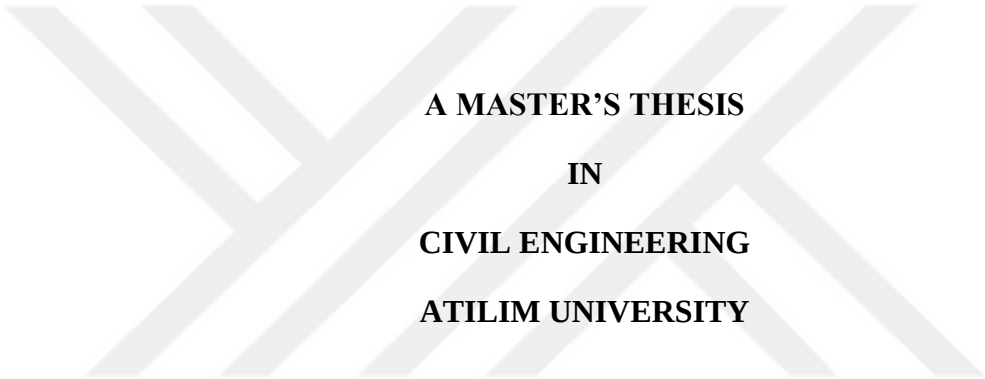


**STRUCTURAL ANALYSIS OF BUILDINGS
WITH HORIZONTAL AND VERTICAL IRREGULARITIES**



**A MASTER'S THESIS
IN
CIVIL ENGINEERING
ATILIM UNIVERSITY**

**BY
BURHAN DUYAR
SEPTEMBER, 2016**

**STRUCTURAL ANALYSIS OF BUILDINGS
WITH HORIZONTAL AND VERTICAL IRREGULARITIES**

**A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE**

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**BY
BURHAN DUYAR**

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DEPARTMENT OF CIVIL ENGINEERING**

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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ABSTRACT

STRUCTURAL ANALYSIS OF BUILDINGS WITH HORIZONTAL AND VERTICAL IRREGULARITIES

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Due to its topographical structure and geological features, Turkey frequently faces natural disasters. Since 1940, nine different seismic codes have brought into force in Turkey, which is a country of high seismicity since it is surrounded by active fault lines. As a result of major earthquakes, improvements in engineering and construction materials, “Specification for Buildings to be Built in Seismic Zones” came into force in 2007, and has been implemented since then. In this thesis, “Irregular Buildings” explained under Article 2.3 in the Technical Specification of 2007 will be analyzed in detail and the specification will be compared and contrasted with the technical specifications in New Zealand, in the United States of America, and Europe, where earthquakes are a part of daily life. In order to compare and contrast the specifications, several buildings with two layouts will be analyzed and designed using commercially available software packages, PROBINA and ETABS. Current limitations and regulations in Turkish Earthquake Code 2007 will be investigated and compared, based on the results of these case studies with respect to the similar earthquake codes in New Zealand, the US and Europe.

Keywords: Structural dynamics, Structural irregularities, Earthquake code

ÖZ

YATAY VE DÜŞEY SÜREKSİZLİĞE SAHİP BİNALARIN YAPISAL ANALİZİ

DUYAR, Burhan

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Yrd. Doç. Dr. Gökhan TUNÇ

Eylül 2016, 120 Sayfa

Topografik ve jeolojik özelliklerinden dolayı, Türkiye sık sık doğal afetlerle karşı karşıyadır. Aktif fay hatları ile çevrili olduğu için yüksek depremselliğe sahip bir ülke olan Türkiye’de, 1940’dan beri 9 farklı deprem şartnamesi yürürlüğe girmiştir. Büyük depremler, mühendislik ve yapı malzemeleri alanındaki ilerlemeler sonucunda “Deprem Bölgelerinde Yapılacak Binalar Hakkında Yönetmelik” 2007 yılında yürürlüğe girmiş olup o zamandan beri de uygulanmaktadır. Bu tezde, 2007 Teknik Şartnamesinin 2.3 nolu başlıklı maddesinde açıklanan “Düzensiz Binalar” detaylı bir şekilde incelenilecek ve depremin günlük yaşamın bir parçası olduğu Yeni Zelanda, Amerika Birleşik Devletleri ve Avrupa’daki teknik yönetmeliklerle karşılaştırılacaktır. Bu yönetmelikleri karşılaştırmak için iki farklı kat planına sahip binalar PROBINA ve ETABS ticari yazılım paketleri kullanılarak analiz edilecektir. Türk deprem yönetmeliğindeki mevcut sınırlamalar ve yönetmelikler, bu vaka çalışmalarının sonuçlarına bağlı olarak araştırılacak, Avrupa, Yeni Zelanda ve ABD’deki benzer deprem yönetmelerine göre karşılaştırılacaktır.

Anahtar Kelimeler: Yapısal Dinamikler, Yapısal Düzensizlikler, Deprem Kodu



To My Family and Friends

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LIST OF ABBREVIATIONS

A1 :	Torsional Irregularity in TEC 07
A2 :	Floor Discontinuities in TEC 07
A3 :	Projections in Plan in TEC 07
ASCE 7-10 :	American Society of Civil Engineers 7-10
B1 :	Interstorey Strength Irregularity-Weak Storey in TEC 07
B2 :	Interstorey Stiffness Irregularity-Soft Storey in TEC 07
B3 :	Discontinuity of Structural Elements in TEC 07
EC8 :	European Code 8
EC8- Part 1 :	Eurocode 8, Design of Structures for Earthquake Resistance
ELF :	Equivalent Lateral Force
FE :	Finite Element
IBC :	International Building Code
Km :	Kilometer
MCE _R :	Risk-Targeted Maximum Considered Earthquake
MRS:	Modal Response Spectrum
N(T,D) :	Near-Fault Factor
N _{max} (T) :	The Maximum Near-Fault Factor
NAFL:	North Anatolian Fault Line
NEHRP:	National Earthquake Hazards Reduction Program
NSCP :	National Structural Code of the Philippines
NZS :	New Zealand Standard, Earthquake Actions

RC :	Reinforced Concrete
RSA :	Response Spectrum Analysis
SDC:	Seismic Design Category
T :	Period
TEC :	Turkish Earthquake Code
THA :	Time History Analysis
TS 498 :	Design Loads for Buildings in Turkish Standards
TS 500:	Requirements for Design and Construction of Reinforced Concrete Structures in Turkish Standards
US :	United States
USGS :	United States Geological Survey
Z :	Hazard Factor
Z1:	Functions of Soil Groups in TEC 07
Z2:	Functions of Soil Groups in TEC 07
Z3:	Functions of Soil Groups in TEC 07
Z4:	Functions of Soil Groups in TEC 07

LIST OF SYMBOLS

a_{gR} :	Reference Peak Ground Acceleration on Type A Ground
A_0 :	Horizontal Acceleration Coefficient
A_e :	Effective Shear Area at any Storey for the Earthquake Direction Considered
A_g :	Sum of Section Areas of Structural Elements
a_g :	Design Ground Acceleration on Type A Ground
a_j :	The Horizontal Offset at Column j
A_k :	Masonry Infill Wall Areas
A_w :	Web Area of Column Cross Section
A_x :	Accidental Torsion
a_x :	Reentrant Corner in x-direction
a_y :	Reentrant Corner in y-direction
b :	Plan Dimension of a Structure
B_B :	Any Size Calculated with the Combination of Mode in MRS Method
B_D :	Amplified Value of B_B
b_j :	The Vertical Distance Between the Base of the Upper Column and the Top of the Lower Column j
$C_h(T)$:	The Spectral Shape Factor
D :	Distance to the Nearest Fault Line
D_i :	Amplification Factor
d_{av} :	The Average of the Displacements
d_{max} :	The Maximum Storey Displacement
e_o :	The Structural Eccentricity
e_{ox} :	Distance Between the Centre of Stiffness and the Centre of Mass
F_a :	Short-Period Site Coefficient
F_v :	Long-Period Site Coefficient

g :	Acceleration of Gravity
H :	Height of a Building
h_i :	Height of i^{th} Storey
h_{i+1} :	Height of $(i+1)^{\text{th}}$ Storey
I :	Building Importance Factor
L :	Length of a Storey
L_x :	Length in x-direction
L_y :	Length in y-direction
$L_{\max}$:	The Larger in Plan Dimension of a Building
$L_{\min}$:	The Smaller in Plan Dimension of a Building
I_s :	The Radius of Gyration of the Floor Mass in Plan
M_S :	Surface Wave Magnitude
N_c :	The Total Number of Columns at the Level Under Consideration
$\bar{N}$:	Average Field Standard Penetration Resistance
$\bar{N}_{\text{ch}}$:	Average Standard Penetration Resistance for Cohesionless Soil Layers
$N_{\max}(T)$:	The Maximum Near-Fault Factor
q :	Behaviour Factor
P_{NCR} :	A Probability Return Period of 10%
p_x :	Reentrant Corner Length in x-direction
p_y :	Reentrant Corner Length in y-direction
R :	The Return Period Factor
r :	The Torsional Radius
R_S :	The Return Period Factor for Ultimate Limit State
R_U :	The Return Period Factor for Serviceability Limit State
$R_a(T_n)$:	Seismic Load Reduction Factor of n^{th} Natural Vibration Periods of a Building
r_x :	The Square Root of the Ratio of the Torsional Stiffness to the Lateral Stiffness in the y Direction.

S :	Soil Factor
$S(T)$:	Spectrum Coefficient
$S_{ae}(T_n)$:	Elasticity Spectrum Ordinate of n^{th} Natural Vibration Periods of a Building
$S_{aR}(T_n)$:	Acceleration Spectrum Ordinate for the n^{th} Natural Vibration Mode
$S_d(T)$:	Design Spectrum
S_{D1} :	The Design Spectral Response Acceleration Parameter at 1 Second Period.
S_{DS} :	The Design Spectral Response Acceleration Parameter at Short Periods.
$S_e(T)$:	Elastic Response Spectrum
S_{M1} :	Spectral Response Acceleration Parameter at 1 Second Period
S_{MS} :	Spectral Response Acceleration Parameter at Short Period
S_s :	Spectral Response Acceleration Parameter at Short Period in MCE_R
S_1 :	Spectral Response Acceleration Parameter at a Period of 1 Second in MCE_R
$\bar{S}_u$:	Average Undrained Shear Strength
T :	The Fundamental Period of a Structure
T_A, T_B :	The Constant Spectral Acceleration
T_C, T_D :	The Constant Spectral Acceleration
T_L :	Long-Period Transition Period
T_{NCR} :	Reference Return Period
T_S :	Short-Period Transition Period
$\bar{v}_s$:	Average Shear Wave Velocity
V_t :	Total Equivalent Seismic Load Acting on a Building in the ELF Method
W_i :	Weight of i^{th} Storey of Building
Z :	The Hazard Factor
Δ_i :	Displacement at i^{th} Floor

Δ_{i+1} :	Displacement at (i+1) th Floor
δ :	Displacement at any Floor
δ_{avg} :	Average Story Drift
δ_{max} :	Maximum Story Drift
β :	Lower Bound Factor for the Horizontal Design Spectrum (Chapter 3)
β :	Coefficient to Determine Lower Limits of Response Quantities (Chapter 4)
γ :	Ratio of Maximum Displacement to Average Displacement
γ_I :	The Importance Factor
η :	Damping Correction Factor
η_{bi} :	The Torsional Irregularity Coefficient
η_{ci} :	The Strength Irregularity Factor
η_{ki} :	The Stiffness Irregularity Factor
λ :	Slenderness

CHAPTER 1

INTRODUCTION

1.1. Introduction

Not too many buildings can be considered fully regular. Due to the complex design and layout choices, irregularity almost always exists. Therefore, the overall behavior of buildings needs to be studied. Thus, it is very important for structural engineers to have the knowledge of the effects of irregularities on buildings and to apply them to the design process.

The current seismic codes separate a building as regular or irregular with reference to mass distribution, discontinuity of elements, shape of the structure etc. Each of these parameters play important roles in determining irregularity. The main difference between a regular and an irregular building lies on its layout. If the layout is uniformly distributed, then the building is considered regular. If one or more properties discussed above are absent, then the building is identified as irregular [1].

As it is briefly described in the following paragraphs, numerous studies, addressing this important issue as a separate topic, have been published about irregularity. Although irregularity is common in all seismic codes, but it is worth noting that there are some differences in its definition. In most seismic codes, irregularity concept is studied in two categories: “*Irregularity in Plan*” and “*Irregularity in Elevation*” or sometimes, they are referred to them as “*Horizontal Irregularities*” and “*Vertical Irregularities*”.

Problems related to irregularity can be defined as discontinuities in load path or load transfer during an earthquake. As expected, if there is a failure in this path such as a failure in structural elements that tie the structure together, a complete collapse can be observed. Therefore, the load path should be continuous in order to prevent the structure from its collapse [2].

As stated before, in several seismic codes, irregularity section is divided into two subsections. These are “*Irregularity in Plan*” and “*Irregularity in Vertical*”. In

this thesis, four seismic codes will be studied to compare and contrast the results of irregularities defined in these codes (In this study, seismic and earthquake words are used interchangeably in defining design and analysis the codes). These four seismic codes are as follows: Turkish Earthquake Code, 2007 (TEC, 2007) [3], American Society of Civil Engineers, 7-10 (ASCE 7/10) [4], New Zealand Standard, Earthquake Actions, 2004 (NZS 1170.5:2004) [5], and Eurocode 8, Design of Structures for Earthquake Resistance, 2004 (EC8- Part 1, 2004) [6]. In order to understand the irregularity concept, parametric studies are conducted. In this study, three different layouts are selected to obtain irregularities in plan and elevation. For this purpose, a total of sixty-six models have been constructed using two commercial software packages, ETABS [7] and PROBINA [8]. ETABS is widely used finite element software in analyzing and designing buildings while PROBINA is mostly used in analyzing and designing reinforced concrete (RC) buildings specifically in Turkey.

The aim of this study is to understand the effects of different approaches defining irregularities according to four seismic codes. For this purpose, both layouts are selected in İznik, Turkey. There are specific goals in choosing this location. First, the seismic region of location is selected to be in first seismic zone also known as the most severe earthquake zone in Turkey. Second, the distance to the nearest fault line is intentionally chosen to be as close as possible so that the effect of fault line can be also studied. Severe seismic zone and near fault line conditions are expected to increase the base shear force on specifically irregular buildings. In order to make comparisons among the four seismic codes, similar conditions for the same layouts are attempted to be simulated in ASCE 7/10, NZS 1170.5:2004 and EC-8. Therefore, it is intended to create similar analytical conditions in evaluating irregularities according to four seismic codes. However, generating the exact same conditions among the four seismic codes is not viable due to differences in the numerical values of the earthquake design parameters. It is because of these parameters that earthquake loads generated from different seismic codes might substantially be different than each other since the aim of this study is to produce similar earthquake forces to those in TEC 07 a series of attempts are tried for the other three seismic codes.

1.2. Background

In this chapter, previous studies are summarized along with different approaches used for irregularities in buildings.

1.2.1. Raven, Elizabeth and López, Oscar A. (1996)

In this article, the concerns regarding the layouts of irregular buildings were discussed. The article covered an architectural view of selecting irregular plans with respect to some topics, such as the functionality, environmental issues and aesthetic advantages of designed layouts. It was aimed in this study to evaluate the analysis and design of irregular plans addressing both their advantages and disadvantages including a comparative study about their costs. For this purpose, three different layouts were modeled. One of the layouts was modeled as regular, while the rest were modeled as irregular. Additional columns were the difference main difference between the irregular buildings. In their conclusion, they stated that irregular shaped buildings offered long term benefits, such as economy in maintenance and energy, in comparison with a regular building [9].

1.2.2. Ercomert, Merva (2007)

In this thesis, floor discontinuities and projections in plan irregularities were studied. The effects of these irregularities on multi-story buildings and their associated penalties in TEC 07 were aimed to be investigated. For this purpose, buildings that contain these two irregularities were selected Linear Modal Superposition Method and Nonlinear Incremental Modal Superposition Methods were used. The buildings were conducted using SAP2000 [10] commercially software. The results of the building analyses modeled without any span changes using with Linear Modal Superposition Method did not affect substantially in comparison of the analysis on the regular structure. However, the analysis performed by Nonlinear Incremental Modal Superposition Method indicated that earthquake behavior of irregular buildings showed some certain discrepancies compared to the regular building [11].

1.2.3. Herrera, Raul González and Soberón, Consuelo Gómez (2008)

In this article, analytical descriptions of damages resulting from various plan irregularities were studied. For this purpose, different layouts were selected. The effect of geometric shape was also studied as an additional parameter. The Mexican Code [12] was applied to the buildings that were modeled in SAP2000 , The authors

analyzed the effects of different irregularities imposed on the systems that were based on the displacement variations. The results of the article showed that buildings modeled with asymmetric layouts were more susceptible to displacement when degree of irregularity increased [13].

1.2.4. *Sadashiva, V.K., MacRae, G.A. and Deam, B.L. (2010)*

In this article, plan and vertical irregularities were studied according to the NZS 1170.5:2004. The purpose of this study was on the analysis methods mandated by the code. To achieve this purpose, vertical (e.g. mass, strength-stiffness irregularities), and horizontal irregularities (horizontal diaphragm flexibility, torsional irregularity) were discussed to evaluate an existing used equation for developing the methodologies in New Zealand seismic code 1170.5, and to provide some technical comments for additional revisions to the current provision [14].

1.2.5 *Basli, Duygu (2011)*

In this thesis, the effects of torsional irregularity, interstorey strength irregularity, and interstorey stiffness irregularity listed in TEC 07 were examined. The analyses were divided into two parts: the frames with and without infill walls, and the frames with and without shear walls located in different parts of the buildings under consideration. To do this, nine different layouts were considered to examine the variations of torsional irregularities according to the number of spans and stories. In addition to this parametric study, with five different layouts including with and without infill walls buildings were modeled. The result showed that the maximum value of the irregularity type for interstorey stiffness irregularity appeared in building without infill walls. In conclusion, the study indicated that the location and the number of shear walls played very important role in determining the torsional irregularity. The infill walls had a distinct effect on stiffness, period, lateral displacement, base shear force and the structural behavior [15].

1.2.6. *Harmankaya, Z.Y. and Soyluk, Asena (2012)*

In this article, irregularities were studied from an architectural point of view. The article emphasized the relationships between the damages caused by earthquakes and irregularities or so-called architectural design failures. Irregularities in buildings were described with illustrations. The approach that needs to be followed to avoid these irregularities, if possible, was investigated. In this study, goal of seismic codes

to effectively guide designers specifically from an architectural point of view was discussed so that the adverse effects of irregularities could be comprehended well before the layout is selected [16].

1.2.7. Inan, Tugba and Korkmaz, Koray (2012)

In this article, vertical structural irregularities were studied according to TEC 07. Architectural concerns about earthquake reliability of a building and its architectural design process in vertical direction were explained briefly in this study. The aim of this article was to understand the vertical irregularities entirely and comprehend the underlying causes of these types of irregularities with their solutions in literature [17].

1.2.8. Landingin, J., Rodrigues, H., Varum, H., Arêde, A., and Costa, A. (2012)

In this study, comparisons of three different seismic design codes, National Structural Code of the Philippines (NSCP 2010) [18], European Code 8 (EC-8), and International Building Code (IBC 2009) [19] were presented on regular and irregular reinforced concrete (RC) buildings modeled with four and eight storeys. Four types of RC buildings were designed in this study, and they were: 4-storey regular frame, 4-storey irregular frame (with shear walls), 8-storey regular frame, and 8-storey irregular frame (with shear walls). Different load combinations for the horizontal loads were taken into account in applying the response spectrum method. SAP2000 was used to analyze the buildings. A total of five different columns were examined and based on the analyses' results; the columns according to EC-8 required an additional 20% to 40% more reinforcement when compared to the results from the other two seismic codes [20].

1.2.9. Santos, S.H.D.C, Zanaica L., Bucur C., Lima S.D.Z. and Arai, A (2013)

Although this article did not include any information about irregularities, the study focused on the comparison of seismic codes by taking the followings into account: seismic input, recurrence period, soil conditions, seismic zonation and procedures for the seismic analyses. The analyses were conducted using two commercially available software packages, SAP2000 and SOFiSTiK [21]. In conclusion, a comparative study of International, European and American Seismic

Codes was presented. The results indicated that there are some agreements were concerning the results emphasized the significance of simplicity, symmetry and uniformity in evaluating the seismic resistant buildings according to different seismic codes [22].

1.3. Problem Statement

The provisions of seismic codes are intended to guarantee that structures can tolerably resist seismic forces during an earthquake. These provisions are the symbol of best assistance on how structures should be designed and constructed so that risks can be limited to minimum. However, there might be omissions, additions or changes to the provisions resulting from new researches as technology progresses. These provisions also include the performances of structures based on past earthquakes [23]. It is a known fact that, more revisions are made to the existing provisions in the last decade since a lot more research has been conducted. For example, the extended and more detailed version of Turkish Earthquake Code was first published in 1997 but was modified in 2006. Currently, another major revision is underway, and the revised one is expected to be released sometime in late 2016. Similar to the revisions made in TEC 07, ASCE 7/10 and EC-8 are both being revised as well.

In this study, the horizontal and vertical structural irregularities existing in four seismic codes, TEC 07, ASCE 7/10, NZS 1170.5:2004, and EC-8, will be investigated. The current regulations regarding the two irregularity types stated in TEC 07 will be compared to those in other three seismic codes ASCE 7-10, NZS 1170.5:2004 and EC8. Since the common construction type for buildings in Turkey is reinforced concrete (RC), the buildings with two layouts selected for this study will also be RC buildings. In order to understand the effects of irregularities, several parameters are used in the analysis phase. One of these parameters is the near fault effect. This effect is completely ignored in TEC 07. However, in the NZS 1170.5:2004 code, the near fault factor is defined for three ranges. The first range covers the distance up to 2 kilometers, including 2 kilometers. The second range starts from 2 kilometers and ends at 20 kilometers. In the third region, there is no effect on the near fault factor. In parallel to the definition stated in NZS 1170.5:2004 code, the prototype buildings selected for this study are intentionally all located at 2

kilometers away from a major fault line. Therefore, the buildings studied according to the TEC 07 are located 2 km away from an active fault line situated in the North Anatolian Fault Line (NAFL) in İzmit, which is a town of Bursa, is therefore selected as the location for the prototype building. The locations of buildings in the US, New Zealand and Europe are all selected by following the selection criteria used in TEC 07.

The other parameter in studying the irregularity deals with the framing type and the geometric shape of buildings. For this purpose, three different layouts are selected. Non-symmetrical L-shaped type buildings are considered to study the effects on irregularities in plan and elevation. Since the focus of this study is on the effects of irregularity, the preliminary design was conducted to determine structural member sizes for the three layouts. The structural member sizes are selected intentionally larger than their optimized sizes. Thus, it is intended to eliminate any possibility of a member failure.

In this research, the seismic performances of buildings are evaluated using the response spectrum method. Two commercially available software packages, ETABS and PROBINA, are used to model and analyze the prototype buildings. The details about the analysis process are given in Chapters 3 and 4. A total of sixty-six buildings resulting from the three layouts are modeled in ETABS and PROBINA. ETABS is used for all buildings by complying with the requirements of the four earthquake codes, while PROBINA is used considered to examine the buildings located only in Turkey.

1.4. Scope

As stated before, different seismic codes have different approaches in considering the effects of irregularities. In order to understand the differences among various seismic codes addressing irregularities, four codes are selected. TEC 07, ASCE 7/10, NZS 1170.5:2004 and EC-8 are selected. To study the effects of layouts, three layouts are used to generate a total of sixty-six buildings. The scope of this research is to understand how the current TEC 07 addresses irregularities when they are compared to those in the other three seismic codes. The analyses results derived from the four seismic codes are compared to each other to determine the similarities or differences among the sixty-six buildings. The main challenge in this comparison

is to determine similar earthquake forces according to four seismic codes since they differ from each other due to the different parameters used in constructing the response spectrum.

1.5. Conclusion

This research focuses on the effects of different methodologies that exist for irregularities in the four seismic codes. In order to understand the effects of seismic activity and dynamic behaviors on irregular buildings, a total of sixty-six buildings are generated from the three layouts. ETABS and PROBINA are used in the analysis phase of this research. The results from the analyses are compared to each other to understand the adequacy of the definition for the irregularities in TEC 07. Also, the seismic loads calculated based on the response spectrum method have become one of the most important topics of this thesis. Furthermore, the significance of near fault effect is also introduced as an additional parameter in obtaining the response spectrum.

This thesis consists of 5 chapters. Chapter 2 covers a general review of irregularities in the current seismic codes of Turkish Earthquake Code, New Zealand, Europe and ASCE. Chapter 3 covers the details of the finite element (FE) analysis models of the buildings constructed in ETABS and PROBINA. Different floor heights, floor layouts and soil types are also investigated in the same chapter. Chapter 4 discusses the results of the FE models. In the same chapter, the comparisons are presented for irregularities according to the four seismic codes. In Chapter 5, overall conclusions are listed along with the recommendations on the basis of the results examined and discussed in Chapter 4.

CHAPTER 2

DEFINITIONS OF STRUCTURAL IRREGULARITIES FOR SEISMIC CODES

In this chapter, structural irregularities on Reinforced Concrete (RC) buildings will be studied according to the following four seismic codes: (a) Turkish Earthquake Code, 2007 (TEC 07), (b) American Society of Civil Engineers, 7/10 (ASCE 7/10), (c) New Zealand Standard, Earthquake Actions, 2004 (NZS 1170.5:2004), and (d) Eurocode 8, Design of Structures for Earthquake Resistance, 2003 (EC8- Part 1, 2003). Detailed information about the structural irregularities described in each of these codes will be provided in the following sections.

2.1. Turkish Earthquake Code, 2007 (TEC 07)

In TEC 07, Section 2.3 describes the structural irregularities. In this section, irregularities are classified in two groups, plan and elevation irregularities. (see Table 2.1 and 2.2). The irregularity in plan consists of three types of structural irregularities. These three types are denoted as A1 (torsional irregularity), A2 (floor discontinuities), and A3 (projections in plan). Irregularity in elevation consists of three types of structural irregularities and they are denoted as B1 (interstorey strength irregularity-weak storey), B2 (interstorey stiffness irregularity-soft storey), and B3 (discontinuity of structural elements).

Table 2.1. Irregularities in Plan in TEC 07 [3]

A- IRREGULARITIES IN PLAN
A-1 Torsional Irregularity: The case where Torsional Irregularity Factor η_{bi} which is defined for any of the two orthogonal earthquake directions as the ratio of the maximum storey drift at any storey to the average storey drift at the same storey in the same direction, is greater than 1.2 $[\eta_{bi} = (\Delta_i)_{\max} / (\Delta_i)_{\text{ort}} > 1.2]$
A-2 Floor Discontinuities: In any floor; I - The case where the total area of the openings including those of stairs and elevator shafts exceeds 1/3 of the gross floor area, II – The cases where local floor openings make it difficult the safe transfer of seismic loads to vertical structural elements, III – The cases of abrupt reductions in the in-plane stiffness and strength of floors.
A-3 Projections in Plan: The cases where projections beyond the re-entrant corners in both of the two principal directions in plan exceed the total plan dimensions of the building in the respective directions by more than 20%.

Table 2.2. Irregularities in Vertical in TEC 07 [3]

B- IRREGULARITIES IN VERTICAL
B1 – Interstorey Strength Irregularity (Weak Storey) : In reinforced concrete buildings, the case where in each of the orthogonal earthquake directions, Strength Irregularity Factor η_{ci}, which is defined as the ratio of the effective shear area of any storey to the effective shear area of the storey immediately above, is less than 0.80. $[\eta_{ci} = (\Sigma Ae)_i / (\Sigma Ae)_{i+1} < 0.80]$ Definition of effective shear area in any storey : $\Sigma Ae = \Sigma Aw + \Sigma Ag + 0.15 \Sigma ak$
B2 – Interstorey Stiffness Irregularity (Soft Storey) : The case where in each of the two orthogonal earthquake directions, Stiffness Irregularity Factor η_{ki}, which is defined as the ratio of the average storey drift at any storey to the average storey drift at the storey immediately above or below, is greater than 2.0. $[\eta_{ki} = (\Delta_i/h_i)_{\text{ort}} / (\Delta_{i+1}/h_{i+1})_{\text{ort}} > 2.0 \text{ or } \eta_{ki} = (\Delta_i/h_i)_{\text{ort}} / (\Delta_{i-1}/h_{i-1})_{\text{ort}} > 2.0]$
B3 – Discontinuity of Vertical Structural Elements : The cases where vertical structural elements (columns or structural walls) are removed at some stories and supported by beams or gusseted columns underneath, or the structural walls of upper stories are supported by columns or beams underneath.

2.1.1. Irregularities in Plan

In TEC 07, the irregularities in plan are classified in three types. They are represented as A1 (torsional irregularity), A2 (floor discontinuities), and A3 (projections in plan). These three irregularities will be briefly explained below.

2.1.1.1. Torsional Irregularity (A1)

Torsional irregularity is described as the ratio of the maximum storey drift at any storey to the average one at the same storey in the same direction for any earthquake directions [3]. This irregularity exists in various seismic codes of different countries since it has a destructive effect on buildings during earthquakes [24]. As illustrated in *Figure 2.1*, if the torsional irregularity coefficient (η_{bi}) is greater than 1.2 at any storey of a building, then torsional irregularity occurs. The definition of η_{bi} is provided in *Figure 2.1*.

