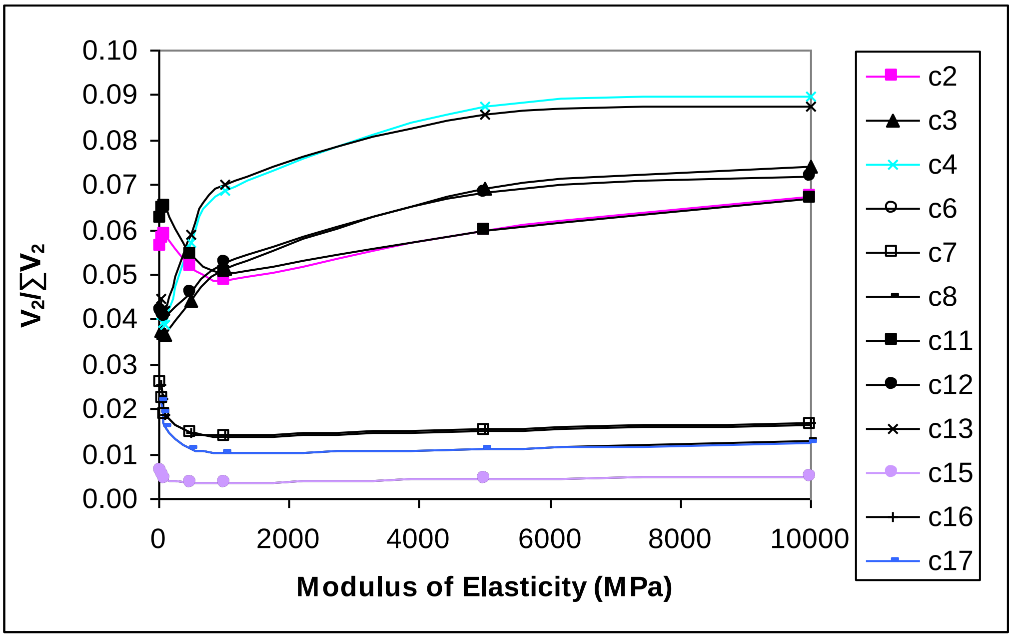

Figure (4.18) Base shear ratio for some columns vs. modulus of elasticity of soil of Jordan Gate tower using equivalent static method

4.4 Response-Spectrum Analysis

Response-spectrum analysis is an elastic dynamic analysis of a structure utilizing the peak dynamic response of all modes.

The dynamic equilibrium equations associated with the response of a structure to ground motion are given by:

$$\boldsymbol{K}\ \boldsymbol{u}(t)+\boldsymbol{C}\ \dot{\boldsymbol{u}}(t)+\boldsymbol{M}\ \ddot{\boldsymbol{u}}(t)=\boldsymbol{m}_x\ \ddot{u}_{gx}(t)+\boldsymbol{m}_y\ \ddot{u}_{gy}(t)+\boldsymbol{m}_z\ \ddot{u}_{gz}(t)$$

Where ***K*** is the stiffness matrix; ***C*** is the proportional damping matrix; ***M*** is the diagonal mass matrix; u, $\dot{u}$ and $\ddot{u}$ are the relative displacements, velocities, and accelerations, respectively with respect to the ground; m_x, m_y, and m_z are the unit acceleration loads; and $\ddot{u}_{gx}$, $\ddot{u}_{gy}$, and $\ddot{u}_{gz}$ are the components of uniform ground acceleration, respectively.

Response-spectrum analysis seeks the likely maximum response to these equations rather than the time history. The earthquake ground acceleration in each direction is given as a digitized response spectrum curve of pseudo spectral acceleration response versus period of the structure.

Eventhough accelerations may be specified in three directions; only a single, positive result is produced for each response quantity. The response quantities include displacements, forces, stresses, frequencies and damping. Each computed result represents a statistical measure of the likely maximum magnitude for that response quantity.

Response- spectrum analysis is performed using mode superposition (Wilson and Button, 1982). Modes may be computed using eigenvalue analysis or Ritz vector analysis.

The response- spectrum curve for a given direction was defined by digitized points of pseudo- spectral acceleration response versus period of the structure in SAP2000.

The spectral response method provides a quick and inexpensive approximation of the peak response of a structure due to design spectrum compatible excitation, and is derived from the principle of modal superposition. Eigenvalue analysis is first used to extract modal data. For each model, the response may be calculated by applying the peak acceleration from the response spectrum at the modal frequency to the modal properties. These individual modal responses are then combined to provide the total response of the system.

The UBC response spectrum is used according to the given soil profile and proper zone factor for each zone, UBC assigns two seismic coefficients; (C_a) related to acceleration and (C_v) related to velocity. C_a and C_v are given according to the soil profile at the site under consideration. The design spectrum for each zone is then given as function of the factors C_a and C_v as shown in Figure (4.19).

In this work, response-spectrum curve function was defined using UBC, Amman lies in zone (2A) and the soil type is S_B, zone factor is 0.15 so as in code C_a and C_v both equal to 0.15, the response spectrum acceleration curve which was used for all dynamic analysis is shown in Figure (4.20).

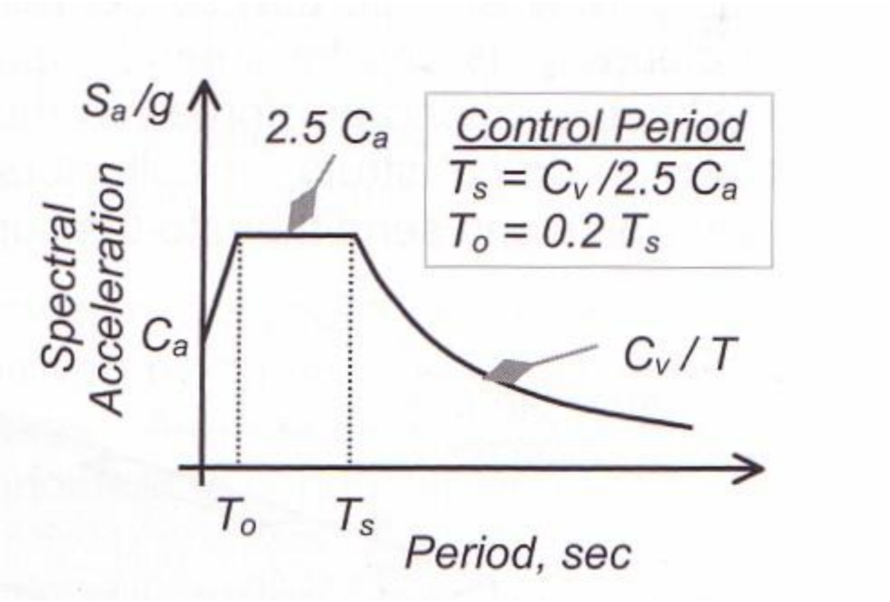

Figure (4.19) UBC Design Response Spectra

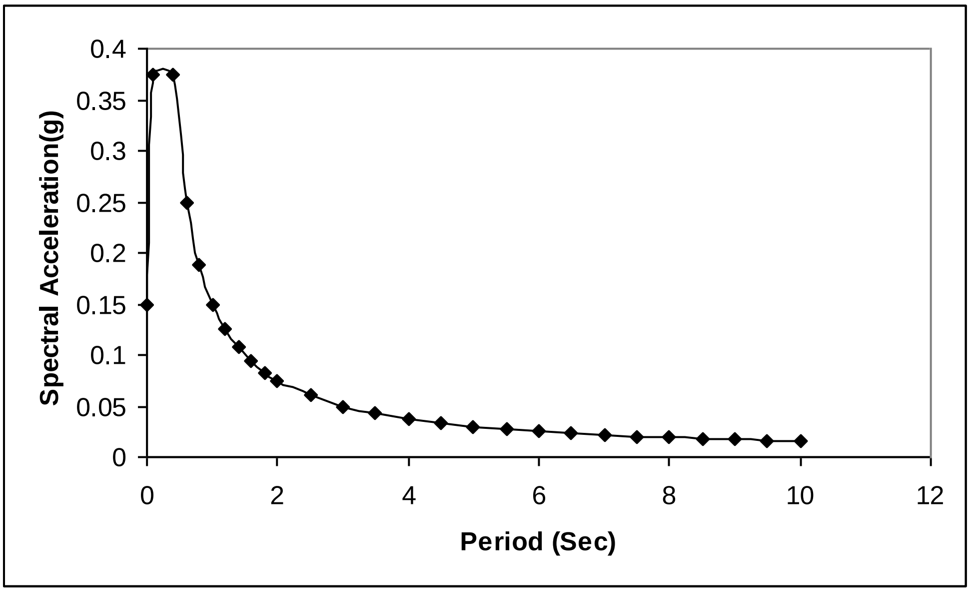

Figure (4.20) Response Spectrum Acceleration Curve

The response-spectrum curve chosen should reflect the damping that is present in the structure being modeled. Note that the damping is inherent in the shape of the response-spectrum curve itself. A constant value of damping ratio of 5% was considered for all cases.

