

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

CASCADE EARTHQUAKE AND TSUNAMI HAZARD
ASSESSMENT: CASE STUDY AT YALOVA, TURKIYE

SÜLEYMAN FIRAT ŞENTÜRK

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING
EARTHQUAKE AND STRUCTURAL ENGINEERING
PROGRAM

ADVISOR: ASSIST. PROF. DR. CEREN ÖZER SÖZDİNLER

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ABSTRACT

Being located at the intersection of Tectonic plates, Türkiye experiences high seismic activity, making it a unique research area in terms of not only earthquake damage and destruction but also secondary triggered disasters. Among these secondary disasters, tsunamis—which can cause significant damage and loss of life—should be analyzed particularly in the context of cascading disaster impacts in the Marmara Region. Over the past 4,100 years, more than 300 destructive earthquakes have occurred in the Sea of Marmara, 40 of which triggered significant tsunamis. Earthquakes and especially the submarine landslides triggered by earthquakes pose the potential for destructive near-field effects in the Marmara Sea. Thus, in coastal areas of the Marmara Region, structural damage from an earthquake can be more effective by tsunami flooding, resulting in further secondary damage. This situation emphasizes the importance of disaster management, evacuation planning, and resilience-building measures.

In this study, the impacts of earthquakes with a 475-year recurrence period on a selected reinforced concrete structure with 5-stories in the pilot area of Çınarcık town, Yalova are assessed, along with the effects of tsunamis potentially triggered by submarine landslides in the Sea of Marmara and their impacts on damaged or collapsed buildings. Analyses have been made using open-source bathymetric data obtained from The General Bathymetric Chart of the Oceans (GEBCO) and geographical data from OpenTopography. High-resolution sea and land data including building and coastline information are prepared for the Çınarcık region via GIS software.

In the analyses, seismic effects on structures are simulated using the ETABS program; buildings' story displacements are checked with pushover analyses, and collapse and damage statuses are determined. Furthermore, the initial sea surface deformation caused by a major earthquake as a Mw 7.3 earthquake offshore Prince Islands in the Marmara Sea and a submarine landslide triggered at Çınarcık Basin with a slump volume of 0.8 km^3 is calculated using Okada (1985) and empirical predictive equation, respectively. Tsunami hydrodynamic parameters in the entire Marmara Sea and inundation zone of Çınarcık town are computed via 2D tsunami numerical modeling. Tsunami load applied on the building is calculated using the tsunami simulation results of both earthquake and submarine landslide scenario focusing on inundation depth and current velocity. Tsunami load is then applied as the secondary load to the structure that is already affected by the earthquake and the final condition is evaluated.

As a result of this study, the potential damage from the expected major Marmara Earthquake and the cascading tsunami generated by the earthquake and triggered submarine landslide in Çınarcık town is evaluated. The earthquake loading of the building causes about 110mm drift that corresponds to 0.73% and 60 mm residual drift that corresponds to 0.4% compared with the height of the building. This means the structure does not exceed 2% target story drift which is not likely to have significant damage on the structure. Tsunami numerical modeling due to major earthquake scenario estimates maximum flow depth of 0.87 m at Çınarcık town while a submarine landslide at Çınarcık Basin offshore Tuzla estimates a significant inundation depth of about 6.1 m while these values are corresponding to 0.60 m and 6.1 m in front of the selected building.

The tsunami load due to submarine landslide is applied on the structure after the earthquake drift occurs, as the cascading effect of tsunami inundation. The numerical

tsunami analysis gives the drift of 62 mm after tsunami loading that corresponds to 0.41%. The effect of tsunami generated by the earthquake is not creating additional drift on the building. The results show that tsunami load exerted on a selected reinforced concrete building, that has already been affected by the earthquake, can create extra drifts.



Key Words: Marmara Earthquake, Tsunami, Cascading disasters, Numerical Modeling, Submarine Landslides

ÖZET

Tektonik plakaların kesiştiği konumu nedeniyle yüksek bir depremselliğe sahip olan Türkiye, deprem esnasında oluşan hasarların ve yıkımın yanında, ayrıca ikincil afetlerin de meydana geldiği özel bir araştırma alanıdır. Bu ikincil afetlerden oldukça etkili hasar ve can kaybına sebep olabilecek tsunamiler, özellikle Marmara Bölgesinde ardışık afet etkisi açısından incelenmelidir. Son 4100 yıl boyunca, Marmara Denizi'nde 300'den fazla yıkıcı deprem meydana gelmiştir ve bunlardan 40 tanesi tsunami yaratmıştır. Depremler ve özellikle depremlerin tetiklediği deniztabanı heyelanları Marmara Denizinde yıkıcı yakın alan etkisi gösterebilme potansiyeline sahiptir. Bu anlamda, Marmara Bölgesinde kıyı alanlarında deprem nedeniyle meydana gelebilecek yapısal hasar sonrasında oluşabilecek tsunami su baskını ikincil başka bir hasar durumu yaratabilecektir. Bu durum afet yönetimi, tahliye planları ve afetlere karşı dirençlilik konularında önem kazanmaktadır.

Bu çalışma kapsamında Marmara bölgesinde meydana gelecek, tekrarlama periyodu 475 yıl olan depremlerin Yalova Çınarcık pilot bölgesinde seçilen 5 katlı betonarme binaya olan etkileri ve aynı zamanda Marmara Denizinde tetiklenebilecek deniz tabanı heyelanı kaynaklı tsunaminin yapıda yol açabileceği ilave hasarlar birlikte değerlendirilmiştir.. Yapılan analizlerde The General Bathymetric Chart of the Oceans (GEBCO) açık kaynak batimetri verileri ve Opentopography açık kaynaklı coğrafi veriler kullanılmış olup; ayrıca GIS yazılımları ile, binalar ve kıyı çizgisi dahil olmak üzere Çınarcık bölgesi için deniz ve kara verileri yüksek çözünürlükte hazırlanmıştır. Yapıya ait sismik etkiler ETABS programı kullanılarak analiz edilmiş; itme analizleriyle kat ötelemeleri kontrol edilmiş ve göçme/hasar durumları belirlenmiştir. Ayrıca, Marmara Denizi'nde Prens Adaları açıklarında Mw 7,3 büyüklüğünde bir deprem ve Çınarcık Çukuru'nda 0,8 km³ kayma hacmine sahip bir denizaltı heyelanı senaryosu için, sırasıyla Okada (1985) yöntemi ve ampirik denklemleriyle oluşan ilk deniz yüzeyi deformasyonu hesaplanmıştır. Tüm Marmara Denizi ile Çınarcık yerleşim alanı için 2 boyutlu tsunami sayısal modellemesiyle tsunami hidrodinamik parametreleri ve taşkın bölgesi belirlenmiştir. Tsunaminin yapıya uygulayacağı yük, hem deprem hem de heyelan senaryolarından elde edilen su yüksekliği ve akım hızı sonuçlarına dayalı olarak hesaplanmış, depremden zarar görmüş yapıya ikincil yük olarak uygulanmış ve son durum değerlendirilmiştir.

Bu çalışmanın sonucunda, beklenen büyük Marmara Depremi ve deprem kaynaklı tetiklenen denizaltı heyelanının yol açtığı ardışık tsunami etkileriyle birlikte, Çınarcık ilçesindeki olası yapısal hasar değerlendirilmiştir. Binaya etkileyen deprem yüklemesi yaklaşık 110 mm'lik (bina yüksekliğinin %0,73'ü oranında) bir ötelenmeye ve yaklaşık 60 mm'lik (bina yüksekliğinin %0,4'ü oranında) bir kalıcı ötelenmeye neden olmaktadır. Bu değerler, hedeflenen %2 kat ötelenme sınırının altında kaldığı için yapıda önemli bir hasarın meydana gelmesi beklenmemektedir. Büyük deprem senaryosuna bağlı yapılan sayısal tsunami modellemesi, Çınarcık ilçesinde maksimum 0,87 m akış derinliği öngörürken; Tuzla açıklarındaki Çınarcık Havzası'nda meydana gelen denizaltı heyelanı sonucunda yaklaşık 6,1 m'lik önemli bir su baskını derinliği tahmin edilmiştir. Bu değerler, seçilen binanın önünde sırasıyla 0,60 m ve 6,1 m olarak hesaplanmaktadır.

Ardışık etkiler kapsamında, tsunami yükü binaya, deprem ötelenmesi oluştuktan sonra uygulanmıştır. Sayısal tsunami analizi, tsunami yüklemesi sonrası yapıda yaklaşık 62 mm'lik (bina yüksekliğinin %0,41'i oranında) bir ötelenme meydana geldiğini göstermektedir. Deprem kaynaklı tsunami ise yapıda ek ötelenmeye neden olmamaktadır. Sonuçlar, depremten etkilenmiş olan seçilen betonarme yapıya tsunami yükünün ek ötelenmeler oluşturabileceğini ortaya koymaktadır.



Anahtar Kelimeler: Marmara Depremi, Tsunami, Ardışık Afetler, Sayısal Modelleme, Deniz tabanı Heyelanı

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LIST OF SYMBOLS AND ABBREVIATIONS

V_t	: Base shear
F_i	: Story force
E_x	: Earthquake load x direction
m_t	: Total mass of structure
S_{aR}	: Reduced design spectral acceleration
T_p^x	: Natural period of x direction
I	: Building importance factor
S_{DS}	: Short period design spectral acceleration coefficient
g	: Gravity acceleration
η_{max}	: Maximum initial amplitude of submarine landslide incidents
d	: Initial submergence
λ_0	: Characteristic tsunami wavelength
ρ_s	: Minimum fluid mass density
k_s	: Fluid density factor
F_d	: Tsunami load
ρ_{sw}	: Density of sea water
I_{tsu}	: Tsunami importance factor
C_d	: Drag coefficient
h_e	: Inundation height in front of structure
u	: Current velocity
$(V_s)_{30}$	: Average shear wave velocity in the top 30 meters
$(N_{60})_{30}$	: Average standard penetration test blow count in the top 30 meters
c_u	: Undrained shear strength
n	: Live load participation factor
BKS	: Building occupancy classification

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1. INTRODUCTION

1.1. Scope of This Study

Turkiye is in one of the most active seismic regions in the world due to the intersection of the Tectonic plates. Northern most of Türkiye is host to one of the most active strike-slip faults in the world called North Anatolian Fault “NAF”. Marmara Region in Turkey, which is the region located around the Sea of Marmara. Marmara Region only covers 8.5% of the surface area, but around 31.3% of Türkiye’s population lives in the Marmara Region. Also 41.1% of the industrial activities in Turkey takes place in the Marmara Region. Because of the western part of NAF, Marmara Region is familiar with the frequent earthquakes with high magnitudes.

Turkish Earthquake Standards have been drastically improved in the last 50 years. Fault Maps of Türkiye and Earthquake Building Standards in Türkiye are adequate when compared to international standards. But natural phenomena like earthquakes usually come with cascading effects. Because NAF travels under the Sea of Marmara, one of the cascading effects that an Earthquake can trigger is tsunami.

When the tsunamigenic potential of the Sea of Marmara is assessed, over 40 tsunamis have taken place during the course of an observational period of about 2000 years [3]. Generally, a strike-slip fault such as NAF does not have immense tsunami potential. However, in the Sea of Marmara, there are several submarine landslides located on edges of the basins, which have high energy tsunami potentials. It has been observed throughout history that large tsunamis took place in the Sea of Marmara which caused significant damage to the Marmara Coasts.

Many different studies are conducted around the Marmara Region which evaluate the potential earthquake damage in different types of structures, also a number of research are completed which conducts numerical analysis of possible Tsunami scenarios based on earthquake rupture or submarine landslides.

In this study, tsunami inundation effects exerted on reinforced concrete structures after an earthquake have been studied. Analysis has been conducted using the Nonlinear Pushover Analysis Method and structural damage has been evaluated based on Turkish

Building Earthquake Code 2018 [1]. After the Pushover analysis, tsunami loads based on ASCE 7-22 have been calculated and applied to the deformed structure as nonlinear loads. Final structural damage has been evaluated based on TBEC 2018. This procedure is carried out with a case study carried out in a 5-story residential building located in the coastline of Çınarcık, Yalova.

Çınarcık, a coastal town in Yalova province located at the southeastern coasts of Marmara Sea, is chosen as the pilot study area in this thesis. As being close to Istanbul, Çınarcık is a popular location for summer houses with a population reaching around 300,000 in high season. The fact that buildings near the coast were built at least 30 years ago reveals that they were not constructed in accordance with the recent building earthquake standard, creating high vulnerability in the event of the expected major Marmara earthquake. In that sense, it is essential to make earthquake damage estimation as well as tsunami hazard assessment in Çınarcık town.

As a result of these studies, the potential damage from the expected major Marmara Earthquake and the cascading tsunami in Yalova, Çınarcık pilot area is evaluated. Damage assessment did not only focus on individual structures but also the urban locations of potentially damaged or collapsed buildings to identify evacuation challenges that may arise after the cascading disasters are determined.

In this study, Chapter 1 of this study provides information regarding the scope of the study. It also gives general information about the previous research on the field in the literature research section. The methodology behind the research is explained in Chapter 2 that gives detailed explanations on the potential of the earthquake and tsunami that can occur in the region. This section provides detailed information regarding the earthquake analysis methods and also provides information on tsunami generating mechanisms. Chapter 3 explains the data processing for the pilot region, tsunami scenarios and tsunami load calculation for pilot region. It also provides information and results on numerical structural analysis and cascading tsunami analysis on the structure. The discussion of results and conclusion are given in Chapter 4, where overall information about the work done for this research and suggestions for the future possible studies are provided.

1.2. Literature Research

In this section, academic research about previous studies on Tsunami Risk Analysis and Earthquake analysis are provided.

Altinok and Ersoy (2000), investigates the tsunamis observed on the Turkish coasts and provides information regarding tsunami records in Türkiye over a 3000-year period. Even though there are lack of studies in all the tsunamis observed on Türkiye's Coasts, there are historical sources that provide information on the major earthquakes that caused tsunamis in Türkiye's Coasts; 1509 Istanbul Earthquake, 1894 Istanbul Earthquake, 1963 Eastern Marmara Earthquake, 1999 İzmit Earthquake, 1938 Erzincan Earthquake, 1968 Bartın Earthquake and 1598 Amasya Earthquake. Yıldız and Ersoy (2000) provide detailed information on casualties based on historical sources [2].

Altinok and Ersoy (2001) evaluates the historical tsunamis in the Sea of Marmara and presents that there are over 40 tsunamis happened in the Sea of Marmara in last 2000 years and provides information on the Major Tsunamis occurred in the Sea of Marmara, including the last one happened after 1999 İzmit Earthquake [3].

Ambraseys (2002) investigates the sea-waves due to seismic activity in the Marmara Sea region during the last 20 centuries and also provides detailed historical information on tsunami events that happened in the Sea of Marmara in the last 2000 years [4].

Studies in Hebert et al. (2005) provide numerical analysis for earthquakes and landslides that generated tsunamis which can occur in the Sea of Marmara. Based on the analysis conducted by Hebert et al. 2005, both submarine earthquakes and submarine landslides have capacity to generate tsunamis in the Sea of Marmara, but submarine landslide related tsunamis are devastating for region [5].

In the work of Gazioglu et al. (2005), submarine landslides in the Sea of Marmara is investigated using the recent bathymetric data, with the advanced GIS software [6].

In Gokceoglu et al. (2009) one of the most critical landslides in the Sea of Marmara called Tuzla Landslide in the northern edge of Çınarcık Basin is investigated. In this study, detailed bathymetry, morphology, landslide scenarios, materials with sliding materials are investigated [7].