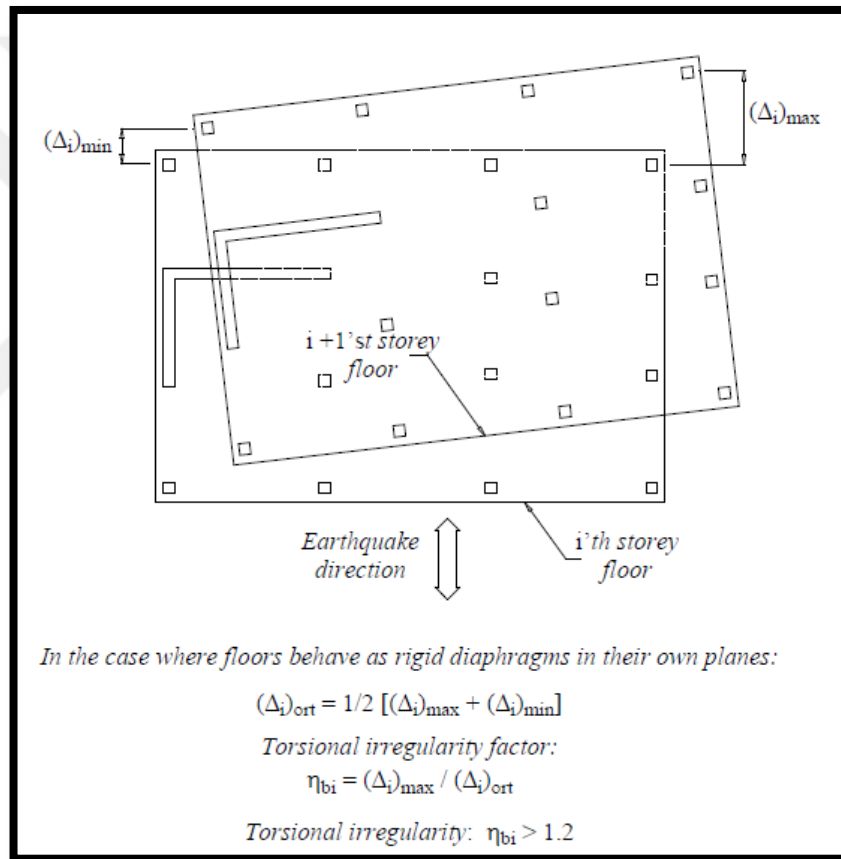


Figure 2.1. Torsional Irregularity in TEC 07 [3]

2.1.1.2. Floor Discontinuities (A2)

In TEC 07, the A2 type irregularity, which is known as floor discontinuities, is stated as follows:

“In any floor;

- i. The case where the total area of the openings including those of stairs and elevator shafts exceeds $1/3$ of the gross floor area,
- ii. The cases where local floor openings make it difficult the safe transfer of seismic loads to vertical structural elements,
- iii. The cases of abrupt reductions in the in-plane stiffness and strength of floors.”

Figure 2.2 illustrates floor discontinuities for the three cases listed above. In some floor layouts, it is possible to have a combination of two or even three of these cases. For example, the last layout in Figure 2.2 has both “ii” and “iii”.

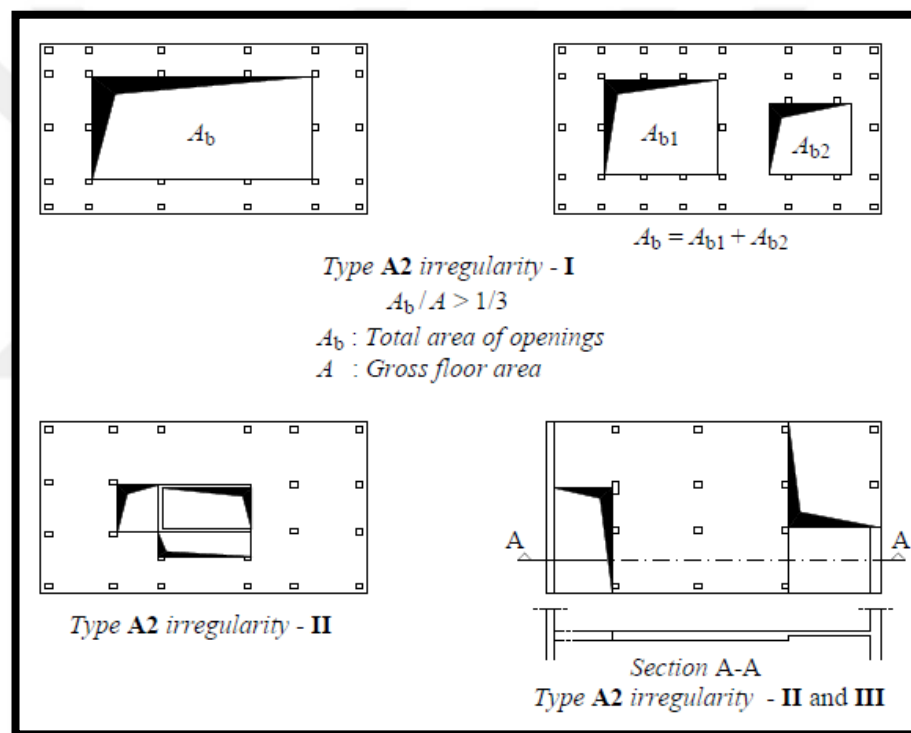


Figure 2.2. Floor Discontinuities in TEC 07 [3]

2.1.1.3. Projections in Plans (A3)

The last irregularity in plan is called “projections in plan”, or denoted by A3. The code describes the projections in plans as follows: “The cases where projections beyond the re-entrant corners in both of the two principle directions in plan exceed the total plan dimensions of the building by more than 20% in the respective

directions”. *Figure 2.3* shows the three most common floor layouts that exhibit this type of irregularity.

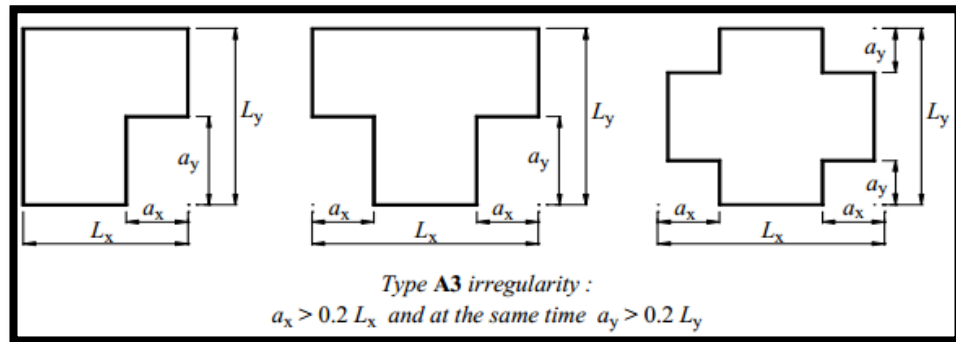


Figure 2.3. Projections in Plan in TEC 07 [3]

2.1.2. Irregularities in Vertical

The second type of irregularity occurs in the vertical direction and sometimes is called irregularity in elevation. This type of irregularity includes three specific types. They are denoted as B1 (interstorey strength irregularity-weak storey), B2 (interstorey stiffness irregularity-soft storey), and B3 (discontinuity of structural elements). The detailed information, regarding these three types, are given below.

2.1.2.1. Interstorey Strength Irregularity – Weak Storey (B1)

In TEC 07, the definition in the code is as follows: “The case where in each of the orthogonal earthquake directions Strength Irregularity Factor, η_{ci} , which is defined as the ratio of the effective shear area of any storey to the effective shear area of the storey immediately above, is less than 0.80”. *Figure 2.4* illustrates a sketch representing this irregularity.

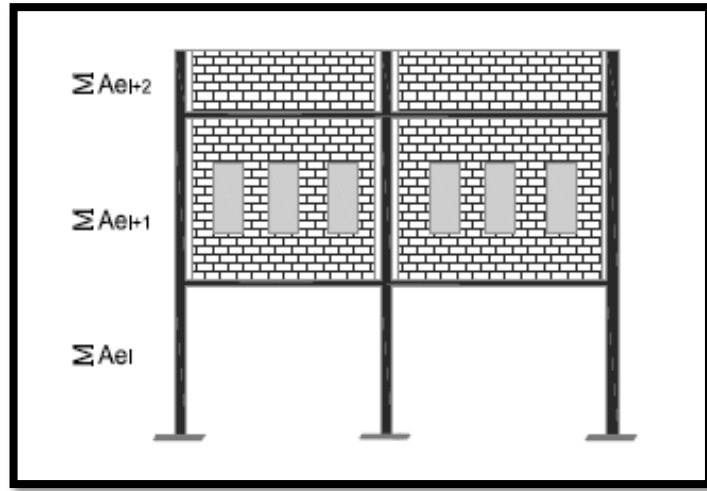


Figure 2.4. Weak Storey Mechanism in TEC 07 [16]

$$\sum A_e = \sum A_w + \sum A_g + 0.15 \sum A_k \quad (2.1)$$

$$\eta_{ci} = (\sum A_e)_i / (\sum A_e)_{i+1} < 0.80 \quad (2.2)$$

where:

A_e : Effective Shear Area at any Storey for the Earthquake Direction Considered

A_g : Sum of Section Areas of Structural Elements

A_k : Masonry Infill Wall Areas

A_w : Web Area of Column Cross Section

η_{ci} : The Strength Irregularity Factor

2.1.2.2. Interstorey Stiffness Irregularity – Soft Storey (B2)

B2 type in TEC 07 is defined as: “The case where in each of the two orthogonal earthquake directions, Stiffness Irregularity Factor, η_{ki} , which is defined as the ratio of the average storey drift at any storey to the average storey drift at the storey immediately above or below, is greater than 2.0”. The equations for the stiffness irregularity factors are provided in *Eq. 2.3.a* for the immediate above and in *Eq. 2.3.b* for the immediate below of the floor under consideration.

$$\eta_{ki} = \left(\frac{\Delta_i}{h_i} \right)_{\text{ort}} / \left(\frac{\Delta_{i+1}}{h_{i+1}} \right)_{\text{ort}} > 2.0 \quad (2.3.a)$$

$$\eta_{ki} = \left(\frac{\Delta_i}{h_i} \right)_{\text{ort}} / \left(\frac{\Delta_{i-1}}{h_{i-1}} \right)_{\text{ort}} > 2.0 \quad (2.3.b)$$

where:

η_{ki} : The Stiffness Irregularity Factor

Δ_i : Displacement at i^{th} Floor

Δ_{i-1} : Displacement at $(i-1)^{\text{th}}$ Floor

Δ_{i+1} : Displacement at $(i+1)^{\text{th}}$ Floor

h_i : Height of i^{th} Storey

h_{i-1} : Height of $(i-1)^{\text{th}}$ Storey

h_{i+1} : Height of $(i+1)^{\text{th}}$ Storey

2.1.2.3. Discontinuity of Structural Elements (B3)

The definition of B3 type irregularity in TEC 07 is “The cases where vertical structural elements (columns or structural walls) are removed at some stories and supported by beams or gusseted columns underneath, or the structural walls of upper stories are supported by columns or beams underneath”. *Figure 2.5* illustrates four separate cases describing this type of irregularity. In the text below these four cases are explained further since some of them are not permitted according to the code. This information is directly excerpted from TEC 07.

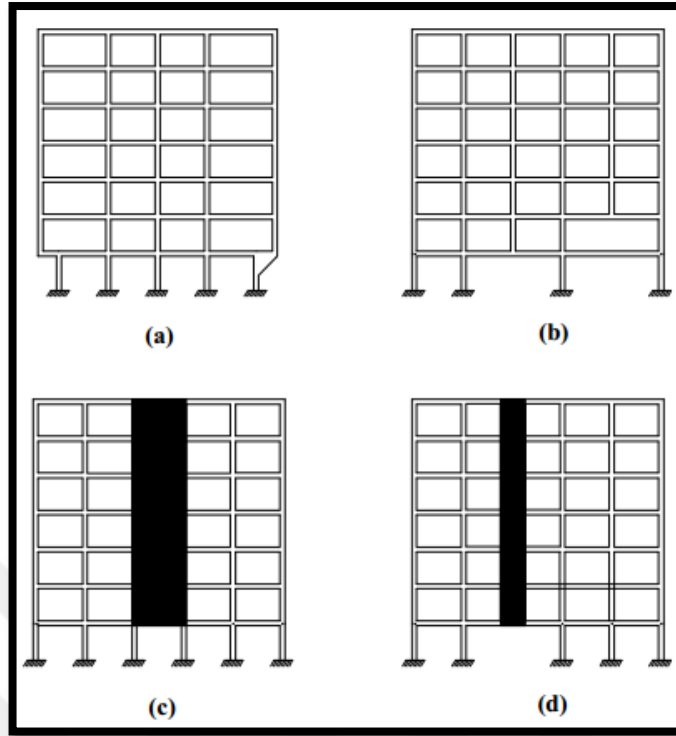


Figure 2. 5. Type B3 Irregularity in TEC 07 [3]

“ where:

- a) In all seismic zones, columns at any storey of the building shall in no case be permitted to rest on the cantilever beams or on top of at the tip of the gussets provided in the columns underneath (see *Figure 2.5.a*).
- b) In the case where a column rests on a beam which is supported at both ends, all internal force components induced by the combined vertical loads and seismic loads in the earthquake direction considered shall be increased by 50% at all sections of the beam and at all sections of the other beams and columns adjoining to the beam (see *Figure 2.5.b*).
- c) In no case the walls shall be permitted to rest on columns underneath (see *Figure 2.5.c*).
- d) Structural walls shall in no case be permitted in their own plane to rest on the beam span at any storey of the building (see *Figure 2.5.d*)”.

According to TEC 07, the irregularities defined in items a, c and d are not permitted.

2.2. Minimum Design Loads for Buildings and Other Structures (ASCE 7- 10)

In the US, the document of “Minimum Design Loads for Buildings and Other Structures” is the main standard for determining the design forces acting on buildings. In this standard, Section 12.3.2 refers to “Irregular and Regular Classifications”. The irregularities in this standard are classified in two groups: (a) horizontal irregularity, and (b) vertical irregularity. Both of these irregularities are described below in details.

2.2.1. Horizontal Irregularity

This type of irregularity is divided into five subtypes. Table 2.3 includes a copy of the table given in the standard. According to this table, the 5 subtypes are: (1a) torsional irregularity, (1b) extreme torsional irregularity, (2) reentrant corner irregularity, (3) diaphragm discontinuity irregularity, (4) out-of-plane offset irregularity, and (5) nonparallel system irregularity.

Table 2.3. Horizontal Structural Irregularities in ASCE 7/10 [4]

Type	Description	Reference Section	Seismic Design Category Application
1a.	Torsional Irregularity: Torsional irregularity is defined to exist where the maximum story drift, computed including accidental torsion with $A_x = 1.0$, at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts at the two ends of the structure. Torsional irregularity requirements in the reference sections apply only to structures in which the diaphragms are rigid or semirigid.	12.3.3.4 12.7.3 12.8.4.3 12.12.1 Table 12.6-1 Section 16.2.2	D, E, and F B, C, D, E, and F C, D, E, and F C, D, E, and F D, E, and F B, C, D, E, and F
1b.	Extreme Torsional Irregularity: Extreme torsional irregularity is defined to exist where the maximum story drift, computed including accidental torsion with $A_x = 1.0$, at one end of the structure transverse to an axis is more than 1.4 times the average of the story drifts at the two ends of the structure. Extreme torsional irregularity requirements in the reference sections apply only to structures in which the diaphragms are rigid or semirigid.	12.3.3.1 12.3.3.4 12.7.3 12.8.4.3 12.12.1 Table 12.6-1 Section 16.2.2	E and F D B, C, and D C and D C and D D B, C, and D
2.	Reentrant Corner Irregularity: Reentrant corner irregularity is defined to exist where both plan projections of the structure beyond a reentrant corner are greater than 15% of the plan dimension of the structure in the given direction.	12.3.3.4 Table 12.6-1	D, E, and F D, E, and F
3.	Diaphragm Discontinuity Irregularity: Diaphragm discontinuity irregularity is defined to exist where there is a diaphragm with an abrupt discontinuity or variation in stiffness, including one having a cutout or open area greater than 50% of the gross enclosed diaphragm area, or a change in effective diaphragm stiffness of more than 50% from one story to the next.	12.3.3.4 Table 12.6-1	D, E, and F D, E, and F
4.	Out-of-Plane Offset Irregularity: Out-of-plane offset irregularity is defined to exist where there is a discontinuity in a lateral force-resistance path, such as an out-of-plane offset of at least one of the vertical elements.	12.3.3.3 12.3.3.4 12.7.3 Table 12.6-1 Section 16.2.2	B, C, D, E, and F D, E, and F B, C, D, E, and F D, E, and F B, C, D, E, and F
5.	Nonparallel System Irregularity: Nonparallel system irregularity is defined to exist where vertical lateral force-resisting elements are not parallel to the major orthogonal axes of the seismic force-resisting system.	12.5.3 12.7.3 Table 12.6-1 Section 16.2.2	C, D, E, and F B, C, D, E, and F D, E, and F B, C, D, E, and F

2.2.1.1a. Torsional Irregularity

The definition of this irregularity in the standard is as follows: “Torsional irregularity is defined to exist where the maximum storey drift, computed including accidental torsion with $A_x=1.0$, at one end of the structure transverse to an axis is more than 1.2 times the average of the storey drifts at the two ends of the structure. Torsional irregularity requirements in the reference sections apply only to structures in which the diaphragms are rigid or semi rigid” [4]. Figure 2.6 shows the parameters required to determine torsional irregularity. In this figure δ_{avg} is the average displacement of a diaphragm, while δ_{max} is the maximum displacement of a diaphragm.

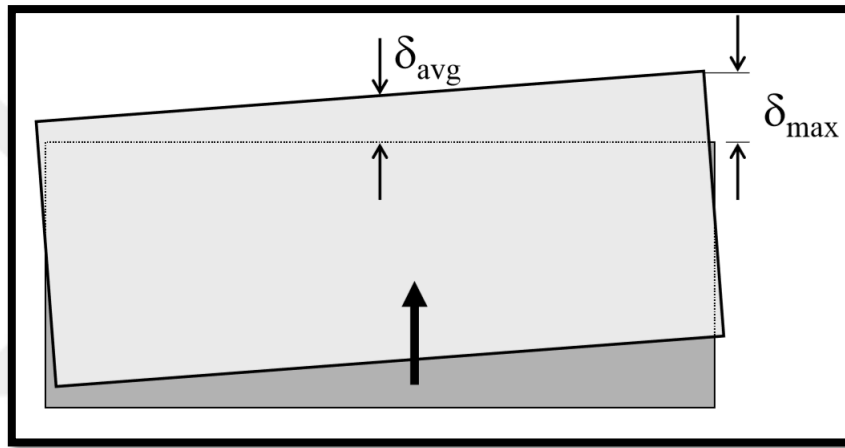


Figure 2.6. Torsional Irregularity in ASCE 7/10 [25]

2.2.1.1b. Extreme Torsional Irregularity

The following excerpt is the definition of extreme torsional irregularity and is taken directly from the standard: “Extreme torsional irregularity is defined to exist where the maximum storey drift, computed including accidental torsion with $A_x=1.0$, at one end of the structure transverse to an axis is more than 1.4 times the average of the storey drifts at the two ends of the structure. Extreme torsional irregularity requirements in the reference sections apply only to structures in which the diaphragms are rigid or semi rigid” [4].

2.2.1.2. Reentrant Corner Irregularity

The standard describes this irregularity as follows: “Reentrant corner irregularity is defined to exist where both plan projections of the structure beyond a reentrant corner are greater than 15% of the plan dimension of the structure in the given direction” [4]. *Figure 2.7* illustrates the effect of this type of irregularity in plan.

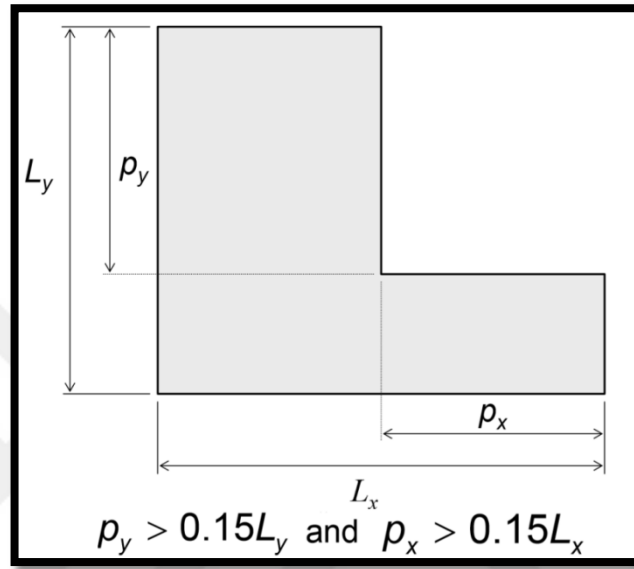


Figure 2.7. Reentrant Corner Irregularity in ASCE 7/10 [25]

2.2.1.3. Diaphragm Discontinuity Irregularity

Diaphragm discontinuity irregularity is a type of plan irregularity and the following text is excerpted directly from the standard. “Diaphragm discontinuity irregularity is defined to exist where there is a diaphragm with an abrupt discontinuity or variation in stiffness, including one having a cutout or open area greater than 50% of the gross enclosed diaphragm area, or a change in effective diaphragm stiffness of more than 50% from one story to the next” [4]. The two layouts given in *Figure 2.8* are examples of this type of irregularity.

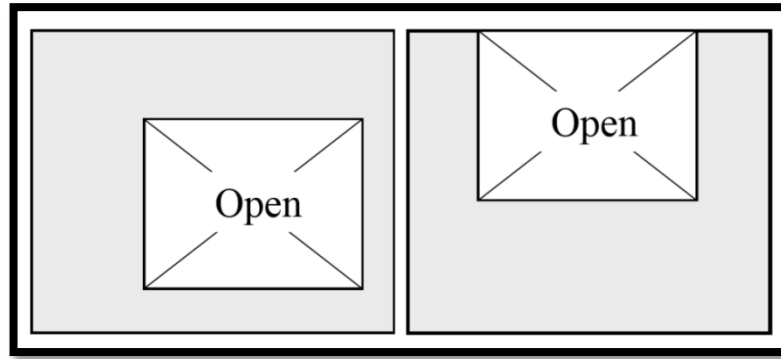


Figure 2.8. Diaphragm Discontinuity Irregularity in ASCE 7/10 [25]

2.2.1.4. Out-of-Plane Offset Irregularity

The definition of out-of-plane offset irregularity is described in the standard as follows: “Out-of-plane offset irregularity is defined to exist where there is a discontinuity in a lateral force-resistance path, such as an out-of-plane offset of at least one of the vertical elements” [4]. *Figure 2.9* illustrates an example to an out of plane offset occurring in a shear wall.

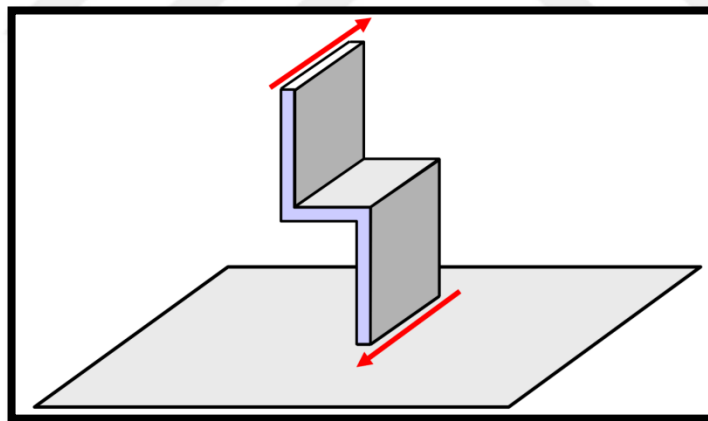


Figure 2.9. Out-of-Plane Offset Irregularity in ASCE 7/10 [25]

2.2.1.5. Nonparallel System Irregularity

The following excerpt is from the standard and describes the nonparallel system irregularity. “Nonparallel system irregularity is defined to exist where vertical lateral force-resisting elements are not parallel to the major orthogonal axes of the

seismic force-resisting system” [4]. The locations of the shear walls in the following layout displayed in *Figure 2.10* causes this type of irregularity.

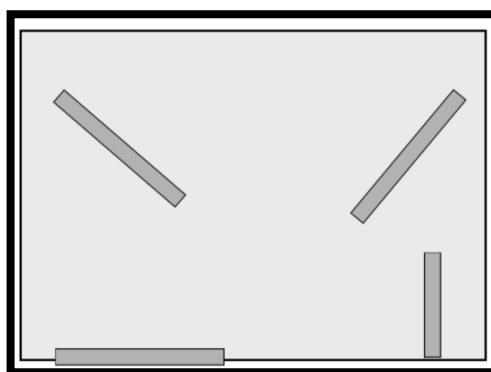


Figure 2.10. Nonparallel System Irregularity in ASCE 7/10 [25]

2.2.2. Vertical Irregularity

The vertical irregularity, according to ASCE 7-10, is described by using five different subtypes. Table 2.4 includes the list of these types along with their descriptions [4]. In the following sections, a brief description regarding to these types of irregularities are provided.

Table 2.4. Vertical Structural Irregularities in ASCE 7/10 [4]

Type	Description	Reference Section	Seismic Design Category Application
1a.	Stiffness-Soft Story Irregularity: Stiffness-soft story irregularity is defined to exist where there is a story in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above.	Table 12.6-1	D, E, and F
1b.	Stiffness-Extreme Soft Story Irregularity: Stiffness-extreme soft story irregularity is defined to exist where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above.	12.3.3.1 Table 12.6-1	E and F D, E, and F
2.	Weight (Mass) Irregularity: Weight (mass) irregularity is defined to exist where the effective mass of any story is more than 150% of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered.	Table 12.6-1	D, E, and F
3.	Vertical Geometric Irregularity: Vertical geometric irregularity is defined to exist where the horizontal dimension of the seismic force-resisting system in any story is more than 130% of that in an adjacent story.	Table 12.6-1	D, E, and F
4.	In-Plane Discontinuity in Vertical Lateral Force-Resisting Element Irregularity: In-plane discontinuity in vertical lateral force-resisting elements irregularity is defined to exist where there is an in-plane offset of a vertical seismic force-resisting element resulting in overturning demands on a supporting beam, column, truss, or slab.	12.3.3.3 12.3.3.4 Table 12.6-1	B, C, D, E, and F D, E, and F D, E, and F
5a.	Discontinuity in Lateral Strength–Weak Story Irregularity: Discontinuity in lateral strength–weak story irregularity is defined to exist where the story lateral strength is less than 80% of that in the story above. The story lateral strength is the total lateral strength of all seismic-resisting elements sharing the story shear for the direction under consideration.	12.3.3.1 Table 12.6-1	E and F D, E, and F
5b.	Discontinuity in Lateral Strength–Extreme Weak Story Irregularity: Discontinuity in lateral strength–extreme weak story irregularity is defined to exist where the story lateral strength is less than 65% of that in the story above. The story strength is the total strength of all seismic-resisting elements sharing the story shear for the direction under consideration.	12.3.3.1 12.3.3.2 Table 12.6-1	D, E, and F B and C D, E, and F

2.2.2.1a. Stiffness – Soft Storey Irregularity

The definition of stiffness-soft storey irregularity in the standard is as follows: “Stiffness - soft storey irregularity is defined to exist where there is a story in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above” [4]. *Figure 2.11* illustrates a frame exhibiting this type of irregularity.

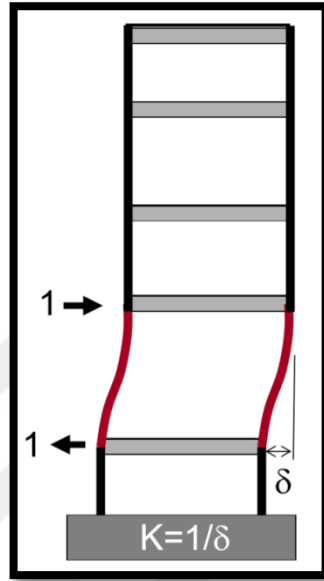


Figure 2.11. Stiffness-Soft Storey Irregularity in ASCE 7/10 [25]

2.2.2.1b. Stiffness – Extreme Soft Storey Irregularity

In the standard, this irregularity is described as follows: “Stiffness – extreme soft storey irregularity is defined to exist where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above” [4].

2.2.2.2. Weight (Mass) Irregularity

The definition of this type of irregularity in the standard is as follows: “Weight (mass) irregularity is defined to exist where the effective mass of any story is more than 150% of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered” [4]. *Figure 2.12* shows this irregularity on a simple frame case where one floor’s mass is heavier than the ones from the other floors.

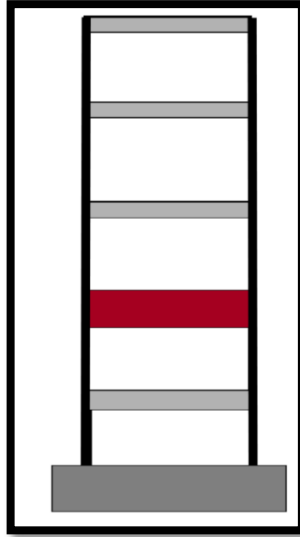


Figure 2.12. Stiffness-Extreme Soft Storey Irregularity in ASCE 7/10 [25]

2.2.2.3. Vertical Geometric Irregularity

The following excerpt is taken directly from the standard, and it describes the vertical geometric irregularity. “Vertical geometric irregularity is defined to exist where the horizontal dimension of the seismic force-resisting system in any story is more than 130% of that in an adjacent story” [4]. *Figure 2.13* illustrates a case where this type of irregularity exist.

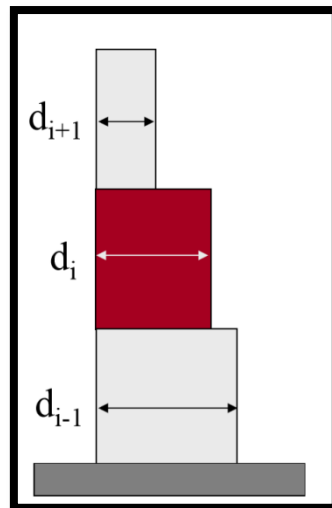


Figure 2.13. Vertical Geometric Irregularity in ASCE 7/10 [25]

2.2.2.4. In-Plane Discontinuity in Vertical Lateral Force-Resisting Element Irregularity

In the standard the definition of this irregularity is expressed as follows: “In-plane discontinuity in vertical lateral force-resisting element irregularity is defined to exist where there is an in-plane offset of a vertical seismic force-resisting element resulting in overturning demands on a supporting beam, column, truss, or slab” [4]. As shown in *Figure 2.14*, if the offset value is greater than the width (d), then this irregularity occurs.