4.4.1 Response-Spectrum Analysis Results

The modal contributions are combined using the SRSS method. The method does not take in to account any coupling of modes. Two responses were calculated to represent the effect of SSI; lateral displacements and base shear forces using response spectrum method.

4.4.1.1 Lateral Displacements

Lateral displacements in the direction of seismic motion were calculated to establish the relationship between the soil type and the lateral displacement for buildings of different heights.

Figures (4.21) and (4.22) show that lateral displacement decreases when the soil type goes from soft to rock.

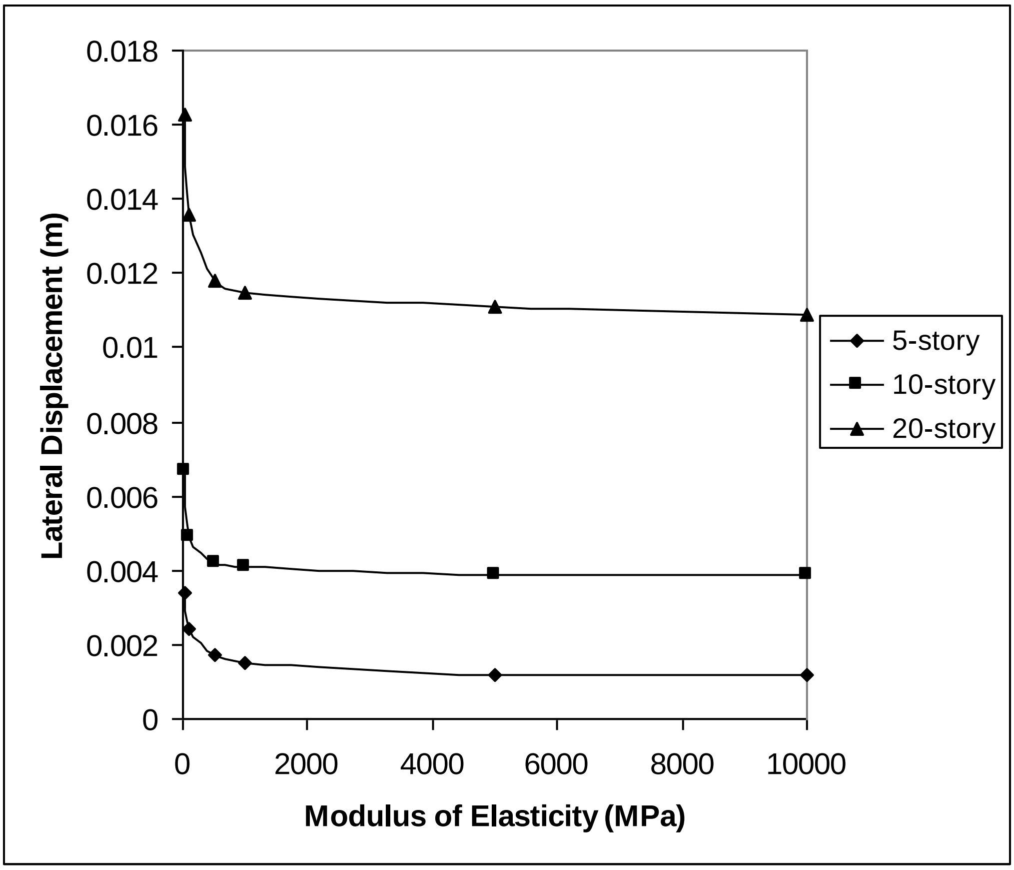

Figure (4.21) Lateral displacement vs. modulus of elasticity of soil using response spectrum method

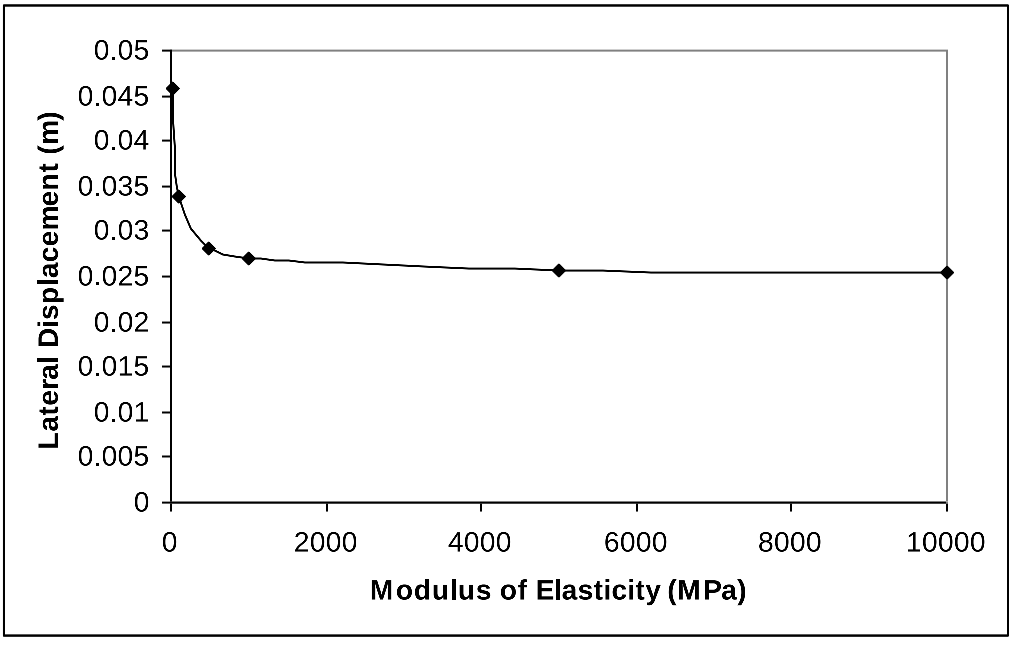

Figure (4.22) Lateral displacements vs. modulus of elasticity of soil of Jordan Gate tower building using response spectrum method

4.4.1.2 Base Shear Forces

Ratios of base shear ($V_2/\sum V_2$) were calculated and tabulated for response spectrum analysis.

As with the equivalent static analysis, the response spectrum analysis for base shear shows that the value of share of each column of the total base shear ($V_2/\sum V_2$) shows a lot of fluctuation in soft soils but becomes stable in stiff soils. This change varies from one column to another; most of the external columns have a relatively higher ratio in soft soil than in stiff soil, the reverse is true for internal columns as shown in Figures (4.23) to (4.34).

As the increased forces in the external columns are noted both in the dynamic and static approach ,one may conclude that there stem from the interaction between the soil and the external columns where by these take a bigger portion than if the base is assumed rigid.