Latcharote et al. (2016) investigates the worst-case tsunami scenarios in the Sea of Marmara. Larcharote et al. considers both submarine earthquakes and submarine landslide related tsunamis and compares the capacity of the tsunamis generated. Latcharote et al also considers the tsunami generated by the combined effect of submarine earthquakes and submarine landslides. In the calculations, Latcharote et al uses 90m bathymetric and topographic data of the entire Sea of Marmara. Latcharote et al. compares the results of the analysis to define the worst-case scenario for tsunami hazard in the Sea of Marmara [8].

In the studies of Petrone et al. (2017) application of the calculated tsunami loads to a Reinforced Concrete structure and the analysis method of Reinforced Concrete structures under tsunami loads are investigated. To evaluate the results of different analysis methods, nonlinear dynamic analysis results are compared to nonlinear static analysis methods such as constant-height pushover (CHPO) and variable-height pushover (VHPO). Results of the different analysis methods are compared considering the parameters such as engineering demands and fragility curves are generated for a case study RC Moment Resisting Frame building [9].

Biguera, Marco & Rossetto, Tiziana & Robertson, Ian & Petrone, Crescenzo. (2022) “A Procedure for Performing Nonlinear Pushover Analysis for Tsunami Loading to ASCE 7” provides information on the comparison of the structure-based tsunami analysis and component-based tsunami analysis. The results show that the structure can resist lateral loads described in ASCE 7-16 but fails in component-based loading [10].

Yeh et al. (2014) examines the exiting guidelines of structural design related to tsunami forces and provide information regarding which approaches on guidelines are rational. It also examines the effects of buoyant forces on structures and its effects on the structural integrity of the buildings [11].

Chock (2016) provides detailed explanation regarding the methodology and technical information on tsunami resistant structure design based on ASCE 7 Chapter 6. ASCE 7 gives information on probabilistic offshore tsunami amplitude maps and inundation maps of tsunami design zones [12].

Macabuag et al. (2018) explains the tsunami analysis methodologies for both American and Japanese Standards and compares the differences between these approaches. It also outlines the considerations not yet covered by these standards [13].

Esteban et al. (2015) is a handbook of coastal mitigation for engineers and planners. It provides detailed global case studies including 2004 Indian Ocean tsunami, Java tsunami, Hurricane Katrina etc. It also provides hard structural solutions and softer structural measures on mitigation measures. It also provides future resilience information considering such as climate change and sea level rise.



2. METHODOLOGY

2.1. Earthquake Hazard

2.1.1. History of Earthquake Analysis in Turkiye

Turkiye is located at the intersection of Tectonic plates, which makes it a seismic active region. Due to this activity, Turkiye gets tested with catastrophic seismic activities throughout the time.

Marmara Region in Turkiye, hosts one of the most seismically active faults in Eurasia called North Anatolian Fault (NAF). North Anatolian Fault is a 1200-km-long strike slip characteristic fault spanning the northern part of Turkiye. In the last century, this region experienced unusual seismic activities with nine strong events having $M > 7.0$ (Kalkan et al. 2009) [14]. Because of the high seismicity of the region, it has always been a challenge to construct structures that can withstand those catastrophic and repetitive earthquakes. To withstand these conditions and provide safety to the region, Earthquake Hazard Maps are developed and regulated in Turkiye to guide the structural designers in Turkiye.

First unofficial Earthquake Hazard Maps for Turkiye were developed by Siberg in 1932. But the official Hazard Map of Turkiye was published in 1945. Earthquake Hazard Maps of Turkiye later updated in 1947, 1948, 1963, 1972, 1996 and 2018.

Most recent Hazard Map of Turkiye is 2018 Hazard Map of Turkiye, which uses Probabilistic Seismic Hazard Analysis Method and returns the Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) based on the probability of exceedance of 2% with return period of 2475 years, 10% with return period of 475 years, 50% with return period of 72 years and 68% with return period of 43 years. Hazard maps of Turkiye is given in the **Figure 2.1**.

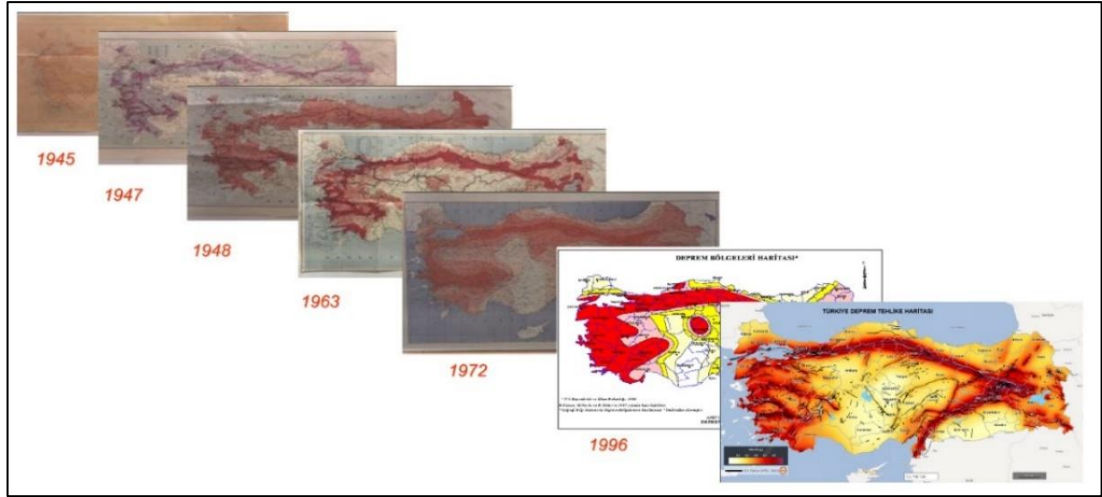


Figure 2.1: Turkey earthquake hazard maps [15].

The Peak Ground Acceleration (PGA) is the most referred parameter in evaluating a Hazard Map. During an earthquake, maximum acceleration occurring in the ground is called Peak Ground Acceleration and represented in the unit of gravitational acceleration ($g= 9.81 \text{ m/s}^2$).

2.1.2. Methods of Analysis

Due to the high seismicity of Türkiye, demand for structural analysis standards has occurred and developed in the last century. Turkish Seismic Design Code studies started with the 1939 Erzincan Earthquake and the first seismic design code was published in 1940 inspired by the Italian Seismic Code. With the preparation of the Turkish Hazard Maps, seismic codes have been utilized and improved since 1940's. Since the first publications, Turkish Seismic Code has been revised in 1947, 1953, 1961, 1968, 1975, 1998, 2007 and 2018.

With the improvement in Technology, seismic design criteria and methodology have changed in Türkiye and in the world. Improvement in both the computer sciences and testing mechanism provide opportunities to create safer, cheaper and more complex structures. The latest Turkish Seismic Code that is in use today is the Turkish Earthquake Code 2018 [1]. TBEC 2018 allows structures to be designed with Linear and Non-Linear Structural Design principles. Both methods have their different advantages to create sufficient design based on the demands of the structures.

2.1.3.1. Linear Analysis Method

Linear analysis is an analysis method that assumes that the material properties of the analyzed structure will remain in the linear material part of the stress-strain curve and act following Hooke's Law. This method is a more conservative approach to structural behavior and requires less complex computational force. Thus, it is more commonly used to practice worldwide.

There are two linear analysis methods that can be used to analyze the structures. These methods are;

- Equivalent Lateral Force Method
- Modal Response Spectrum Analyses Method

2.1.3.1.1. Equivalent Lateral Force Method

The Equivalent Lateral Force Method (ELF) is a method to determine the lateral static loads acting on the structure due to horizontal seismic loads. It is the oldest analysis method in use to calculate the seismic loads on structures. It is based on Newton's second law of motion. ELF is meant for structures in their mass participation; their fundamental period of vibration is dominant. Also, ELF requires the structure to not have significant discontinuity.

The main target on ELF is to calculate the base shear and distribute the lateral loads to the stories of the structure relative to the weight of the stories. Formulas to calculate the base shear and story lateral forces are given in Equation 2.1 and Equation 2.2.

$$V_{tE}^{(x)} = m_t * S_{aR} * (T_p^{(x)}) \geq 0.04 * m_t * I * S_{DS} * g \quad (2.1)$$

$$F_{iE}^{(x)} = (V_{tE}^{(x)} - \Delta F_{NE}^{(x)}) * \frac{m_i * H_i}{\sum_{j=1}^N m_j * H_j} \quad (2.2)$$

2.1.3.1.2. Modal Response Spectrum Analysis Method

Modal Response Spectrum Analysis (MRS) is the method which takes mode shapes of the structures into consideration. A structure has N number of corresponding mode shapes with independent and normalized displacement pattern to its N number of degrees of freedom. Modal shapes of a structure is given in **Figure 2.2**.

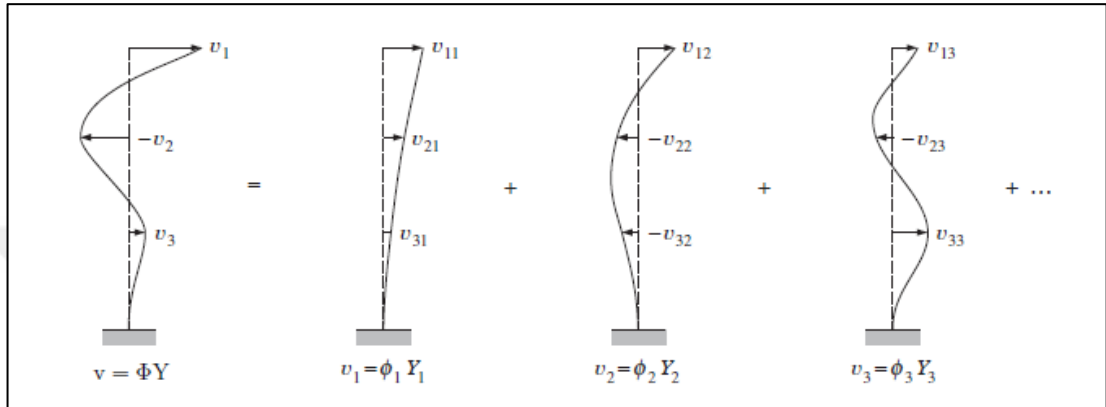


Figure 2.2: Modal shapes of structure [16].

There are two modal analysis methods that can be used, Mode Superposition Method and Mode Summation Method. These methods can be used for all structures which are to be designed based on Linear Analysis Methods.

Mode Superposition Method is used with a response spectrum and computes the maximum response of each mode based on the response spectrum. Modal responses are combined with Square Root of the Sum of Squares (SRSS) and Complete Quadratic Combination (CQC) based on their mass participation ratios.

In the Mode Summation Method, Earthquake is considered affecting the structure concurrently in two perpendicular directions and modal responses calculated for each frequency are calculated using modal calculation method in time history domain. After calculating the adequate number of concurrent modal responses, responses are summed, and largest responses are calculated to use in the design process [1].

2.1.3.2. Nonlinear Analysis Method

In the field of structural engineering materials, sections and structures do have nonlinear properties and characteristics. Calculating these nonlinearities requires advanced calculations for various scenarios. These calculations were unapplicable because of the difficulty computing these calculations by hand. But with the advancement of technology, these advanced and complex calculations can be completed with modern computers easily. Nonlinear Analysis Methods still take more computational power than Linear Analysis, but Nonlinear analysis is more effective and realistic compared to Linear Analysis due to its consideration of factors such as yielding, cracking, large deformations, and dynamic instability.

There are two types of Nonlinear Analysis Method that can be used in structural analysis in Türkiye, based on TBEC 2018. These are;

- Nonlinear Static (Pushover) Analysis
- Nonlinear Dynamic (Time-History) Analysis

2.1.3.2.1. Nonlinear Static (Pushover) Analysis

The main philosophy of Nonlinear Static (Pushover) Analysis is to define the capacity of the structure by applying incremental lateral load to the structure until the structure reaches target displacement based on the following standard. A capacity curve for structure and top displacement- base shear relationship is obtained with the application of this method to the structure.

If the Modal Load participation ratio of the dominant mode in the pushover direction is larger than 0.7, and if the torsional irregularity coefficient of the structure is smaller than 1.4, the structure can be analyzed using the Single-Mode Pushover Analysis, otherwise the structure has to be analyzed using Multi-Mode Pushover Analysis Method. The main difference between Single-Mode and Multi-Mode Pushover Analysis is Single Mode analysis considers only the dominant mode of the structure and conducts the analysis based on that variable, on the other hand Multi-Mode Pushover analysis considers the effect of each mode to the structure.

2.1.3.2.2. Nonlinear Dynamic (Time History) Analysis

The main philosophy of Nonlinear Dynamic (Time History) Analysis is to solve the differential equation of motion with respect to change in the stiffness matrix of the structure due to nonlinear parameters caused by the dynamic ground motion input to the structure. Ground motion input is provided by scaling and applying ground motion records that have similar characteristics with the ground motion which is expected to the structure's region. Normally, solving stiffness matrices and equations of motions in every time step of a ground motion record is very complex and requires immense computational power, but with the advancements in technology, it is possible to do with regular computers.

Both Nonlinear Analysis Methods have to be applied considering the nonlinear parameters of the structure. These parameters are;

- Material Nonlinearity
- Section Nonlinearity
- Geometric Nonlinearity

For Material Nonlinearity, based on stress-strain relations, materials have elastic and plastic regions. Elastic region is the region of a material with an applied load to return to its original form without any residual deformations when the applied load is removed. Plastic region is the region of a material with an applied load to have permanent deformations when the applied load is removed. Materials with larger plastic regions are called ductile materials. In construction, ductile materials are used to maintain the structural integrity of the structure with the increment of the load.

Reinforced concrete is a unique combination where highly ductile steel and brittle concrete works together and becomes a material that represents the characteristics of both materials. In order to calculate the exact properties of the Reinforced Concrete Sections, Nonlinear Material Models have to be used. TBEC 2018 recommends using the Mander Material Model in order to calculate the properties of the RC Sections. Nonlinear material models are given in Figure 2.3 and Figure 2.4 below.

In terms of section nonlinearity, plastic hinges are considered. In the structural members, plastic hinges are formed due to excessive loading where the sections start the plastic deformation and rotate in the hinge region, while keeping the rest of the members in the elastic region and preventing the sudden failure of the sections.

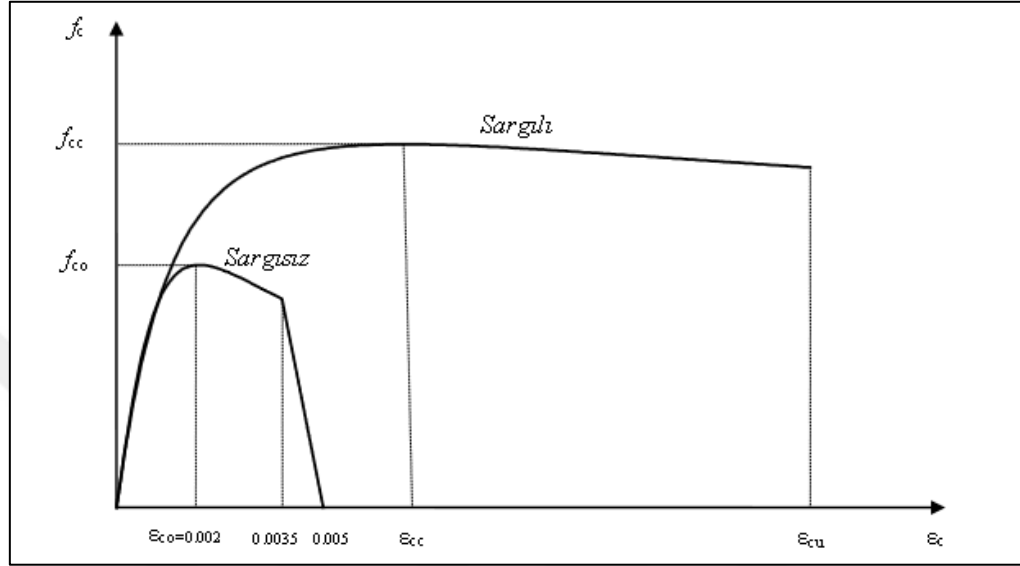


Figure 2.3: Unconfined and confined concrete properties [1].