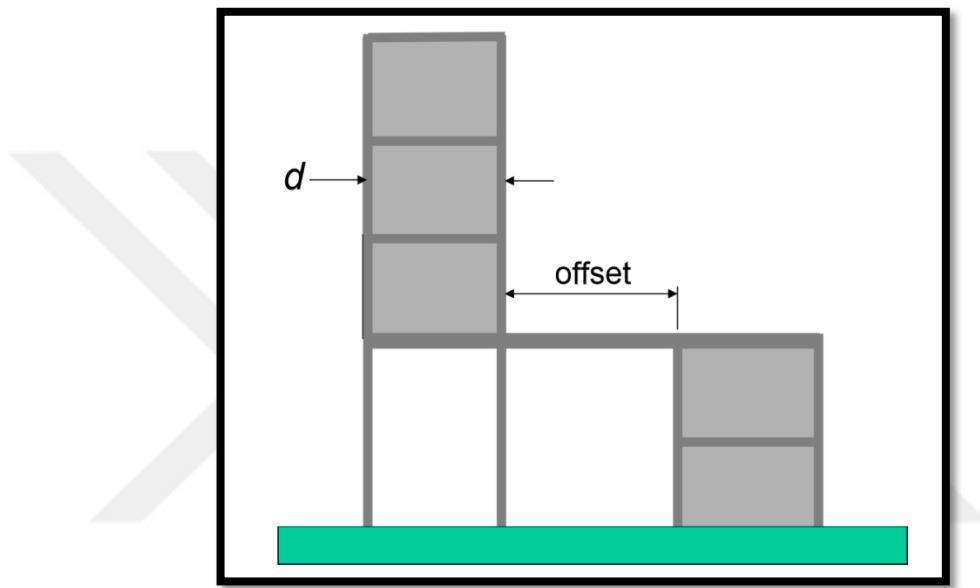


Figure 2.14. In-Plane Discontinuity in ASCE 7/10 [25]

2.2.2.5a. Discontinuity in Lateral Strength – Weak Story Irregularity

This type of irregularity is described in the standard as follows: “Discontinuity in lateral strength – weak story irregularity is defined to exist where the story lateral strength is less than 80% of that in the story above. The story lateral strength is the total lateral strength of all seismic-resisting elements sharing the story shear for the direction under consideration” [4]. *Figure 2.15* illustrates this type of irregularity in a simple frame.

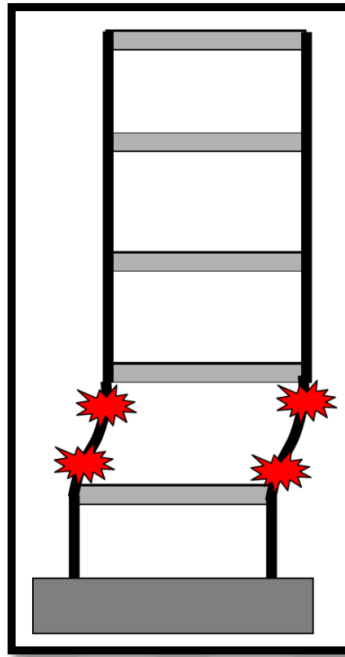


Figure 2.15. Strength – Weak Story Irregularity in ASCE 7/10 [25]

2.2.2.5b. Discontinuity in Lateral Strength – Extreme Weak Story Irregularity

In the standard, this type of irregularity is defined as follows: “Discontinuity in lateral strength – extreme weak story irregularity is defined to exist where the story lateral strength is less than 65% of that in the story above. The story lateral strength is the total lateral strength of all seismic-resisting elements sharing the story shear for the direction under consideration” [4].

2.3. Structural Design Actions (NZS 1170.5:2004 – New Zealand)

New Zealand Design Code states that a structure will be considered as irregular only if it has any of the features listed in the code about the vertical and plan irregularities. *Figure 2.16* has the illustration of vertical and plan irregularities. The code has exceptions for one storey penthouses or roofs with a weight less than 10% of the level below for them not to be considered when applying the criteria for irregularities [5].

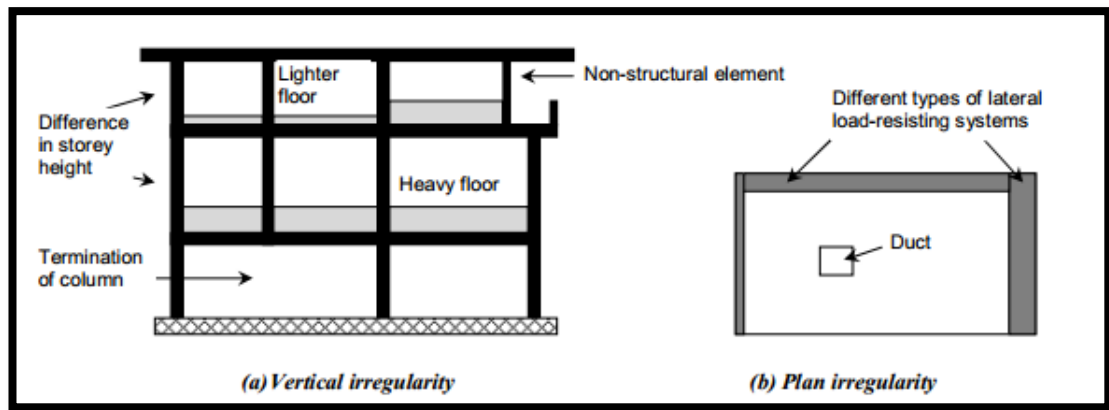


Figure 2.16. Structural Irregularities in NZS [9]

2.3.1. Vertical Irregularity

This type of irregularity consists of the four specific types. These are (a) weight (mass) irregularity, (b) vertical stiffness irregularity, (c) discontinuity in capacity-weak storey, and (d) vertical geometric irregularity.

2.3.1.1. Weight (Mass) Irregularity

This irregularity is defined as “Weight irregularity shall be considered to exist where the weight, W_i , of any storey is more than 150% of the weight of an adjacent storey. A roof that is lighter than the floor below need not be considered” [5].

2.3.1.2. Vertical Stiffness Irregularity

The definition of this irregularity is given in the code as follows: “Vertical stiffness irregularity shall be considered to exist when the lateral stiffness of the primary structure in a storey is less than 70% of the stiffness of any adjacent storey, or less than 80% of the average stiffness of the three storeys above or below” [5].

2.3.1.3. Discontinuity in Capacity – Weak Storey

This irregularity type is described as follows: “A weak storey is one in which the storey shear strength is less than 90% that in the storey above. The storey shear strength is the total strength of all vertical seismic-resisting elements of the primary structure sharing the storey for the direction under consideration” [5].

2.3.1.4. Vertical Geometric Irregularity

The definition of this irregularity in the code is provided as follows: “Vertical geometric irregularity shall be considered to exist where the sum of the horizontal dimensions of the vertical elements of the primary structure in the direction under consideration in any storey is more than 130% of that in an adjacent storey” [5].

2.3.2. Plan Irregularity

The plan irregularity is divided into three groups. The information about these groups is provided below.

2.3.2.1. Horizontal Offsets of Columns in Moment-Resisting Frames

The following excerpt is from the code, and it describes this irregularity [5]: “Horizontal plan irregularity shall be considered to exist where, in the direction under consideration, in-plane or out-of-plane offsets of columns at any floor level are present where either

- a) The average of the absolute values of the tangent of the offset angle:

$$\frac{\sum_{j=1}^{N_c} \left| \frac{a_j}{b_j} \right|}{N_c} > 0.1 \quad (2.4.a)$$

where,

a_j = The horizontal offset at column j

b_j = The vertical distance between the base of the upper column and the top of the lower column j

N_c = The total number of columns at the level under consideration

- b) For any single column j , the tangent of the offset angle” ;

$$\frac{a_j}{b_j} > 0.4 \quad (2.4.b)$$

2.3.2.2. Out-of-Plane Offsets of Lateral Force Resisting Walls

Horizontal plan irregularity shall be considered to exist in lateral force resisting walls where out-of-plane offsets occur that conform to Equations 2.4.a and 2.4.b

2.3.2.3. Torsional Sensitivity

The following expression is taken directly from the code and it defines the torsional sensitivity. “Horizontal plan irregularity resulting from torsional sensitivity shall be considered to exist when the ratio γ exceeds 1.4 when calculated as follows” [5].

The ratio γ_i for each level “i” according to the following equation is determined independently for each orthogonal direction:

$$\gamma_i = \frac{d_{\max}}{d_{\text{av}}} \quad (2.5)$$

where,

d_{av} = The average of the displacements at the extreme points of the structure at level “i” produced by the actions above this level.

$d_{\max}$ = The maximum storey displacement at the extreme points of the structure at level “i” in the direction of the earthquakes induced by the equivalent static actions acting at distances ± 0.10 times the plan dimension of the structure, b , from the centres of mass at each floor.

γ = The maximum of all values γ_i in both orthogonal directions.

2.4. Eurocode 8 (EC8 - EN 1998-1:2004)

In this code, structures are categorized as regular and non-regular structures. (see Section 4.2.3.1 of EC-8). The irregularity is studied both in plan and in elevation. The explanations about these two irregularities are provided different than those from the other three seismic codes. EC-8 evaluates layouts and buildings based on the fact that if they are regular or not. If a building violates the rules for regularities than depending on the violated rule, the building is considered either irregular in plan and/or in elevation. In the following two subsections, the descriptions about the two criteria for plan and elevation irregularities are discussed.

2.4.1. Criteria for Regularity in Plan

The following excerpts describing a list of eight items are taken directly from the code and not edited or modified [6].

1. “With respect to the lateral stiffness and mass distribution, the building structure shall be approximately symmetrical in plan with respect to two orthogonal axes.”

2. “The plan configuration shall be compact, i.e., each floor shall be delimited by a polygonal convex line. If in plan set-backs (reentrant corners or edge recesses) exist, regularity in plan may still be considered as being satisfied, provided that these set-backs do not affect the floor in-plan stiffness and that, for each set-back, the area between the outline of the floor and a convex polygonal line enveloping the floor does not exceed 5% of the floor area.”

3. “The in-plan stiffness of the floors shall be sufficiently large in comparison with the lateral stiffness of the vertical structural elements, so that the deformation of the floor shall have a small effect on the distribution of the forces among the vertical structural elements. In this respect, the L, C, H, I and X plan shapes should be carefully examined, notably as concerns the stiffness of the lateral branches, which should be comparable to that of the central part, in order to satisfy the rigid diaphragm condition. The application of this paragraph should be considered for the global behaviour of the building.”

4. “The slenderness ($\lambda = L_{\max} / L_{\min}$) of the building in plan, shall be not higher than 4, where $L_{\max}$ and $L_{\min}$ are respectively the larger and the smaller in plan dimension of the building, measured in orthogonal directions.”

5. “At each level and for each direction of analysis x and y , the structural eccentricity e_o and the torsional radius r shall be in accordance with two conditions below, which are expressed for the direction of analysis y :

$$e_{ox} \leq 0,3 r_x \quad (a)$$

$$r_x \geq l_s \quad (b)$$

where,

e_{ox} is the distance between the centre of stiffness and the centre of mass, measured along the x direction, which is normal to the direction of analysis considered.

r_x is the square root of the ratio of the torsional stiffness to the lateral stiffness in the y direction (torsional radius).

l_s is the radius of gyration of the floor mass in plan (square root of the ratio of (a) the polar moment of inertia of the floor mass in plan with respect to the centre of mass of the floor to (b) the floor mass).

“The definitions of centre of stiffness and torsional radius r are provided in 6 to 8 of this clause”

6. “In single storey buildings the centre of stiffness is defined as the centre of the lateral stiffness of all primary seismic members. The torsional radius r is defined as the square root of the ratio of the global torsional stiffness with respect to the centre of lateral stiffness, and the global lateral stiffness, in one direction, taking into accounts all of the primary seismic members in this direction.”

7. “In multi-storey buildings only approximate definitions of the centre of stiffness and of the torsional radius are possible. A simplified definition, for the classification of structural regularity in plan and for the approximate analysis of torsional effects, is possible if the following two conditions are satisfied:

a) All lateral load resisting systems, such as cores, structural walls or frames, run without interruption from the foundations to the top of the building.

b) The deflected shapes of the individual systems under horizontal loads are not very different. This condition may be considered satisfied in the case of frame systems and wall systems. In general, this condition is not satisfied in dual systems.”

8. “In frames and in systems of slender walls with prevailing flexural deformations, the position of the centres of stiffness and the torsional radius of all storeys may be calculated as those of the moments of inertia of the cross-sections of the vertical elements. If, in addition to flexural deformations, shear deformations are also significant, they may be accounted for by using an equivalent moment of inertia of the cross-section.”

2.4.2. Criteria for Regularity in Elevation

The following excerpts, again, are taken directly from the code and it describes the criteria for regularity in elevation [6].

1. “For a building to be categorized as being regular in elevation, it shall satisfy all the conditions listed in the following paragraphs.”

2. “All lateral load resisting systems, such as cores, structural walls, or frames, shall run without interruption from their foundations to the top of the building or, if set-backs at different heights are present, to the top of the relevant zone of the building.”

3. “Both the lateral stiffness and the mass of the individual storeys shall remain constant or reduce gradually, without abrupt changes, from the base to the top of a particular building.”

4. “In framed buildings the ratio of the actual storey resistance to the resistance required by the analysis should not vary disproportionately between adjacent storeys. Within this context the special aspects of masonry in-filled frames are treated in 4.3.6.3.2.”

5. “When set-backs are present, the following additional conditions apply:

a) For gradual set-backs preserving axial symmetry, the set-back at any floor shall not be greater than 20% of the previous plan dimension in the direction of the set-back (*Figure 2.17.a* and *Figure 2.17.b*)

b) For a single set-back within the lower 15% of the total height of the main structural system, the set-back shall be not greater than 50% of the previous plan dimension (*Figure 2.17.c*). In this case the structure of the base zone within the vertically projected perimeter of the upper storeys should be designed to resist at least 75% of the horizontal shear forces that would develop in that zone in a similar building without the base enlargement.”

6. “If the set-backs do not preserve symmetry, in each face the sum of the set-backs at all storeys shall be not greater than 30% of the plan dimension at the ground floor above the foundation or above the top of a rigid basement, and the individual set-backs shall be not greater than 10% of the previous plan dimension (*Figure 2.17.d*).”

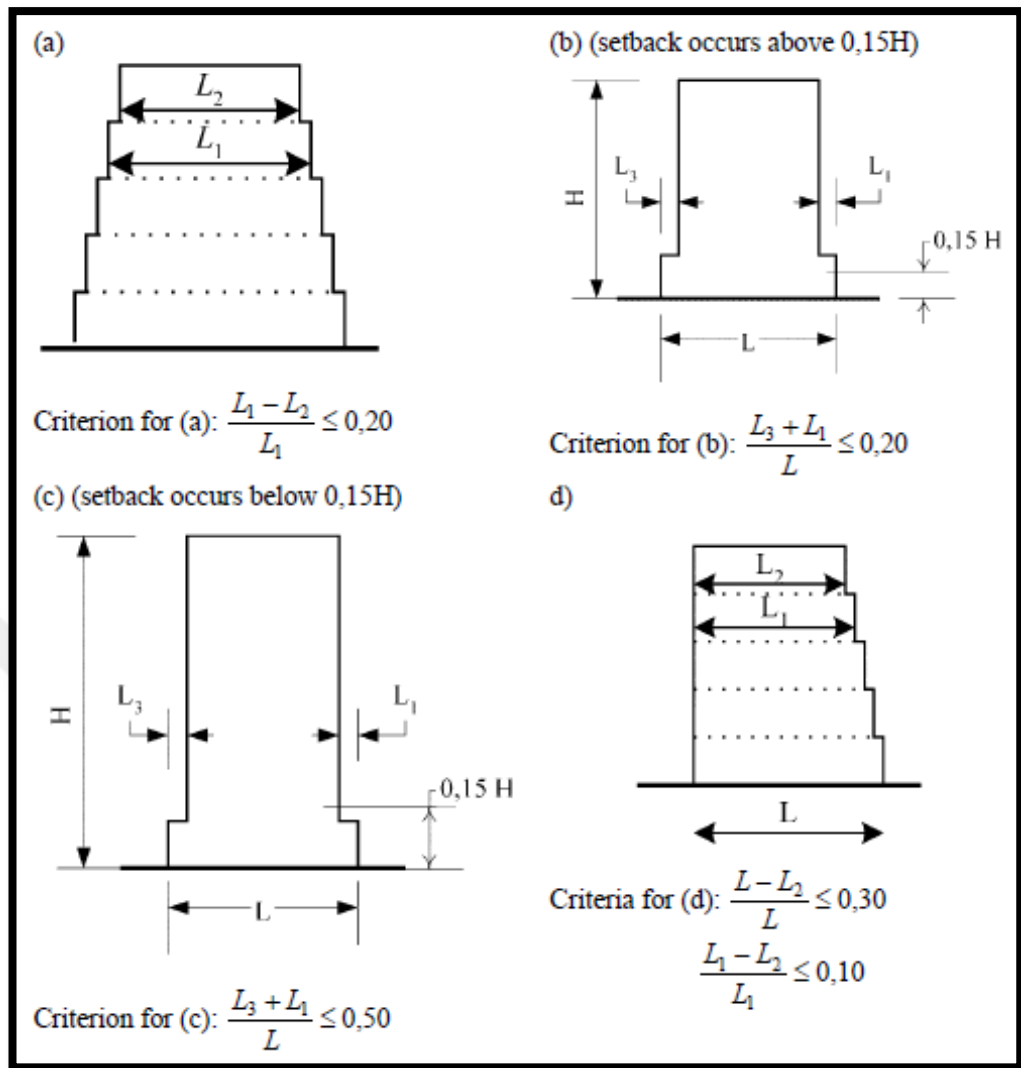


Figure 2.17. Criteria for Regularity of Buildings with Set-backs in EC-8 [6]

CHAPTER 3

INPUT DATA FOR ANALYTICAL STUDIES

3.1. Introduction

In this chapter, the details of the finite element (FE) models for the buildings constructed in ETABS and PROBINA will be discussed. In order to understand the seismic activity and its dynamic effects on buildings, a total of sixty-six models are all studied. These models are different from each other since they have different floor heights, floor layouts and soil types. The goal of these sixty-six models is to understand the degree of effects on the analysis phase resulting from different floor heights, layouts and soil types. In order to achieve this goal, the procedure required to construct the models and to perform structural analyses will be discussed. A total of sixty buildings each with twenty storeys will be examined. For the sake of this study, these buildings are all assumed to be residential.

3.2. Vertical and Horizontal Loads

In this section, the vertical and horizontal loads on twenty storeys buildings will be explained in details. First, the vertical loads (dead, live and superimposed dead load) and the horizontal loads (lateral loads) will be described. Then, the load combinations will be explained.

3.2.1. Load Cases

A total of four load cases are used in this study. The details of the load cases and the corresponding notations are listed in *Table 3.1*.

Table 3.1. Load Cases in ETABS

Load Case Number	Load Cases	Description
1	D	Dead Load
2	L	Live Load
3	SD	Superimposed Dead Load
4	E_{rx} , E_{ry}	Response Spectrum

As listed above, the top 3 load cases are used to define gravity loads while the last one is used to define lateral loads.

3.2.1.1. Dead Load

The self-weight of building is defined dead load. In each of the sixty six models under consideration, the building type is all assumed reinforced concrete. A 2.5 t/m^3 unit weight of reinforced concrete is used to calculate the self-weight of buildings in the analyses. This load is assigned directly by the FE programs, and therefore no user interface is needed.

3.2.1.2. Superimposed Dead Load

The magnitudes of superimposed dead load and partition walls vary according to the functionality of building types. In this study, the architectural details regarding the types of floor finishes and partition walls are all considered to be included in the live load category. The reason for this load category selection comes from the fact that the architectural details for floor coverings and partition walls might significantly increases the total load value. Therefore, to maximize the effects of these loads, the total weight generating both from superimposed dead loads and partition walls are all assumed to exist as part of a live load acting at all floor levels. The total magnitudes of these two loads are assumed 150 kgf/m^2 .

3.2.1.3. Live Load

Live loads in a building are the results of dynamic equipment and occupational loads. Their magnitudes are not easy to determine, and are subject to change depending on their locations. In this study, the live load values are obtained from a Turkish Code, TS 498 [25]. This code is used to determine live loads for

buildings. TS 498 includes a list of various live loads anticipated in a building. Although the magnitudes of live loads vary from room to room depending on its functionality, for the sake of simplicity, a constant live load is assigned to exist at each floor level. The constant value of live load in TS 498 for a typical room in a residential building is 200 kg/m^2 . Including an additional live load of 150 kgf/m^2 resulting from the combination of superimposed dead load and partition walls, the total live load acting at each floor level becomes 350 kgf/m^2 . In the structural analyses of buildings, this load is used as uniformly applied surface load acting on floors.

3.2.1.4. Earthquake Loads

Earthquake loads are dynamic loads. They are applied to buildings by following various methods that might differ from each other based on the seismic code under consideration. As explained in Chapter 2, four different building codes are used to apply earthquake loads to a total of sixty-six buildings. These building codes are follows:

- (a) TEC 07
- (b) ASCE 7-10
- (c) NZS 1170.5:2004
- (d) EUROCODE 8

As stated in item 2.6.1 of TEC 07, there are three methods to calculate earthquake loads (Equivalent lateral force method, response spectrum method, and time history analysis). In this study, the response spectrum method is used to analyze the buildings. In the following subsections, the details of earthquake loads generating from the four seismic codes will be discussed in details.

3.2.1.4a. Turkish Earthquake Code (TEC 07)

In this research, the buildings are all assumed to be residential. They are also assumed to be located in a very high seismic region that a potential fault line. Therefore, İznik, a district of Bursa, is chosen to be the right location for the buildings. This particular location is approximately 2 km away from the North Anatolian Fault Line (NAFL). The purpose of selecting a location near a major fault line is to understand the impact of a fault line on the dynamic analyses phase resulting from various earthquake codes.

In TEC 07, three methods are used to determine the earthquake loads. These methods are as follows:

- Equivalent Seismic Load (ESL)
- Response Spectrum Analysis (RSA)
- Time History Analysis (THA)

In this study the RSA method is used for all buildings. As stated in item 2.8.5 of TEC 07, the base shear forces resulting from the response spectrum are compared to the base shear forces obtained from the equivalent seismic analyses. In the RS analysis, three critical parameters that need to be determined. These are: (a) seismic zone, (b) importance factor, I , and (c) local site classes.

a) Seismic Zone

In TEC 07, four seismic zones exist. Seismic zone 1 represents the most severe earthquake region where seismic zone 4 represents the least severe one. Table 3.2 shows details about the seismic zones and their horizontal acceleration coefficients, A_0 . In this study, as stated before, the buildings in Turkey are located in İznik, where the seismic zone is 1 and the associated acceleration coefficient is 0.4.

Table 3.2. Seismic zone classes in TEC 07 [3]

Seismic Zone	Horizontal acceleration coefficient, A_0
1	0.4
2	0.3
3	0.2
4	0.1

b) Importance Factor, I

Table 3.3 has the list of importance factors used for various types of buildings based on their purpose of occupancy. As mentioned before, all buildings are assumed to be residential and therefore, the importance factor in this study is equal to one.

Table 3.3. Importance Factor for Buildings in TEC 07 [3]

<i>Purpose of Occupancy or Type of Building</i>	<i>Importance Factor (I)</i>
<u>1. Buildings to be utilized after the earthquake and buildings containing hazardous materials</u> a) Buildings required to be utilized immediately after the earthquake (Hospitals, dispensaries, health wards, firefighting buildings and facilities, PTT and other telecommunication facilities, transportation stations and terminals, power generation and distribution facilities; governorate, county and municipality administration buildings, first aid and emergency planning stations) b) Buildings containing or storing toxic, explosive and flammable materials, etc.	1.5
<u>2. Intensively and long-term occupied buildings and buildings preserving valuable goods</u> a) Schools, other educational buildings and facilities, dormitories and hostels, military barracks, prisons, etc. b) Museums	1.4
<u>3. Intensively but short-term occupied buildings</u> Sport facilities, cinema, theatre and concert halls, etc.	1.2
<u>4. Other buildings</u> Buildings other than above-defined buildings. (Residential and office buildings, hotels, building-like industrial structures, etc.)	1.0

c) Local Site Class

The third parameter required to construct a response spectrum is called local site class. In TEC 07, a total of four local site classes exist. They are designated as Z1, Z2, Z3 and Z4 (see Table 3.4). These classes are functions of soil groups that are labeled as A, B, C and D (see Table 3.5). In these groups, label A represents rock type soil, and label D represents loose type sand, soft clay and silt type soil. The other two types, B and C, are used to classify soils between rock and loose type sand.

Table 3.4. Local Site Classes in TEC 07 [3]

<i>Local Site Class</i>	<i>Soil Group and Topmost Soil Layer Thickness (h₁)</i>
Z1	Group (A) soils Group (B) soils with h ₁ ≤ 15 m
Z2	Group (B) soils with h ₁ > 15 m Group (C) soils with h ₁ ≤ 15 m
Z3	Group (C) soils with 15 m < h ₁ ≤ 50 m Group (D) soils with h ₁ ≤ 10 m
Z4	Group (C) soils with h ₁ > 50 m Group (D) soils with h ₁ > 10 m

In this study, three soil groups are examined for the buildings under consideration. These soil groups are: A, B and C. The associated local site classes for these three soil groups are Z1, Z2 and Z3, respectively.

Table 3.5. Soil Groups in TEC 07 [3]

<i>Soil Group</i>	<i>Description of Soil Group</i>	<i>Standard Penetration (N/30)</i>	<i>Relative Density (%)</i>	<i>Unconfined Compressive Strength (kPa)</i>	<i>Drift Wave Velocity (m / s)</i>
(A)	1. Massive volcanic rocks, unweathered sound metamorphic rocks, stiff cemented sedimentary rocks 2. Very dense sand, gravel... 3. Hard clay and silty clay...	— > 50 > 32	— 85 – 100 —	> 1000 — > 400	> 1000 > 700 > 700
(B)	1. Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity..... 2. Dense sand, gravel..... 3. Very stiff clay, silty clay...	— 30 – 50 16 – 32	— 65 – 85 —	500 – 1000 — 200 – 400	700 – 1000 400 – 700 300 – 700
(C)	1. Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity 2. Medium dense sand and gravel..... 3. Stiff clay and silty clay.....	— 10 – 30 8 – 16	— 35 – 65 —	< 500 — 100 – 200	400 – 700 200 – 400 200 – 300
(D)	1. Soft, deep alluvial layers with high ground water level 2. Loose sand..... 3. Soft clay and silty clay.....	— < 10 < 8	— < 35 —	— — < 100	< 200 < 200 < 200

According to soil classes Z1, Z2 and Z3, the design acceleration spectrum is constructed. Figure 3.1 illustrates the relationship between period and spectrum coefficients. The spectrum coefficient values provided in *Figure 3.1* are converted values, and are obtained by using the equations given in Chapter 2 of TEC 07. The following equations are used to perform this conversion in constructing a design response spectrum

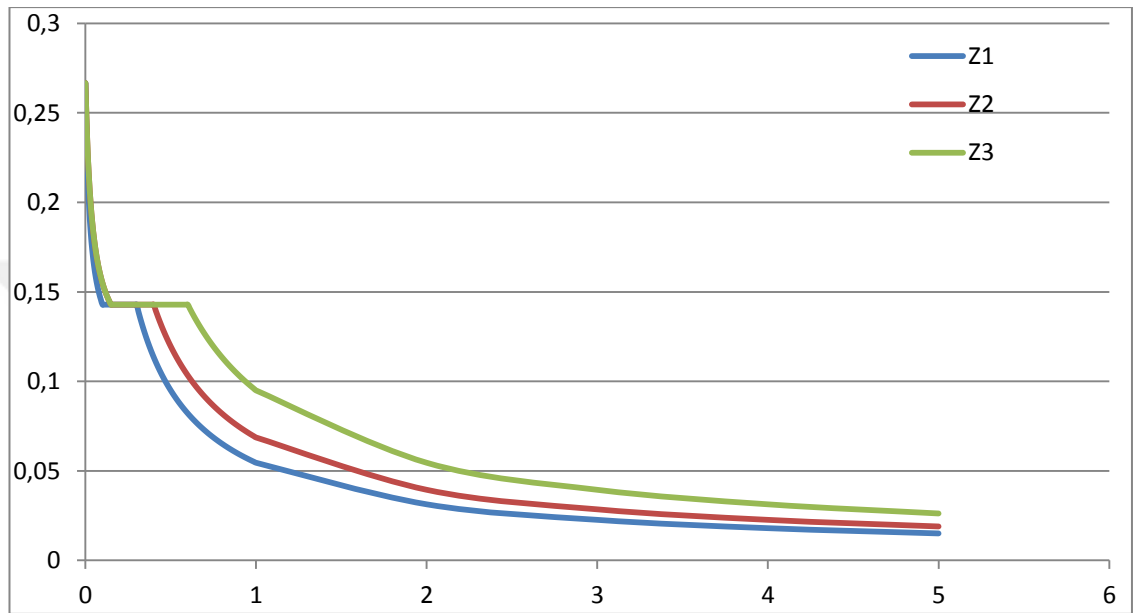


Figure 3.1. Design Response Spectrum in TEC 07

The equation below is used to calculate elastic spectral acceleration

$$S_{ae}(T) = A_0 * I * S(T) * g \quad (3.1)$$

where:

A_0 = Effective Ground Acceleration Coefficient

I = Building Importance Factor

$S(T)$ = Spectrum Coefficient

g = Acceleration of gravity (9.81 m/s^2)

In order to obtain the reduced spectral acceleration for the n^{th} natural vibration mode Eq. 3.2 is used.

$$S_{aR}(T_n) = \frac{S_{ae}(T_n)}{R_a(T_n)} \quad (3.2)$$

where:

$S_{ae}(T_n)$ = Elasticity spectrum ordinate [m/s^2] of n^{th} natural vibration periods of building (seconds)

$R_a(T_n)$ = Seismic Load Reduction Factor of n^{th} natural vibration periods of building (seconds)

$S_{aR}(T_n)$ = Acceleration spectrum ordinate for the n^{th} natural vibration mode (m/s^2)

As previously mentioned, the importance factor (I) in this study is equal to 1,0, and A_0 is 0,4. The spectrum coefficient $S(T)$ given in Eq. 3.1 is calculated separately for the three different regions are specified below:

$$S(T) = 1 + 1.5 * \frac{T}{T_A} \quad (0 \leq T \leq T_A) \quad (3.2.a)$$

$$S(T) = 2.5 \quad (T_A \leq T \leq T_B) \quad (3.2.b)$$

$$S(T) = 2.5 * \left(\frac{T_B}{T}\right)^{0.8} \quad (T_B < T) \quad (3.2.c)$$

T_A and T_B in Equations 3.2.a, b and c are defined as the spectrum characteristic periods. As listed in *Table 3.6*, in this study, T_A and T_B values for local site classes Z1, Z2 and Z3 are respectively as follows: 0.1 and 0.3 for Z1 0.15 and 0.4 for Z2, and 0.15 and 0.6 for Z3.