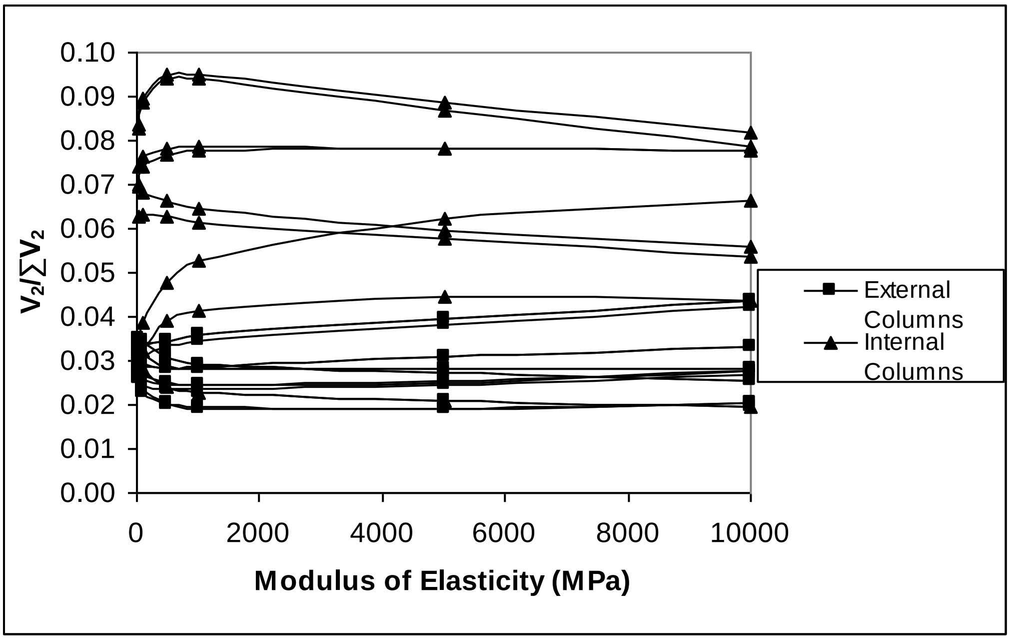

Figure (4.23) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of 5-story R/C building using response spectrum method

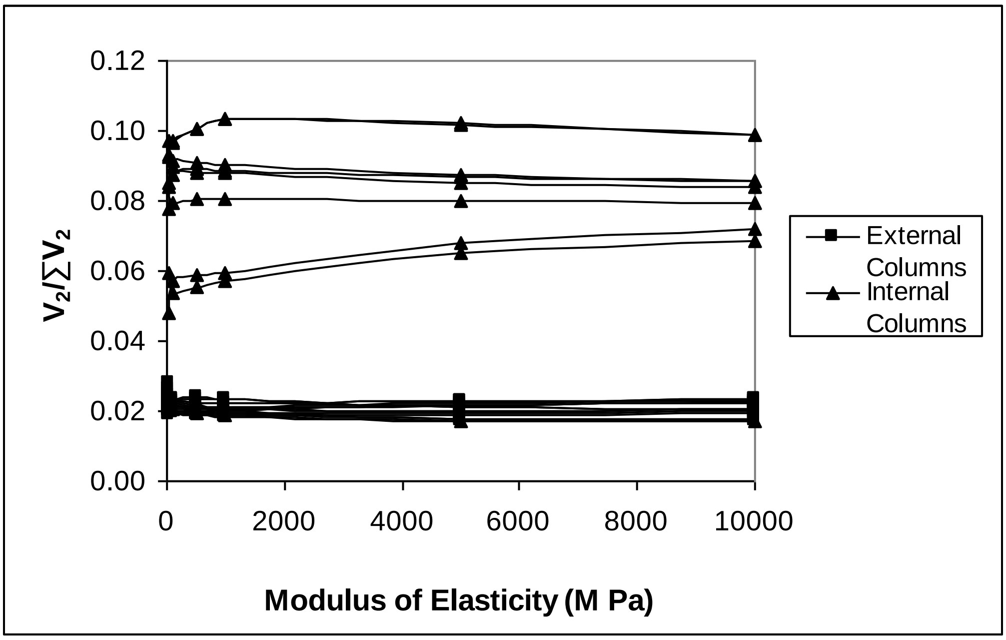

Figure (4.24) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of 10-story R/C building using response spectrum method

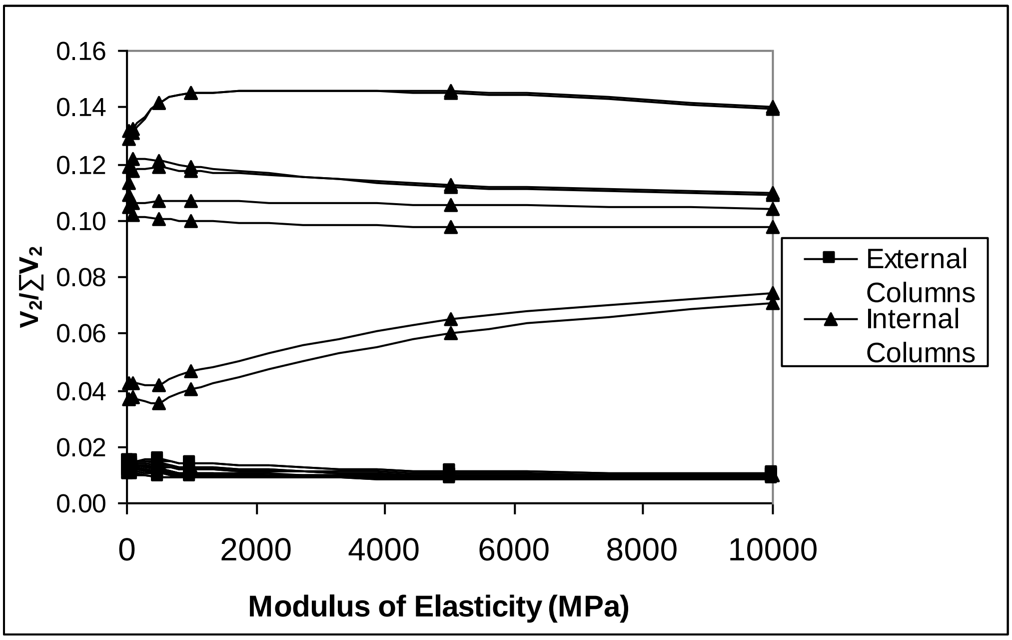

Figure (4.25) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of 20-story R/C building using response spectrum method

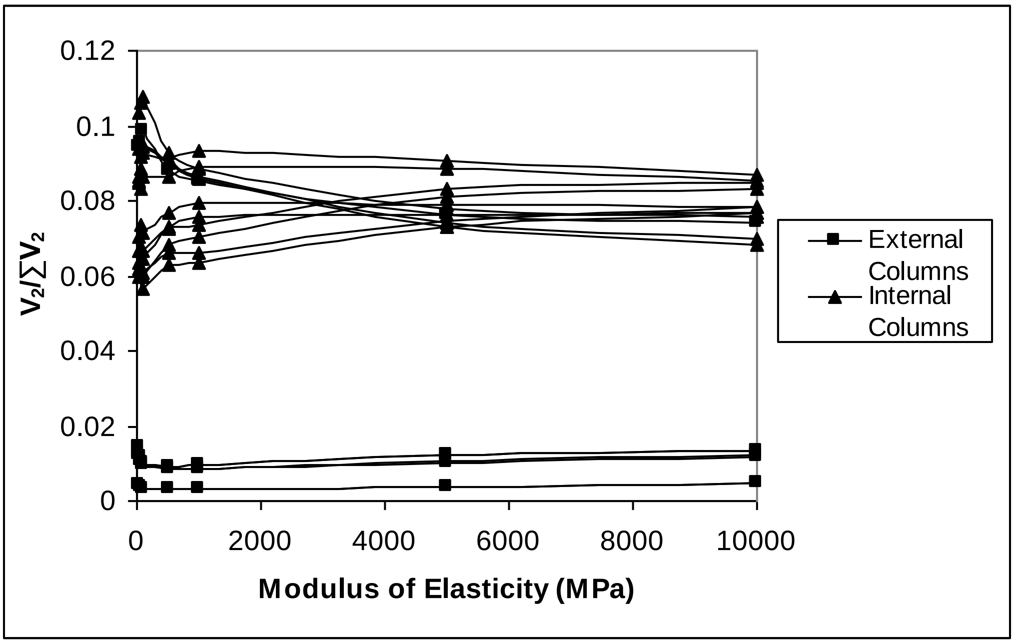

Figure (4.26) Base shear ratio for all columns in first story vs. modulus of elasticity of soil of Jordan Gate tower using response spectrum method