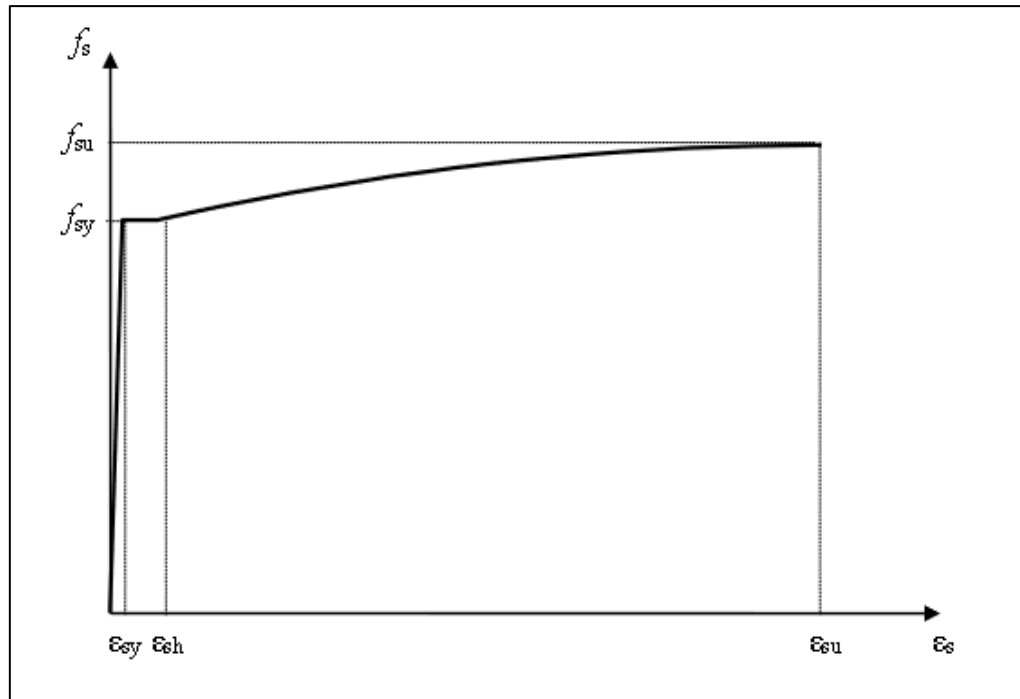


Figure 2.4: Stress-strain graph of rebars [1].

There are two plastic hinge models used in the Nonlinear Analysis Methods, Lumped Plastic Hinge Model and Distributed Plastic Hinge Model. In the Lumped Plastic Hinge Model, plastic deformations are considered to occur in the region called plastic hinge length (l_p) at the end of the beams and columns. In the Distributed Plastic Hinge Model, the entire member is modeled in a nonlinear element with fiber definitions. This method can be used for columns, walls and beams. Distributed Plastic Hinge Model is a more realistic approach than Lumped Plastic Hinge Model, but it requires more computational power to analyze.

In terms of structural nonlinearity, in the nonlinear analysis, second order effects caused by the deformations during the loading of the structure are considered in the analysis procedure. It is also called the P- Δ Effects in structural analysis [17]. P- Δ Effects are shown in **Figure 2.5**.

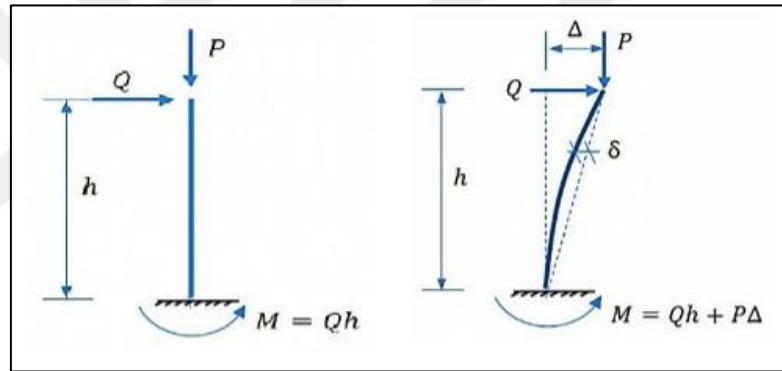


Figure 2.5: P-Delta effects [17].

Referring to the information above, this study follows a nonlinear static (pushover) analysis method to calculate the story drifts and damage level of the structural elements.

2.1.3. Post Earthquake Residual Effects

Residual Effects occur on the structure after an earthquake is residual drift. These residual drifts happen after plastic hinges generated in the structural members due to excessive loadings. Residual drift is evaluated by the standards provided by FEMA 356. In this study, residual effects are considered based on the loading pattern applied to the structure [18]. Inter-story drift vs Time showing the residual drift is given in **Figure 2.6**.

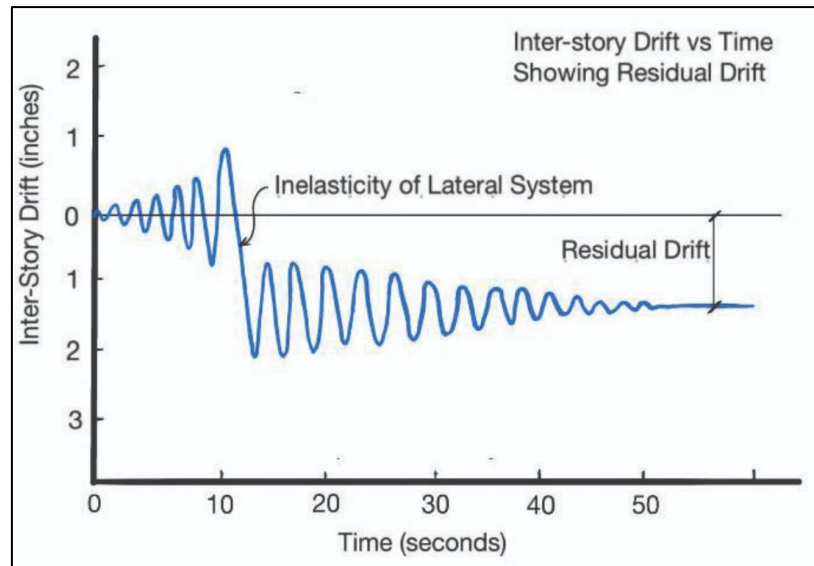


Figure 2.6: Residual drift.

2.2. Tsunami Hazard

Originating from the combination of two Japanese words “tsu” (harbor) and “nami” (wave), tsunamis are sea waves with high energy capacity caused by large water displacements in oceans, seas or large lakes due to an impulsive disturbance. These high energy capacity waves can travel in basins at high speed and affect coastlines during amplification, inundation and runup at widespread areas. One of the most known past tsunami disasters is the 2004 Indian Ocean Tsunami which caused more than 230,000 casualties in 14 countries affected by the 15–30-meter waves caused by the undersea earthquake with Mw 9.1 located in western coast of Sumatra, Indonesia [19], [20]. This was a datemark for tsunami research worldwide due to the fact that it implied the catastrophic effects of mega tsunamis occurred due to subduction zone earthquakes. Another datemark for tsunami research was 2011 Mw 9.0 Great Tohoku Earthquake with huge slip values reaching to 17m and measured maximum runup height of 40.5 m causing many losses of lives and missing people [21]–[24]. The most common cause of tsunamis is observed due to earthquake rupture, especially at subduction zones. The secondary most common tsunami triggering disturbance comes from submarine landslides with the sliding of slumps at the sea bottom shelves. Tsunami triggering mechanisms and the potential tsunami sources in the Marmara Sea, the target area of this study, are described in the following sections.

2.2.1. Tsunami Triggering Mechanisms

There are different mechanisms that trigger large and sudden water displacements and create tsunamis. The three main types of disturbances are: underwater earthquakes concentrated in zones where there is slipping or subduction of Tectonic plates, submarine landslides which are often but not always triggered by earthquakes, and sudden earth surface movements adjacent to the ocean (volcanoes, rock falls, sub-aerial landslides, ship sinking) [25]. Tsunamis move as fast as 600-700 km/h in deep waters, and when a tsunami wave is traveling in deep waters, it is very hard to observe because of the immense wavelengths. When the tsunami waves get closer to the shallow waters, waves become slower but can turn into powerful currents.

2.2.1.1. Earthquake Induced Tsunamis

One of the main mechanisms that creates tsunamis is Tectonic activity. 80% of all the tsunamis are earthquake induced tsunamis [26]. If an undersea earthquake is strong enough and close enough to the surface, it creates a water turbulence, a sinking and rising motion, which disperse in all directions from epicenter, traveling in deep water where it is hard to be observed and affects the shores (**Figure 2.7**).

These earthquakes occur in subduction zones where two Tectonic plates collide with each other. When two Tectonic plates collide, one of the plates slides under the other plate, resulting in immense stress in the friction zone between plates. This accumulated stress distorts the Tectonic plates and creates sudden motion in the water.

The most common region for the occurrence of earthquake induced tsunamis is the Pacific “Ring of Fire” region due to the high seismic activity and existence of huge subduction zones in the ocean basins.

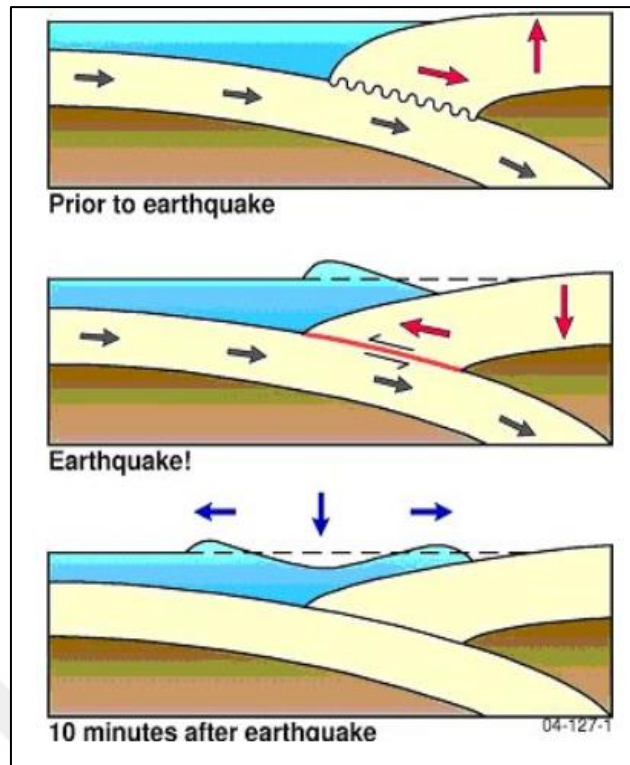


Figure 2.7: Tsunami generation in oceanic subduction zone [27].

2.2.1.2. Submarine Landslides Tsunamis

The secondary most common cause of tsunamis is submarine landslides that can be triggered by a strong ground motion nearby or excess accumulation of slidable material in submarine landslide zones as shown in **Figure 2.8**. Submarine landslides can cause large but nearfield tsunami effects compared to the earthquake induced mechanisms. It is more complicated, and it is harder to assess the landslide related tsunamis because of the underwater kinematics. Because of the unbalanced submarine landslide zones in the Marmara Sea, tsunamis generated by submarine landslides are the most common tsunami triggering mechanisms. Initial tsunami waves triggered by submarine landslides are calculated using two-layer shallow water equations or empirical formulas considering the volume of slump volume as well as sliding depth, speed and duration [28].

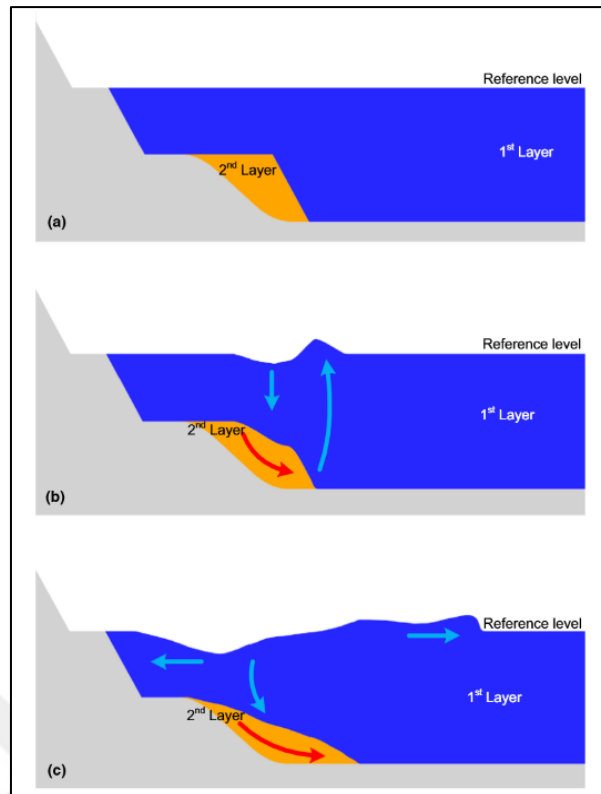


Figure 2.8: Diagram of tsunami waves created by submarine landslides [28].

2.2.1.3. Other Mechanisms

There are also other mechanisms that cause sudden and large displacements in water levels such as volcanic activities, meteorite impacts and atmospheric disturbances (meteotsunamis).

Volcanic tsunamis are generated by a variety of mechanisms, including volcano-Tectonic earthquakes, slope instabilities, pyroclastic flows, underwater explosions, shock waves and caldera collapse [29].

One of the other tsunamis triggering mechanisms is rapid changes in atmospheric pressure. Tsunamis generated by atmospheric disturbances are called meteotsunamis driven by air-pressure disturbances and often associated with fast-moving weather events, such as severe thunderstorms, squalls and other storm fronts. The storm generates a wave that moves towards the shore and is amplified by a shallow continental shelf and inlet, bay or another coastal feature [26]. Meteotsunamis can go up to 2 meters and can happen in the vast majority of places.

2.2.2. Tsunami Potential in the Marmara Sea and Worst-Case Tsunami Scenarios

The sea of Marmara interferes with the Tectonic unstable North Anatolian Fault (NAF), which mostly has strike-slip fault characteristics. Normally, strike-slip faults do not have high tsunami potential due to low level of vertical displacement components. However, over 40 tsunamis happened in this region between 120 and 1999 AC [3], of which generally occurred due to submarine landslides.

The reason why a strike-slip fault can cause significant tsunamis in Marmara Sea is the potential of triggering submarine landslides located at the surface of deep basins in the sea of Marmara. Seismic activity at the fault segments in sub-basins of Marmara Sea can cause sliding of the slump masses at landslide locations and generate tsunamis. Many geomorphologic studies provide the characteristics of submarine landslides with the possible slump volumes, sliding speed as well as duration ([7], Yalciner et al. 2002).

The Marmara trough is a complex system consisting of ridges and basins located in the Marmara Sea. The Marmara Sea has three basins and three ridges. Basins located in the Marmara Sea are called Çınarcık Basin, Central Basin and Tekirdag Basin. Three ridges of Marmara Sea are called Eastern, Central and Western Ridges. There is also a sub-basin in Marmara Sea called Silivri or Kumburgaz Basin [7].

The high-angle continental slopes of the Marmara Sea can produce submarine landslides and slumps, which may trigger tsunamis (Gazioglu et al. 2005). There are 5 major submarine landslide zones in Marmara Sea, and the most significant of submarine landslides in Marmara Sea is Tuzla Submarine Landslide, which is located in the northwestern corner of the Çınarcık Basin [3].

Gokceoglu et al. 2009 defines six different submarine landslide scenarios that can happen in northern slopes of Çınarcık Basin, Tuzla Submarine Landslide. In this paper, Case-1 is described as the most possible scenario, but because of the low amount of slidable material, it has the least hazardous effect. Case-2 is described as the most likely case having three times more material that can slide compared to Case-1, thus making it the most critical scenario. Case-3 has the most slidable material, but it is the least likely scenario to happen in the Tuzla Landslide, due to its large sliding surface and low slope degree of sliding surface (**Figure 2.9**).