Table 3.6. Spectrum Characteristic Periods in TEC 07 [3]

Local Site Class	T_A (second)	T_B (second)
Z1	0.1	0.3
Z2	0.15	0.4
Z3	0.15	0.6
Z4	0.2	0.9

The other parameter that is needed in Equation 3.2 is the seismic reduction factor, $R_a(T)$ which is defined differently for three types of buildings systems. They are: (1) cast-in-situ reinforced concrete buildings, (2) prefabricated reinforced concrete buildings, and (3) structural steel buildings.

In this thesis, the layouts of the buildings consist of both framing and structural walls. Therefore, for the structural system as stated in TEC 07 “Buildings in which seismic loads are jointly resisted by solid structural walls” is used accordingly. In all building models that are constructed both in PROBINA and ETABS, the structural behavior factor, R , is selected to be 7. This value represents high ductility level. The associated seismic load reduction factors, $R_a(T)$, are then determined by using the following equations given in item 2.5.1 in the TEC 07:

$$R_a(T) = 1.5 + (R - 1.5) * \frac{T}{T_A} \quad (0 \leq T \leq T_A) \quad (3.3)$$

$$R_a(T) = R \quad (T_A < T) \quad (3.4)$$

The reduced elastic spectral acceleration, $S_{aR}(T)$, also known as “Design Spectrum”, can be obtained from Equation 3.2, using both $S(T)$ and $R(T)$ functions defined in Equation 3.2 through 3.4. Figure 3.2 displays the design spectrum curves for soil types Z1, Z2 and Z3 with respect to the building’s natural period. The structural behavior factor as described above is selected 7 for all buildings. However, as explained in item 2.5.4.1 of TEC 07, this value of 7 is subjected to a modification as a result of shear force distribution shared between the framing system and the structural walls. Depending on the distribution, the R will be reduced, and therefore

it will be less than 7. This calculation is performed automatically for all buildings modeled in PROBINA. The modified R value calculated in PROBINA is directly used as the new R value for the models constructed in ETABS. By doing so, it is intended to compare the results of PROBINA to ETABS. In the next page the picture is directly taken from excel worksheet, and this referenced picture used as figure in thesis.



TEC 07									
LAYOUT_A h=3.2m					LAYOUT_A h=3.2m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W(t)	14299	14299			W	14459	14459		
Tx(s)	1,16	1,16			Tx	1,17	1,17		
Ty(s)	1,23	1,23			Ty	1,24	1,24		
SPECK	693,19	871,8			SPECK	695,81	875,16		
SPECY	664,01	833,9			SPECY	663,48	835,05		
1151,4									
1154,53									

TEC 07									
LAYOUT_B h=3.2m					LAYOUT_B h=3.2m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	13297,04	13297,04			W	13297,04	13297,04		
Tx	0,99	0,99			Tx	0,99	0,99		
Ty	1,32	1,32			Ty	1,32	1,32		
SPECK	725,23	909,73			SPECK	725,23	909,73		
SPECY	569,88	724,03			SPECY	569,88	724,03		
1252,2									
993									

TEC 07									
LAYOUT_C h=3.2m					LAYOUT_C h=3.2m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	14551,39	14551,39			W	14551,39	14551,39		
Tx	1,06	1,06			Tx	1,06	1,06		
Ty	1,22	1,22			Ty	1,22	1,22		
SPECK	740,04	931,84			SPECK	740,04	931,84		
SPECY	667,71	834,57			SPECY	667,71	834,57		
1286,21									
1151,21									

TEC 07									
LAYOUT_A h=4.5m					LAYOUT_A h=4.5m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	15178,46	15178,46			W	15178,46	15178,46		
Tx	1,33	1,33			Tx	1,33	1,33		
Ty	1,39	1,39			Ty	1,39	1,39		
SPECK	674,06	849,25			SPECK	672,38	844,84		
SPECY	652,54	817,97			SPECY	648,18	815,87		
1173,52									
1131,23									

TEC 07									
LAYOUT_B h=4.5m					LAYOUT_B h=4.5m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	14041,626	14041,626			W	14041,626	14041,626		
Tx	1,27	1,27			Tx	1,27	1,27		
Ty	1,44	1,44			Ty	1,44	1,44		
SPECK	731,81	921,93			SPECK	730,47	908,65		
SPECY	587,05	737,96			SPECY	579,44	722,36		
1271,88									
1020,34									

TEC 07									
LAYOUT_C h=4.5m					LAYOUT_C h=4.5m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	15501,293	15501,293			W	15404,3	15404,3		
Tx	1,19	1,19			Tx	1,22	1,22		
Ty	1,29	1,29			Ty	1,37	1,37		
SPECK	752,28	944,22			SPECK	718,12	896,26		
SPECY	700,93	884,95			SPECY	656,74	822,09		
1306,83									
1222,38									

TEC 07									
LAYOUT_A h=4.5m					LAYOUT_A h=4.5m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	15178,46	15178,46			W	15222,86	15222,86		
Tx	1,33	1,33			Tx	1,33	1,33		
Ty	1,39	1,39			Ty	1,39	1,39		
SPECK	674,06	849,25			SPECK	672,38	844,84		
SPECY	652,54	817,97			SPECY	648,18	815,87		
1173,52									
1131,23									

TEC 07									
LAYOUT_B h=4.5m					LAYOUT_B h=4.5m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	14041,626	14041,626			W	14047,04	14047,04		
Tx	1,27	1,27			Tx	1,11	1,11		
Ty	1,44	1,44			Ty	1,48	1,48		
SPECK	731,81	921,93			SPECK	730,47	908,65		
SPECY	587,05	737,96			SPECY	579,44	722,36		
1271,88									
1020,34									

TEC 07									
LAYOUT_C h=4.5m					LAYOUT_C h=4.5m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	15501,293	15501,293			W	15404,3	15404,3		
Tx	1,19	1,19			Tx	1,22	1,22		
Ty	1,29	1,29			Ty	1,37	1,37		
SPECK	752,28	944,22			SPECK	718,12	896,26		
SPECY	700,93	884,95			SPECY	656,74	822,09		
1306,83									
1222,38									

TEC 07									
LAYOUT_A h=3.2m					LAYOUT_A h=3.2m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	14299	14299			W	14459	14459		
Tx	1,16	1,16			Tx	1,17	1,17		
Ty	1,23	1,23			Ty	1,24	1,24		
SPECK	693,19	871,8			SPECK	695,81	875,16		
SPECY	664,01	833,9			SPECY	663,48	835,05		
1151,4									
1154,53									

TEC 07									
LAYOUT_B h=3.2m					LAYOUT_B h=3.2m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	13177	13177			W	13297,04	13297,04		
Tx	0,97	0,97			Tx	0,99	0,99		
Ty	1,28	1,28			Ty	1,32	1,32		
SPECK	736,5	928,35			SPECK	725,23	909,73		
SPECY	591,35	745,86			SPECY	569,88	724,03		
1280,1									
1030,2									

TEC 07									
LAYOUT_C h=3.2m					LAYOUT_C h=3.2m				
PROBINA					ETABS				
Z1	Z2	Z3			Z1	Z2	Z3		
A0: 0,4	A0: 0,4	A0: 0,4			A0: 0,4	A0: 0,4	A0: 0,4		
W	14537,9	14537,9			W	14551,39	14551,39		
Tx	1,03	1,03			Tx	1,06	1,06		
Ty	1,13	1,13			Ty	1,22	1,22		
SPECK	773,59	970,19			SPECK	740,04	931,84		
SPECY	717,72	905,14			SPECY	667,71	834,57		
1343,42									
1249,69									

3.2.1.4b. American Society of Civil Engineers Standard, ASCE

In the US, a special committee, the American Society of Civil Engineers (ASCE), prepares standards for various design cases. One of these standards is called ASCE 7/10 [4], which is entitled “Minimum Design Loads for Buildings and Other Structures”. In this standard, “seismic design criteria” is explained in Chapter 11. This chapter covers the design and construction criteria for buildings that are subjected to earthquake ground motions. As discussed before, in this study, it is intended to create similar design conditions even if different seismic codes are used. Therefore, a special care is given to earthquake loads that will be generated from these four seismic codes so that, more or less, each of these seismic codes generate produces similar results. However, it is important to emphasize that this attempt is almost unachievable since the parameters involved in the earthquake loads might drastically be different from each other. Keeping this difficulty in mind, it is aimed to produce at least similar earthquake loads to the one from the TEC 07. As a result of this aim, in the following sections, the earthquake parameters are carefully investigated in order to generate similar forces to those from TEC 07.

a) Seismic Design Category, SDC

A seismic design category can be defined based on its use. Seismic Design Category, The SDC, in ASCE 7-10 is divided into five groups, A, B, C, D, E and F (see *Table 3.7*). In this table SDC A represents very small seismic vulnerability, while E and F represent very high seismic vulnerability near a major fault line

Table 3.7. Seismic Design Category in ASCE 7/10 [4]

Seismic Design Category (SDC)	Physical Meaning
A	Very small seismic vulnerability
B	Small to medium seismic vulnerability
C	Medium seismic vulnerability
D	High seismic vulnerability
E and F	Very high seismic vulnerability and near a major fault

In this thesis, the seismic design category “E” is selected based on short period response acceleration and its risk category will be explained in the next paragraphs. In order to determine the seismic design category, the building’s risk category first needs to be identified. In ASCE 7-10, the risk category of a building for major loads divided into four separate groups, I, II, III and IV (see *Table 3.8*). In this study, all buildings, as described before, are assumed to be residential. According to *Table 3.8*, the risk category for residential buildings are defined II. Therefore, the category II is selected to be the risk category for all buildings. After the determination of the risk category, the next step is to identify the seismic design category based on, S_{DS} and S_{D1} values. These two values are calculated using the values of S_S and S_1 including soil classifications. In the standard, the definitions of S_{DS} , S_{D1} , S_S and S_1 are provided as follows:

S_{DS} = Design, spectral response acceleration parameter at short periods based on 5 percent damping

S_{D1} = Design, spectral response acceleration parameter at a period of 1 second based on 5 percent damping

S_S = Mapped MCE_R , (Risk-Targeted Maximum Considered Earthquake), spectral response acceleration parameter at short periods based on 5 percent damping

S_1 = Mapped MCE_R , spectral response acceleration parameter at a period of 1 second based on 5 percent damping

Table 3.8. Risk Category of Buildings and Other Structures for Flood, Wind, Snow, Earthquake, and Ice Loads in ASCE 7/10 [4]

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures that represent a low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life.	III
Buildings and other structures, not included in Risk Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.	
Buildings and other structures not included in Risk Category IV (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, hazardous waste, or explosives) containing toxic or explosive substances where their quantity exceeds a threshold quantity established by the authority having jurisdiction and is sufficient to pose a threat to the public if released.	
Buildings and other structures designated as essential facilities.	IV
Buildings and other structures, the failure of which could pose a substantial hazard to the community.	
Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity exceeds a threshold quantity established by the authority having jurisdiction to be dangerous to the public if released and is sufficient to pose a threat to the public if released. ^a	
Buildings and other structures required to maintain the functionality of other Risk Category IV structures.	
^a Buildings and other structures containing toxic, highly toxic, or explosive substances shall be eligible for classification to a lower Risk Category if it can be demonstrated to the satisfaction of the authority having jurisdiction by a hazard assessment as described in Section 1.5.2 that a release of the substances is commensurate with the risk associated with that Risk Category.	

Design earthquake spectral response acceleration parameter at short period, S_{DS} , and at 1 second period, S_{D1} , are determined from Equations 3.5 and 3.6, respectively.

$$S_{DS} = \frac{2}{3} S_{MS} \quad (3.5)$$

$$S_{D1} = \frac{2}{3} S_{M1} \quad (3.6)$$

“where:

S_{MS} = The MCE_R , spectral response acceleration parameter at short periods adjusted for site class effects based on 5 percent damping

S_{M1} = The MCE_R , spectral response acceleration parameter at a period of 1 second adjusted for site class effects based on 5 percent damping”

S_{MS} and S_{M1} are calculated using the following two equations.

$$S_{MS} = F_a S_s \quad (3.7)$$

$$S_{M1} = F_v S_1 \quad (3.8)$$

“where;

F_a = Short-Period Site Coefficient (at 0.2 second-period), (see *Table 3.9*)

F_v = Long-Period Site Coefficient (at 1.0 second-period), (see *Table 3.10*)”

Table 3.9. Site coefficient, F_a in ASCE 7/10 [4]

Site Coefficient, F_a					
Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE _R) Spectral Response Acceleration Parameter at Short Period				
	$S_s \leq 0.25$	$S_s = 0.5$	$S_s = 0.75$	$S_s = 1.0$	$S_s \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	See Section 11.4.7				

Note: Use straight-line interpolation for intermediate values of S_s .

Table 3.10. Site coefficient, F_v in ASCE 7/10 [4]

Site Coefficient, F_v					
Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE _R) Spectral Response Acceleration Parameter at 1-s Period				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	See Section 11.4.7				

Note: Use straight-line interpolation for intermediate values of S_1 .

As mentioned before, the site soil classification is also needed in determining the SDC. In ASCE 7-10, there is a total of six soil site classes. These are designated by A, B, C, D, E and F. Where “A” is used to define the best type of soil while “F” is for the worst type of soil. In order to decide the soil type, three conditions are needed to be checked. These are the determination of $\bar{v}_s$, $\bar{N}$ or $\bar{N}_{ch}$, and $\bar{s}_u$ (see *Table 3.11*).

Table 3.11. Site Classification* in ASCE 7/10[4]

Site Class	$\bar{v}_s$	$\bar{N}$ or $\bar{N}_{ch}$	$\bar{s}_u$
A. Hard rock	>5,000 ft/s	NA	NA
B. Rock	2,500 to 5,000 ft/s	NA	NA
C. Very dense soil and soft rock	1,200 to 2,500 ft/s	>50	>2,000 psf
D. Stiff soil	600 to 1,200 ft/s	15 to 50	1,000 to 2,000 psf
E. Soft clay soil	<600 ft/s	<15	<1,000 psf
	Any profile with more than 10 ft of soil having the following characteristics: —Plasticity index $PI > 20$, —Moisture content $w \geq 40\%$, —Undrained shear strength $\bar{s}_u < 500$ psf		
F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.3.1		

* For SI: 1 ft/s : 0.3048 m/s ; 1 lb/ft² : 0.0479 kN/m²

“where;

$\bar{v}_s$ = Average Shear Wave Velocity

$\bar{N}$ or $\bar{N}_{ch}$ = Average Field Standard Penetration Resistance, Average Standard Penetration Resistance for Cohesionless Soil Layers

$\bar{s}_u$ = Average Undrained Shear Strength”

The soil parameters used in the analyses conducted according to TEC 07 are given in *Table 3.4*. According to the table, there are four local site classes in the TEC 07. In this study, the physical characteristics of these soil classes are tried to be simulated to find its match in ASCE 7-10 standard. Therefore, the three conditions are used as key parameters in defining the associated soil type in ASCE 7-10. As stated before, the three local site classes from TEC 07 are Z1, Z2 and Z3. As listed in *Table 3.4*, the soil group A is assumed to be the soil in Z1, the soil group B is in Z2 and the soil group C is in Z3. The equivalent soil for both A and B in ASCE 7-10 is determined as site class C. The soil group C, on the other hand, is found to be best represented by site class D in the American standard.

b) Design Response Spectrum

The response spectrum indicates the response of any single degree of freedom system subject to a dynamic movement such as an earthquake. Chapter 11.4.5 in ASCE 7-10 covers the details of how to construct a design response spectrum. *Figure 3.3* illustrates a typical design response spectrum and its key parameters. In

the following text, these parameters will be identified and the associated equations will be provided.

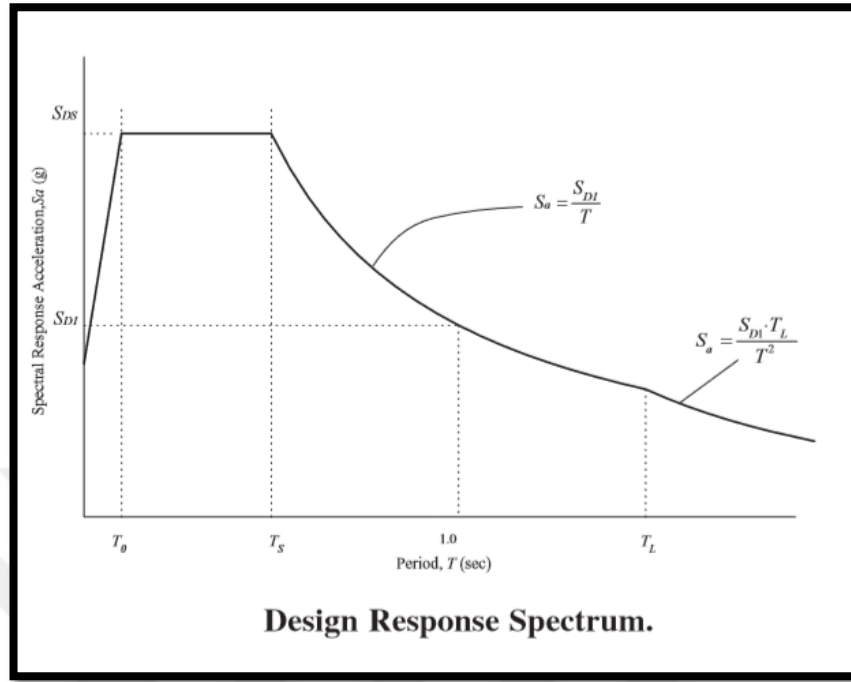


Figure 3.3. Design Response Spectrum in ASCE 7/10 [4]

According to ASCE 7-10

- For periods less than T_0 , the design spectral response acceleration, S_a , shall be determined according to Eq. 3.9

$$S_a = S_{DS} \left(0.4 + 0.6 \frac{T}{T_0} \right) \quad (3.9)$$

- For periods greater than or equal to T_0 and less than or equal to T_S , the design spectral response acceleration, S_a , shall be determined equal to S_{DS} .
- For periods greater than T_S , and less than or equal to T_L , the design spectral response acceleration, S_a , shall be determined as given in Eq. 3.10

$$S_a = \frac{S_{DS1}}{T} \quad (3.10)$$

- For periods greater than T_L , S_a shall be taken as provided in Eq. 3.11

$$S_a = \frac{S_{DS1} T_L}{T^2} \quad (3.11)$$

The definitions of the parameters in Equations 3.9 through 3.11 as follows:

S_{DS} = The design spectral response acceleration parameter at short periods.

S_{D1} = The design spectral response acceleration parameter at 1 second period.

T = The fundamental period of the structure, second

$$T_0 = 0.2 * \frac{S_{D1}}{S_{DS}}$$

$$T_S = \frac{S_{D1}}{S_{DS}}$$

T_L = Long-period transition period (There are maps provided in ASCE 7-10 defining what T_L is, see *Figure 3.4* for the west coast of the US)



Figure 3.4. Long-Period Transition Period (second) in ASCE 7/10 [4]

The T_L is a parameter used to calculate the long-period as part of the design response spectrum. In the hazard maps prepared by the United States Geological Survey (USGS) the periods are designed for 0, 0.1, 0.2, 0.3, 0.5, 1.0 and 2.0 seconds.

3.2.1.4c. Structural Design Actions (NZS 1170.5:2004)

This standard is prepared by the technical committee members from New Zealand and Australia, and is named “Earthquake Actions NZS 1170.5:2004”. In this standard, section 3 which is entitled as “Site Hazard Spectra” defines the procedure how to construct elastic site spectra. In order to construct elastic site spectra the following parameters are needed (a) site subsoil class, (b) hazard factor, (c) near-fault distance and (d) return period factor. As stated in section 3.2.1.4b, the objective in this study is to produce a design response spectrum similar to the one in TEC 07. Therefore, the parameters used in the NZ standard selected in a way that the spectrum forces are closely simulated to those generated in TEC 07. The following subsections cover the details of the parameters used in elastic site spectra.

a) Site Subsoil Class

In the standard, four types of site classification methods are presented. The following text is from the standard and it describes what a subsoil class is [4]:

- 1) From site periods based on four times the shear-wave travel-time through material from the surface to underlying rock.
- 2) From borelogs including measurement of geotechnical properties or by evaluation of site periods from Nakamura ratios or from recorded earthquake motions.
- 3) From boreholes with descriptors but no geotechnical measurements.
- 4) From surface geology and estimates of the depth to underlying rock.

In the NZ standard the site subsoil class is divided into five groups starting from Class A to Class E (see *Table 3.12*). In order to have a soil conditions as close as possible to the one chosen in TEC 07, class C is selected as the site class is in the NZ standard. Again this site class C is a best fit to match the physical properties of the three soil groups, namely A, B and C in TEC 07.

Table 3.12. Site Subsoil Class in NZS [5]

<i>Class A – Strong rock</i> Class A is defined as strong to extremely-strong rock with: (a) Unconfined compressive strength greater than 50 MPa; and (b) An average shear-wave velocity over the top 30 m greater than 1500 m/s; and (c) Not underlain by materials having a compressive strength less than 18 MPa or a shear-wave velocity less than 600 m/s. <i>Class B – Rock</i> Class B is defined as rock with: (a) A compressive strength between 1 and 50 MPa; and (b) An average shear-wave velocity over the top 30 m greater than 360 m/s; and (c) Not underlain by materials having a compressive strength less than 0.8 MPa or a shear-wave velocity less than 300 m/s. A surface layer of no more than 3 m depth of highly-weathered or completely-weathered rock or soil (a material with a compressive strength less than 1 MPa) may be present. <i>Class C – Shallow soil sites</i> Class C is defined as sites where: (a) They are not class A , class B or class E sites; and (b) The low amplitude natural period is less than or equal to 0.6 s; or (c) Depths of soil do not exceed those listed in Table 3.2. The low amplitude natural period may be estimated from four times the shear-wave travel time from the surface to rock, be estimated from Nakamura ratios or from recorded earthquake motions, or be evaluated in accordance with Clause 3.1.3.7 for sites with layered subsoil, according to the hierarchy of methods given in Clause 3.1.3.1. <i>Class D – Deep or soft soil sites</i> Class D is defined as sites: (a) That are not class A , class B or class E sites; and (b) Where low-amplitude natural period is greater than 0.6 s; or (c) With depths of soils exceeding those listed in Table 3.2; or (d) Underlain by less than 10 m of soils with an undrained shear-strength less than 12.5 kPa or soils with SPT N-values less than 6. The low amplitude natural period may be determined in accordance with Clause 3.1.3.4. <i>Class E – Very soft soil sites</i> Class E is defined as sites with: (a) More than 10 m of very soft soils with undrained shear strength less than 12.5 kPa; or (b) More than 10 m of soils with SPT N-values less than 6; or (c) More than 10 m depth of soils with shear-wave velocities of 150 m/s or less; or (d) More than 10 m combined depth of soils with properties as described in (a), (b) and (c) above.

b) Hazard Factor, Z

New Zealand is located at the boundary of Australian and Pacific tectonic plates. Due to its location, New Zealand is a seismic prone country. The severity of the seismic hazards of earthquakes occurring in this country varies from location to location depending on the distance from the active fault lines passing through the country. In order to see the variability of the seismic hazard, “Hazard Factor, Z” needs to be evaluated. *Figure 3.5* and *Figure 3.6* illustrate the Z factors for the northern and southern parts of the island. As shown in the figures, the factor varies from 0.13 to 0.60.

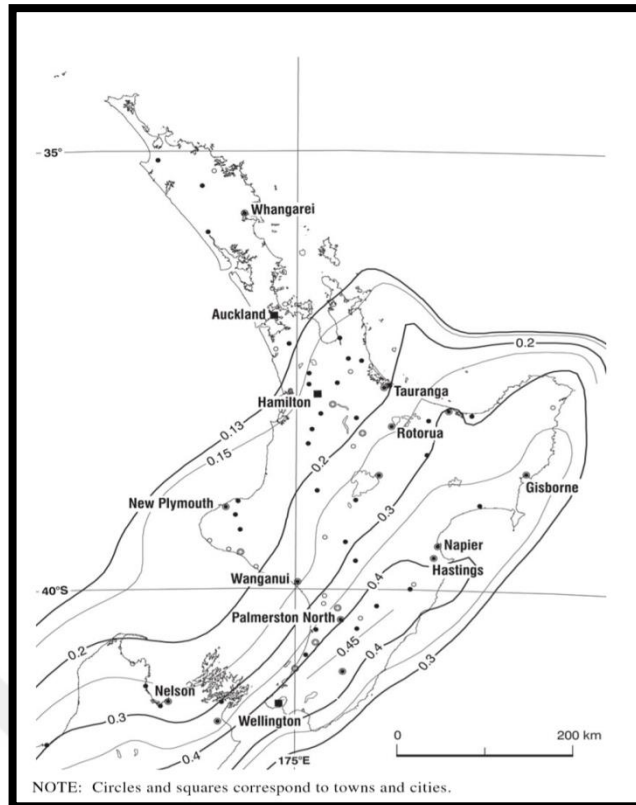


Figure 3.5. Hazard Factor, Z , for the North Island in NZS [5]

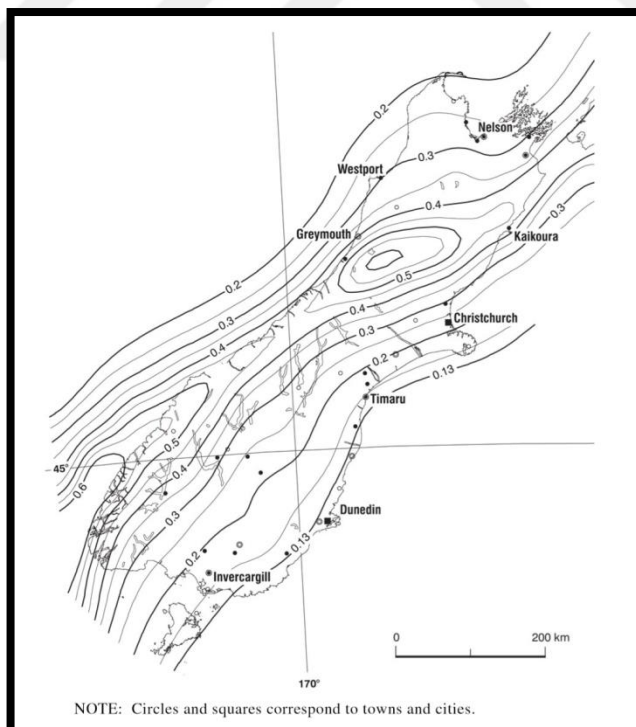


Figure 3.6. Hazard Factor, Z , for the South Island in NZS [5]

c) Return Period Factor, R

There are two types of return period factors in the standard. These are, R_s , which is used for the serviceability limit state and R_u , which is used for the ultimate limit state. The values of R_s and R_u are listed in *Table 3.13* with respect to the annual probability of exceedance.

Table 3.13. Return Period Factor, R, in NZS [5]

Required annual probability of exceedance	R_s or R_u
1/2500	1.80
1/2000	1.70
1/1000	1.30
1/500	1.00
1/250	0.75
1/100	0.50
1/50	0.35
1/25	0.25
1/10	0.20

d) Near Fault Factor, N(T,D)

The near-fault factor, $N(T,D)$, which is a function of period, T and the distance to the nearest fault line, D , can be obtained using Equations 3.12 and 3.13. In these equations, the $N(T,D)$ factor is defined separately for the three types of cases where the distance to the fault line is smaller or equal than 2 km, larger than 2 km but smaller or equal than 20 km, and finally larger than 20 km.

$$N(T,D) = 1.0 \quad (3.12)$$

$$N(T,D) = N_{\max}(T) \quad D \leq 2 \text{ km}$$

$$N(T,D) = 1 + [N_{\max}(T)-1] * \frac{20-D}{18} \quad 2 \text{ km} \leq D \leq 20 \text{ km} \quad (3.13)$$

$$N(T,D) = 1.0 \quad D \geq 20 \text{ km}$$

In which :

D = The shortest distance (in kilometers) from the site to the nearest fault listed in *Table 3.14*.

$N_{\max}(T)$ = The maximum near-fault factor and is linearly interpolated for period T from *Table 3.14*.

Table 3.14 lists the Z and D values for various locations in New Zealand. Therefore, once the location is determined, the Z and D values can be taken directly from this table. Please note that the Z values in this table can also be obtained from the mapped values given in *Figures 3.5* and *3.6*.

In this study, Wellington is selected to be the city that will be investigated for the purpose of constructing a design spectrum. The distance to the major fault line in Wellington varies from zero to eight kilometers as listed in *Table 3.15*. Wellington shows similarities to the location selected in Turkey (İznik, Bursa). İznik, as stated before, is 2 kilometers away from an active fault line.