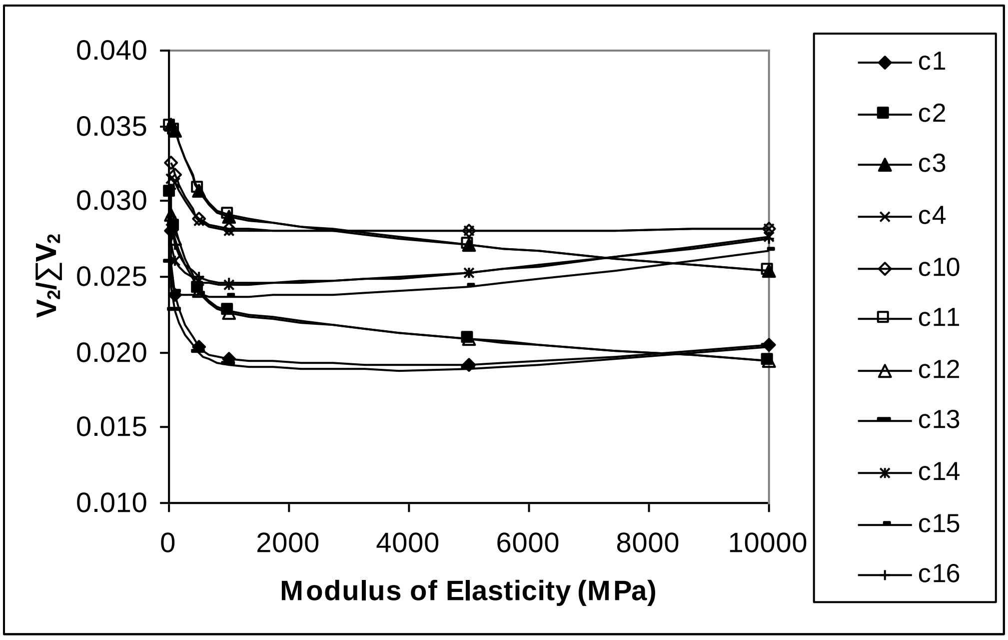

Figure (4.27) Base shear ratio for some external columns in first story vs. modulus of elasticity of soil of 5-story R/C building using response spectrum method

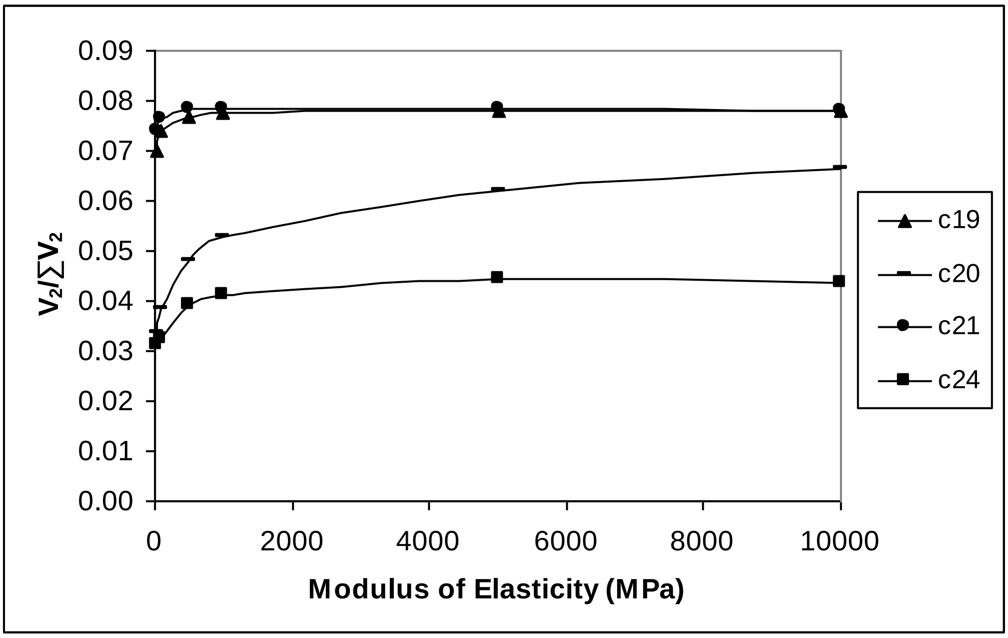

Figure (4.28) Base shear ratio for some internal columns in first story vs. modulus of elasticity of soil of 5-story R/C building using response spectrum method

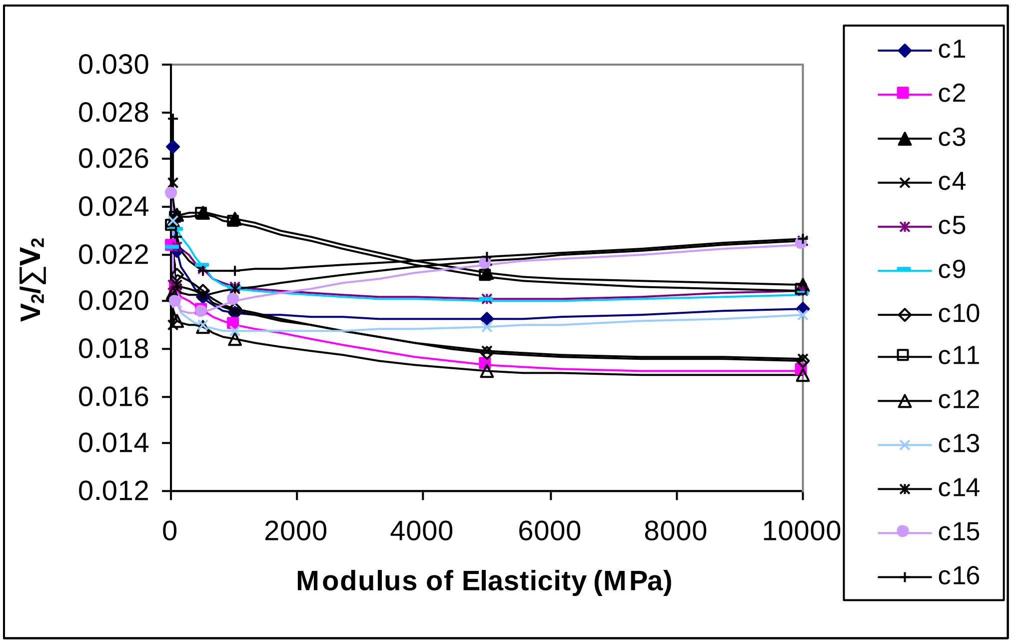

Figure (4.29) Base shear ratio for some external columns in first story vs. modulus of elasticity of soil of 10-story R/C building using response spectrum method

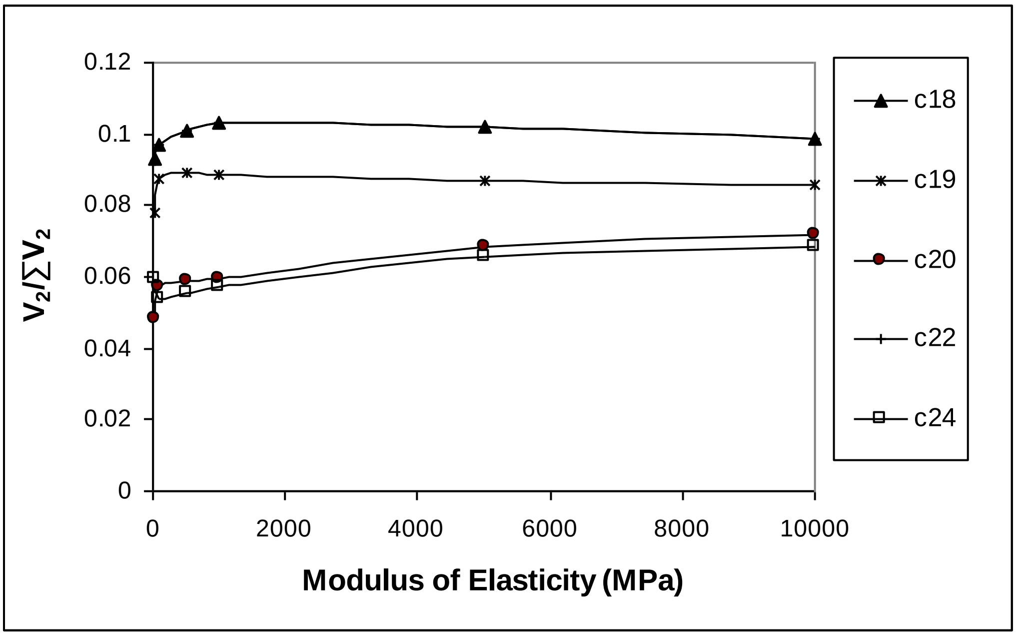

Figure (4.30) Base shear ratio for some internal columns in first story vs. modulus of elasticity of soil of 10-story R/C building using response spectrum method