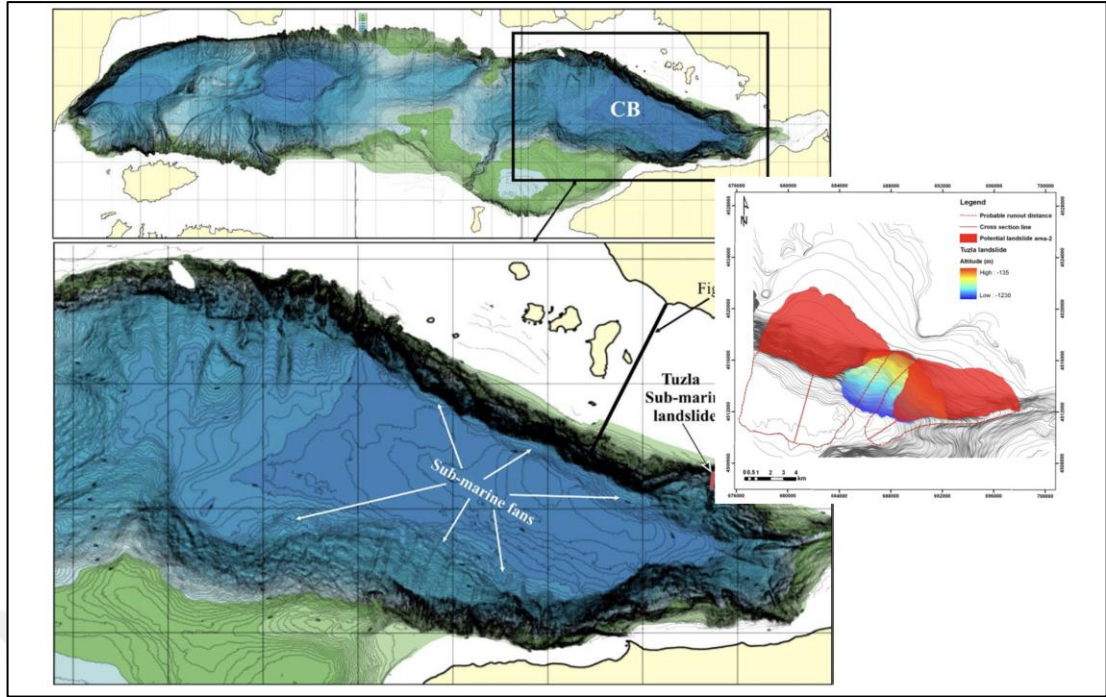


Figure 2.9: Submarine Fans in Çınarcık Basin and possible slump area of Scenario-2 at Tuzla landslide showing the possible maximum runout distances [7].

Possible worst-case scenario for tsunami generation in Marmara Sea is investigated by different studies. One of the most recent and detailed ones is the work of Latcharote et al. 2016. Based on the calculations, comparing the earthquake rupture related tsunamis and submarine landslide generated tsunamis, Latcharote et al. 2016 determined that the maximum tsunami height could reach 3.0, 2.5, and 4.0 m along Istanbul shores for the eastern rupture, the western rupture and the full rupture along the North Anatolian Fault (NAF). The maximum tsunami height for landslide sources with small, medium, and large volumes could reach up to 3.5, 6.0, and 8.0 m, respectively, along Istanbul shores [8]. Based on these studies, it can be said that submarine landslide generated tsunamis are more critical to the Marmara Region due to the characteristics of the region and the NAF.

Likewise, another study about the tsunami scenarios in the Marmara Sea is Hébert et al (2005) performs tsunami hazard analysis in the region considering earthquake and submarine landslide sources located on the northern slope of the Çınarcık basin, with different friction angles and volumes of sliding mass.

The report of Tsunami Modeling, Vulnerability and Hazard Analysis in Istanbul Province Project prepared by METU (2018) for Istanbul Metropolitan Municipality

uses an earthquake and submarine landslide database for the evaluation of tsunami hazard at Istanbul coasts. This report also emphasizes that significant tsunamis are expected either from a major earthquake offshore Prince Islands or a massive submarine landslide.

Following the previous studies that highlights the possibility of tsunami sources in the Marmara Sea, it is observed that even long fault ruptures in the Eastern Basin are not sufficient to generate effective tsunami waves in the Marmara coasts. On the other hand, submarine landslide sources, besides the seismic sources, can be the explanation of the 6 m tsunami run-up, remarked in the historical records of the 1509 Istanbul earthquake ($M7.2 \pm 0.3$). As a result, the tsunami scenarios in this study are focusing on two main tsunami sources: (i) a major earthquake offshore Prince Islands, and (ii) a submarine landslide at Tuzla landslide in Çınarcık Basin. The fault mechanism of Prince Islands earthquake scenario is prepared referring to Eastern Rupture in Latharote et al (2006). The possible sliding slump area is chosen referring to Case-2 described in Gokceoglu et al (2009) (**Figure 2.10**). The details of tsunami scenarios are explained in Chapter 3.1.2.

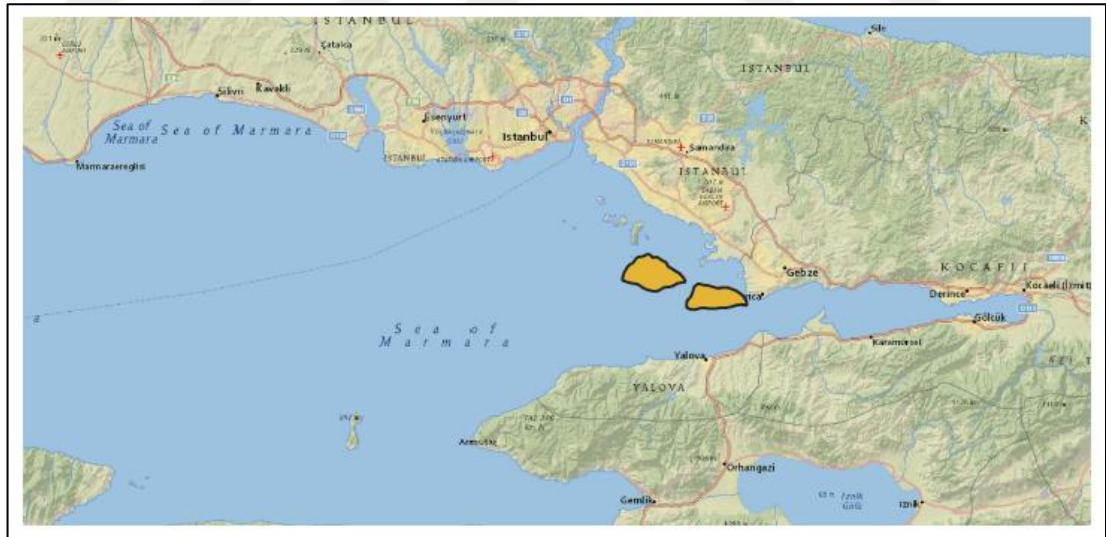


Figure 2.10: Tuzla Submarine Landslide in Çınarcık Basin, Marmara Sea (after [7]).

3. CASE STUDY OF NUMERICAL SIMULATIONS AND PERFORMANCE ANALYSIS

3.1. Numerical Tsunami Simulations

In this study, tsunami propagation, amplification and inundation in 2-Dimensions is calculated using the software NAMIDANCE [35], by solving the Linear and Non-Linear Shallow Water Equations. The numerical code NAMI DANCE is developed based on the code TUNAMI N2 in C++ language, used mainly for tsunami simulations and visualizations and has been applied to several tsunami events by many institutes worldwide [43], [44], [45]. It solves the tsunami motion by shallow water wave equations with finite-difference Technique and leap-frog scheme [46].

Tsunami generation due to earthquake rupture is calculated by Okada (1985) [47] based on seabed deformation. Tsunami initial waves that occurred due to submarine landslides are calculated using empirical formulas from literature providing the wave amplitude and wavelength at the initial sea surface distribution immediately after the sliding of seabed slump. In this section, the details of bathymetric-topographic data processing and tsunami numerical modeling are provided in the following sections.

3.1.1. Data Processing of the Pilot Region

Preparation of the topography and bathymetry of the analysis area for the pilot region using open-source data

To conduct the tsunami analysis, bathymetric and topographic maps of the region have been prepared using third party software and open-source data available for the pilot region. To complete the numeric Tsunami analysis, 3D Elevated maps of the region are prepared in “.grd” format for the subject study area of this thesis, Çınarcık, Yalova, Türkiye.

QGIS Mapping of the Pilot Region

QGIS is an open-source geographic information system (GIS) software. The main objective to use QGIS in this study is to determine the building locations in the pilot region using the satellite images provided by OpenStreetMap. The data process started with acquiring the bathymetric data of Marmara Region with the resolution of 84 meters from İstanbul Metropolitan Municipality.

Topographic data of the region is taken from the OpenTopography interface. OpenTopography provides data from an international project “The Shuttle Radar Topography Mission (SRTM)”, which is conducted by National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The resolution of topographic data of the pilot region is 30 meters.

To carry on with the Tsunami numerical analysis, four nested domains have been created in the Marmara Region. The reason for the preparation of nested domains is to maintain the reliability of calculations in numerical modeling by transmitting the computed hydrodynamic parameters from coarsest to finest study domain from their border connections. These domains are called “Domain B”, “Domain C”, “Domain D” and “Domain E” with the grid sizes of 84 m, 42 m, 21 m and 3 m, respectively (**Figure 3.1**). The resolutions, intended purpose, and the coordinates of the domains are given in **Table 3.1**.

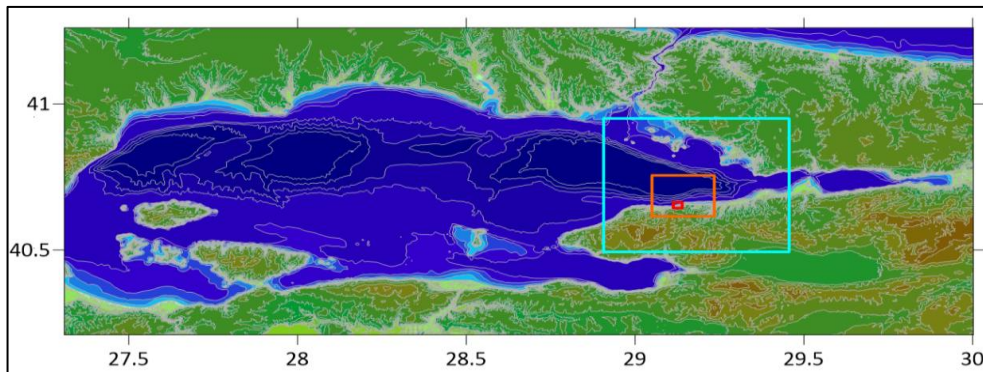


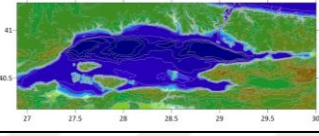
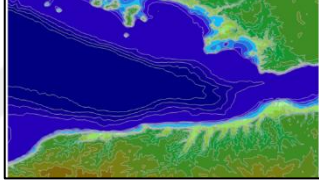
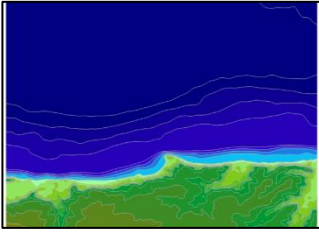
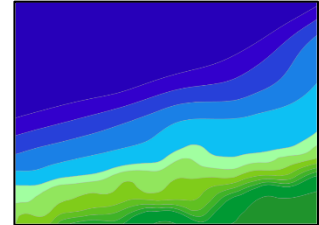
Figure 3.1: Marmara region superpositioned domains.

Interpolation of Bathymetric and Topographic Data

For the calculations, resolutions of the data of each domain interpolated respectively to the predetermined resolutions. For interpolation, the bilinear interpolation method has been used with the help of Golden Software’s Surfer.

With the method of Bilinear Interpolation, 84 m original bathymetric data have been interpolated to 42 m bathymetric data, 21 m bathymetric data and 3 m bathymetric data. Also, 30 m topographic data have been interpolated to 3 m topographic data.

Table 3.1: Nested domains used for the tsunami numerical modelling in the Marmara Sea

Nested Domain	Grid Size (m)	Corner coordinates (left-bottom, right-top)	Domain Map	Info
Domain B	84	40.177083°N, 30.002083°E; 41.285416°N, 26.893750°E		It covers the entire Marmara Sea. It is used for calculating the tsunami generation and having overall estimation of wave propagation in the Marmara Sea due to earthquake and submarine landslides.
Domain C	42	40.506153°N, 29.457501°E; 40.949743°N, 28.902697°E		It covers the eastern part of the Marmara Sea and is used for the transition of numeric calculations from Domain B to Domain D.
Domain D	21	40.615982°N, 29.234383°E; 40.754871°N, 29.049733°E		It covers Çınarcık Basin, Tuzla Landslide zone and Çınarcık District in the Marmara Sea and is used for the transition of numeric calculations from Domain C to Domain E.
Domain E	3	40.643504°N, 29.139389°E; 40.662919°N, 29.112919°E		It is the finest resolution domain that covers Çınarcık District.

Superposition of Bathymetric data, Topographic data and Existing Structures in Domain E

Domain E is the smallest and most detailed domain that the analysis has been conducted. In this domain, bathymetric, topographic and structural data have been put together with QGIS and ArcMap.

Below is the location of the structures in the pilot region (**Figure 3-2**). The shapefile containing heights and locations of the structures is converted to a raster data with 3-meter resolution using QGIS. Bathymetry, topography and structural raster data is put together using ArcMap and Domain E final data has been obtained (**Figure 3.3; 3.4**).

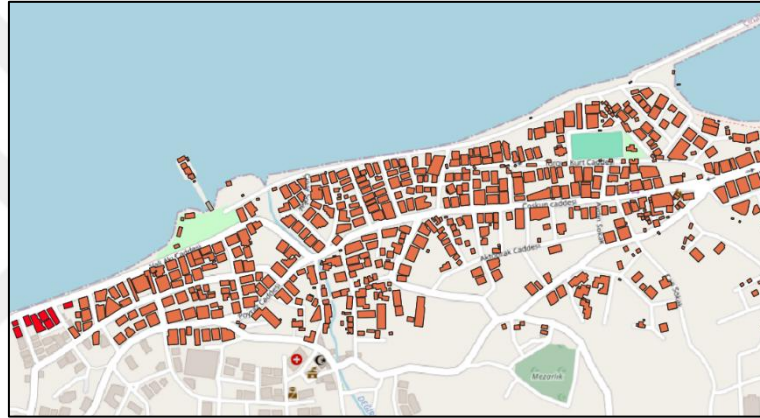


Figure 3.2: Structure locations in Çınarcık, Yalova.

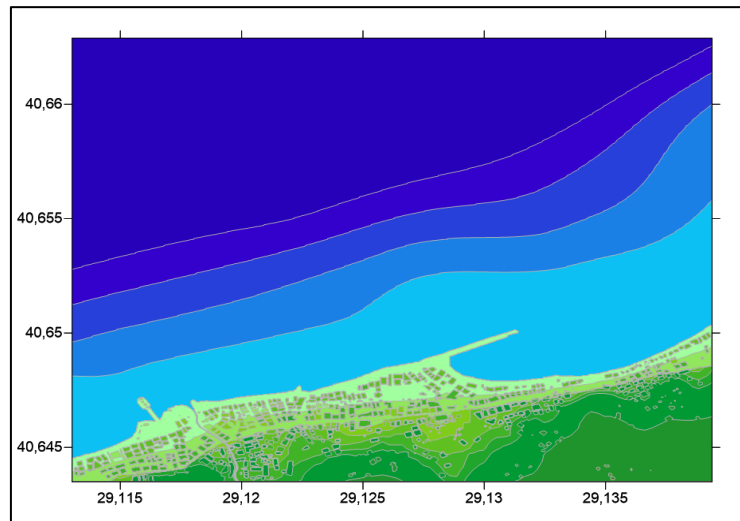


Figure 3.3: Elevation Map of Çınarcık, Yalova including Structures.