Table 3.14. Maximum Near-Fault Factors, $N_{\max}(T)$, in NZS [5]

Period, T , [s]	$N_{\max}(T)$
≤ 1.5	1.00
2	1.12
3	1.36
4	1.60
≥ 5	1.72

Table 3.15. Z-Values and Shortest Major Fault Distances, D, in NZS [5]

#	Location	Z	D(km) ¹	#	Location	Z	D(km) ¹
1	Kaitia	0.13	-	48	Raetihi	0.26	-
2	Paihia/Russell	0.13	-	49	Ohakune	0.27	-
3	Kaikohe	0.13	-	50	Waiouru	0.29	-
4	Whangarei	0.13	-	51	Napier	0.38	-
5	Dargaville	0.13	-	52	Hastings	0.39	-
6	Warkworth	0.13	-	53	Wanganui	0.25	-
7	Auckland	0.13	-	54	Waipawa	0.41	-
8	Manakau City	0.13	-	55	Waipukurau	0.41	-
9	Waiuku	0.13	-	56	Taihape	0.33	-
10	Pukekohe	0.13	-	57	Marton	0.30	-
11	Thames	0.16	-	58	Bulls	0.31	-
12	Paeroa	0.18	-	59	Feilding	0.37	-
13	Waihi	0.18	-	60	Palmerston North	0.38	8 – 16
14	Huntly	0.15	-	61	Dannevirke	0.42	10
15	Ngaruawahia	0.15	-	62	Woodville	0.41	≤ 2
16	Morrinsville	0.18	-	63	Pahiatua	0.42	8
17	Te Aroha	0.18	-	64	Foxton/Foxton Beach	0.36	-
18	Tauranga	0.20	-	65	Levin	0.40	-
19	Mount Maunganui	0.20	-	66	Otaki	0.40	-
20	Hamilton	0.16	-	67	Waikanae	0.40	15 – 20
21	Cambridge	0.18	-	68	Paraparaumu	0.40	14 – 20
22	Te Awamutu	0.17	-	69	Masterton	0.42	6 – 10
23	Matamata	0.19	-	70	Porirua	0.40	8 – 12
24	Te Puke	0.22	-	71	Wellington CBD (north of Basin Reserve)	0.40	≤ 2
25	Putaruru	0.21	-	72	Wellington	0.40	0 – 8
26	Tokoroa	0.21	-	73	Hutt Valley–south of Taita Gorge	0.40	0 – 4
27	Otorohanga	0.17	-	74	Upper Hutt	0.42	≤ 2
28	Te Kuiti	0.18	-	75	Eastbourne–Point Howard	0.40	4 – 8
29	Mangakino	0.21	-	76	Wainuiomata	0.40	5 – 8
30	Rotorua	0.24	-	77	Takaka	0.23	-
31	Kawerau	0.29	-	78	Motueka	0.26	-
32	Whakatane	0.30	-	79	Nelson	0.27	-
33	Opotiki	0.30	-	80	Picton	0.30	16
34	Ruatoria	0.33	-	81	Blenheim	0.33	0 – 5
35	Murupara	0.30	-	82	St Arnaud	0.36	≤ 2
36	Taupo	0.28	-	83	Westport	0.30	-
37	Taumarunui	0.21	-	84	Reefton	0.37	-
38	Turangi	0.27	-	85	Murchison	0.34	-
39	Gisborne	0.36	-	86	Springs Junction	0.45	3
40	Wairoa	0.37	-	87	Hammer Springs	0.55	2 – 6
41	Waitara	0.18	-	88	Seddon	0.40	6
42	New Plymouth	0.18	-	89	Ward	0.40	4
43	Inglewood	0.18	-	90	Cheviot	0.40	-
44	Stratford	0.18	-				
45	Opunake	0.18	-				
46	Hawera	0.18	-				
47	Patea	0.19	-				

#	Location	Z	D(km) ¹	#	Location	Z	D(km) ¹
91	Greymouth	0.37	-	111	Cromwell	0.24	-
92	Kaikoura	0.42	12	112	Wanaka	0.30	-
93	Harihari	0.46	4	113	Arrowtown	0.30	-
94	Hokitika	0.45	-	114	Alexandra	0.21	-
95	Fox Glacier	0.44	≤ 2	115	Queenstown	0.32	-
96	Franz Josef	0.44	≤ 2	116	Milford Sound	0.54	-
97	Otira	0.60	3	117	Palmerston	0.13	-
98	Arthurs Pass	0.60	12	118	Oamaru	0.13	-
99	Rangiora	0.33	-	119	Dunedin	0.13	-
100	Darfield	0.30	-	120	Mosgiel	0.13	-
101	Akaroa	0.16	-	121	Riverton	0.20	-
102	Christchurch	0.22	-	122	Te Anau	0.36	-
103	Geraldine	0.19	-	123	Gore	0.18	-
104	Ashburton	0.20	-	124	Winton	0.20	-
105	Fairlie	0.24	-	125	Balclutha	0.13	-
106	Temuka	0.17	-	126	Mataura	0.17	-
107	Timaru	0.15	-	127	Bluff	0.15	-
108	Mt Cook	0.38	-	128	Invercargill	0.17	-
109	Twizel	0.27	-	129	Oban	0.14	-
110	Waimate	0.14	-				

1 The near-fault factor N(T,D) shall be considered for locations with the distance D to the nearest major fault specified

e) Elastic Site Spectra

The goal in section 3.2.1.4c is to construct an elastic site spectrum. The parameters required for this goal are already discussed with their values in the previous subsections. In the New Zealand standard the evaluation of site hazard spectrum for horizontal loading, $C(T)$, for a given return period can be calculated by using Equation 3.14 :

$$C(T) = C_h(T) * Z * R * N(T,D) \quad (3.14)$$

where :

$C_h(T)$ = The spectral shape factor (see *Figures 3.7 and 3.8*)

Z = The hazard factor

R = The return period factor R_S or R_U

$N(T,D)$ = The near-fault factor

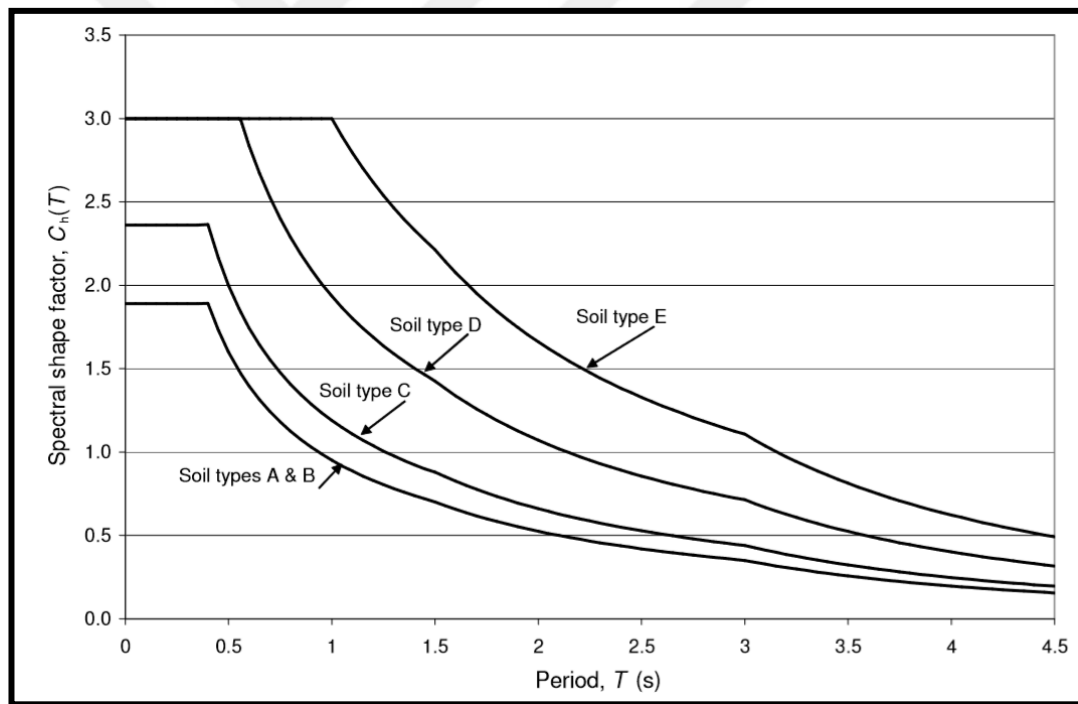


Figure 3.7. Spectral Shape Factor, $C_h(T)$ in NZS [5]

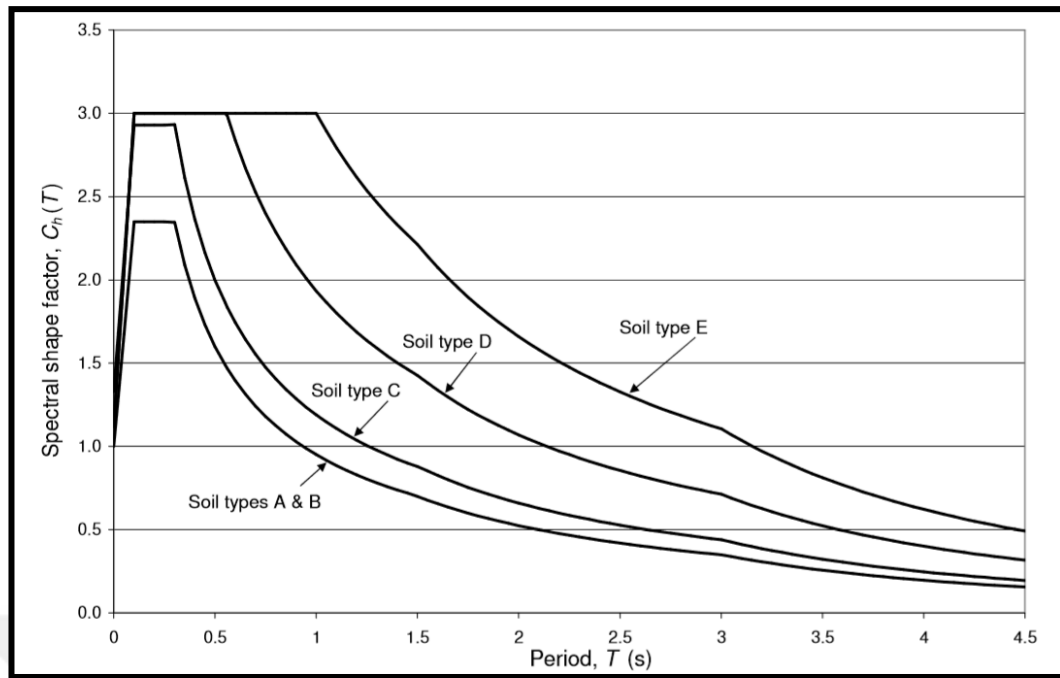


Figure 3. 8. Spectral Shape Factor, $C_h(T)$ for Modal Analysis in NZS [5]

The values given in Figure 3.8 correspond to spectral values required for modal response spectrum and the numerical integration time history methods. In this study, as stated before, Wellington is selected to be the city for the construction of elastic site spectrum. The magnitudes of the specific parameters used in NZS are as follows: $Z = 0.45$, $R = 1.8$, $D = 2$ km and Site Subsoil Class is C.

3.2.1.4d. Eurocode 8 (EC-8)

Eurocode is a set of combined technical rules created by a special committee, called European Committee for Standardization (ECS), for designing structures and related works in boundary of European Union. From 1990 to nowadays, ten separated specifications have been developed and published. These publications are as follows:

- EN 1990 : Basis of structural design
- EN 1991 (Eurocode 1) : Actions on structures
- EN 1992 (Eurocode 2) : Design of concrete structures
- EN 1993 (Eurocode 3) : Design of steel structures
- EN 1994 (Eurocode 4) : Design of composite steel and concrete structures
- EN 1995 (Eurocode 5) : Design of timber structures
- EN 1996 (Eurocode 6) : Design of masonry structures

- EN 1997 (Eurocode 7) : Geotechnical design
- EN 1998 (Eurocode 8) : Design of structures for earthquake resistance
- EN 1999 (Eurocode 9) : Design of aluminum structures

Eurocode 8 (EC-8), which is the standard used in this study, is divided into six different sections. These sections and their descriptions are as follows:

- EN1998-1 : General rules, seismic actions and rules for buildings
- EN1998-2 : Bridges
- EN1998-3 : Assessment and retrofitting of buildings
- EN1998-4 : Silos, tanks and pipelines
- EN1998-5 : Foundations, retaining structures and geotechnical aspects

In this study, EN 1998 (Eurocode 8) which is entitled “Design of structures for earthquake resistance (EC-8)” and subsection EN 1998-1 which is entitled “General rules, seismic actions and rules for buildings” used in analyzing the prototype buildings based on the seismic forces. The section 3 in EC-8 explains ground type and seismicity and its title is called “Ground conditions and seismic action”.

In EC-8, ground types are divided into 7 different groups. These groups are labeled as A, B, C, D, E, S_1 and S_2 . The parameters of these ground types are provided in *Table 3.16*.

Table 3.16. Ground Types and Parameters in EC-8 [6]

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800	—	—
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterised by a gradual increase of mechanical properties with depth	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $v_s > 800$ m/s			
S_1	Deposits consisting – or containing a layer at least 10 m thick – of soft clays/silts with high plasticity index (PI > 40) and high water content	< 100 (indicative)	—	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			

As explained in TEC 07, three separate soil types are used in this thesis. These soil types are soil type A for soil group Z1, soil type B for soil group Z2, and soil type C for soil group Z3. Similar soil properties that are selected in TEC 07 are tried to be simulated in EC-8 as well. For this purpose, the soil parameters in TEC 07 are tried to be matched to those in EC-8. Therefore, soil type A in TEC 07 is represented by the ground type B in EC-8, soil type B in TEC 07 is represented by the ground type C in EC-8, and finally the soil type C in TEC 07, again, is represented by the ground type C in EC-8.

The reference peak ground acceleration, for each seismic zone is provided by the committee, corresponding to the reference return period T_{NCR} (for the no-collapse requirement or equivalently the referenced probability of exceedance in 50 years, P_{NCR}). According to this reference return period, the importance class is III, and the importance factor, γ_I , for residential units is 1.0 (see Table 3.17).

Table 3.17. Importance classes of buildings in EC-8* [6]

Importance class	Buildings
I	Buildings whose integrity during earthquakes is of vital importance for civil protection, e.g. hospitals, fire stations, power plants, etc.
II	Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institutions etc.
III	Ordinary buildings, not belonging to the other categories
IV	Buildings of minor importance for public safety, e.g. agricultural buildings, etc.

*The recommended values of γ_I for importance classes I, II and IV are equal to 1.4, 1.2 and 0.8. For importance class III, γ_I is recommended as 1.0.

In EC-8, there are two types of elastic spectrum curves. These curves are the elastic response spectrum, and the elastic design spectrum curves. In the following text, first the elastic response spectrum and then the design spectrum will be studied.

The elastic response spectrum $S_e(T)$ as illustrated in *Figure 3.9* is formulated as follows in terms of a_g as follows:

$$0 \leq T \leq T_B \quad S_e(T) = a_g * S * \left[1 + \frac{T}{T_B} * (\eta * 2,5 - 1)\right] \quad (3.15)$$

$$T_B \leq T \leq T_C \quad S_e(T) = a_g * S * \eta * 2,5 \quad (3.16)$$

$$T_C \leq T \leq T_D \quad S_e(T) = a_g * S * \eta * 2,5 * \frac{T_C}{T} \quad (3.17)$$

$$T_D \leq T \leq 4s \quad S_e(T) = a_g * S * \eta * 2,5 * \frac{T_C T_D}{T^2} \quad (3.18)$$

where :

$S_e(T)$ = Elastic response spectrum

T = Vibration period of a linear single-degree-of-freedom system

a_g = Design ground acceleration on type A ground ($a_g = \gamma_I \cdot a_{gR}$)

a_{gR} = Reference peak ground acceleration on type A ground

T_B, T_C = Limits of the constant spectral acceleration branch

T_D = Value defining the beginning of the constant displacement response range of the spectrum

S = Soil factor

η = Damping correction factor with reference value $\eta = 1$ for 5% viscous damping

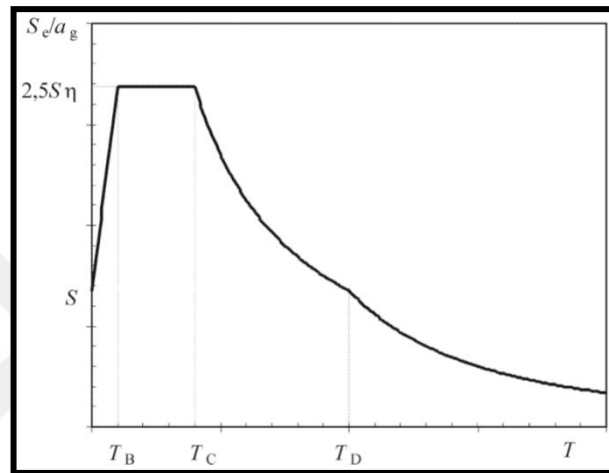


Figure 3.9. Shape of Elastic Response Spectrum in EC-8 [6]

In EC-8, the elastic response spectrum is divided into two different types. Type 1 and Type 2. If the surface wave magnitude, M_S , is greater than or equal to 5,5, type 1 (see *Table 3.18* and *Figure 3.10*) is recommended to be used, otherwise, type 2 (see *Table 3.19* and *Figure 3.11*) is recommended. As listed in *Table 3.18*, the specific period values for T_B , T_C and T_D are given with respect to ground types and soil factors. According to this data, lower the quality of soil the lower the elastic response spectrum values become, and higher the quality of soil, the higher the elastic response spectrum values become.

Table 3.18. Parameters for Type 1 in EC-8 [6]

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,15	0,4	2,0
B	1,2	0,15	0,5	2,0
C	1,15	0,20	0,6	2,0
D	1,35	0,20	0,8	2,0
E	1,4	0,15	0,5	2,0

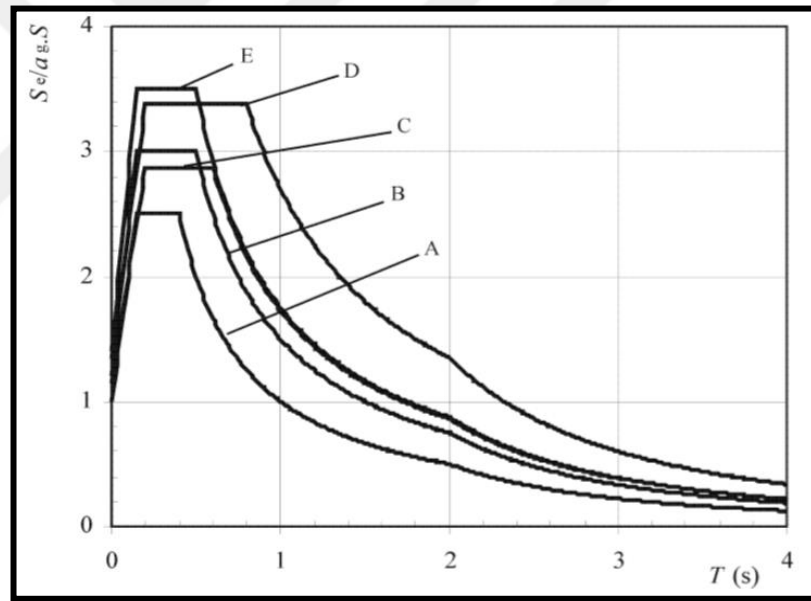


Figure 3.10. Recommended Type 1 Elastic Response Spectrum in EC-8 [6]

As similar to the explanation provided for Type 1 elastic response spectrum, Type 2 elastic response spectrum values are given below. It is important to emphasize that the higher the magnitude of earthquake, the higher the soil factor is since higher elastic response spectrum is to be produced.

Table 3.19. Parameters for Type 2 in EC-8 [6]

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,05	0,25	1,2
B	1,35	0,05	0,25	1,2
C	1,5	0,10	0,25	1,2
D	1,8	0,10	0,30	1,2
E	1,6	0,05	0,25	1,2

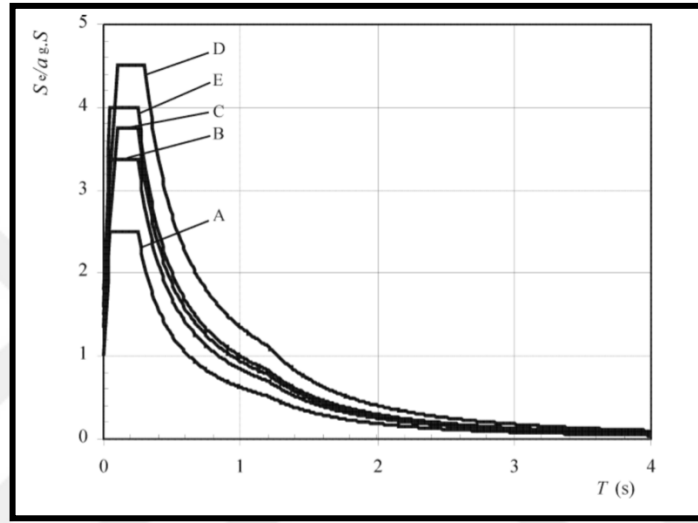


Figure 3.11. Recommended Type 2 Elastic Response Spectrum in EC-8 [6]

In EC-8, the design spectrum for elastic analysis, $S_d(T)$, is formulated as follows :

$$0 \leq T \leq T_B \quad S_d(T) = a_g * S * \left[\frac{2}{3} + \frac{T}{T_B} * \left(\frac{2,5}{q} - \frac{2}{3} \right) \right] \quad (3.19)$$

$$T_B \leq T \leq T_C \quad S_d(T) = a_g * S * \frac{2,5}{q} \quad (3.20)$$

$$T_C \leq T \leq T_D \quad S_d(T) = a_g * S * \frac{T_C}{T} * \frac{2,5}{q} \quad (3.21)$$

$$S_d(T) \geq \beta * a_g$$

$$T_D \leq T \quad S_d(T) = a_g * S * \frac{2,5}{q} * \frac{T_C T_D}{T^2} \quad (3.22)$$

$$S_d(T) \geq \beta * a_g$$

“where:

$S_d(T)$ = Design spectrum

q = Behaviour factor

β = Lower bound factor for the horizontal design spectrum”

In this study, no specific location is selected since the goal of this research is to simulate similar earthquake design conditions to those from TEC 07. Therefore, earthquake parameters in Messina, Italy are similar to those generated in TEC 07. In the structural analyses of the buildings, the following parameters are used to construct an elastic design spectrum.

Design Ground Acceleration, $a_g = 0.4$

Spectrum Type = 1

Ground Type = B (Type A in TEC 07) , C (Type B and C in TEC 07)

Lower Bound Factor, $\beta = 0.2$

Behaviour Factor, $q = 4.32$

3.2.2. Load Combination

Since the scope of this study is to evaluate the analyses results to determine irregularities on buildings, the design part is not included. Therefore, no load combinations are used in this thesis.

3.3. Description of Buildings

In this study, three types of non-symmetrical and L-shaped buildings are selected. The reason for non-symmetrical L-shaped buildings is to produce irregularities both in plan and elevation. For this purpose, three layouts A, B and C are selected. *Figure 3.12* illustrates the in-plane dimensions and the floor layouts for these three layouts. As shown in *Figure 3.12*, the floor plans for each layout changes as the number of floors increase. For example, in layout A, the building starts with a 36 meter by 24 meter L-shaped layout and first gets reduced to a 36 meter by 24 meter rectangular layout at 15th and then to a 24 meter by 18 meter rectangular layout at 19th floor. By changing the floor sizes, the intention is to capture the in-plane

irregularities more effectively. As for the in-plane dimensions, floor-to-floor heights are also studied as an additional parameter in searching for the vertical irregularity. Each layout is analyzed for two types of floor heights. For example, layout A is divided into two parts, and they are called A1 and A2. This labeling is valid for layouts B and C as well. In this notation the number 1, next to layout label indicates a constant floor-to-floor height of 3,2 meters. The number 2, however, indicates varying floor heights. In this case, the first and the last four floor heights are increased from 3,2 meters to 4,5 meters while the rest are kept at 3,2 meters. The total height of buildings labeled with number 1 is 64 meters and the buildings with number 2 is 74,4 meters. The main difference among layouts A, B and C is on the opening sizes and the wall configurations. As illustrated in *Figure 3.12*, by changing the opening sizes and the wall configurations, specifically the torsional behavior and diaphragm flexibilities of buildings are intended to be studied. Therefore, these layouts are selected not for the practical purpose but rather for the purpose of capturing the behaviors of irregularities. All buildings in this study are assumed to have equal number of basement floors. Therefore, in each layout, the bottom two floors are enclosed by basement walls along the perimeter of the buildings. Also, in order to simulate a real case scenario that might be anticipated right above the first basement floor (e.g. ground floor ceiling) which is the entrance to the building, the slab around the openings are removed from the models as shown in *Figure 3.13*, through *Figure 3.20* for layouts for A, B and C.