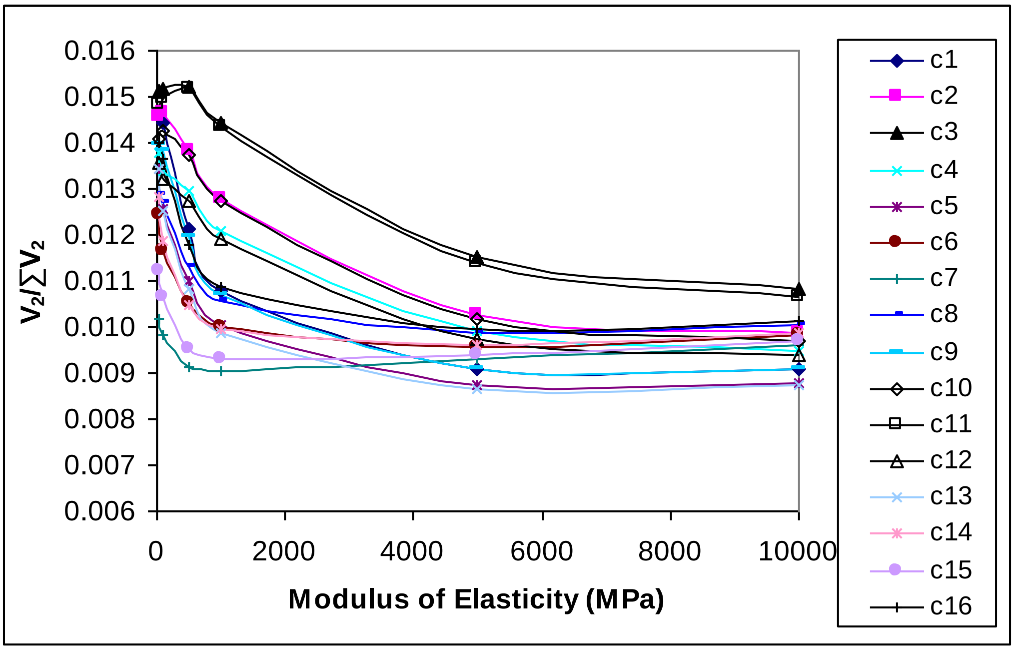

Figure (4.31) Base shear ratio for all external columns in first story vs. modulus of elasticity of soil of 20-story R/C building using response spectrum method

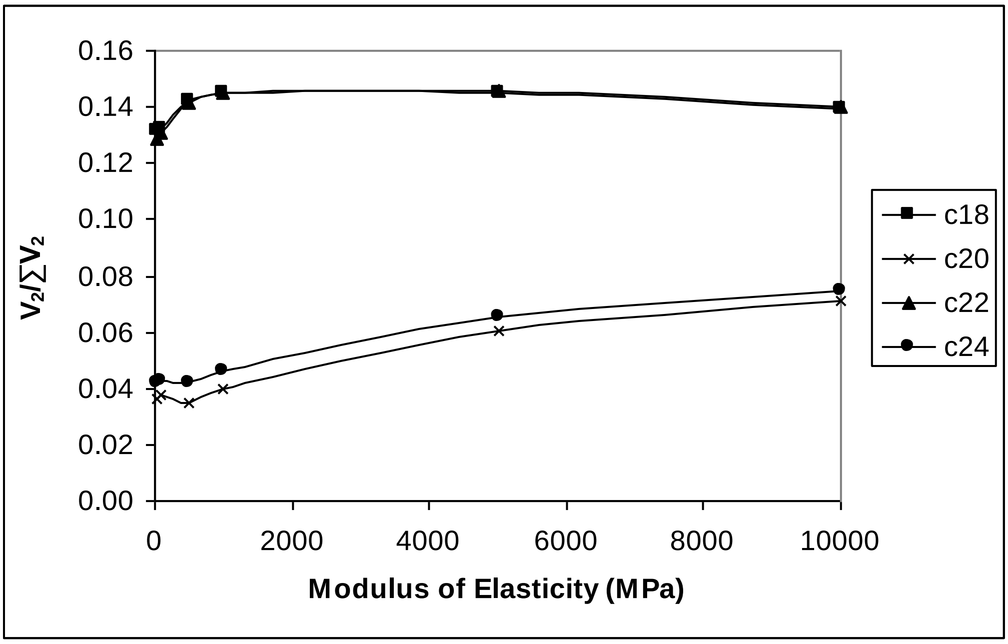

Figure (4.32) Base shear ratio for some internal columns in first story vs. modulus of elasticity of soil of 20-story R/C building using response spectrum method

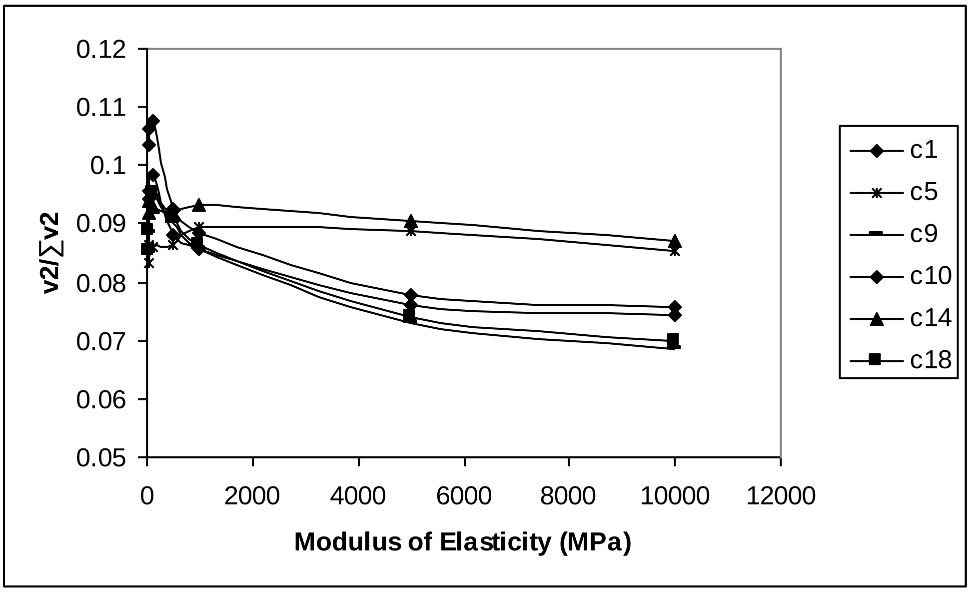

Figure (4.33) Base shear ratio for some columns in first story vs. modulus of elasticity of soil of Jordan Gate tower using response spectrum method

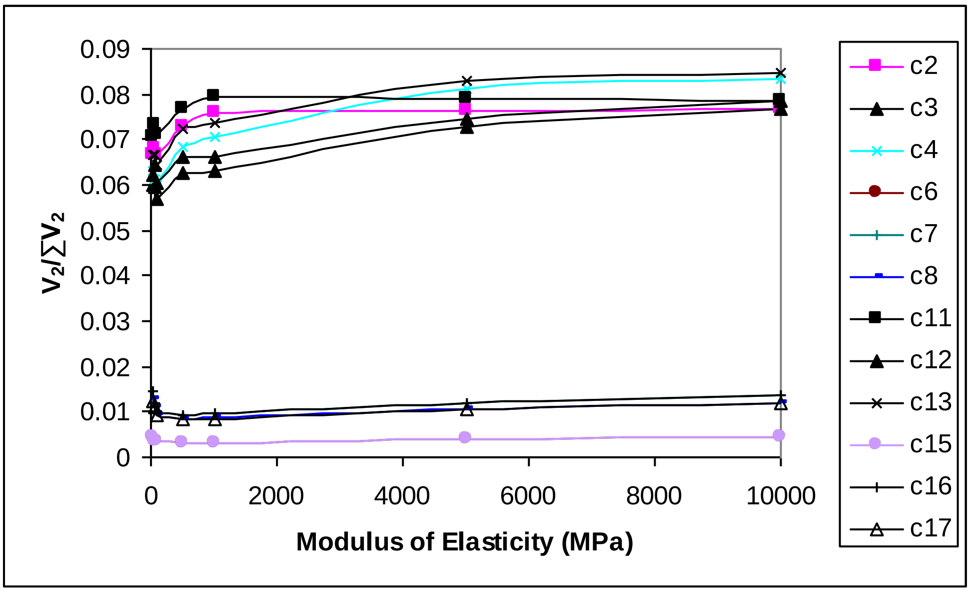

Figure (4.34) Base shear ratio for some columns in first story vs. modulus of elasticity of soil of Jordan Gate tower using response spectrum method

4.4.1.2.1 Base Shear Forces of Jordan Gate

In Jordan Gate there are columns which have a larger ratio ($V_2/\sum V_2$) in the case of soft soil than the ratio in the case of rigid base; these columns are c1, c5, c9, c10, c14, and c18 as shown in Table (4.1). These columns have 19.8%, 11.8%, 35.7%, 28%, 17.8%, and 30.7% respectively, increment of base shear ratio ($V_2/\sum V_2$) in soft soil larger than the ratio in rigid base, so that the value of base shear at these columns must be treated correctly.