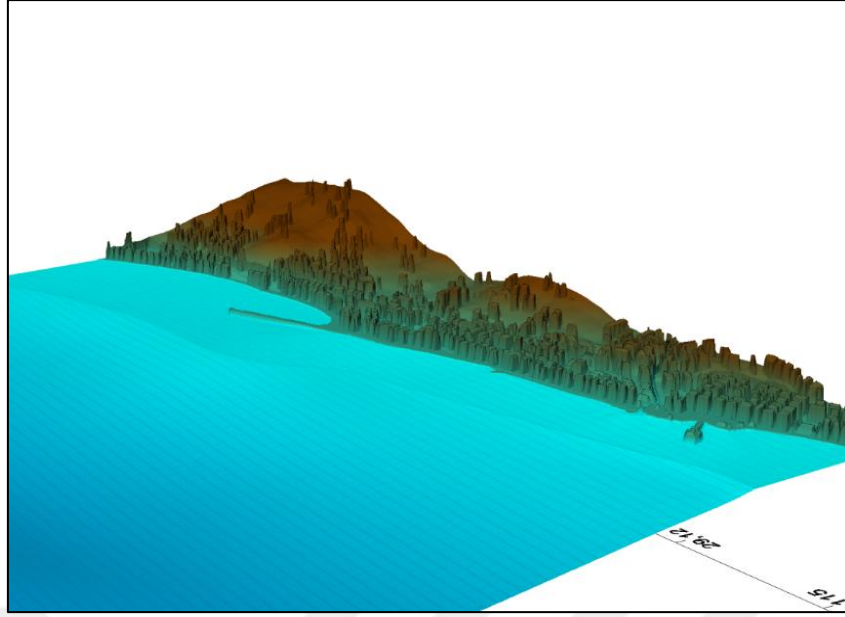


Figure 3.4: 3-Dimensional topographic elevation of Çınarcık, Yalova.

3.1.2. Tsunami Scenarios and Calculation of Tsunami Initial Wave

As described in Chapter 2.2.2, two tsunami scenarios are defined in this study based on a major earthquake offshore Prince Islands and a massive submarine landslide in Çınarcık Basin in the Marmara Sea as: Scenario-1 Mw7.3 Prince Islands earthquake, and Scenario-2 Tuzla Landslide.

Scenario-1: Prince Islands Mw 7.3 Earthquake Scenario

The fault mechanism for this scenario is taken from Latcharote et al. (2016) in which the fault geometry and parameters were considered as the same as Hebert et al. (2005), while the slip value was re-determined based on the idea of realistic worst-case scenario [48], [49]. The fault parameters used in the tsunami generation, and the initial wave amplitudes calculated by Okada (1985) are given in **Table 3.2**. The initial wave after earthquake rupture is plotted in **Figure 3.5**. Here we see that the ascending waves are expected along the northern coasts of Marmara Sea while descending of sea surface is estimated at southern coasts including Çınarcık, Yalova. The calculated initial wave height is about 1.2m.

Table 3.2: Fault parameters of Mw7.3 Prince Islands earthquake (Scenario-1)

Epicenter	Depth (km)	Length (km)	Width (km)	Fault directivity (Strike, Dip, Rake) (Degree)	Slip displacement (m)	Initial wave amplitude (m)
29.07E 40.80 N	10	40	15	117, 67, -120	4.3	0.2752 -0.9462

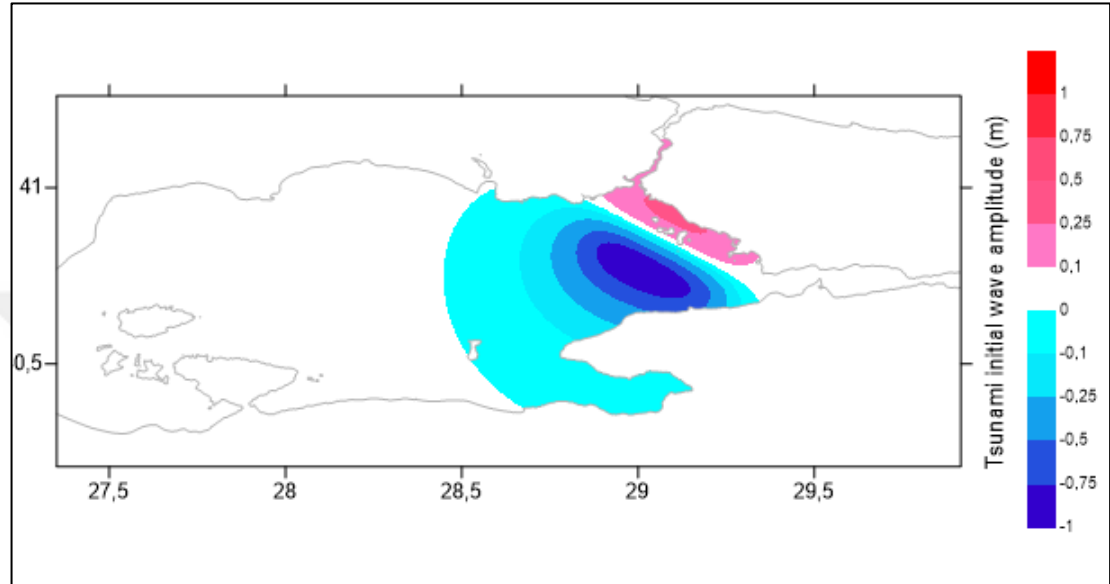


Figure 3.5: Tsunami initial water surface elevation occurred due to Mw7.3 Prince Islands Earthquake.

Scenario-2: Tuzla Landslide

Tuzla landslide is selected as the tsunami source in Scenario-2 referring to the proposal in Gokceoglu et al (2009) as described in Chapter 2.2.2. The eastern slump given in Case-2 of Gokceoglu et al (2009) is considered as the tsunami triggering submarine landslide with a volume of 0.8 km^3 as half of the foreseen possible sliding amount. The seabed slump and the possible runout distance used in this scenario are shown in Figure 3-6.

The bathymetric change before and after the sliding of slump shown in **Figure 3.6** is calculated and used in tsunami numerical modeling for the purpose of having more reliable wave velocity calculations due to change of water depth (**Figure 3.7**).

The initial tsunami wave amplitude generated by the submarine landslide is calculated using empirical equations proposed by several previous studies in literature. Grilli and Watts (2005) [50] [51] performed numerical simulations with a two-dimensional 2D

fully nonlinear potential flow (FNPF) model for tsunami generation by two idealized types of submarine mass failure SMF as underwater slides and slumps. They converted the results from numerical simulations into empirical curve fits predicting characteristic tsunami amplitudes which are only valid in the vicinity of the tsunami sources immediately after the sliding [50], [51].

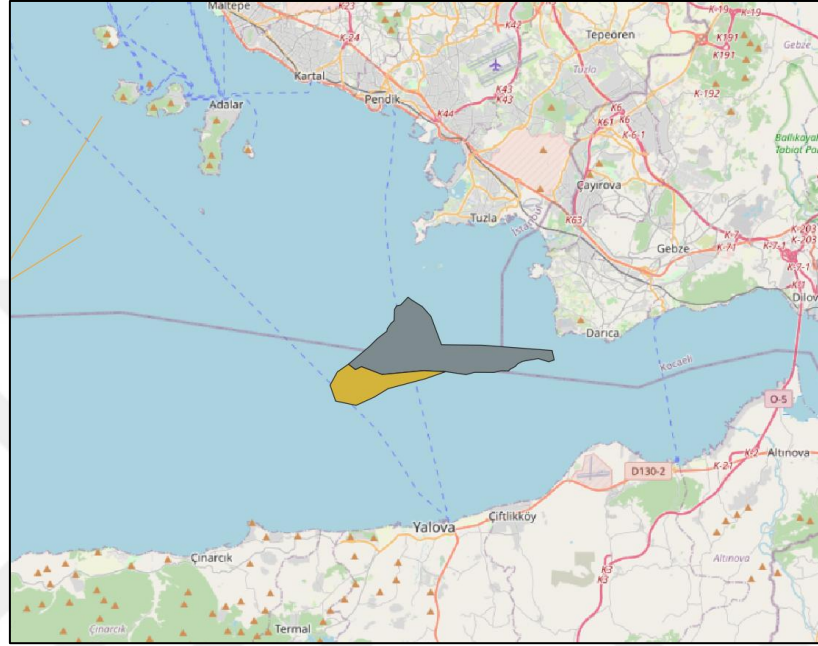


Figure 3.6: Seabed slump and possible runout distance used in Scenario-2 Tuzla Landslide referring to the proposal in Gokceoglu et al. (2009) [7].

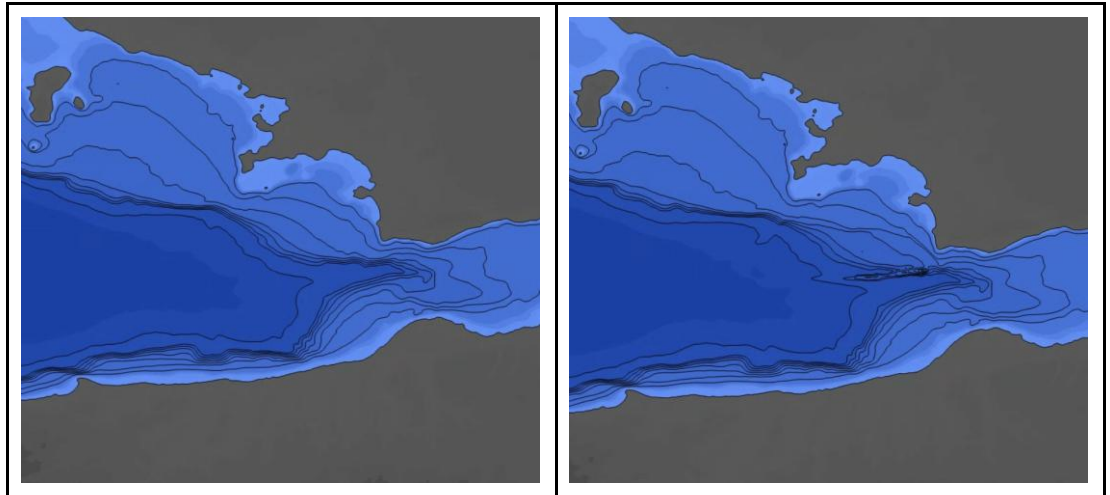


Figure 3.7: Bathymetric change in Domain B referring to the situation before and after submarine sliding; Tuzla Landslide in Çınarcık Basın-eastern slump.

It is important to highlight that tsunamis caused by SMFs are only limited in amplitude by the SMF vertical displacement [52] [56]. The main parameters defining the initial wave amplitude due to sliding of submarine slumps are the volume of slump and the initial water depth where the sliding initiates [53]. Many of the previous studies that propose empirical equations to predict the initial wave amplitude occurred due to the slump movement are reviewed to decide the most reliable calculation [55], [56], [57] [58], [59]. Sabeti and Heidarzadeh (2020) [54] analyse the existing empirical equations to predict the maximum initial amplitude ($\eta_{\max}$) of submarine land-slide-generated waves and studies their performance in reproducing real-world landslide incidents. They compare the empirical solutions with the real observations after landslide-induced tsunami events worldwide. Their results indicate that the slide volume and water depth where the sliding initiates (notated by d and called initial submergence) are among the most sensitive parameters for the calculation of maximum initial amplitude. As a result, in Equation 3.1 Sabeti and Heidarzadeh (2020) [54] develop a new predictive equation by fitting an equation to actual submarine landslide tsunamis as:

$$\eta_{\max} = 50.67 \times (V/d)^{0.34} \quad (3.1)$$

where V is the slide volume (km^3), d is initial submergence depth (m), and $\eta_{\max}$ is in meters.

Figure 3.8 shows the cross-section of a submarine landslide with the slump volume, initial submergence d , water depth h and the sliding slope θ . For the Tuzla landslide, the eastern slump of Case-2 in Gokceoglu et al (2009) is chosen and the half of proposed possible sliding volume is taken as 0.8 km^3 as the tsunami source of Scenario-2.

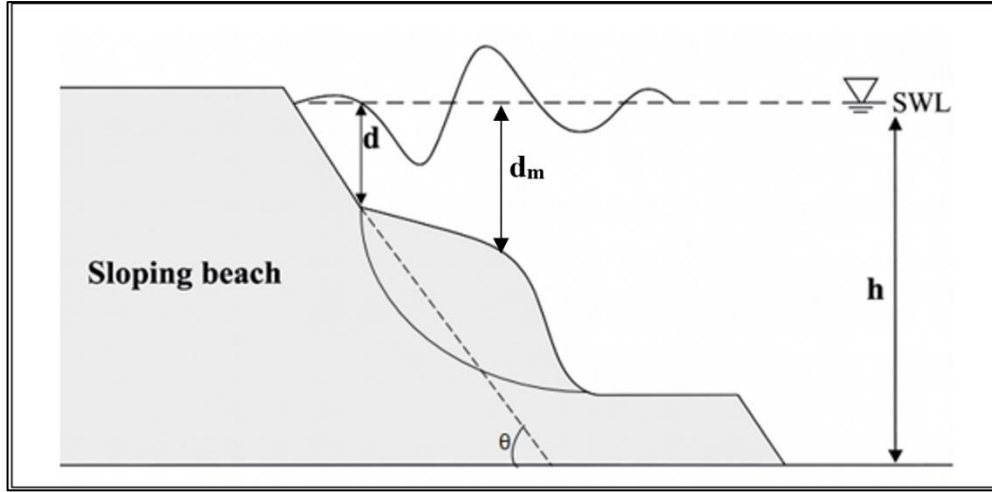


Figure 3.8: The cross-section of submarine landslide. showing the slump volume, and initial submergence d , mid-submergence height d_m , water depth h and the bathymetric slope θ .

The sliding slope is found from the slope of the seabed at bathymetric data and estimated as 11° . The initial submergence d is determined from the bathymetric data as 260 m and the mid-depth of slump, d_m , is calculated as 527 m referring to the sliding slope of 11° . Using these values together with the slump volume of 0.8 km^3 in Eqn. (1), maximum initial amplitude is calculated as:

$$\eta_{max} = 50.67 \times (0.8/260)^{0.34} = 7.2 \text{ m}$$

In order to predict the initial water surface disturbance that occurred due to landslide-induced tsunami, the wavelength should be calculated. In Equation 3.2, Watts et al (2005) proposes the characteristic tsunami wavelength by deriving a characteristic time of motion t_0 and using the submergence d_m at the middle of sliding slump as:

$$\lambda_0 = t_0 \times \sqrt{g \times d_m} \quad (3.2)$$

Watts et al (2005) proposed time of motion t_0 for 1999 Izmit Earthquake as 47sec, similar to the duration of the earthquake. Assuming the triggering of Tuzla landslide with a major earthquake in the Marmara Sea at least with 60 seconds rupture time, t_0 is assumed as 60 seconds for Scenario-2. Using d_m as 527m and t_0 as 60 seconds in Eqn. (2), the wavelength is calculated as;

$$\lambda_0 = 60 \times \sqrt{9.81 \times 527} = 4314 \text{ m}$$

The maximum initial tsunami generated by the Tuzla landslide is defined with a maximum initial wave amplitude of 7.2 m and wavelength of 4300 m shown as **Figure 3.9**.