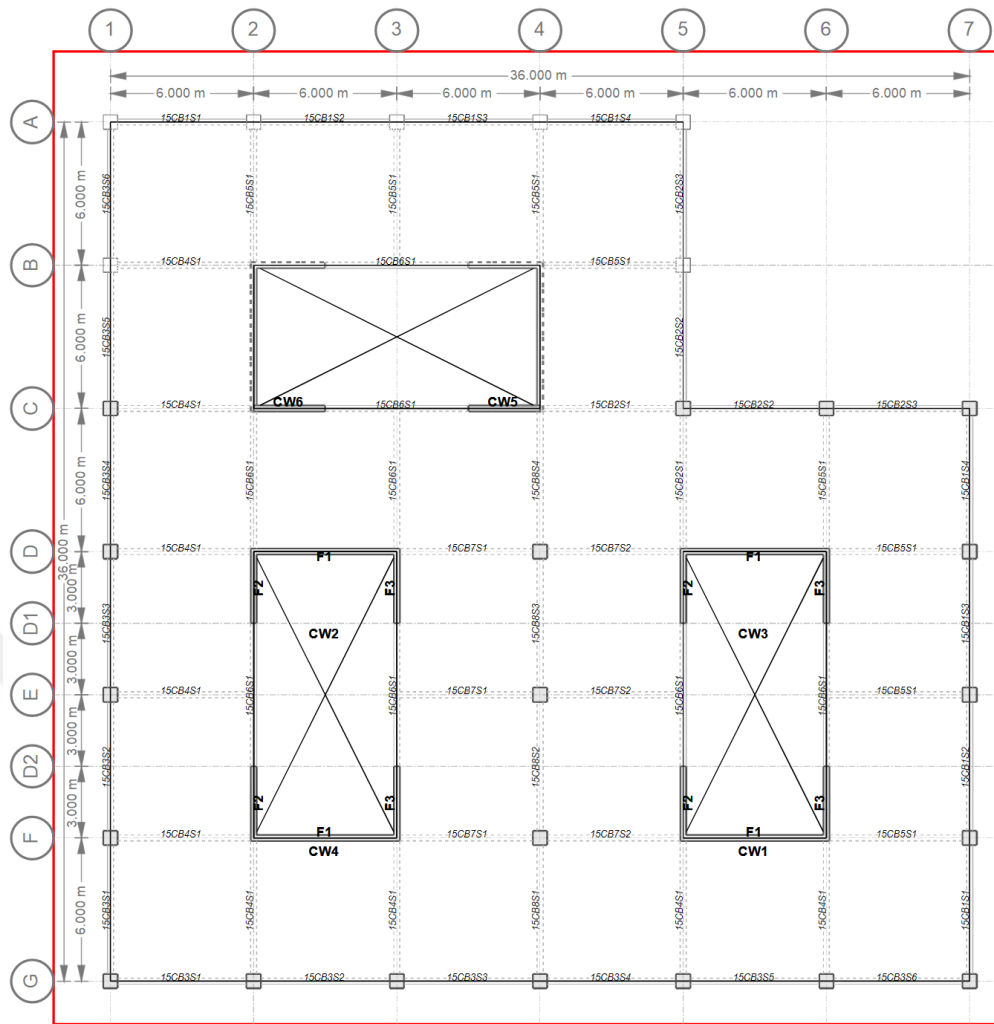


Figure 3.12. Layout A: Floor 1 to 14

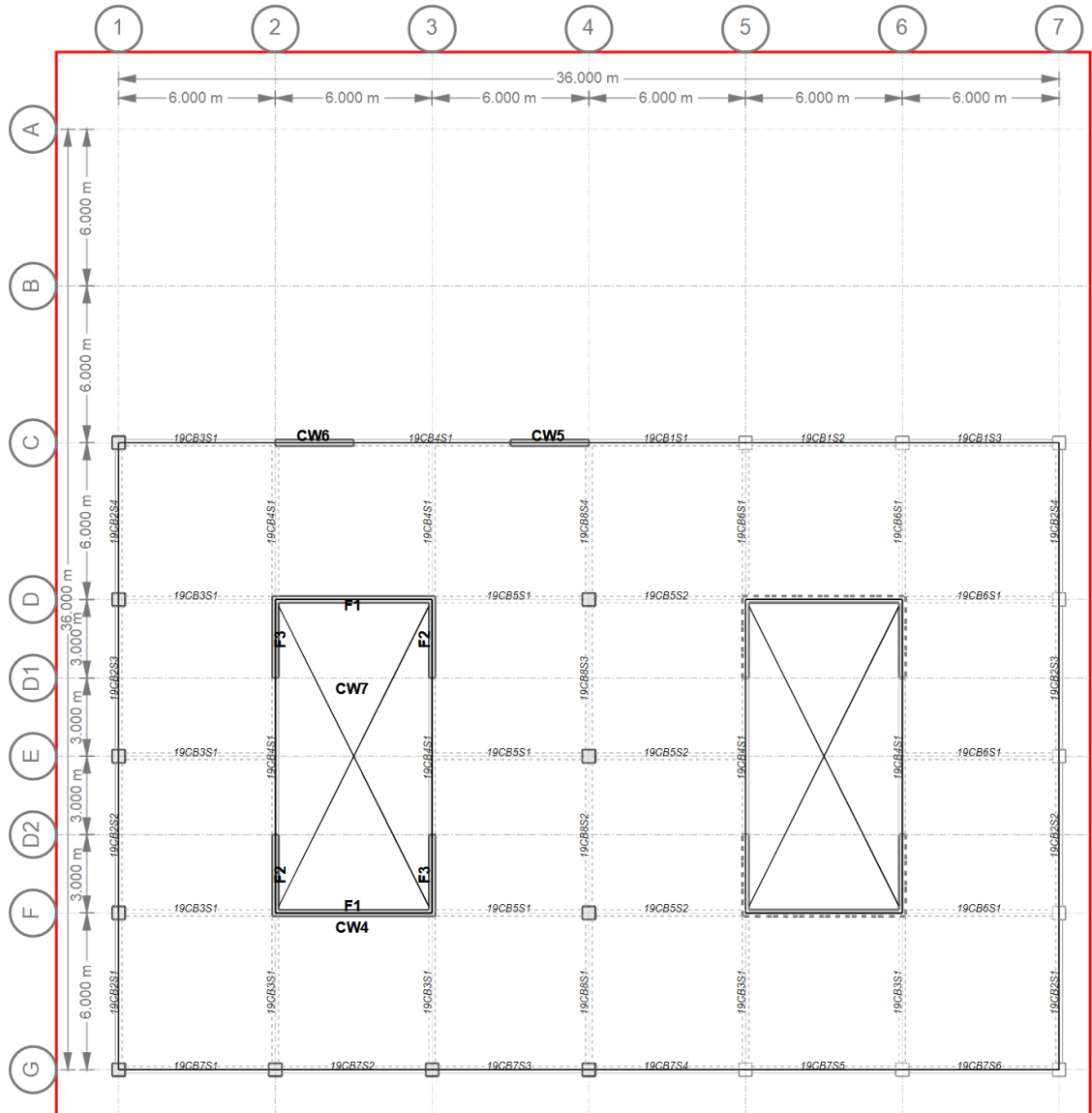


Figure 3.13. Layout A: Floor 15 to 18

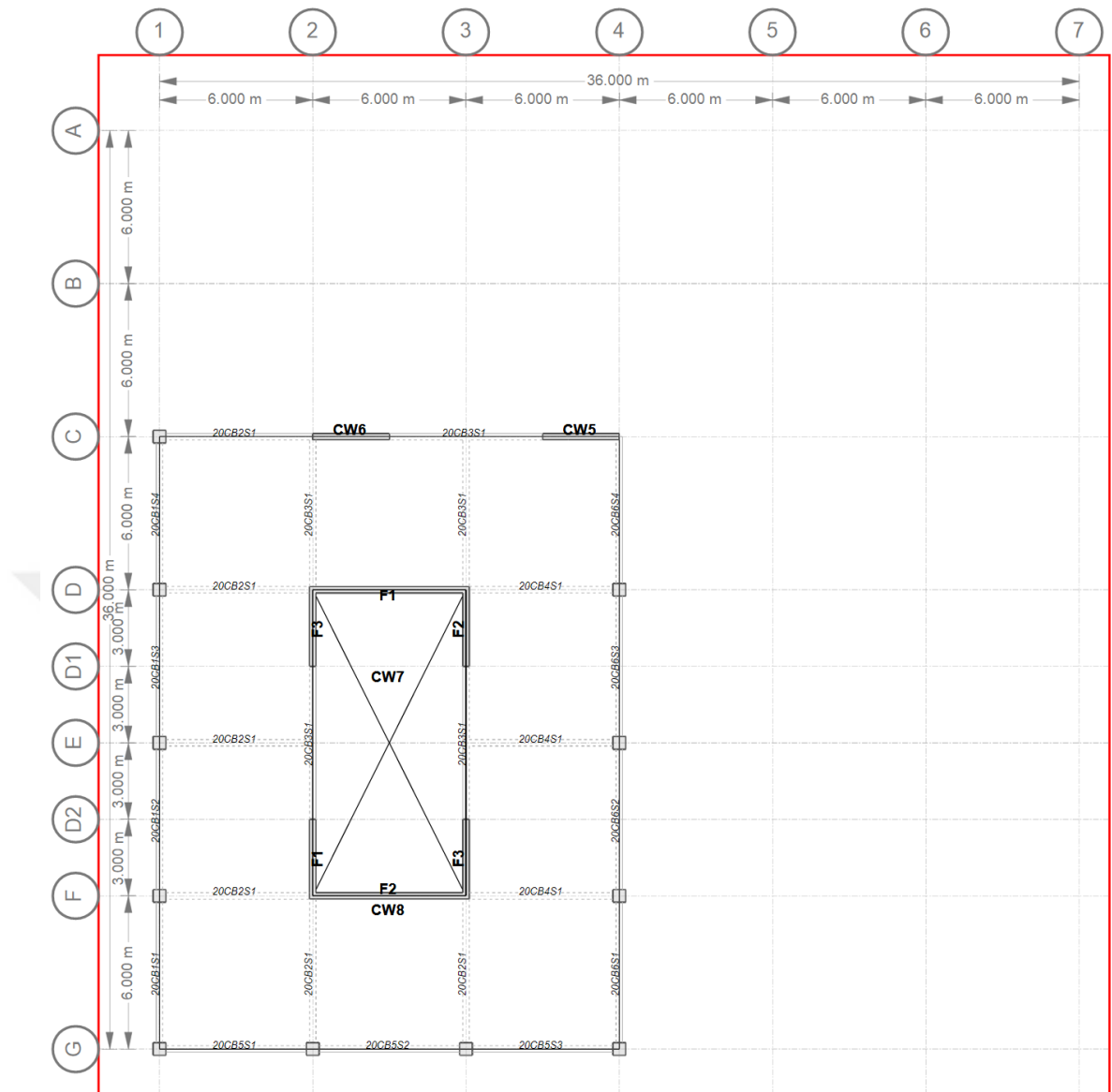


Figure 3.14. Layout A: Floor 19 to 20

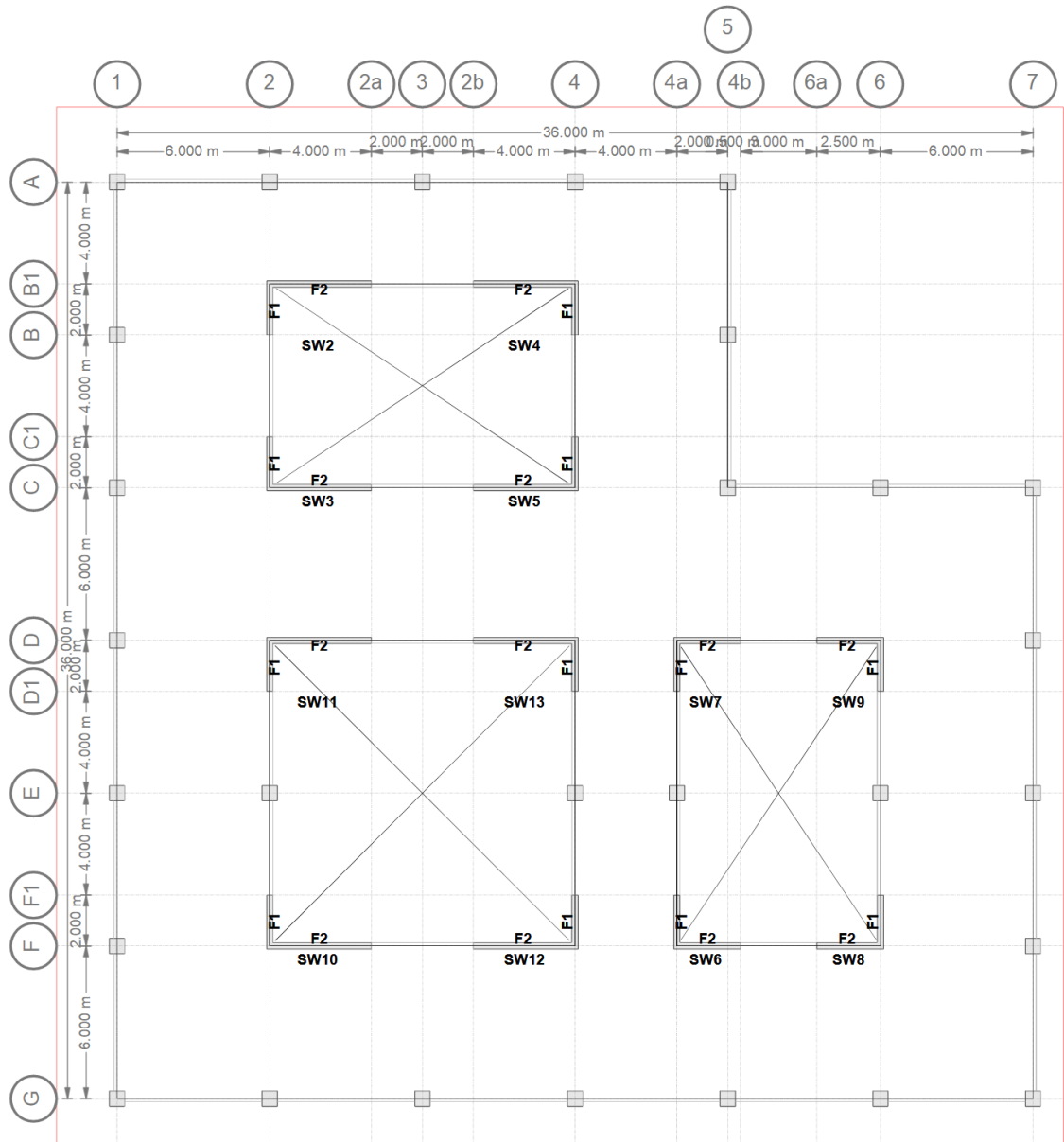


Figure 3.15. Layout B: Floor 1 to 14

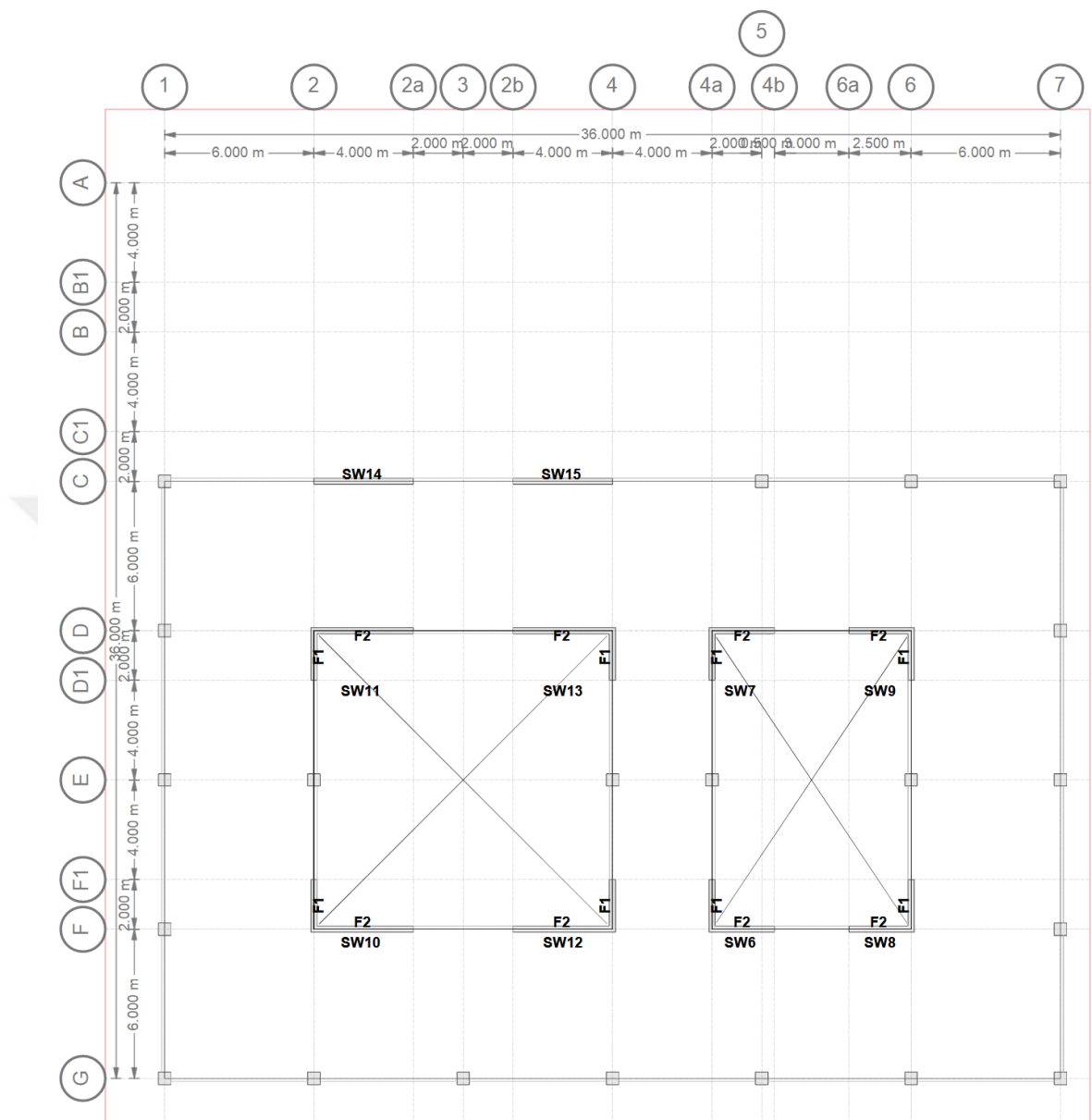


Figure 3.16. Layout B: Floor 15 to 18

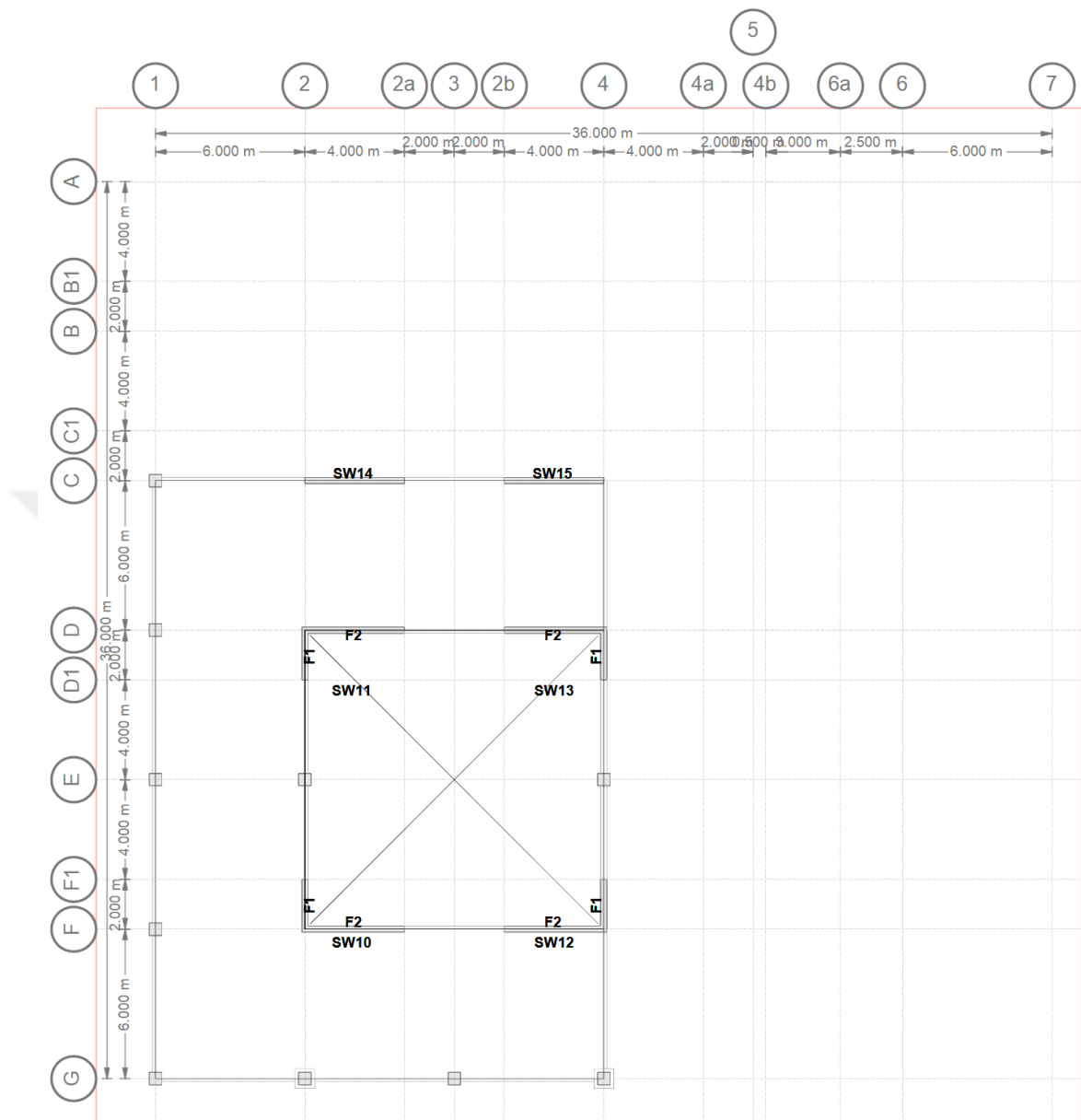


Figure 3.17. Layout B: Floor 19 to 20

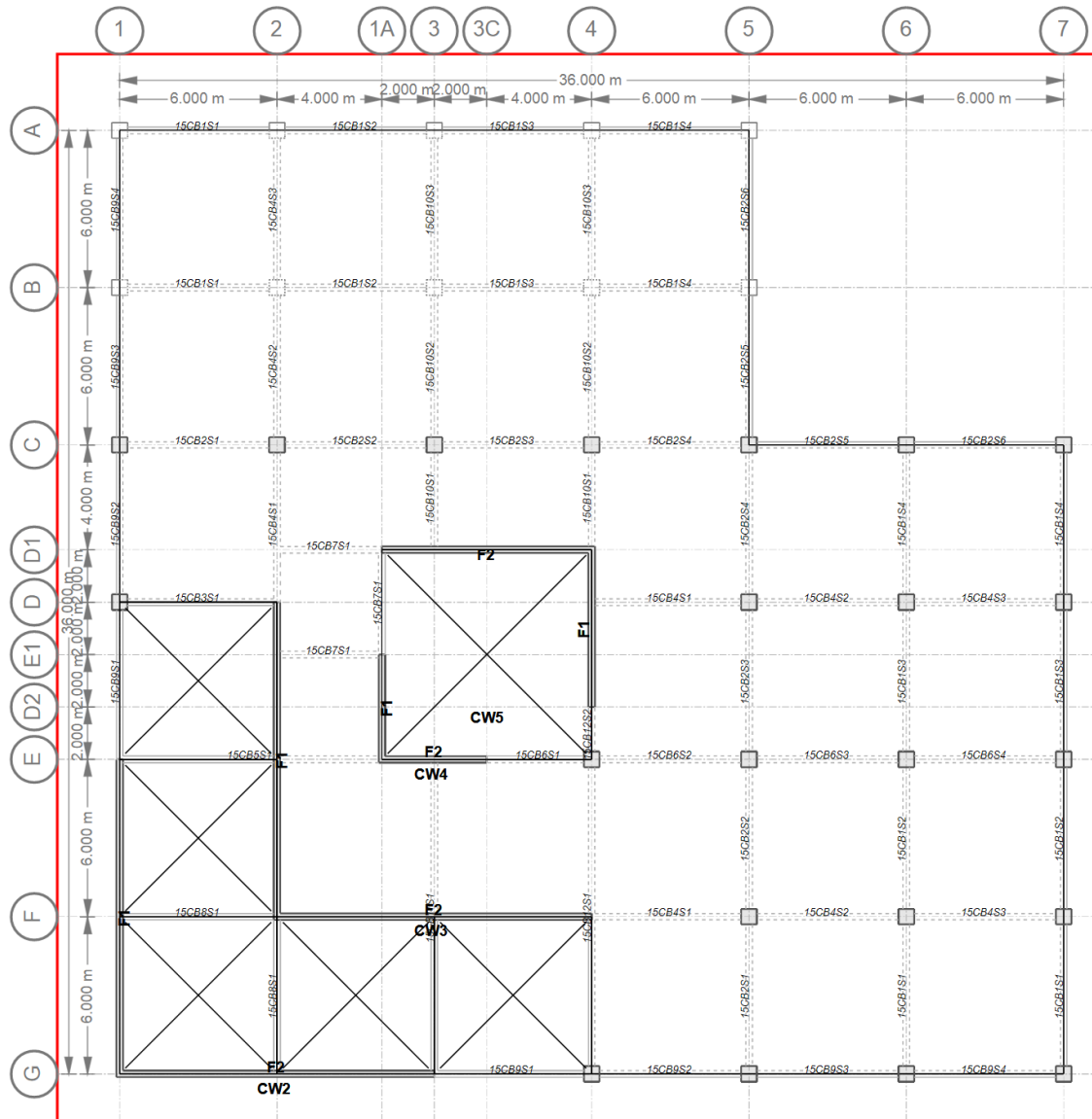


Figure 3.18. Layout C: Floor 1 to 14

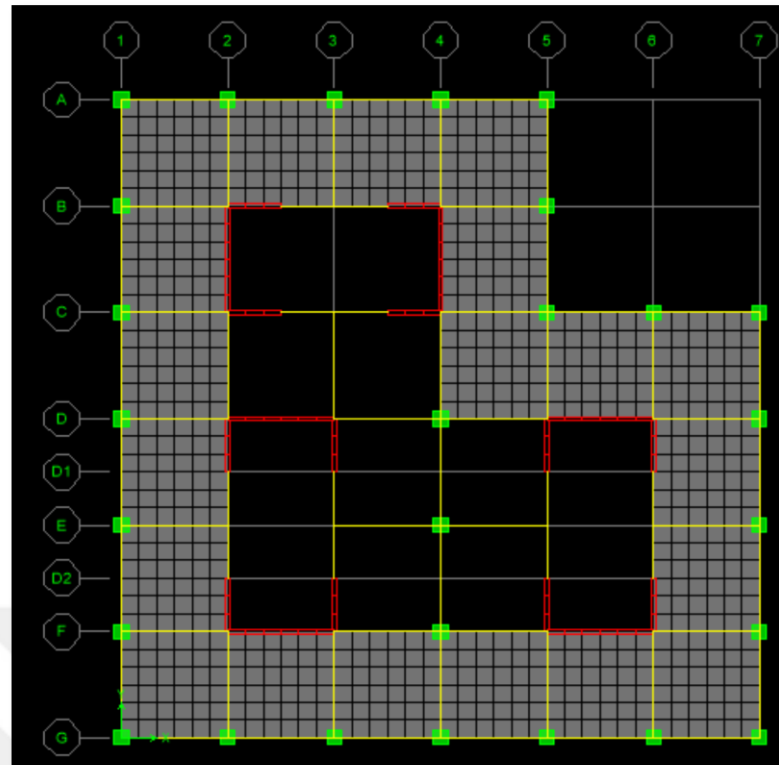


Figure 3.21. Openings in Layout A in 3rd Floor

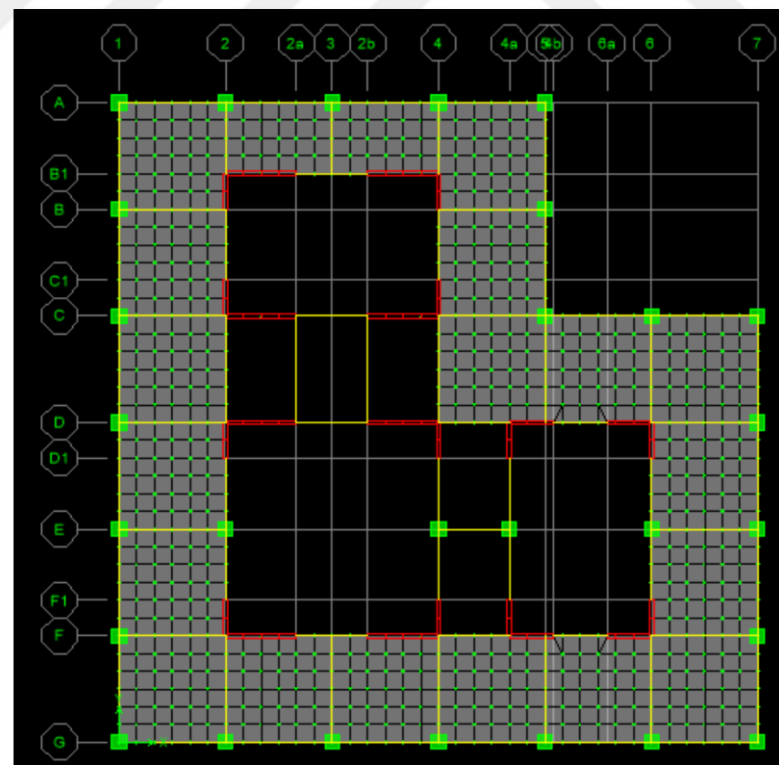


Figure 3.22. Openings in Layout B in 3rd Floor

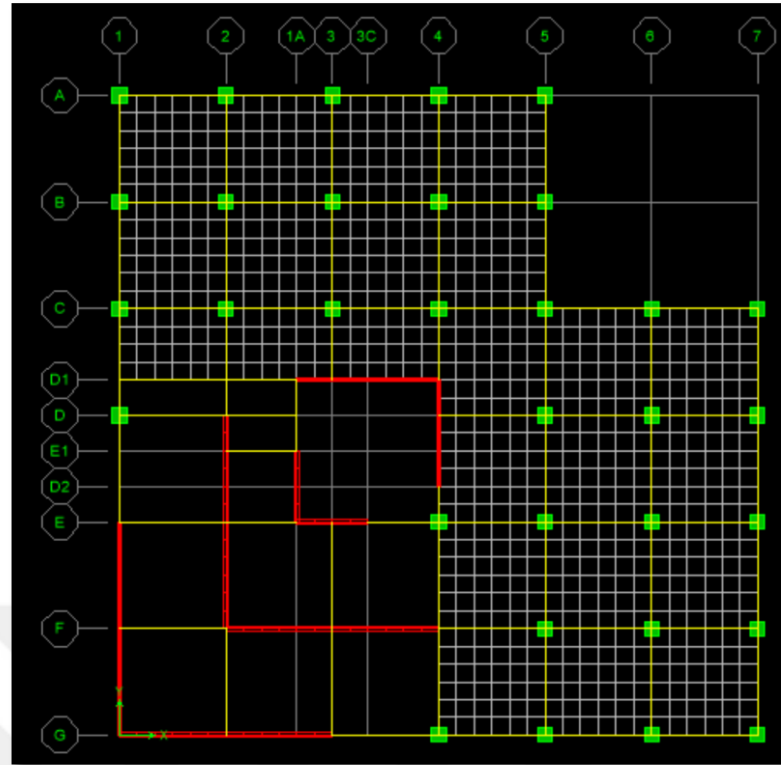


Figure 3.23. Openings in Layout C in 3rd Floor

Thus, a high ceiling is achieved at the main entrance of each building. Although the slab at the second floor level (in other words, right above the two basement floors) is removed, the beams are left intact to prevent buckling of columns that might occur near the base due to high axial loading.

The dimension of structural members (columns, beams, slabs and shear walls) are listed in *Table 3.20*. The larger six columns are used in the lower five floors, and their sizes are reduced by 10 cm at every five floors. Therefore, for twenty-story buildings, the largest column size is selected to be 80 cm by 80 cm and the smallest one is 50 cm by 50 cm. Unlike the change in column dimension, beam, slabs and shear wall sizes are not modified along the height of each building. The dimensions of structural members are intentionally selected to be slightly larger than their optimized sizes. By doing so, it is intended to eliminate any possibility of member failures. All buildings in this study are assumed to have fixed support cases at their bases, therefore, support types are not studied in this thesis.

Table 3.20. Dimensions of Members

Storey Number	Column (cm)	Beam (cm)	Slab (cm)	Shear Wall (cm)
1 to 5	80x80	25x60	14	25
6 to 10	70x70	25x60	14	25
11 to 15	60x60	25x60	14	25
16 to 20	50x50	25x60	14	25

3.4. Material Properties

As described in Turkish Standards 500 (TS 500) [26] C30, and its concrete class is selected for all structural members and modulus of elasticity is 6,400,000 ton/m². The Poisson's ratio for concrete is assumed to be 0.2 as described in TS 500. In the self-weight calculation, the unit weight of reinforced concrete is assumed to be equal to 2.5 ton/m³. Since the focus of this thesis is not on the design part of structural members, no material properties are assigned to re-bars. Therefore, this designation is not included in the ETABS models.

3.5. Modeling of Building

There are numerous software packages that deal with structural analysis and design of buildings. In this study, ETABS and PROBINA programs are used. PROBINA program is mainly used in Turkey to analyze and design specifically reinforced concrete buildings. The program fully complies with the requirements outlined both in TEC 07 and TS 500. This feature allows us to follow all the limitations and requirements mandated in TEC 07. Also, the program output is used as a reference to compare the results of ETABS so that the results from the two programs can be checked to verify the compatibility between two programs. ETABS is used for all buildings to meet the requirements of four seismic codes and standards (TEC 07, ASCE 7-10, NZS 1170.5:2004 and EC-8).

In this study, the seismic performances of buildings are evaluated using the response spectrum method. The details of the response spectrum curves evaluated

from the four seismic codes and standards are described in the previous sections. Therefore, they will not be restated here again.

Table 3.21 has the list of all model names with respect to different earthquake codes and standards. As stated before, the 18 models listed under TEC 07, are constructed using both PROBINA and ETABS programs. However, the other models from ASCE 7-10, EC-8, and NZS 1170.5:2004 are all constructed in ETABS.

The formatting of each model includes the following logic. The first letter represents the layout. The number next to it, is used to define the floor heights (number 1 is used for equal floor heights of 3,2 meters and number 2 is used for mixed floor heights of 3,2 and 4,5 meters). The abbreviation next to numbers represents the different earthquake codes and standards used in this study. For this purpose “TEC” is used for Turkish Earthquake Code, “ASCE” is used for the American code, “EC-8” is used for the European code, and finally “NZS” is used for the New Zealand Standard. The letter that immediately follows the above abbreviations is used to indicate the soil type in each seismic code. So the explanation for model name A2ASCED is as follows. The first letter “A” represents the layout name. The number “2” next to the letter “A” denotes the height variation in layout “A”. The abbreviation right next to number “2”, which is “ASCE” is used to describe the earthquake code used in this study. Finally, the very last letter “D” indicates the soil type equivalency of the same building designed according to TEC 07. As listed in *Table 3.21*, a total of sixty-six models including the first 18 models modeled both in PROBINA and ETABS are analyzed in this study.