Table (4.1) ($V_2/\sum V_2$) of columns for different soil type in Jordan Gate tower

	Modulus of Elasticity							
Columns	**30MPa**	**50MPa**	**100MPa**	**500MPa**	**1000MPa**	**5000MPa**	**10000MPa**	**Rigid Base**
1	0.0942	0.0957	0.0985	0.0882	0.0855	0.0760	0.0744	0.0755
2	0.0667	0.0678	0.0666	0.0729	0.0758	0.0764	0.0766	0.0827
3	0.0598	0.0595	0.0567	0.0628	0.0632	0.0728	0.0770	0.0835
4	0.0633	0.0611	0.0598	0.0682	0.0704	0.0811	0.0834	0.0816
5	0.0863	0.0834	0.0862	0.0863	0.0893	0.0887	0.0854	0.0762
6	0.0045	0.0036	0.0034	0.0030	0.0030	0.0039	0.0046	0.0066
7	0.0146	0.0118	0.0100	0.0091	0.0097	0.0120	0.0135	0.0189
8	0.0126	0.0108	0.0094	0.0085	0.0086	0.0105	0.0121	0.0179
9	0.0850	0.0885	0.0945	0.0900	0.0857	0.0730	0.0684	0.0546
10	0.1034	0.1061	0.1077	0.0926	0.0885	0.0776	0.0757	0.0744
11	0.0705	0.0734	0.0712	0.0769	0.0794	0.0790	0.0786	0.0828
12	0.0621	0.0644	0.0606	0.0661	0.0660	0.0747	0.0783	0.0834
13	0.0665	0.0667	0.0644	0.0725	0.0738	0.0831	0.0849	0.0820
14	0.0938	0.0919	0.0929	0.0915	0.0933	0.0906	0.0870	0.0772
15	0.0044	0.0036	0.0034	0.0030	0.0030	0.0039	0.0046	0.0067
16	0.0144	0.0118	0.0100	0.0092	0.0098	0.0121	0.0136	0.0191
17	0.0125	0.0108	0.0094	0.0084	0.0085	0.0104	0.0119	0.0177
18	0.0854	0.0888	0.0952	0.0908	0.0864	0.0740	0.0700	0.0592

4.5 Static vs. Dynamic Analysis - Comparative Study

Comparative studies for results of dynamic and static analysis for the summation of base shear for all columns ($\sum V_2$), as well as the base shear ratio for all R/C buildings and Jordan Gate tower were made.

According to UBC code, the corresponding design base shear obtained using response spectrum procedures may be reduced to a code defined fraction of the base shear obtained by static force procedure, but shall not be less than that. If the base shear obtained by static force procedure is designated as V_{SF}, and if the design base shear (that constitutes value obtained from computer run and divided by R) obtained from response spectrum is designated as V_{RS}, the reduction in the response spectrum results may be expressed in the following form:

1. Regular structures: $V_{RS} \geq 90\%.\ V_{SF}$
2. Irregular structures: $V_{RS} \geq 100\%.\ V_{SF}$

The code is not concerned about the value of the base shear as obtained from response spectrum analysis, but rather, is concerned about the distribution of the force inside the structure. Consequently, the force distribution inside the structure must be maintained with revised values according to the conditions above (Armouti, 2004).

In this research there are three regular buildings, (five-, ten-, and twenty-story) and one irregular building, (Jordan Gate tower), since V_{SF} is larger than the response base shear, V_{RS}, the final result that are obtained from the computer for elastic response must be increased to match V_{SF} for Jordan Gate tower and to match 90% of V_{SF} for five, ten, and twenty story buildings.

Response spectrum method is normalized such that response spectrum method and equivalent static method equal at 1000 MPa, as shown in figures (4.35) to (4.37).

The curves of normalization among equivalent static method and response spectrum method for 5-story building are almost the same, but they are different for 10-, and 20-story buildings at soft soil.

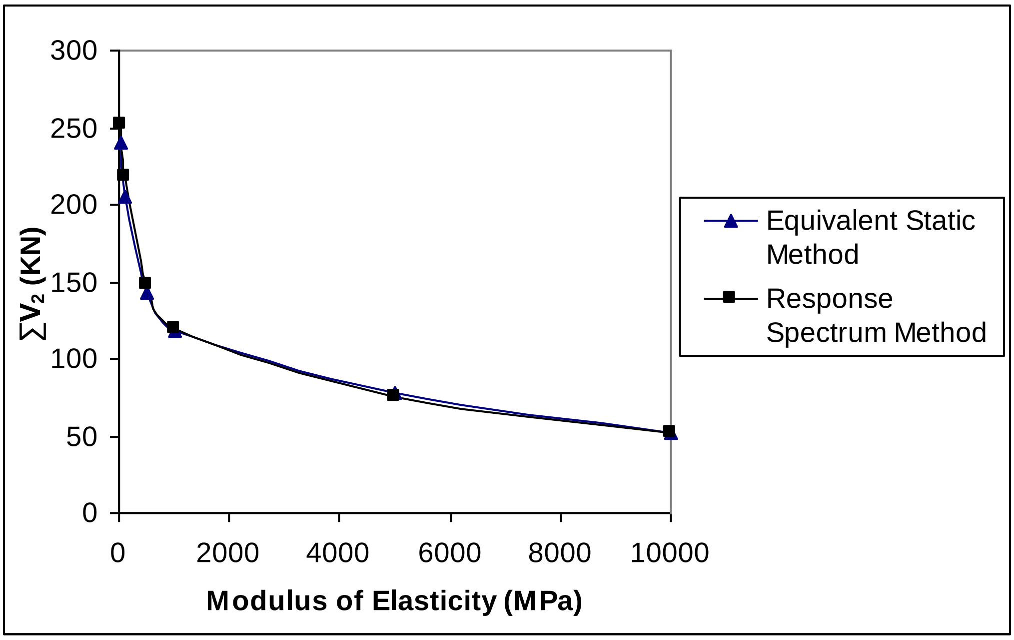

Figure (4.35) Total base shear of columns in first story vs. modulus of elasticity of soil of 5-story R/C building.

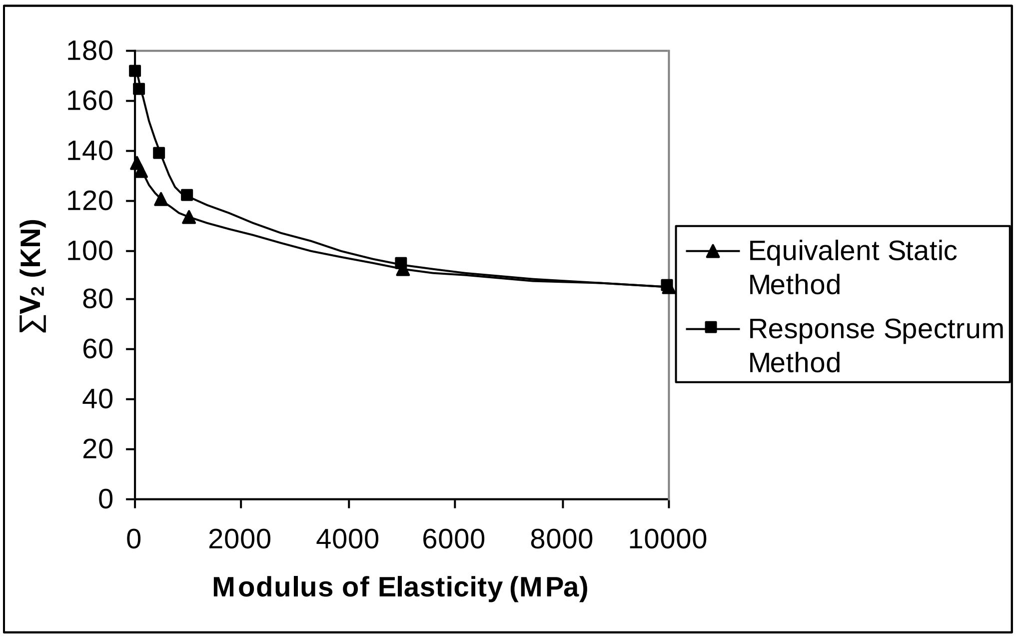

Figure (4.36) Total base shear of columns in first story vs. modulus of elasticity of soil of 10-story R/C building.