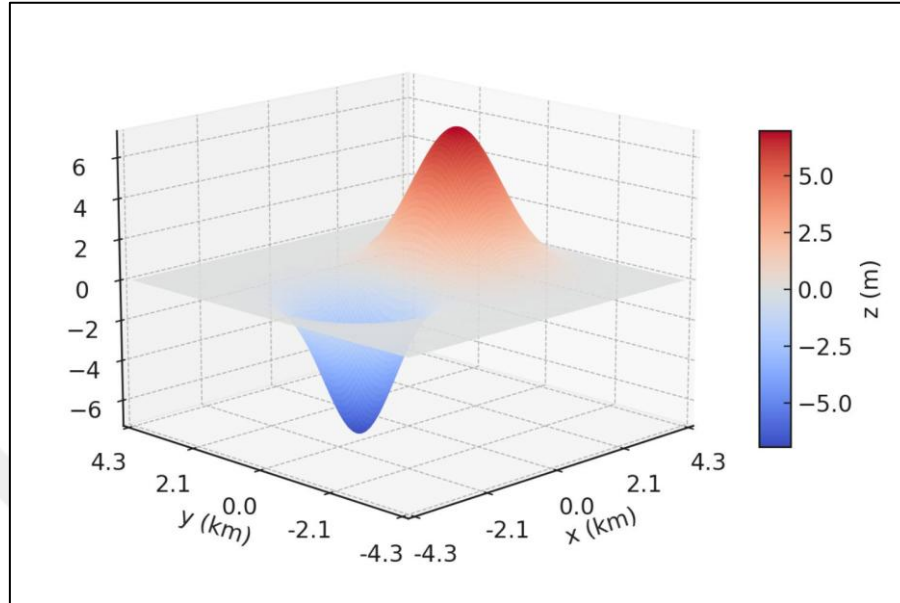


Figure 3.9: Initial maximum tsunami calculated by the empirical equation in Sabeti & Heiderzadeh (2020).

The calculated initial tsunami is used as the “static” tsunami source of Scenario-2 in numerical modeling. The details of calculations are given in Chapter 3.1.3.

3.1.3. Tsunami Numerical Modelling

The overall scheme of tsunami numerical modeling conducted in this study is shown in **Figure 3.10**. As seen here, numerical modeling is done in two parts as “static” and “dynamic” input analysis.

Numerical modeling conducted by NAMIDANCE is based on shallow wave theory that calculates tsunami hydrodynamic parameters by following finite difference methods and leapfrog scheme (NAMIDANCE, 2012). There are two ways of making the calculations using: (i) the initial sea surface distribution values occurred by earthquake rupture or submarine landslide, named “static” input, (ii) time series of water surface elevations calculated in “static” input analysis at the northern border of smallest domain, named “dynamic” input.

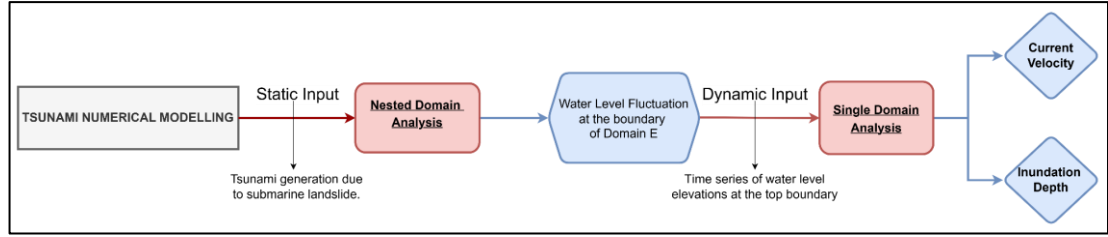


Figure 3.10: Initial maximum tsunami calculated by the empirical equation in Sabeti & Heiderzadeh (2020).

3.1.3.1. PI Mw 7.3 Earthquake Scenario

Static Input Analysis of Scenario-1

The initial wave calculated for Scenario-1 in Chapter 3.1.2 and shown in **Figure 3.5** is used as static input in the numerical modeling and tsunami hydrodynamic parameters are obtained for 120 minutes simulation time. The maximum positive and maximum negative water surface elevations and the maximum current velocities calculated in the entire Marmara Sea are given in **Figure 3.11**, **Figure 3.12** and **Figure 3.13**, respectively. The snapshots of wave propagation after 0th, 10th, 20th, 30th, 60th and 90th minutes of the rupture in Scenario-1 Mw 7.3 Prince Islands Earthquake are given in **Figure 3.14**.

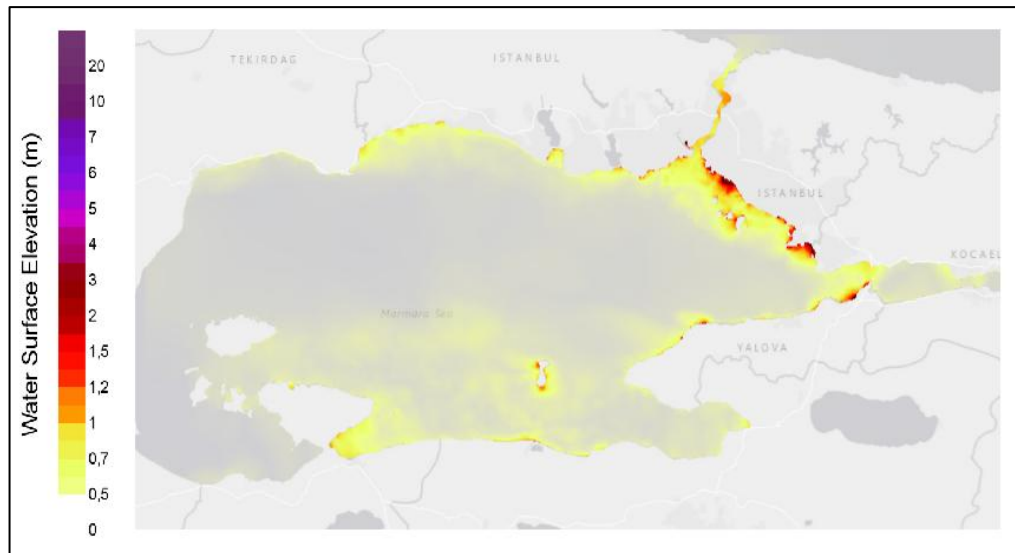


Figure 3.11: The maximum positive water surface elevations calculated in the entire Marmara Sea for Scenario-1 Mw 7.3 PI Earthquake.

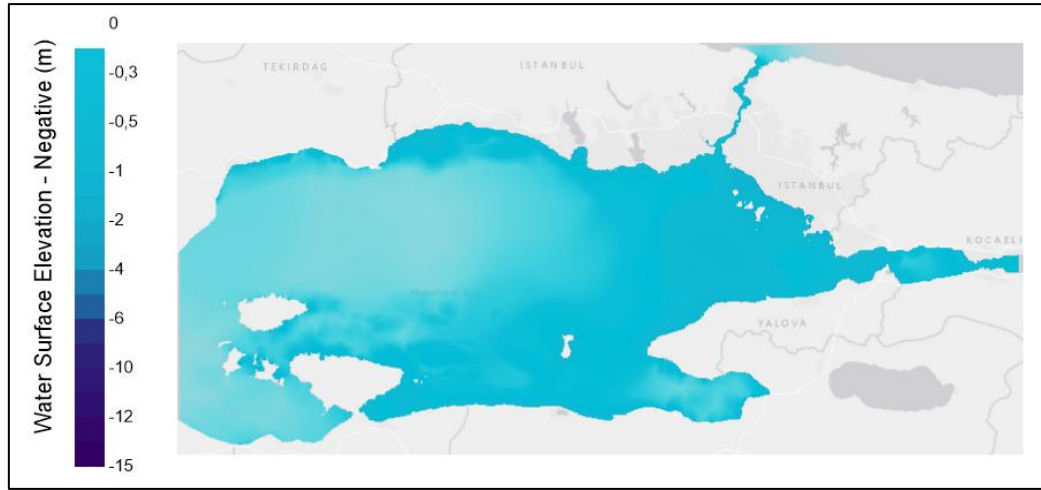


Figure 3.12: The maximum negative water surface elevations calculated in the entire Marmara Sea for Scenario-1 Mw 7.3 PI Earthquake.

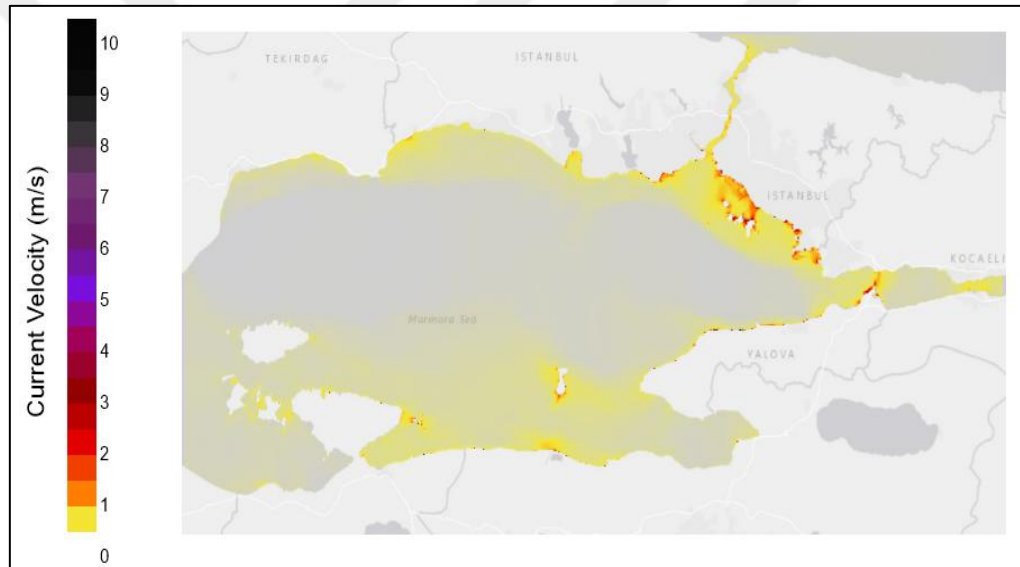


Figure 3.13: The maximum current velocities calculated in the entire Marmara Sea for Scenario-1 Mw 7.3 PI Earthquake.

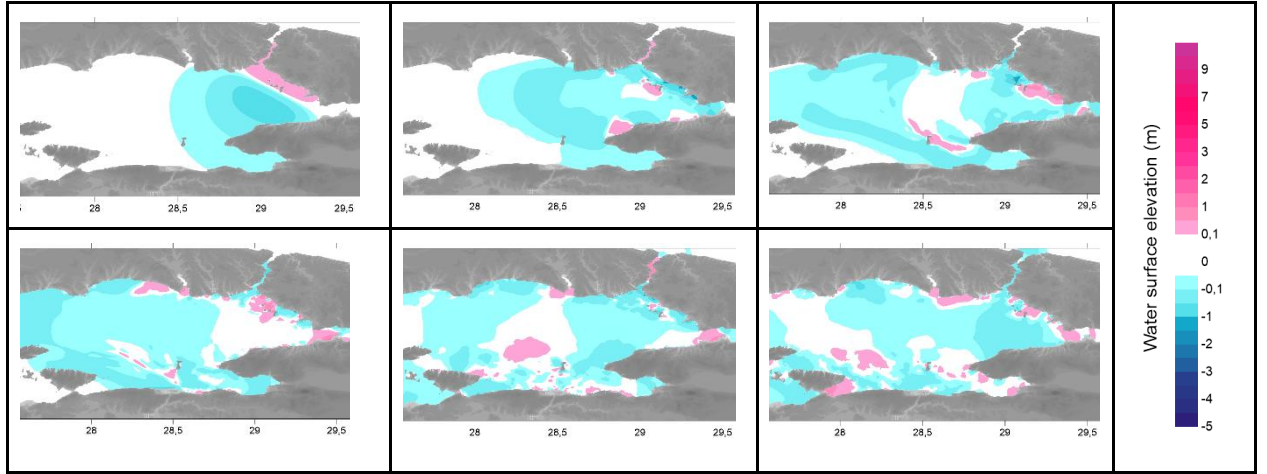


Figure 3.14: The snapshots of wave propagation after 0th, 10th, 20th, 30th, 60th and 90th minutes of the rupture in Scenario-1 Mw 7.3 Prince Islands Earthquake.

Dynamic Input Analysis of Scenario-1

Synthetic gauge points are located in Domain D where the northern border of Domain E overlaps and the water level fluctuations are calculated in static input analysis of nested domains for 120 minutes simulation time. This time series data is used as an input of tsunami in Domain E, named “dynamic” input analyses, calculated at every numerical calculation time step of 0.03 seconds (**Figure 3.15**). The maximum water surface elevation at the border data is about 0.2m. The flow depths are calculated inland and tsunami inundation map is plotted for Çınarcık town (**Figure 3.16**). The maximum flow depth calculated in Scenario-1 for Çınarcık is 0.87m.

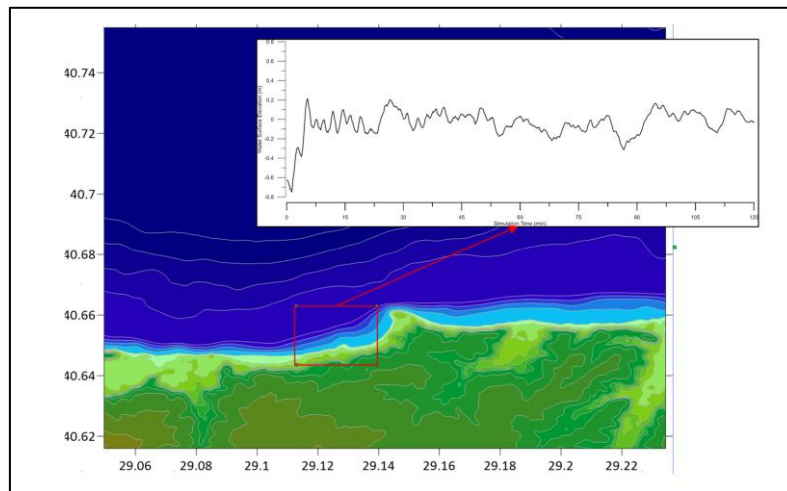


Figure 3.15: Time series of water surface elevation calculated in static source analysis at the northern border of Domain E and used in dynamic input analysis as tsunami source for Scenario-1.

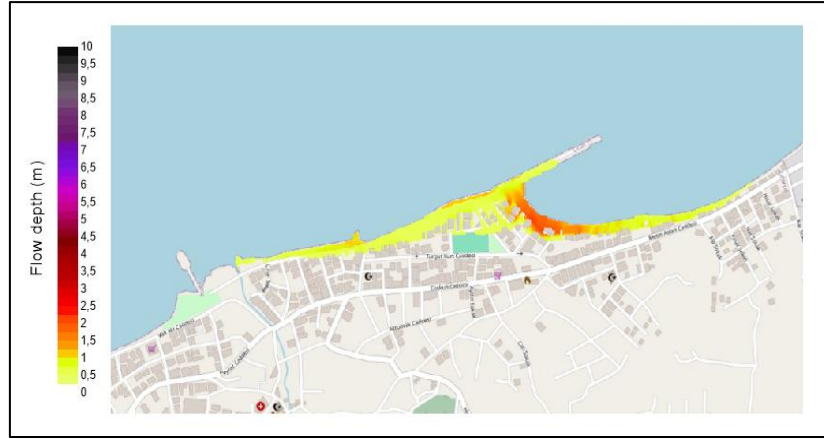


Figure 3.16: Tsunami inundation map of Çınarcık town for Scenario-1 Mw 7.3 Prince Islands Earthquake.