Since the soil types are the most critical parameters in evaluating the results from different seismic codes and standards, more in-depth explanation will be provided to make this comparison more understandable. *Table 3.22* has the list of all soil types and their equivalences with respect to different earthquake codes and standards. As shown in *Table 3.22* three site classes Z1, Z2 and Z3 are defined according to TEC 07 will be used as reference site classes. For each of these site classes, the associated soil groups are selected to be A, B and C. After this selection, similar properties of soil tried to be matched for the other three seismic codes and standards. According to ASCE 7-10, the soil groups A, B and C are represented as “C” and “D” only. Therefore, soil groups A and B in TEC 07 are represented by “C” in ASCE 7-10, and “C” in TEC 07 is represented by “D” in “ASCE 7/10”. Similar comparison is made to match the soil properties of TEC 07 to EC-8. The soil groups

A, B and C in TEC 07 are represented by two ground types “B” and ”C” in EC-8. Therefore, the soil groups A in TEC 07 is represented by ground type “B” in EC-8 and the soil groups B and C in TEC 07 are represented by ground type “C” in EC-8. Finally, the same comparison is made for the NZS 1170.5:2004. Three soil groups A, B and C in TEC 07 are represented by just one soil type called “C” in NZS 1170.5:2004.



Table 3. 21. Model Names

LAYOUT	TEC 07		ASCE 7/10		EC-8		NZS 1170.5:2004	
A	A1TECA A1TECB A1TECC	A2TECA A2TECB A2TECC	A1ASCEC A1ASCED	A2ASCEC A2ASCED	A1EC8B A1EC8C	A2EC8B A2EC8C	A1NZSC	A2NZSC
B	B1TECA B1TECB B1TECC	B2TECA B2TECB B2TECC	B1ASCEC B1ASCED	B2ASCEC B2ASCED	B1EC8B B1EC8C	B2EC8B B2EC8C	B1NZSC	B2NZSC
C	C1TECA C1TECB C1TECC	C2TECA C2TECB C2TECC	C1ASCEC C1ASCED	C2ASCEC C2ASCED	C1EC8B C1EC8C	C2EC8B C2EC8C	C1NZSC	C2NZSC

Table 3. 22. Soil Type Equivalency

TEC 07	ASCE 7/10	EC-8	NZS 1170.5:2004
A(Z1)	C	B	C
B(Z2)		C	
C(Z3)	D		

CHAPTER 4

PARAMETRIC STUDIES AND ANALYSES RESULTS

4.1 Introduction

The goal of this chapter is to explain how models are created, based on the rules and regulations expressed in TEC 07, NZS 1170.5:2004, ASCE 7-10 and EC8, using PROBINA and ETABS.

For this purpose, three different layouts are selected. As discussed before, all buildings are assumed to be located in Iznik, Bursa, Turkey. Iznik is a town situated in the most severe earthquake region, and is close to a major fault line called the North Anatolian Fault Line (NAFL). The seismic behaviors of the location in Turkey are attempted to be simulated in determining three other locations according to ASCE 7/10, NZS and EC-8. The main reason for selecting the most severe earthquake region is linked to attempt to obtain the highest base shear forces. The other reason is attributed to the inclusion of the effect of fault lines into FE calculations. By doing so, severe earthquake zone and nearest fault line parameters that will increase the effects of base shear specifically on irregular buildings are decided to be investigated.

As stated in the previous chapters, this study focuses on creating similar design conditions on buildings with plan and elevation irregularities even if different seismic codes are used. However, it is expected to face with some design discrepancies among seismic codes since each code is one way or another different than the other. It is because of these parameters severe earthquake zone and nearest fault line that earthquake loads generating from different seismic codes can substantially be different, while the aim of this study is to obtain similar earthquake forces to those resulting from TEC 07.

In the seismic design analysis, a total of sixty-six building models are constructed. In each of these models, the response spectrum method is used according to the rules and regulations of the four seismic codes. The response spectrum curves are applied to the buildings separately in the global “x” and “y”

directions. The buildings in Turkey are located in İzmit, Bursa, Turkey. The buildings in the US are located in Daly City, San Francisco, and the ones in Europe are located in Messina, Italy, and finally the ones in New Zealand are located in Wellington.

All buildings in this study are assumed to be residential buildings, and their importance factors are selected according to the regulations outlined in these four seismic codes. The main focus of this study is to determine the effects of structural irregularities for the selected buildings that are subjected to different seismic loads generating from the four seismic codes. Therefore, only load cases are considered (i.e., no load combinations are included in this study) in the structural analyses conducted both in PROBINA and ETABS.

The gravity loads are the key components in a seismic analysis of a building. The self-weight of the structural members are automatically included by the program. As opposed to the dead load, the live loads and the superimposed dead loads, after all, are user assigned loads and are applied as a pressure load to each floor level.

The magnitude of the live loads for all models is assumed to be same. Although the magnitude of live loads varies from room to room depending on its functionality, for the sake of simplicity, a constant live load is assigned to each floor level. In order to maintain the same seismic weight for all buildings modeled according to EC-8, NZS 1170.5:2004 and ASCE 7/10, 350 kgf/m^2 of live load is applied to all models.

According to the four seismic codes, the seismic weight of a building is determined by the combinations of dead and a portion of live loads. The dead load is fully included while only a portion of live load is assumed to exist on floors during an earthquake. The contribution of live load to the total seismic weight varies according to each seismic code. In this study, 30% of the live load is added to the total seismic weight. This participation factor is the same for New Zealand and Turkish seismic codes while the European and American codes show some differences. In ASCE 7/10 according to values in “Chapter 4 – Live Loads: Table 4-1” for “Residential” subsection, the participation factor is calculated 0.4. In EC-8, the participation factor is 0.24 for residential units (but not including roof). However, as

noted in “Table A1.1” of EN 1991-1-1:2002 [27], these values are recommended values and are subject to change by individual countries listed in the code.

In the modeling phase conducted in ETABS and PROBINA, two options exist in defining floor diaphragms. Floor diaphragms can either be modeled as rigid or semi-rigid. Since the focus of the study was not on the diaphragm behavior, rigid diaphragm is selected to simulate the structural behavior of all floor diaphragms. For layouts with multiple openings, it is assumed that the lateral forces are adequately transferred from one part of the opening to the other part. In other words, multiple diaphragms are not considered in this study. All buildings modeled in ETABS and PROBINA are assumed to have fixed supports. Therefore, as in the diaphragm case, no parametric study concerning this parameter is investigated. It is also important to note that the effect of soil-structure interaction that exists in foundation and building design is ignored in this study, as well.

4.2 Parametric Studies

In this chapter, the results of the sixty-six FE models constructed in PROBINA and ETABS are discussed. As mentioned in Chapter 1, the aim here is to understand the effects of irregularities on the overall behavior of buildings resulting from the four seismic codes. Therefore, four key groups are decided to be studied in depth. These groups are as follows: (a) periods, (b) earthquake loads, (c) base shear, and (d) irregularities. In the following subsections, the analyses’ result will be evaluated for each one of these groups.

4.2.1 Periods

In this study, a total of sixty-six models are examined to investigate the dynamic behaviors of buildings. In these analyses, a total of forty-eight models out of sixty-six are constructed in ETABS based on all four seismic codes (TEC 07, ASCE 7/10, NZS 1170.5:2004 and EC-8) while the remaining eighteen models are modeled only in PROBINA. The results of the eighteen models constructed in PROBINA using TEC 07 are compared to those constructed in ETABS using the same seismic code. Table 4.1 has the list of periods for all models based on these seismic codes. In this table, each layout is divided into two columns and they are denoted as A1, A2, B1, B2, C1 and C2. As stated in Section 3.5, the number “1” and “2” next to the letters “A”, “B” and “C” represents the variation in building layout.

Table 4.1. Periods (sec)

SEISMIC CODE	Layout A		Layout B		Layout C	
	A1	A2	B1	B2	C1	C2
TEC 07	1.24	1.39	1.33	1.48	1.22	1.37
ASCE7/10	1.26	1.42	1.35	1.51	1.24	1.40
NZS	1.24	1.39	1.33	1.48	1.22	1.37
EC-8	1.22	1.37	1.31	1.46	1.20	1.35

The fundamental period of a building is the most critical one to evaluate its dynamic response. Depending on a building's mass and its stiffness, the fundamental period represents the dynamic behavior of a building under seismic loads. The fundamental period of a building is directly affected by many factors such as regularity/irregularity, number of floors, members' sizes and their locations, etc. However, there are two key parameters defining the period of a building. They are mass and stiffness. The mass is called seismic mass and is equal to the summation of dead load and a portion of live load at each floor level. The portion of live load is represented by a factor called "Live Load Participation Factor". The value of this participation factor varies for each seismic code. In both TEC 07, and NZS 1170.5:2004 it is 0.3, in ASCE 7/10 the same value is 0.4, and in EC-8 is 0.24. A period of a building is directly proportional to its weight and therefore, the larger the weight, the higher the period becomes. As shown in Table 4.1, the largest periods, therefore are obtained from ASCE 7/10. Since the code has the largest live load participation factor. Similar to this discussion, the smallest periods are obtained from EC-8. Based on the data presented in Table 4.1, for each seismic code, the smallest periods are all obtained from layout C and the largest periods are all obtained from layout B.

4.2.2 Earthquake Loads

Earthquake loads are applied to the buildings using the response spectrum method. Figures 4.1 through 4.4 illustrate the spectrum curves plotted for the four seismic codes. In this study, as stated before the response spectrum curves generated from TEC 07 is taken as a reference in generating the other curves from the other three seismic codes. In this process of generating the curves, some approximations

are needed to be made since the seismic parameters in TEC 07 are somewhat different than the parameters in the other three seismic codes (for further information see Section 3.5).

Figure 4.1 illustrates the spectrum curve plotted according to TEC 07 for three different site classes Z1, Z2 and Z3. The vertical axis in this figure defines the acceleration in “g” (g is the gravitational force), and the horizontal axis defines the periods (T) in seconds. Since the curve is modified according to S(T) and R(T) values, the magnitude of the spectral acceleration at T=0 becomes the largest when compared to the rest of the spectral acceleration values. As expected, as the soil type gets better, the width of the plateau defining the constant acceleration becomes shorter.

The spectrum curve of ASCE 7/10 is plotted in Figure 4.2. In the process of generating this curve, the physical characteristics of soil classes defined in TEC 07 are tried to be simulated as accurately as possible. As discussed in Chapter 3, there are some differences in the parameters required to construct a response spectrum curve according to various seismic codes. These parameters are: (a) soil class, (b) attenuation relations and (c) return period. To overcome this difficulty in eliminating the differences to absolute minimum, the three soil classes of TEC 07 used in this study are tried to be matched to the two corresponding site classes in ASCE 7/10. These site classes are “Class C” and “Class D”. The equivalent soil classes of Z1 and Z2 in TEC 07 are determined to be represented as “Class C”, and the soil class Z3 is represented by “Class D”. In Figure 4.2, the vertical and horizontal axes define the acceleration in “g” and the period (T) in seconds respectively. As shown in the figure, the acceleration value for T=0 is 0.1g for the site classes “Class C” and “Class D”. The maximum acceleration value is recorded 0.26g and it occurs between T=0.1 and 0.6 seconds. As expected, the plateau defining the constant spectral acceleration increased as soil class worsened.

Figure 4.3 displays the response spectrum curve of EC-8. In order to compare the results of EC-8 to those in TEC 07, the physical characteristics of local site classes in TEC 07 are, again, tried to be matched to those in EC-8. As a result of this attempt, the “Ground Type B” of EC-8 is used to represent the local site class Z1 of TEC 07. Similarly, the “Ground Type C” of EC-8 is used to replace the local site

classes Z2 and Z3 of TEC 07. In Figure 4.3, the vertical axis is used for the spectral acceleration value in “g”. The horizontal axis is used for the periods in seconds. As shown in the figure, the curve closely follows the pattern obtained from TEC 07. The maximum spectral acceleration is calculated 0.32g and is obtained when $T=0$ for the “Ground Type B”. As expected, the plateau defining the constant spectral acceleration widens when the soil type gets worsened.

The spectrum curve illustrated in Figure 4.4 is plotted according to NZS 1170.5:2004 for only one soil class, which is defined as “Site Subsoil Class C”. This soil class represents the characteristics of all local site classes, Z1, Z2 and Z3 of TEC 07. The vertical and horizontal axes in Figure 4.4 define the acceleration in “g”, and the periods in seconds. The spectral acceleration value at $T=0$ is 0.11g, and its maximum value is 0.24g and it occurs between $T=0.1$ and 0.3 seconds.

As stated in Section 4.2.1, the smallest period of the total of forty-eight models is obtained based on the EC-8 requirements, and its value is 1.20 seconds. Based on this period value, the amplitude of the largest spectral acceleration is 0.16g, and is obtained from the spectrum curve of ASCE 7/10 for soil “Class D”. The smallest spectral acceleration value is approximately 0.05g, and is obtained from TEC 07 for site class Z1. The spectral acceleration values corresponding to the fundamental period of 1.20 seconds are for EC-8 and NZS 1170.5:2004 vary from 0.11g to 0.0878g, respectively.

Based on the data from Figures 4.1 through 4.4, the ratio of spectral acceleration corresponding to the smallest natural period of ASCE 7/10 to TEC 07 is calculated as 3.2. The same ratio is around 1.45 for EC-8, and is 1.8 for NZS.1170.5:2004 when their spectral accelerations are compared to that of TEC 07. The reason behind the largest ratio of spectral acceleration occurring between ASCE 7/10 and TEC 07 is attributed to the difference definition of recurrence periods for an earthquake. In TEC 07, the probability of exceedance of the design earthquake within a period of 50 years is assumed 10 % which is equal to a return period of 475 years, However, in ASCE 7/10 the probabilistic earthquake is intended to have a probability of exceedance of 2% in 50 years which is equal to a return period of 2475 years.

Figure 4.5 through 4.7 illustrate the defined shapes of the first fundamental periods for the buildings representing layouts A, B and C. In Figure 4.5 the first fundamental period is 1.24 seconds and calculated for model A1TECA. Similarly, figures 4.6 and 4.7 display the periods for models B1TECA and C1TECA, and their respected values are 1.32 seconds and 1.22 seconds. The figures of first mode shapes resulting from all sixty-six models are not displayed in this thesis. Instead, three models are arbitrarily selected just to give an idea about how buildings deform in their first mode shapes.



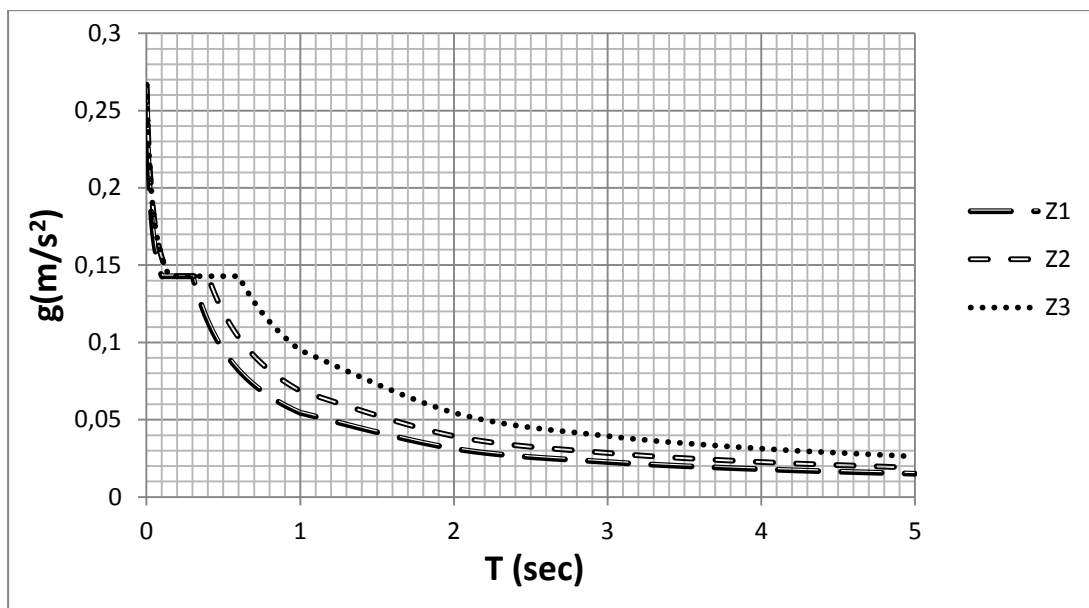


Figure 4.1. Response Spectrum in TEC 07

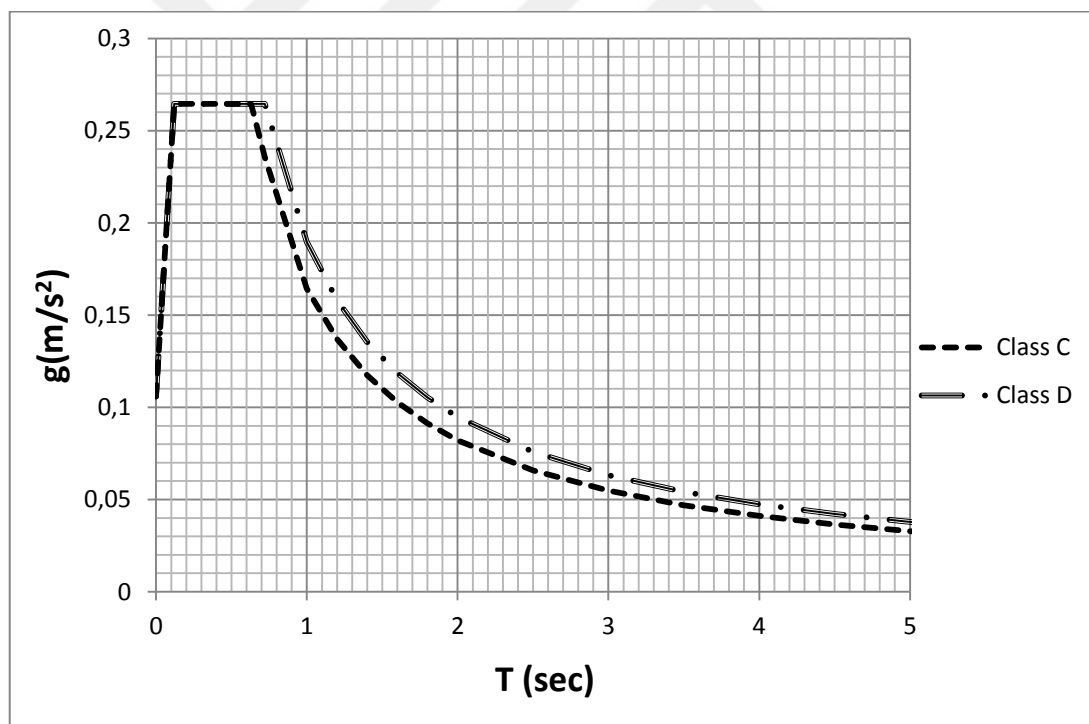


Figure 4.2. Response Spectrum in ASCE 7/10

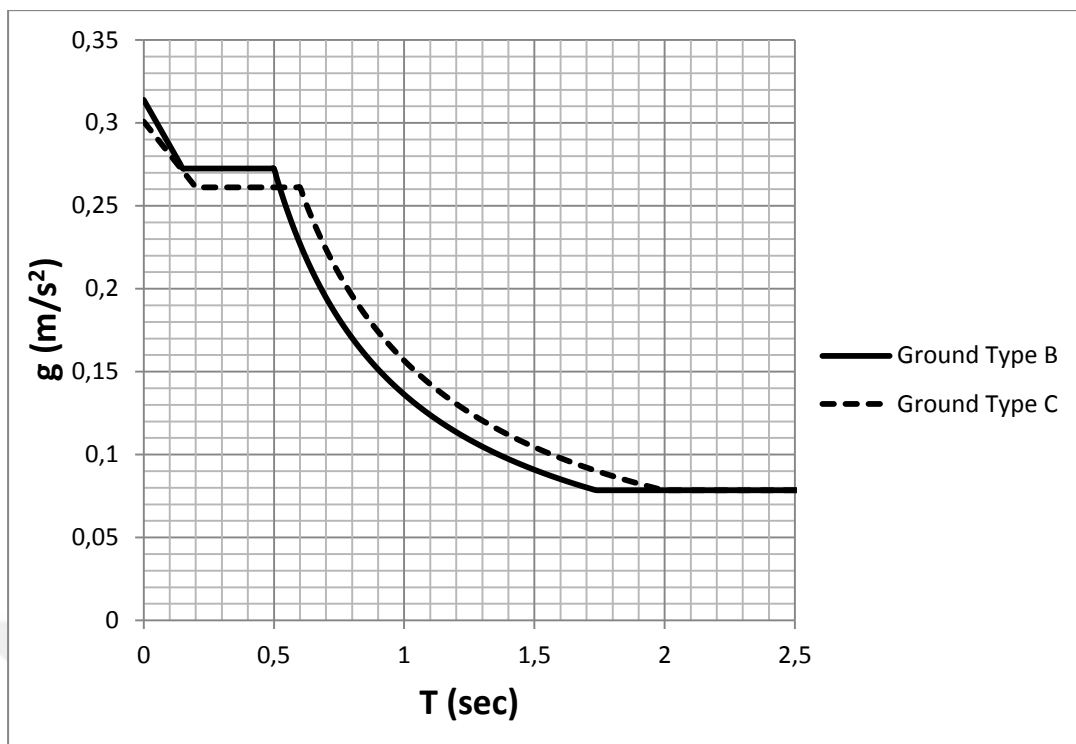


Figure 4.3. Response Spectrum in EC-8

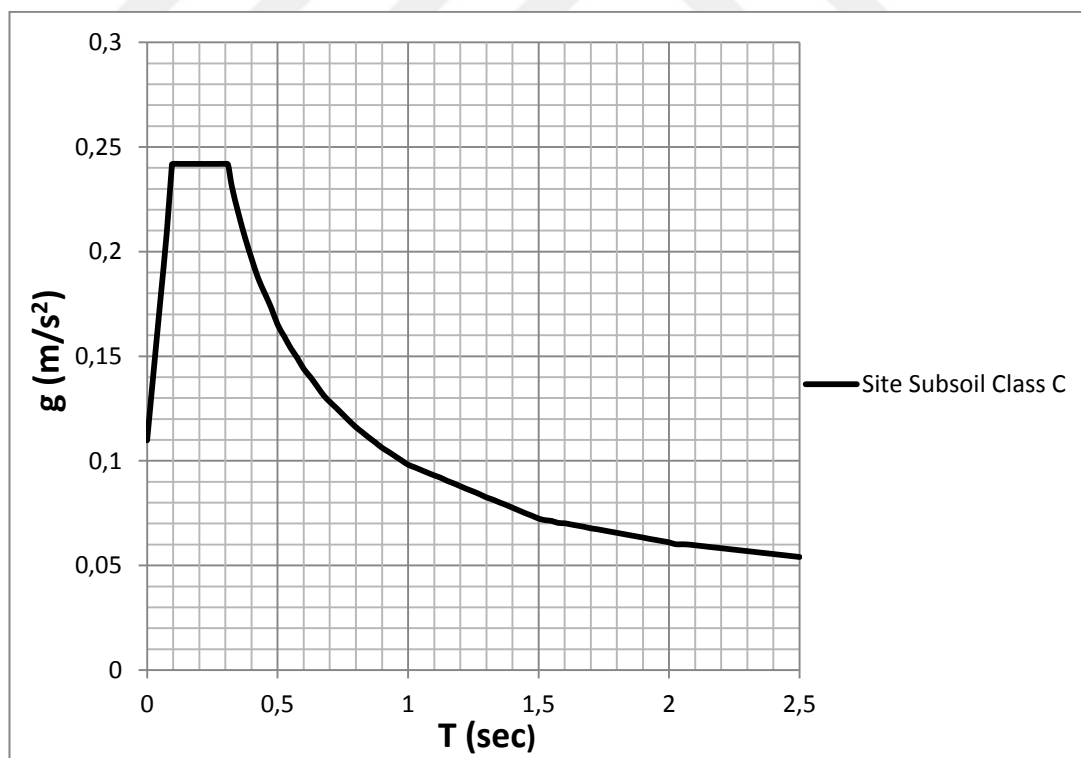


Figure 4.4. Response Spectrum in NZS 1170.5:2004

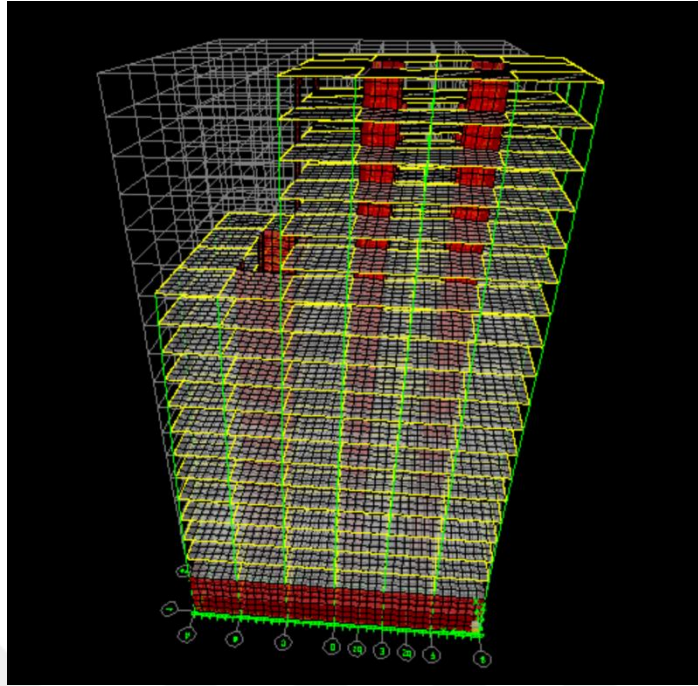


Figure 4.5. Model A1TECA – 1st Mode

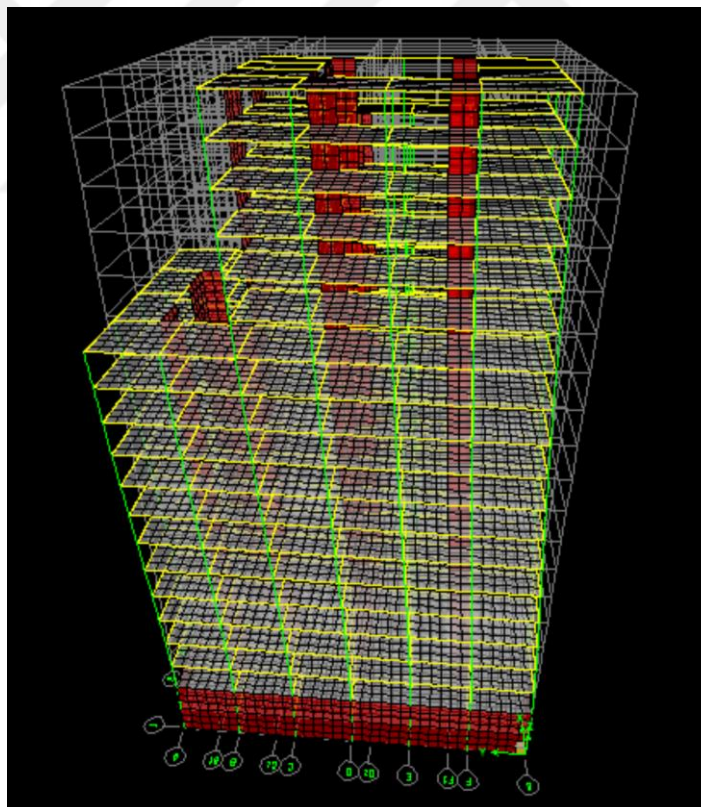


Figure 4.6. Model B1TECA – 1st Mode

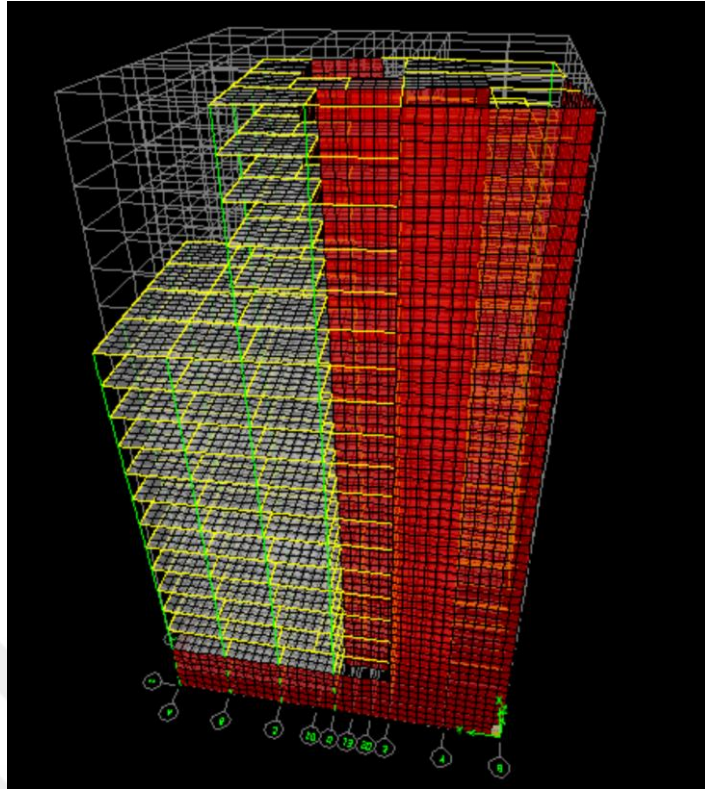


Figure 4.7. Model C1TECA – 1st Mode

4.2.3 Base Shear

In the dynamic analysis of a building, the base shear is an important parameter that needs to be examined carefully. In this thesis, a total of forty-eight models are evaluated for a thorough study of different soil classes and groups with respect to the constructed response spectrum generated according to the seismic codes of TEC 07, ASCE 7/10, EC-8, and NZS 1170.5:2004 for the three layouts denoted by A, B, and C.

The response spectrum method is applied to each model both in the “x and “y” directions separated by using the dynamic properties discussed in Section 3.2.1. The base shear forces that are obtained from each of these forty-eight models are listed in Table 4.2 for both “x” and “y” directions.