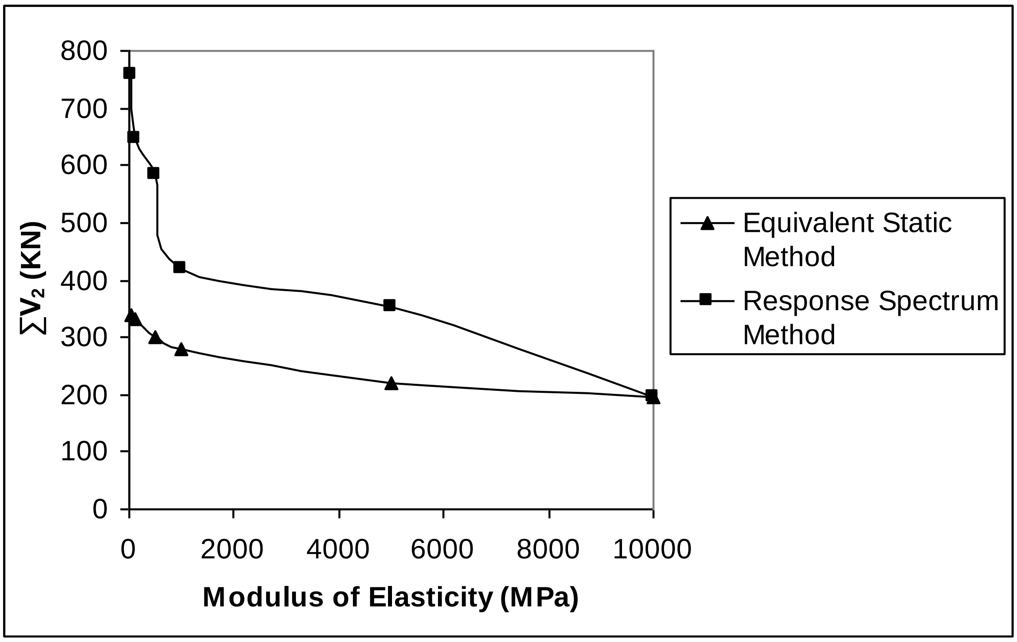

Figure (4.37) Total base shear of columns in first story vs. modulus of elasticity of soil of 20-story R/C building.

Figure (4.38) show that summation of base shear for all columns ($\sum V_2$) increases for high rise building for soft soil and this increase become smaller for stiff soil.

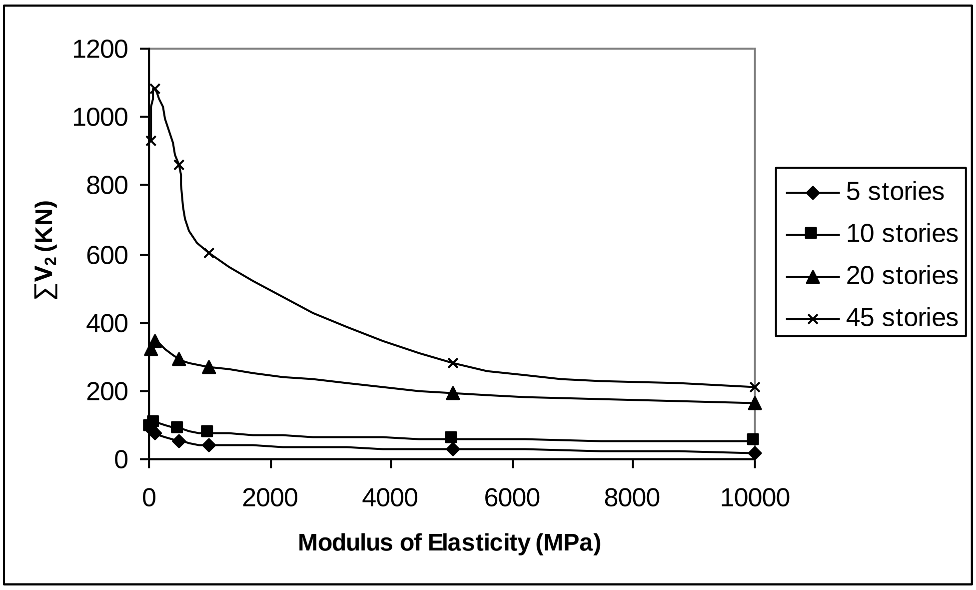

Figure (4.38) Total base shear of columns in first story vs. modulus of elasticity of soil using response spectrum method

Figures (4.39) to (4.42) show the dynamic to static base ratio vs. modulus of elasticity of soil; these figures show that the dynamic to static ratio of base shear fraction attributable to a particular column is larger for low rise buildings (5-story) than it is for latter buildings (20-story) .

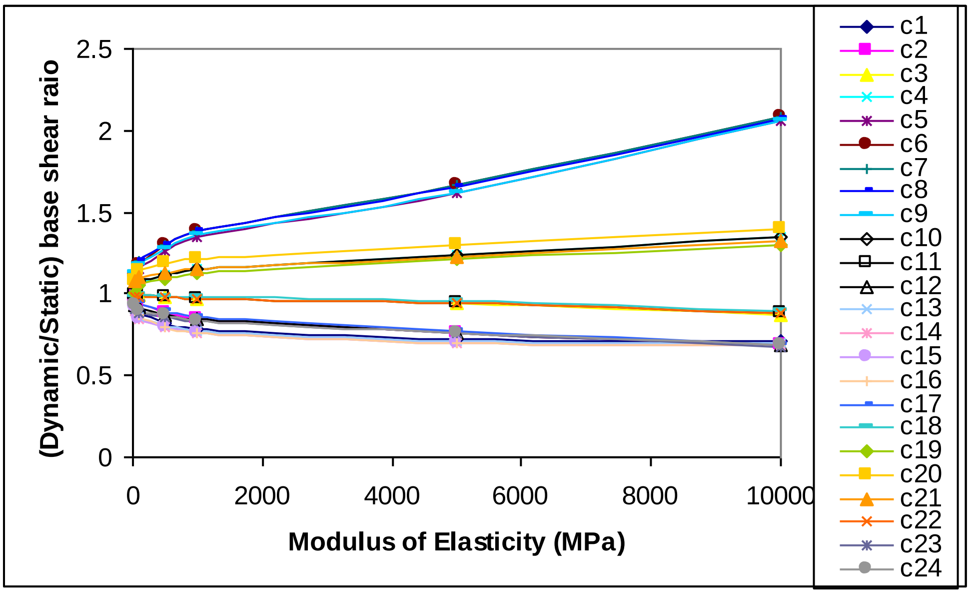

Figure (4.39) Dynamic to static base ratio vs. modulus of elasticity of soil for 5-story R/C building