3.1.3.2. Tuzla Landslide Scenario

Static Input Analysis of Scenario-2

The initial wave calculated for Scenario-2 Tuzla landslide in Chapter 3.1.2 and shown in Figure 3-9 is used as static input in the numerical modeling and tsunami hydrodynamic parameters are obtained for 120 minutes simulation time. The maximum positive and maximum negative water surface elevations and the maximum current velocities calculated in the entire Marmara Sea are given in **Figure 3.17**, **Figure 3.18** and **Figure 3.19**, respectively. The snapshots of wave propagation after 0th, 10th, 20th, 30th, 60th and 90th minutes of the rupture in Scenario-2 Tuzla landslide are given in **Figure 3.20**.

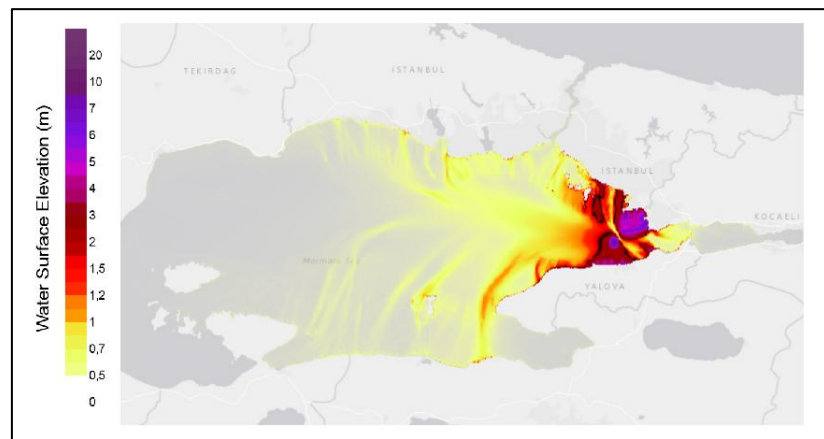


Figure 3.17: The maximum positive water surface elevations calculated in the entire Marmara Sea for Scenario-2 Tuzla landslide.



Figure 3.18: The maximum negative water surface elevations calculated in the entire Marmara Sea for Scenario-2 Tuzla landslide.

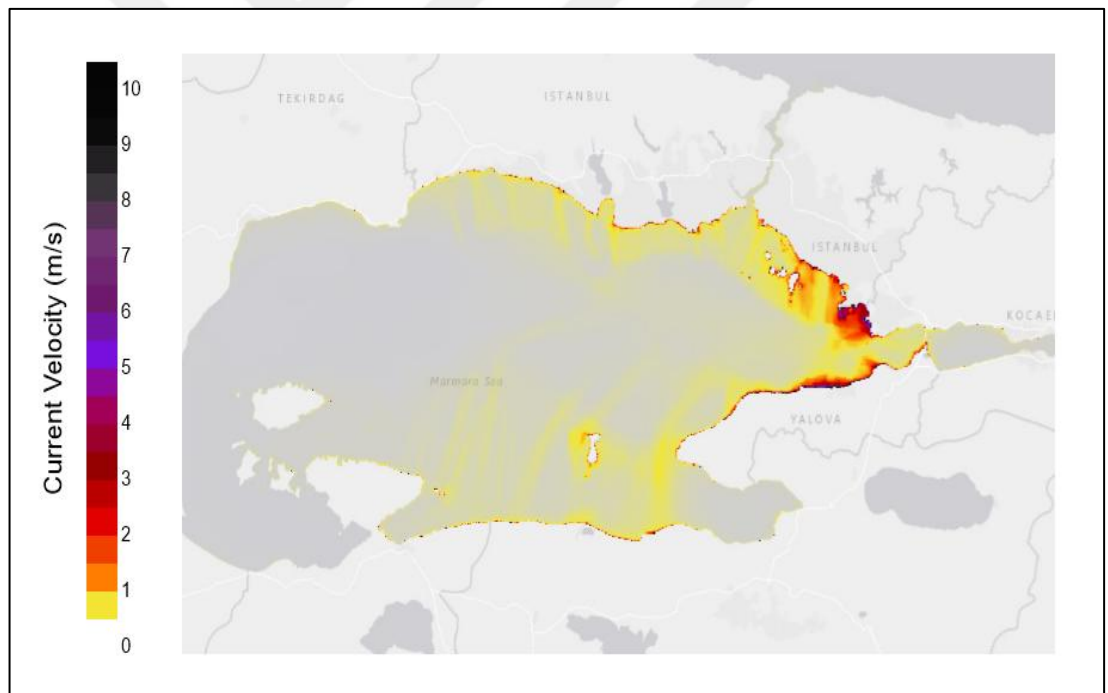


Figure 3.19: The maximum current velocities calculated in the entire Marmara Sea for Scenario-2 Tuzla landslide.

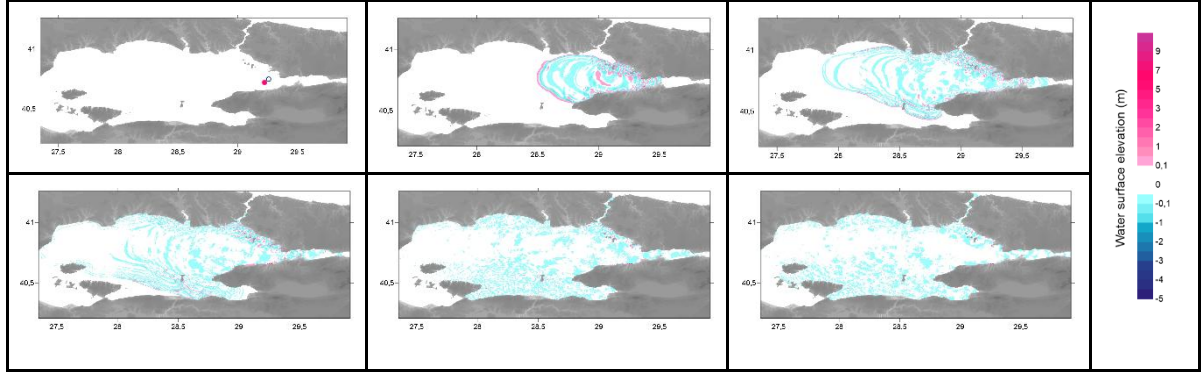


Figure 3.20: The snapshots of wave propagation after 0th, 10th, 20th, 30th, 60th and 90th of the rupture in Scenario-2 Tuzla landslide.

Dynamic Input Analysis of Scenario-2

Similar to Scenario-1, the water level fluctuations that are calculated in static input analysis at the border of Domain E are used as an input of tsunami source in Domain E, named “dynamic” input analyses, at every numerical calculation time step of 0.03 seconds (**Figure 3.21**). The maximum water surface elevation at the border data is about 1.8m. The flow depths are calculated inland and tsunami inundation map is plotted for Çınarcık town (**Figure 3.22**). The maximum flow depth calculated in Scenario-2 for Çınarcık is 6.1m, that is quite high and effective.

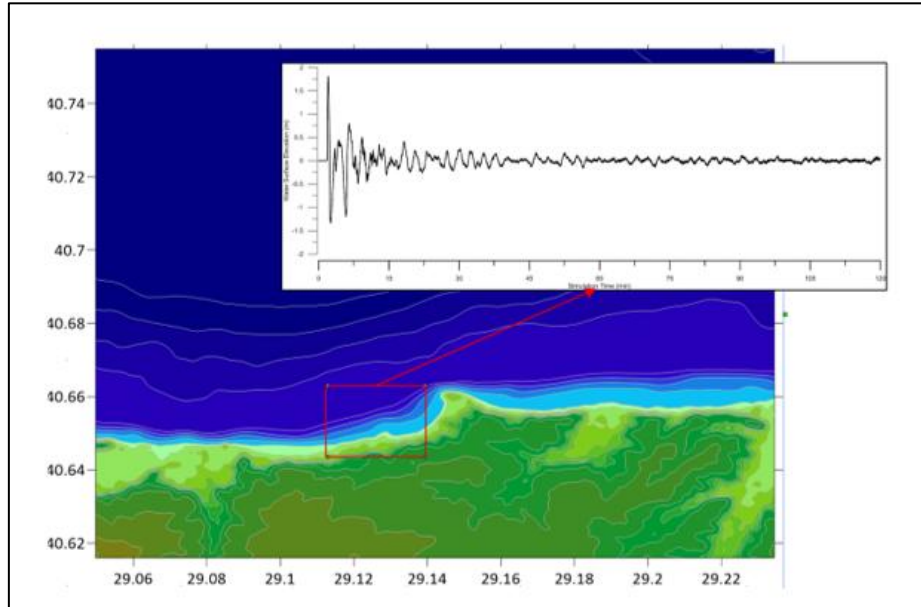


Figure 3.21: Time series of water surface elevation calculated in static source analysis at the northern border of Domain E and used in dynamic input analysis as tsunami source for Scenario-2 Tuzla landslide.



Figure 3.22: Tsunami inundation map of Çınarcık town for Scenario-2 Tuzla landslide.

The summary of results obtained from the numerical modeling due to Scenario-1 and Scenario-2 are given in **Table 3.3**. The results show that Tuzla landslide creates significant tsunami in the entire Marmara Sea and Çınarcık town. The maximum flow depth calculated in Çınarcık for landslide case is more than 6m at the locations close to the shoreline which corresponds to 2 story buildings. The flow depth on land in the Marmara Sea is defined as NA for both sides since Domain-D in static input analyses is not having fine-gridded DEM data and building data at the coastal areas. Therefore, the calculated flow depth inland is less likely to be reliable.

Table 3.3: Summary of results obtained from the analyses of tsunami scenarios in the whole Marmara Sea and at Çınarcık, Yalova

	PI Mw 7.3 Earthquake Scenario		Tuzla Landslide Scenario	
	Marmara Sea	Çınarcık, Yalova	Marmara Sea	Çınarcık, Yalova
Maximum water surface elevation (m)	3.22	16.81	15.47	23.16
Minimum water surface elevation (m)	-3.56	-18.40	-8.67	-26
Maximum flow depth on land (m)	NA	0.87	NA	6.10

3.1.4. Calculation of the Tsunami Loads

“Minimum Design Loads and Associated Criteria for Buildings and Other Structures” Version 7-22 published by American Society of Civil Engineers in 2022 (ASCE, 7-22) defines the tsunami loads exerted on buildings in tsunami inundation zone. According to ASCE 7-22, drag force is the most significant tsunami load that can be considered in tsunami design zone, that is directly proportional with the inundation depth and current velocity exerted in front of the building. **Figure 3.23** shows the effects of relative sea level change and seismic subsidence on the buildings in the inundation zone.

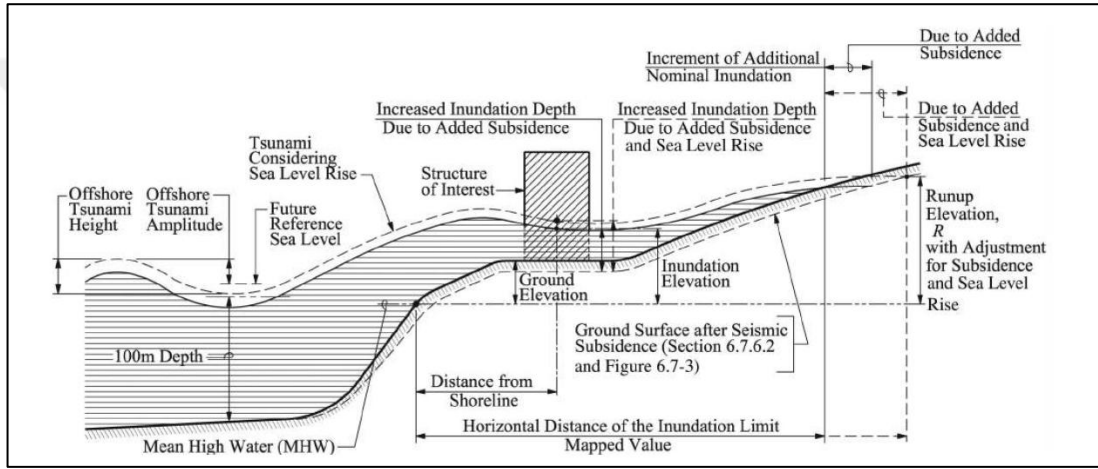


Figure 3.23: Tsunami inundation map of Çınarcık town for Scenario-2 Tuzla landslide.

Section 6.8.3 “Structural Performance Evaluation” of ASCE 7-22 defines different load cases for numerical tsunami damage analysis. Among them, Load Case 1 defining the condition of “*an exterior inundation depth not exceeding the maximum inundation depth nor the lesser of one story or the height of the top of the first-story windows*” is used in this thesis for a selected building in Çınarcık town. The hydrodynamic load, the drag force, is taken as the tsunami load exerted on the building with the maximum flow depth and current velocity calculated in front of the building. Equation 6.10-4 in ASCE 7-22 is used for the calculation of drag force as given in Equation 3.3.

$$F_d = \frac{1}{2} \times \rho_s \times I_{tsu} \times C_d \times b \times (h_e \times u^2) \quad (3.3)$$

Here, ρ_s is the minimum fluid mass density, I_{tsu} is tsunami importance factor, C_d is the drag coefficient, b is the width of structure subject to force, h_e is the inundation height in front of the structure and u is the current velocity in front of the structure. ρ_s is calculated using Equation 6.8-5 of ASCE 7-22 is calculated as in Equation 3.4:

$$\rho_s = k_s \times \rho_{sw} \quad (3.4)$$

where k_s is the fluid density factor that shall be taken as 1.1 and ρ_{sw} is the density of sea water that can be used as 1025 kg/m³. Therefore, ρ_s is calculated as;

$$1.1 \times 1025 = 1127.5 \text{ kg/m}^3.$$

I_{tsu} is related to the tsunami risk category of the selected building and is determined according to Table 6.8-1 of ASCE 7-22. The selected building in Çınarcık town is not designated as vertical evacuation shelter or a critical facility; therefore, it is estimated in Tsunami Risk Category II and has I_{tsu} tsunami importance factor of 1.0.

The drag coefficient C_d for rectilinear structures are obtained from Table 6-10-1 of ASCE 7-22 according to the width to inundation depth ratio, that is smaller than 12. Therefore, C_d is selected as 1.25.

The tsunami load exerted on a reinforced concrete building selected in Çınarcık town is calculated using the results of numerical simulations for Scenario-1 and Scenario-2 (**Figure 3.24**). For Scenario-1, the maximum inundation height and current velocity calculated in front of the building are about 0.6 m and 1.9 m/s², respectively. For Scenario-2, the values of maximum inundation height and current velocity are calculated as 2.5m and 4.7 m/s², respectively. Using these values in Equation 3.3, the tsunami loads calculated in front of the selected building are given in each scenario below:

Scenario-1:

$$F_d = \frac{1}{2} \times 1127.5 \frac{\text{kg}}{\text{m}^3} \times 1.1 \times 1.25 \times 16\text{m} \times (0.6\text{m} \times 1.9^2\text{m/s}) = 53.7 \text{ kN}$$

Scenario-2:

$$F_d = \frac{1}{2} \times 1127.5 \frac{kg}{m^3} \times 1.1 \times 1.25 \times 16m \times (2.54m \times 4.7^2 m/s) = 695 \text{ kN}$$

These tsunami loads are taken as the hydrodynamic force exerted on the building and used for numerical tsunami analysis in Chapter 3.2.4.2.