As explained in Chapter 3.5, due to the varying soil classes and groups defined in each of the four seismic codes, there are differences in the V_x and V_y values obtained from each model that is constructed based on these three seismic codes. In order to obtain these V_x and V_y values, both the “Equivalent Lateral Force Method (ELF Method)” and the “Modal Response Spectrum Method (MRS Method)” are used. In order to include the effects of a nonlinear response in system, a parameter called “Response Modification Factor”, which is commonly denoted by “R”, is integrated into these seismic codes through the ELF method. The “R” factor is described as follows in NEHRP Recommended Provisions: “an empirical response modification (reduction) factor intended to account for both damping and ductility inherent in a structural system at displacements great enough to approach the maximum displacement of the system” [28]. The theory behind the equivalent static lateral force comes from the seismic loads can be applied laterally at different floor levels of a building. These lateral loads are concentrated loads, and are directly proportional to the height of a building. Therefore, as the height of a building increases, the magnitude of the concentrated lateral load away from the base also increases. The MRS method is an analysis method that is used by utilizing the corresponding contribution from each mode shape to address the total seismic response of a building. The response spectrum analysis determines overall dynamic behavior of a building through accelerations and displacements that are given as function of structural periods.

In this study, the design base shear forces calculated based on the ELF method are compared to those from the MRS method as described according to the four seismic codes. If a base shear value obtained from the ELF method is less than that from the MRS method, then all internal force and displacement quantities need to be multiplied by a factor called “ β ” as described in TEC 07. The β factor is the ratio of the base shear force from the ELF method to the base shear force from the MRS method.

In the modal analysis, mass participation factors play significant role in determining the base shear forces. In this study, these participations factors meet the minimum requirement of 90% of the total seismic mass as described in TEC 07, ASCE 7/10, EC-8, and NZS 1170.5:2004. The seismic mass includes the full participation of the total dead load and a portion of live load (for further information, see Section 4.1).

In this thesis, it is intended to evaluate the effects of seismic loads acting on the buildings with same layouts but with different soil classes, earthquake return periods and attenuation relationships. The goal is to understand the potential problems related to the adaption of seismic code from international one (such as ASCE 7/10) either partially or fully, when preparing the Turkish Earthquake Code.

According to Table 4.2, the largest base shear forces for all layouts are obtained from ASCE 7/10. In ASCE 7/10, for model A1, the maximum base shear force value in the x direction 1937 tons, and in the y direction is 1925 tons. Using the same seismic code, the maximum base shear force value in the x direction for model A2 is 1799 tons and in the y direction is 1794 tons. In layout B1, the maximum base shear force value in the x and y directions are 1631 tons and 1638 tons, respectively. Similarly, the maximum base shear forces for models B2, C1 and C2 are, again, obtained from ASCE 7/10. Their respected values in tons for both “x” and “y” directions are as follows: 1540 and 1542 for layout B2, 1947 and 1936 for layout C1, and finally 1801 and 1793 for model C2. Out of forty-eight models, the magnitudes of the largest base shear forces both in the “x” and “y” directions are 1947 tons and 1936 tons, and they are all obtained from the same model called C1ASCED. The smallest base shear forces, however, are generated by TEC 07 and is valid from models A2TECA and B1TECA. Their magnitudes in the “x” and “y” directions are

672 tons for model A2TECA and 570 tons for B1TECA, respectively. The base shears generated from ASCE 7/10 produce almost the same forces both in the “x” and “y” directions. However, in EC-8, NZS 1170.5:2004 and TEC 07, the base shear forces in the “x” directions are always larger than their counterparts in the “y” direction. For all models, the larger differences between the forces in the “x” and “y” directions are obtained from TEC 07 and NZS 1170.5:2004.

As listed in Table 4.2, the computed base shear forces calculated based on the seismic codes of ASCE 7/10, EC-8, and NZS 1170.5:2004 are much higher than those of TEC 07. The specific reasons for obtaining the smallest base shear forces in TEC 07 can be attributed to the differences in the parameters given in the following list: (a) parameters of soil groups and classes, (b) earthquake return periods, and (c) attenuation relationships.

Table 4.2. Base Shear Forces

TEC 07			ASCE 7/10			EC-8			NZS 1170.5:2004		
Model	Vx [Tons]	Vy [Tons]	Model	Vx [Tons]	Vy [Tons]	Model	Vx [Tons]	Vy [Tons]	Model	Vx [Tons]	Vy [Tons]
A1TECA	696	663	A1ASCEC	1660	1656	A1EC8B	1208	1146	A1NZSC	1481	1418
A1TECB	875	835				A1EC8C	1317	1265			
A1TECC	1210	1155									
A2TECA	672	648	A2ASCEC	1556	1561	A2EC8B	1163	1119	A2NZSC	1417	1370
A2TECB	845	816				A2EC8C	1254	1222			
A2TECC	1168	1129									
B1TECA	725	570	B1ASCEC	1407	1409	B1EC8B	1023	998	B1NZSC	1500	1222
B1TECB	910	724				B1EC8C	1140	1099			
B1TECC	1252	993									
B2TECA	730	579	B2ASCEC	1332	1329	B2EC8B	998	953	B2NZSC	1450	1169
B2TECB	909	722				B2EC8C	1094	1078			
B2TECC	1237	988									
C1TECA	740	668	C1ASCEC	1685	1668	C1EC8B	1150	1007	C1NZSC	1582	1431
C1TECB	932	835				C1EC8C	1261	1092			
C1TECC	1286	1151									
C2TECA	718	657	C2ASCEC	1561	1544	C2EC8B	1115	1000	C2NZSC	1530	1369
C2TECB	896	822				C2EC8C	1228	1088			
C2TECC	1235	1128									

4.2.4 Structural Irregularities

Many buildings in nowadays have irregular configurations both in the horizontal and vertical directions. It is important that these buildings that might one day be subjected to destructive earthquakes. Therefore, it is required to accurately identify the overall performance of buildings against natural disasters primarily earthquakes. However, there are times that irregularities might not be avoided in a building design. Nevertheless, in the structural behaviors of building during earthquakes need to be carefully examined. However, there is a lack of understanding in the seismic response of buildings with irregularities. Therefore, a comprehensive evaluation of the effect of vertical and horizontal irregularities on the seismic demand of a building is greatly needed. All current earthquake codes define structural configuration as either regular or irregular in terms of size and shape of a building, layouts of its structural and nonstructural elements, distribution of its mass etc.

4.2.4.1 Irregularities in TEC 07

The structural irregularities in plan and elevation are examined separately for the four seismic codes that are under consideration. TEC 07 encourages the design of buildings with regular systems. Building irregularities in TEC 07 are classified in two main groups: (a) irregularities in plan, and (b) irregularities in elevation. Irregularities in plan are defined as torsional irregularity designated as A1, floor discontinuities designated as A2, and projections in plan designated as A3. Irregularities in elevation are described as interstorey strength irregularity-weak storey designated as B1, interstorey stiffness irregularity-soft storey designated as B2 and discontinuity of vertical structural elements designated as B3.

The results of the eighteen models constructed in PROBINA are compared to those constructed in ETABS using the same earthquake code of TEC 07. The results, however, are obtained from the PROBINA models, and the ETABS models are used to verify the PROBINA results. For all layouts, the results concerning to A1, A2 and A3 plan irregularities are listed in Table 4.3. The penalties concerning to irregular buildings are stated in Section 2.3.2.1 of TEC 07. If a building has irregularity types A1 and B2, then the selection for the method of seismic analysis, as specified in Section 2.6 of TEC 07 will be determined accordingly. Also, for buildings that have

irregularity type A1, at any i^{th} floor such that the condition $1.2 < \eta_{bi} \leq 2.0$ is satisfied, then $\pm 5\%$ additional eccentricity as stated in section 2.7.3.3 of TEC 07 will be applied to the related floor including amplification factor, D_i , which will be used to further increase the $\pm 5\%$ eccentricity. D_i , which will be included in both earthquake directions, is given in Eq. 4.1.

$$D_i = \left(\frac{\eta_{bi}}{1.2} \right)^2 \quad (4.1)$$

D_i : Amplification factor to be applied in ELF Method to $\pm 5\%$ additional eccentricity at i^{th} floor of a torsionally irregular building

η_{bi} : Torsionally Irregularity Factor defined at i^{th} floor of a building

The penalty for type A2 irregularity is described in Section 2.3.2.2 of TEC 07. In addition to type A2 irregularity, type A3 irregularity is also included in the same section. The associated penalty states that a verification must be performed for the floor of building systems that are located in the first and second seismic zones such that the floors are capable of safely transferring seismic loads to vertical structural elements. Another penalty for irregularity type A2 is explained in Section 2.7.3.2 of TEC 07 and the related section indicates that if A2 exists in a building and its floors do not behave as rigid diaphragm, an additional eccentricity needs to be considered through by distributing mass over each floor through shifting by $\pm 5\%$ times the floor length in perpendicular to the related earthquake direction.

As listed in Table 4.3, for all models that are analyzed according to TEC 07, A1, A2, and A3 type plan irregularities are observed. The plan irregularities in TEC 07 are intentionally inserted into the building layouts by arranging their floor plans. The reason for this is to determine the severity of penalties resulting from TEC 07 so that the outcomes due to irregularity can be compared to those from the other three seismic codes.

The analytical results of this study for all layouts are examined for irregularities in elevation. Depend on the parameters defined in TEC 07 the types of irregularities in elevation are listed in Table 4.4. As shown in the table, type B2 irregularity is the only irregularity that exists in all layouts. This type of irregularity is also defined as soft storey, and its penalty is explained in Section 2.3.2.1 of TEC

07. According to the section type A2, if exists, is associated to a penalty that indicates the selection for the method of seismic analysis as specified in Section 2.6 of TEC 07. In all models, B1 or B3 irregularities are not encountered. B1 irregularity is the type of irregularity that is determined based on the analyses results. However, it is not practical to include or exclude this irregularity by simply reviewing a layout of a building. Therefore, in this study, the outcome reveals the fact that in none of the models, B1 type irregularity occurs. Since the layouts are arranged intentionally not to include it. B3 type irregularity is not encountered in all layouts.

In TEC 07, there is also a penalty for the existence of A1, B2 or B3 types of irregularities both in plan and elevation. For the layouts, if at least one of the irregularities of type A1, B2 or B3 exists then the β coefficient needs to be determined the lower limits of all internal force and displacement quantities calculated based on the MRS method. For this purpose, the base shear forces resulting from the ELF method is divided by the one from the MRS method. If A1, B2 or B3 exists, then β is equal to 0.9, otherwise it is 0.8. The following equation formulates the scaling of forces by using the β coefficient.

$$B_D = \frac{\beta * V_t}{V_{tB}} * B_B \quad (4.2)$$

B_D : Amplified value of B_B

B_B : Any size calculated with the combination of mode contributions in the MRS method

β : Coefficient used to determine lower limits of response quantities calculated by MRS method

V_t : In the ELF, total equivalent seismic load acting on the building (base shear) in the earthquake direction considered

4.2.4.2 Irregularities in ASCE 7/10

As stated in Chapter 2.3, ASCE 7/10 addresses the irregularities in two categories, (a) horizontal structural irregularities, and (b) vertical structural irregularities. The Horizontal structural irregularities are divided into six types. These are as follows: (1a) torsional irregularity, (1b) extreme torsional irregularity,

(2) reentrant corner irregularity, (3) diaphragm discontinuity irregularity, (4) out-of-plane offset discontinuity, and (5) nonparallel system irregularity. The Vertical structural Irregularities are divided into seven types, and they are: (1a) stiffness-soft story irregularity, (1b) stiffness-extreme soft story irregularity, (2) weight (mass) irregularity, (3) vertical geometric irregularity, (4) in-plane discontinuity in vertical lateral force-resisting element irregularity, (5a) discontinuity in lateral strength-weak story irregularity, and (5b) discontinuity in lateral strength-extreme weak storey irregularity.

In this study, ETABS is used to analyze the models for irregularities that might exist in layouts A, B and C. Tables 4.5 and 4.6 list the results of horizontal and vertical irregularities, respectively. As shown in Table 4.5, according to the analyses results, Type 1b (extreme torsional irregularity), Type 2 (reentrant corner irregularity) and Type 3 (diaphragm discontinuity irregularity) irregularities exist in plan. In other words, none of the models exhibited any horizontal irregularity other than those with Types 1b, 2 and 3. As far as the vertical irregularities are concerned, only Type 2 (weight irregularity) exists in all layouts. If one compares the results of ASCE 7/10 to those of TEC 07, then it would be clear to see that the torsional irregularity in TEC 07 turned into an extreme torsional irregularity in ASCE 7/10. The A3 type irregularity of TEC 07 that exists in this study also appeared as Type 2 in ASCE 7/10. The A2 type irregularity of TEC 07, exists in all models, but, Type 3 irregularity in ASCE 7/10 only appeared in layout C, since its definition for the open area specified in a floor is different than the one in ASCE 7/10.

Similar to the discussion that is made for the irregularities in plan, the outcomes of the irregularities in elevation from ASCE 7/10 to TEC 07 are also evaluated. As stated before, in TEC 07, only Type B2 (soft storey) irregularity exists in all models. However, due to the differences in the definition of soft story, the same irregularity is not observed in ASCE 7/10. Likewise, Type 2 irregularity (weight irregularity) of ASCE 7/10 which appears in all models is not included in TEC 07. Therefore, this irregularity is completely omitted. ASCE 7/10 restricts the analyses' results depending on their seismic design categories, but the standard has some limitations and additional requirements for buildings with structural irregularities are listed in Table 12.3-1 of ASCE 7/10. In this thesis, the seismic design category for all buildings is "E". In response to the horizontal irregularity that exists in this study

(Type 1b), the related section of ASCE 7/10 for the Design Category E is 12.3.3.1. According to this section, buildings assigned to Seismic Design Category E with horizontal irregularity Type 1b is not permitted to be constructed. There are other horizontal irregularities for the models, and these are, as stated before, Type 2 and Type 3. The penalty for Type 2 and Type 3 irregularities is described in Section 12.3.3.4 of ASCE 7/10 and is as follows: “the design forces must be increased 25 percent for the connections of diaphragms to vertical elements and to collectors, and the collectors and their connections, including connections to vertical elements of the seismic force resisting system” [4]. For the vertical irregularity type 2, the penalty is again as same as the one for horizontal irregularity Type 2 and Type 3. It is important to note that these penalties are completely different than those mandated in TEC 07.

4.2.4.2 Irregularities in NZS 1170.5:2004

The irregularities in plan and elevation are also investigated for the same models. But based on NZS code, the structural irregularity is discussed in Clause 4.5 and is divided into two categories, vertical irregularity and plan irregularity. The vertical irregularity consists of four specific irregularity types (a) weight (mass) irregularity, (b) vertical stiffness irregularity, (c) discontinuity in capacity- weak storey, and (d) vertical geometric irregularity. Tables 4.7 and 4.8 include a summary of plan and vertical irregularities. Based on the analyses results, one plan irregularity (torsional sensitivity) and two vertical irregularities (weight and vertical stiffness) exist for layouts A, B and C.

When the results from NZS are compared to those from TEC 07, it is observed that the existing irregularities in TEC 07 outnumber the irregularities in NZS. This outcome is a direct result of layout configuration selected for A, B and C. In other words, no horizontal or out-of-plane offsets are permitted in these three layouts and therefore, they do not exist in NZS. However, for all layouts both TEC 07 and NZS exhibit the same irregularity type in plan which is called torsional irregularity. The vertical irregularities between TEC 07 and NZS are also compared. Based on this comparison, it was observed that both seismic codes generated the same irregularity type which is called B2 in TEC 07 and vertical stiffness irregularity

in NZS. But as it happened in ASCE 7/10, one additional irregularity was observed in NZS, which is described as weight irregularity.

The penalties associated to the plan and vertical irregularities are described in NZS. As stated in Clause 6.1.3.2 of NZS, three-dimensional analyses must be used when a building is classified as torsionally irregular as it occurred in this study. In addition to this requirement, the standard indicates that for buildings over 15 meters in height and having at least one of the irregularities listed in Clause 4.5, then the buildings' diaphragms must be modeled to conduct using three-dimensional analyses.

4.2.4.3 Irregularities in Eurocode 8, EC-8

As occurred in the other three seismic codes, the analyses' results according to EC-8 contain plan and vertical irregularities. Although the other seismic codes discuss this issue as irregularity, structural irregularity in EC-8, it is outlined as "Structural Regularity". The regularity is listed in Section 4.2.3, and is divided into two categories, regularity in plan and regularity in elevation. The regularity in plan is divided into five criteria and they are: (a) symmetry in plan, (b) set-backs in plan, (c) in-plan stiffness, (d) slenderness, and (e) eccentricity and torsional radius. The details of these five criteria are given in Section 2.4 of this thesis. The regularity in elevation is divided into four criteria. These regularities are as follows: (a) discontinuity of elements, (b) change of stiffness and mass, (c) resistance check and (d) set-backs. Their details are again provided in Section 2.4.

Tables 4.9 and 4.10 summarize the lists of plan and vertical regularities for the models under consideration. The analyses' results indicate that, two plan irregularities (symmetry in plan, eccentricity, and torsional radius) and one vertical irregularity (set-backs) exist for layouts A, B and C. The results from EC-8 are compared to those from TEC 07. Similar to the outcome based on the comparison between NZS 1170.5:2004 and TEC 07, the irregularities in TEC 07 outnumber the irregularities in EC-8. However, the irregularities that exist for all layouts in EC-8 do not have their exact match when compared to the existing irregularities in TEC 07. This clearly states the fact that there are additional irregularities considered for the layouts in EC-8.

The penalties related to these irregularities are given in EC-8. In buildings that are irregular in elevation, the behavior factor “q” is reduced by 20% in comparison to the buildings that are regular both in elevation and plan. There is also a detailed table in EC-8 (Table 4.1) that describes the limitations determining the analysis method and behavior factor depending on the case where regularity plan and/or elevation exists.



Table 4.3. Irregularities in Plan in TEC 07⁽¹⁾

IRREGULARITIES IN PLAN	Layout A						Layout B						Layout C					
	A1			A2			B1			B2			C1			C2		
	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3
A1 – Torsional Irregularity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
A2 – Floor Discontinuities	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
A3 – Projections in Plan	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

⁽¹⁾ ✓ = Irregularity exists

x = Irregularity does not exist

Table 4.4. Irregularities in Vertical in TEC 07⁽¹⁾

IRREGULARITIES IN VERTICAL	Layout A						Layout B						Layout C					
	A1			A2			B1			B2			C1			C2		
	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3
B1 – Interstorey Strength Irregularity (Weak Storey)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
B2 – Interstorey Stiffness Irregularity (Soft Storey)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
B3 – Discontinuity of Vertical Structural Elements	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

⁽¹⁾ ✓ = Irregularity exists

x = Irregularity does not exist

Table 4.5. Horizontal Structural Irregularities in ASCE 7/10⁽¹⁾

HORIZONTAL STRUCTURAL IRREGULARITIES	Layout A				Layout B				Layout C			
	A1		A2		B1		B2		C1		C2	
	C	D	C	D	C	D	C	D	C	D	C	D
1a. Torsional Irregularity	x	x	x	x	x	x	x	x	x	x	x	x
1b. Extreme Torsional Irregularity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2. Reentrant Corner Irregularity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Diaphragm Discontinuity Irregularity	x	x	x	x	x	x	x	x	✓	✓	✓	✓
4. Out-of-Plane Offset Irregularity	x	x	x	x	x	x	x	x	x	x	x	x
5. Nonparallel System Irregularity	x	x	x	x	x	x	x	x	x	x	x	x

⁽¹⁾ ✓ = Irregularity exists

x = Irregularity does not exist

Table 4.6. Vertical Structural Irregularities in ASCE 7/10⁽¹⁾

VERTICAL STRUCTURAL IRREGULARITIES	Layout A				Layout B				Layout C			
	A1		A2		B1		B2		C1		C2	
	C	D	C	D	C	D	C	D	C	D	C	D
1a. Stiffness-Soft Story Irregularity	x	x	x	x	x	x	x	x	x	x	x	x
1b. Stiffness-Extreme Soft Story Irregularity	x	x	x	x	x	x	x	x	x	x	x	x
2. Weight (Mass) Irregularity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Vertical Geometric Irregularity	x	x	x	x	x	x	x	x	x	x	x	x
4. In Plane Discontinuity in Vertical Lateral Force-Resisting Element Irregularity	x	x	x	x	x	x	x	x	x	x	x	x
5a. Discontinuity in Lateral Strength-Weak Story Irregularity	x	x	x	x	x	x	x	x	x	x	x	x
5b. Discontinuity in Lateral Strength-Extreme Weak Story Irregularity	x	x	x	x	x	x	x	x	x	x	x	x

⁽¹⁾ ✓ = Irregularity exists

x = Irregularity does not exist

Table 4.7. Horizontal Irregularities in NZS 1170.5:2004⁽¹⁾

HORIZONTAL IRREGULARITIES	Layout A		Layout B		Layout C	
	A1	A2	B1	B2	C1	C2
	C	C	C	C	C	C
Horizontal Offsets of Columns in Moment-Resisting Frames	x	x	x	x	x	x
Out-of-Plane Offsets of Lateral Force Resisting Walls	x	x	x	x	x	x
Torsional Sensitivity	✓	✓	✓	✓	✓	✓

⁽¹⁾ ✓ = Irregularity exists

x = Irregularity does not exist

Table 4.8. Vertical Irregularities in NZS 1170.5:2004⁽¹⁾

VERTICAL IRREGULARITIES	Layout A		Layout B		Layout C	
	A1	A2	B1	B2	C1	C2
	C	C	C	C	C	C
Weight Mass Irregularity	✓	✓	✓	✓	✓	✓
Vertical Stiffness Irregularity	✓	✓	✓	✓	✓	✓
Discontinuity in Capacity-Weak Storey	x	x	x	x	x	x
Vertical Geometric Irregularity	x	x	x	x	x	x

⁽¹⁾ ✓ = Irregularity exists

x = Irregularity does not exist

Table 4.9. Regularity in Plan in EC-8 ⁽¹⁾

REGULARITY IN PLAN	Layout A				Layout B				Layout C			
	A1		A2		B1		B2		C1		C2	
	B	C	B	C	B	C	B	C	B	C	B	C
Symmetry in Plan (Item # 2)	x	x	x	x	x	x	x	x	x	x	x	x
Set-Backs in Plan (Item # 3)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
In-Plan Stiffness (Item # 4)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Slenderness (Item # 5)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Eccentricity (e_0), Torsional Radius (r) (Item # 6)	x	x	x	x	x	x	x	x	x	x	x	x

⁽¹⁾ ✓ = Regularity exists

x = Regularity does not exist

Table 4.10. Regularity in Elevation in EC-8 ⁽¹⁾

REGULARITY IN ELEVATION	Layout A		Layout B		Layout C	
	A1	A2	B1	B2	C1	C2
	B	C	B	C	B	C
Discontinuity of Elements (Item # 2)	✓	✓	✓	✓	✓	✓
Change of Stiffness and Mass (Item # 3)	✓	✓	✓	✓	✓	✓
Resistance Check (Item # 4)	✓	✓	✓	✓	✓	✓
Set-Backs (Item # 5)	x	x	x	x	x	x

⁽¹⁾ ✓ = Regularity exists
x = Regularity does not exist

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The goal of this research is to analyze irregular buildings according to Turkish Earthquake Code 2007, and to compare the results generated by this code to those from the United States, New Zealand and European Union. In order to achieve this goal, three different layouts are selected in constructing the buildings located in İznik, Bursa, Turkey. İznik is selected to be the right location since the town is located in the most severe seismic region which is also defined as the first seismic zone in Turkey. The other reason for choosing İznik is primarily related to the town's proximity to the active fault line in the NAFL. Thus, it is intended to understand the effect of near fault line in determining the seismic forces acting on a building. It is expected that severe seismic zone and near fault line conditions would increase the base shear specifically on irregular buildings. In order to make comparisons among the results of four seismic codes, similar seismic conditions regarding the seismic activity of a region, soil conditions, proximity to an active fault line are attempted to be simulated for the buildings according to the other three seismic codes ASCE 7/10, NZS 1170.5:2004, and EC-8. For this purpose, Daly City located near San Francisco is selected for ASCE 7/10 in the US, Wellington is selected for NZS 1170.5:2004 in New Zealand, and finally Messina is selected for EC-8 in Italy.

In this thesis, the ideal condition is to establish design parameters as close as possible to each other for all four seismic codes. However, generating the same seismic conditions according the four seismic codes is not practical due to the differences in the earthquake design parameters. Therefore, the generated earthquake loads expected to be are different to an extent from each other.

In this study, a total of sixty-six twenty-story buildings constructed from the three specific layouts are modeled according to the four seismic codes by using commercially available software packages, ETABS and PROBINA, and in order to understand the significance of seismic activities and their dynamic effects on the selected buildings. These buildings are assumed to be all residential. However, there are some differences in buildings' layouts due to the change in their floor heights, floor layouts and soil types. These differences are there to understand their effects on the buildings' overall dynamic behavior.

The irregularity concept in TEC 07 is intended to be discussed in detail by comparing the results from TEC 07 to those from the other three seismic codes. The irregularity is studied in two categories, plan and elevation. In order to evaluate the current regularities of TEC 07, regarding this topic, the layouts are intentionally altered so that the all available irregularities in TEC 07 can be captured. However, as stated in Chapter 4, based on the analyses results, it is observed that this goal is not fully achieved since some irregularities are not captured. Even though all the irregularities are not captured, the cross-comparisons among the results of all four seismic codes that are subject of this thesis are presented. By doing so, the limitations and associated penalties enforced in TEC 07 are compared to those from the other seismic codes. The goal in this comparison is to evaluate how accurate or complete the definitions of plan and vertical irregularities in TEC 07.

5.2 Conclusions

The presence of structural irregularity changes according to the seismic response of a building. The seismic response is heavily affected by the type of structural irregularities. In this study, the conclusions are drawn individually for each layout addressing the issues related to the seismic codes. The following list includes more of these general conclusions. The specifics of detailed observations regarding irregularities are given in Chapter 4, and therefore, it is decided not to repeat them here in this section.

- The comparison of the results of ASCE 7/10 to those of TEC 07 indicates that the A1 (torsional irregularity) type irregularity in TEC 07, changed to an extreme torsional irregularity in ASCE 7/10. Therefore, the penalty for this irregularity that exists in TEC 07 should be revised. In ASCE 7/10, the torsional irregularity is divided into two part, torsional irregularity and extreme torsional irregularity. In the torsional irregularity the penalty is a lot more complex than the one in TEC 07 (see sections 12.3.3.4, 12.7.3, 12.8.4.3, 12.12.1, 16.2.2 and Table 12.6-1 in ASCE 7/10). In the extreme torsional irregularity, for the current layout and seismic group, no permission is allowed. Therefore, the layouts need to be significantly altered to accolade permission for thesis construction.
- The A3 (projections in plan) type irregularity of TEC 07 that exists in the layouts of this study also appears as Type 2 irregularity in ASCE 7/10.
- The A2 (floor discontinuities) type of irregularity in TEC 07 only occurs in layout C in ASCE 7/10 since the definition for the open area in a floor in TEC 07 is different than the one in ASCE 7/10, and the penalty regarding this irregularity in the same seismic code is a lot more severe than the one in TEC 07 (all internal forces corresponding to the member connecting to the opening must be increased by 25%).
- In TEC 07, only Type B2 (soft storey) plan irregularity exists in all models. However, due to the differences in the definition of a soft story, the same irregularity is not observed in ASCE 7/10. Although, this type of irregularity does not occur in ASCE 7/10, the associated penalty is again a lot more severe than the one in TEC 07. In ASCE 7/10, this type of irregularity is divided into two parts: stiffness-soft storey and stiffness-extreme soft storey. In the stiffness-soft storey, the penalty is the same as the one in TEC 07. However, in the stiffness-extreme soft storey, the penalty enforces that the layout under consideration to be not permitted.
- Type 2 irregularity (weight irregularity) of ASCE 7/10 that appears in all models is not an irregularity in TEC 07. Therefore, in order to account for the effect of this irregularity it should be included as a new irregularity in TEC 07.

- The results from NZS 1170.5:2004 are also compared to those from TEC 07. Based on the results, it is observed that the existing irregularities in TEC 07 outnumber the irregularities in NZS 1170.5:2004. This outcome states the fact that the three layouts caused more effects on irregularities when the results of TEC 07 are compared to those of NZS 1170.5:2004.
- No horizontal or out-of-plane offsets exist in the three layouts and therefore, they are not observed in NZS 1170.5:2004. Although, these irregularities are permitted in NZS 1170.5:2004 by penalizing the structural system to determine its analysis method, they might not be permitted in TEC 07 if the vertical elements are walls but not columns.
- Although in some cases there are differences between the results of TEC 07 and NZS 1170.5:2004 it is fair to say that, there is full conformity between their results. For example, in all layouts, both TEC 07 and NZS 1170.5:2004 produce the same irregularity type in plan (torsional irregularity).
- Based on the results of the vertical irregularity comparisons, both TEC 07 and NZS codes generate the same irregularity type B2, soft storey in TEC 07, and vertical stiffness irregularity in NZS 1170.5:2004.
- The weight (or mass) irregularity defined in ASCE 7/10 is observed under the same title in NZS 1170.5:2004.
- The results from EC-8 are compared to those from TEC 07. Similar to the comparison between NZS 1170.5:2004 and TEC 07, the irregularities in TEC 07 outnumber the irregularities in EC-8. However, the irregularities that exist for all layouts according to EC-8 do not have their exact match when they are compared to the irregularities in TEC 07. These outcomes state the fact that there are additional irregularities included only in EC-8 and they should be also incorporated into TEC 07.

5.3 Suggestions for Future Work

This research has been carried out for three building layouts. However, buildings with different layouts and different framing systems can also be studied in order to understand their effects on irregularities. For example, stepped building frames constitute a category of vertical irregularity in some earthquake codes, but these types of buildings have not received adequate attention in TEC 07. Therefore, stepped building layouts should also be studied to understand their impacts on irregularities so that this irregularity can be incorporated into TEC 07. Furthermore, an economical evaluation and the analysis of irregular plans with their advantages and disadvantages should also be investigated. The detailed design of structural members included in these types of irregular buildings should be studied as additional parameter in order to determine their cost effects on building construction.

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