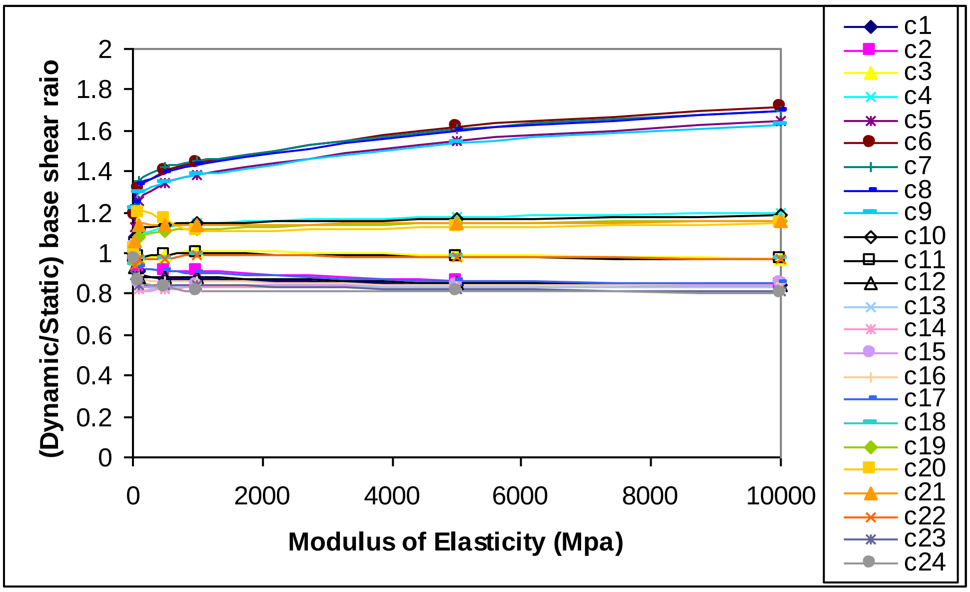

Figure (4.40) Dynamic to static base ratio vs. modulus of elasticity of soil for 10-story R/C building

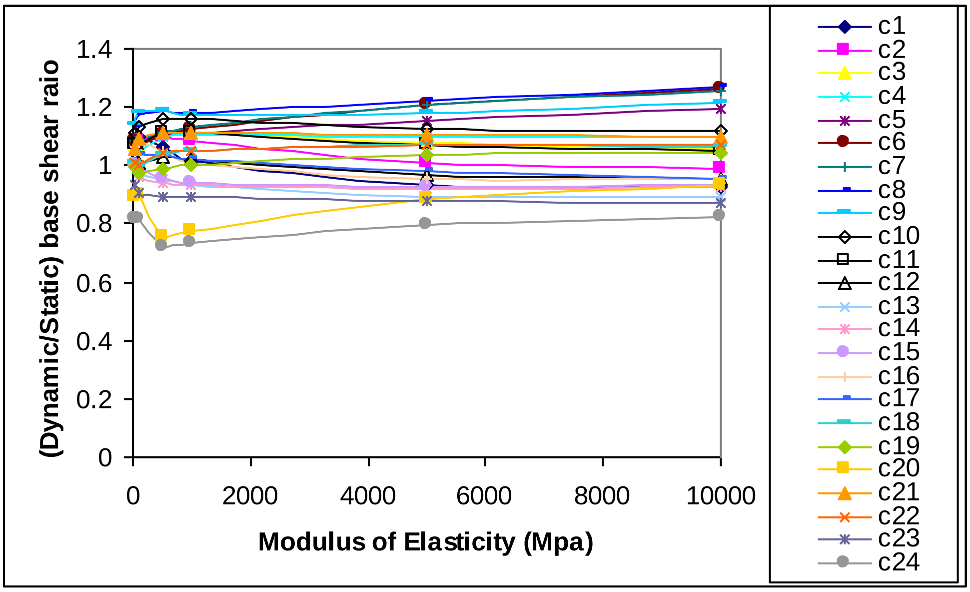

Figure (4.41) Dynamic to static base ratio vs. modulus of elasticity of soil for 20-story R/C building

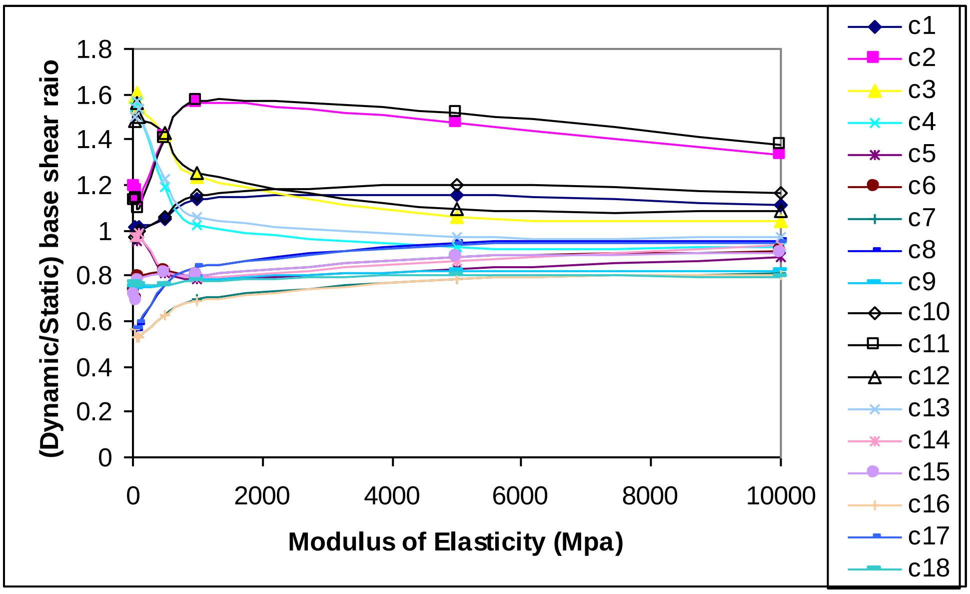

Figure (4.42) Dynamic to static base ratio vs. modulus of elasticity of soil for Jordan Gate tower

CONCLUSIONS, AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn:

1. Numerical models are readily implemented in commercial software, such as SAP2000 and ETABS. Such models successfully represent structural system response of soil structure systems.

2. Incorporating the soil in the model of the structure results in a system with a large period of vibration than that of the structure modeled as fixed to a rigid foundation.

3. If the ground motion is applied at the base of the soil rather than the base of the structure, amplification of motion takes place and this depends on the stiffness of the soil with the amplification being highest for soft soil and lowest for rock strata.

4. Soil structure interaction is more significant when the soil is softer than when it is stiffer. The base shear distribution between columns shows considerable fluctuation for soft soil and the distribution ratios become stable when the strata are stiff.

5.2Recommendations

1- With available software, it is essential that practicing engineers develop a sense of the significance of SSI for the specific project that they embark on designing. Where SSI is significant it should be allowed for in design.

2- Only linear behavior has been studied in this thesis. Material nonlinearity in the soil is quite significant and studies should focus on this phenomenon. In such studies the magnitude of the earthquake becomes important and substantial degradation of soil is expected during sever earthquakes.

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التفاعل الديناميكي للمنشأ و التربة- حالة دراسة في الأردن

اعداد:
هدى رضا الكساسبة

الاشراف:
أ.د حسان سفاريني

الملخص

في هذه الدراسة تم دراسة التفاعل الديناميكي للمنشأ و التربة لأبنية متعددة الطوابق تحت تأثير أحمال ستاتيكية و ديناميكية حيث جرت العادة على اعتبار أن أساس المبنى ثابت و الغاء تأثير التربة في التحليل ، لكن مرونة الأساس تؤثر على الخصائص الديناميكية للمبنى.

الهدف من هذه الرسالة هو حساب الاستجابة الدينامبكية للمبنى بوجود التربة ، و تأثيراهتزاز الأرض عليها، فقد تم ذلك من خلال بناء نموذج رياضي لثلاثة مبان (خمس و عشرة وعشرين طابق) وبرج مكون من اثنين و أربعين طابقا يدعى (Jordan Gate)، حيث تم تحليل هذه المباني باستخدام برنامج للعناصر الحدية يدعى (SAP2000) الذي استخدم لاجراء التحليل الستاتيكي و الديناميكي لمعرفة توزيع القوى على المبنى و فهم سلوكه تحت تأثير هذه القوى.

أيضا تم عمل دراسة لفترة المبنى الأساسية و الازاحة الأفقية للمبنى و قوى القص القاعدي للأعمدة، و ذلك لأنواع مختلفة من التربة، اذ لوحظ أن مرونة الأساس تزيد من الفترة الاهتزازية للمبنى، كما لوحظ أن التفاعل الديناميكي للمنشأ و التربة له تأثيرواضح عندما تكون التربة طرية لكن هذا التأثير يتلاشى عندما تكون التربة قاسية.