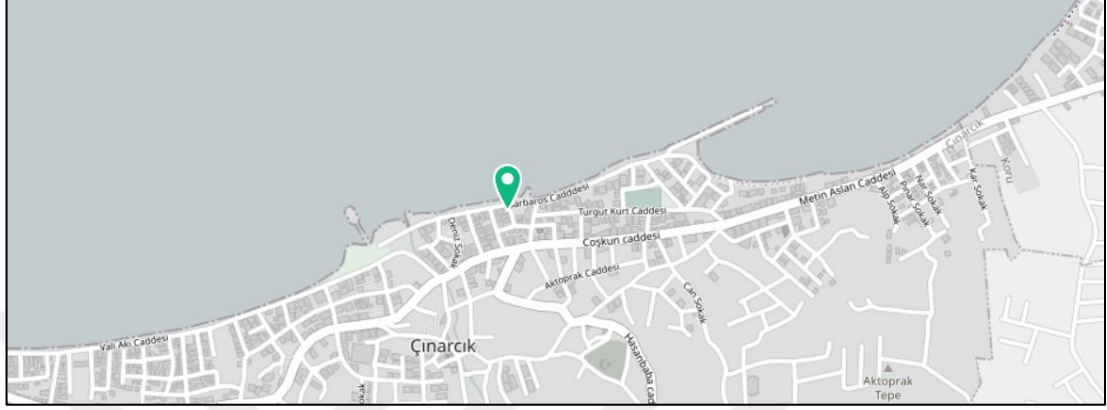


Figure 3.24: Tsunami inundation map of Çınarcık town for Scenario-2 Tuzla landslide.

3.2. Numerical Earthquake Pushover Analysis

In this thesis, a case study of an earthquake analysis based on DD2 design earthquake is conducted for a building located in the coastline of Çınarcık, Türkiye. The location of the building was selected to investigate the cascading tsunami effects after the initial pushover analysis performed to determine the structure's condition after the DD2 earthquake.

For the analysis, commonly used structural element details have been used. The building is assumed to be built in 1980's using the Turkish Earthquake Code 1975. The structural parameters have been provided in the next section.

Earthquake analysis is performed using Single Mode Nonlinear Static (Pushover) Analysis.

Mander Material Model has been used to determine the material properties of the sections.

Structural analysis has been performed with CSI ETABS software. To calculate the hinge properties, XTRACT software has been used. Turkish Earthquake Code 2018

has been used to perform the structural analysis and define the status of the structural elements.

The building shown in Figure 3-24 is located at the center part of Çınarcık, Yalova. The structure is a 5-story building spans 24 meters in Y-direction and 16 meters in X-direction. The structure has 7 column axis in Y direction and 5 column axis in X direction. The structure has 4-meter spans in both X and Y direction.

Below is the analysis model created for the building. The model has been created in ETABS Software in order to conduct the 3D Pushover analysis. **Figure 3.25** is the plan view and the 3D view of the building. **Figure 3.26** and **Figure 3.27** are the elevation view of the structure in two different axes.

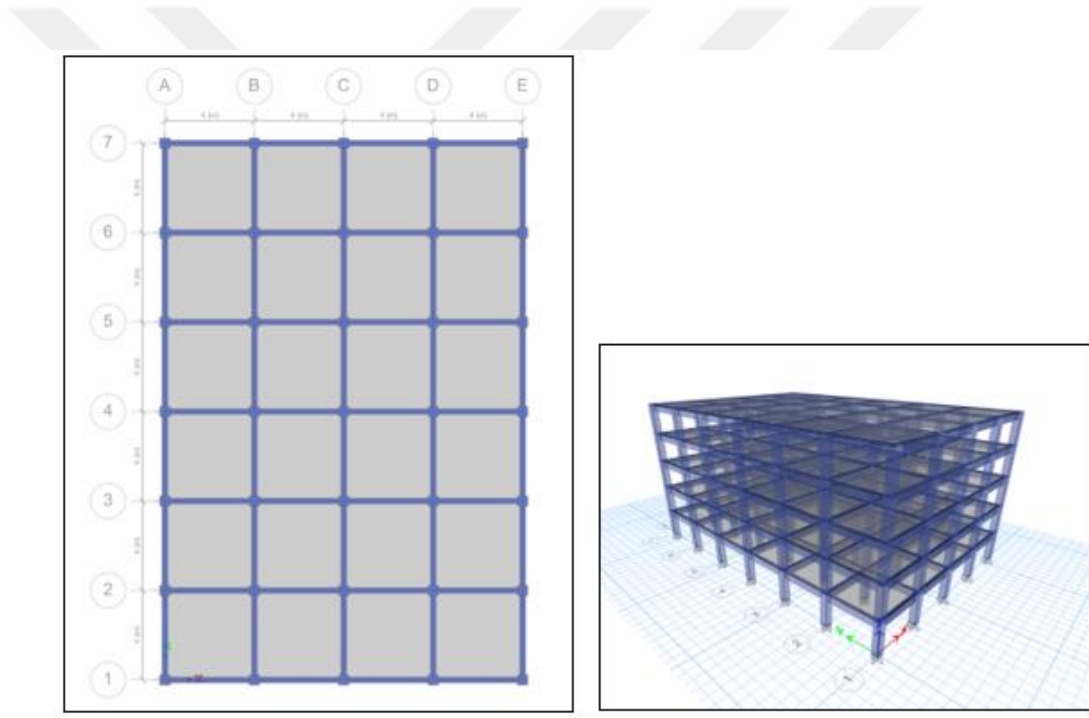


Figure 3.25: 3D Analysis Model of Building.

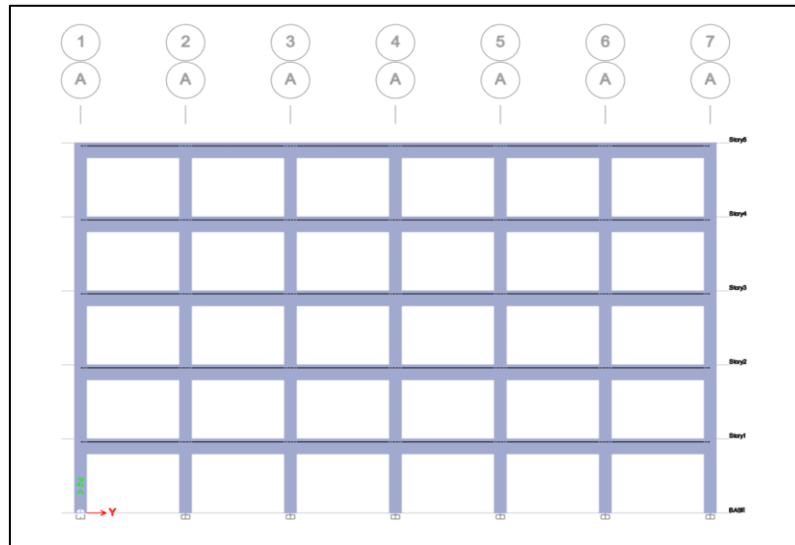


Figure 3.26: Plan and elevation view of building.

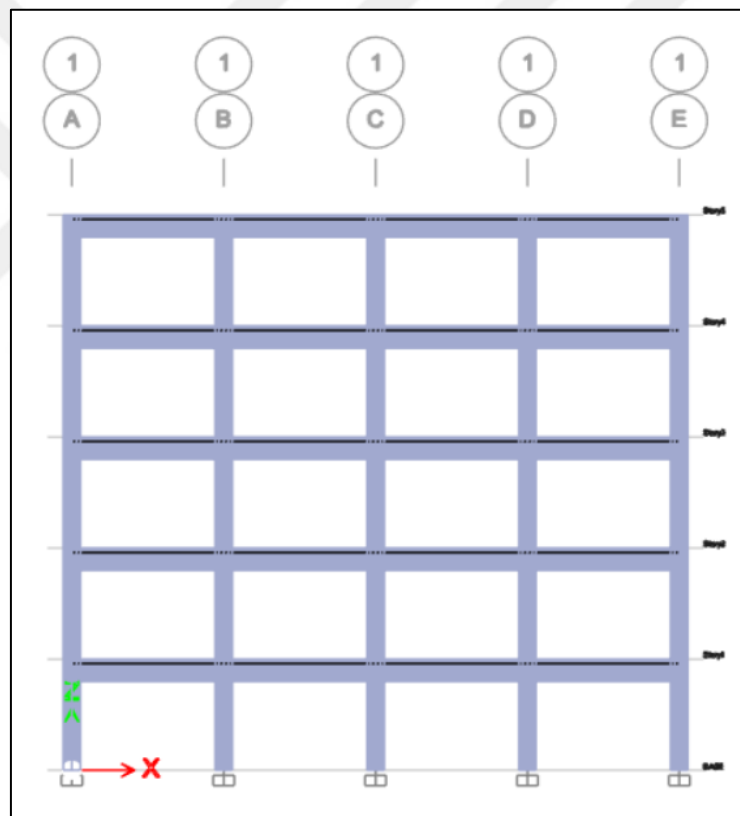


Figure 3.27: 1-1 Axis elevation view of building.

3.2.1. Properties of the Structure

The structure is designed as RC Moment Resisting Frames. The structure is designed using the Turkish Earthquake Code 1975 with minimum demands from the Earthquake Code 1975. The section parameters are given in **Table 3.4** below.

Table 3.4: Properties of the structure

Unconfine Concrete Class	C16	Beam Top Longitudinal Rebar	3 ϕ 16
Rebar Grade	S220	Beam Bottom Longitudinal Rebar	3 ϕ 14
Column Dimension (cm)	60X60	Beam Confinement Rebar	ϕ 10/200mm
Column Longitudinal Rebar	12 ϕ 20	Slab Thickness (cm)	12
Column Confinement Rebar	ϕ 10/200mm	Slab Live Load (kN/m ²)	2
Beam Dimension (cm)	25X60	Slab Dead Load (kN/m ²)	4

3.2.2. Earthquake Parameters of the Structure

Based on the Turkish Earthquake Code 2018, earthquake parameters are taken from the AFAD database (**Figure 3.28**). Analysis has been conducted based on DD2 type earthquakes. Also, analysis parameters provided by the Turkish Earthquake Code 2018 are provided below.

Based on the coordinates of the structure, earthquake parameters used for structures are based on the coordinates 40.644609° N, 29.114279° E. The soil class where the buildings are located is assumed to be ZC based on the general characteristics of the region. The selected structure is a residential building with the importance factor of 1 and live load participation factor of 0.3 based on Turkish Earthquake Code 2018.

Below are the earthquake ground motion parameters obtained from AFAD, which is Turkish government agency that provides ground motion parameters in the selected region of Turkiye. Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) are provided for the selected region where our structure is located.

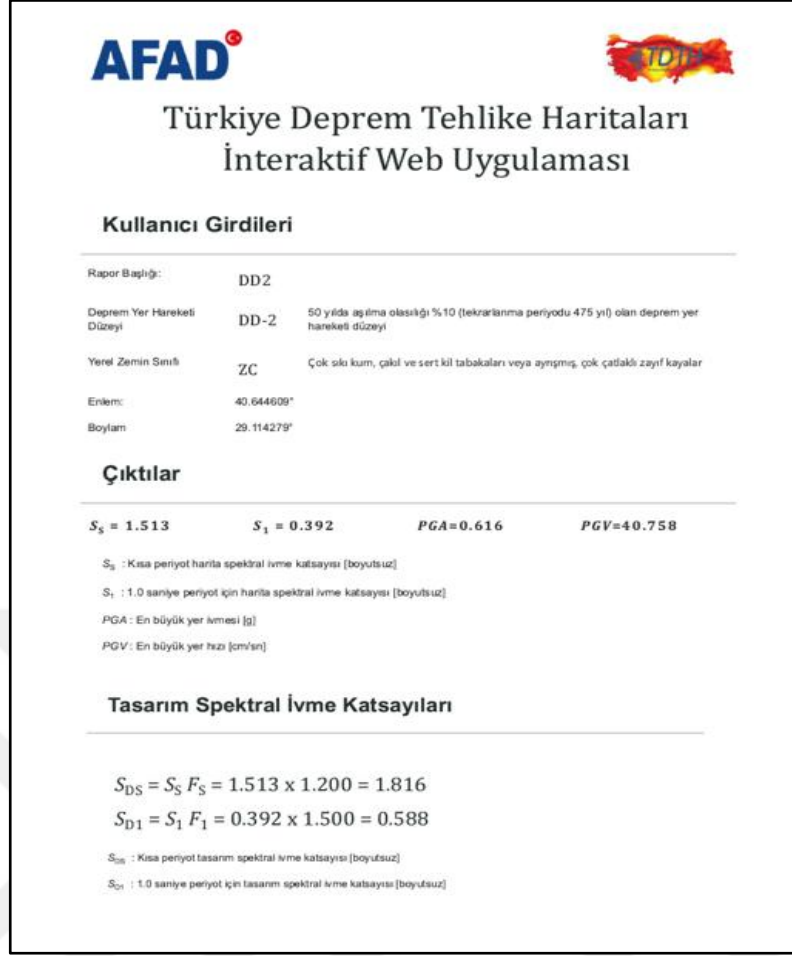


Figure 3.28: Hazard Map of Buildings Based on AFAD.

Turkish Earthquake Code classifies soil properties in five groups. These Groups are “ZA”, “ZB”, “ZC”, “ZD”, “ZE” (**Figure 3.29**). This classification is conducted by the V_{s30} value of the soil in the site. Based on the general characteristics of the region, the Soil Class of the region where our structure is located is ZC.

Soil Class	Soil Type	Average in the upper 30 meters		
		$(V_s)_{30}$ [m/s]	$(N_{60})_{30}$ [pulse /30 cm]	$(c_u)_{30}$ [kPa]
ZA	Strong, hard rocks	> 1500	–	–
ZB	Weak altered, medium strong rocks	760 – 1500	–	–
ZC	Very stiff sand, gravel and hard clay layers or latered, very cracked weak rocks	360 – 760	> 50	> 250
ZD	Medium-hard sand, gravel or very hard clay layers	180 – 360	15 – 50	70 – 250
ZE	Soft sand, gravel or soft-hard clay layers or profiles containing a soft clay layer ($c_u < 25$ kPa) of a total thickness of 3 meters providing conditions of $PI > 20$ and $w > 40\%$	< 180	< 15	< 70

Figure 3.29: Soil Types Based on TBEC 2018.

Importance Coefficient of the structure has to be determined in accordance with Turkish Earthquake Code. Based on the use of the building, there are 3 Importance factors for structures defined in Turkish Earthquake Code. Designed structure is BKS=3 which has the importance coefficient of 1.0 (**Figure 3.30**).

Building Use Class	Purpose of Use of the Building	Building Importance Coefficient (I)
BKS = 1	Buildings that need to be used after the earthquake, buildings where people are long-term and intensive, buildings where valuable goods are stored and buildings containing dangerous materials a) Buildings that need to be used immediately after the earthquake (Hospitals, dispensaries, health centers, fire brigade buildings and facilities, PTT and other communication facilities, transportation stations and terminals, energy production and distribution facilities, province, district governorship and municipality administration buildings, first aid and disaster planning stations) b) Schools, other educational buildings and facilities, dormitories and dormitories, military barracks, prisons, etc. c) Museums & Museums d) Buildings where toxic, explosive, flammable, etc. substances with properties are located or stored	1.5
BKS = 2	Buildings where people are located for a short time and intensively are shopping malls, sports facilities, cinemas, theaters, concert halls, places of worship, etc.	1.2
BKS = 3	Other buildings that do not fall within the definitions given for BKS=1 and BKS=2 (Residences, workplaces, hotels, building-type industrial structures, etc.)	1.0

Figure 3.30: Purpose of Usage of Buildings Based on TBEC 2018.

Structures are assumed to be under effect of a factored live load at a time based on the purpose of usage of the building. Live Load reduction factor (n) has to be determined in accordance with the Turkish Earthquake Code, based on the purpose of the building. For the analysed structure, the live load reduction factor is 0.3 (**Figure 3.31**).

Purpose of the Building	n
Warehouse etc.	0.8
School, student dormitory, sports facility, cinema, theatre, concert hall, place of worship, restaurant, store etc.	0.60
House, workplace, hotel, hospital, parking lot, etc.	0.3

Figure 3.31: Live Load Reduction Factor of Building Based on TBEC (2018).

Response spectrum of the structure is provided based on the Spectral Acceleration provided by the AFAD Database and soil properties of the region. The Response Modification (R) is taken as 1 and the overstrength factor is taken as 1. Also, the occupancy importance factor of the building is 1 based on TBEC (2018) as shown in **Figure 3.32**.

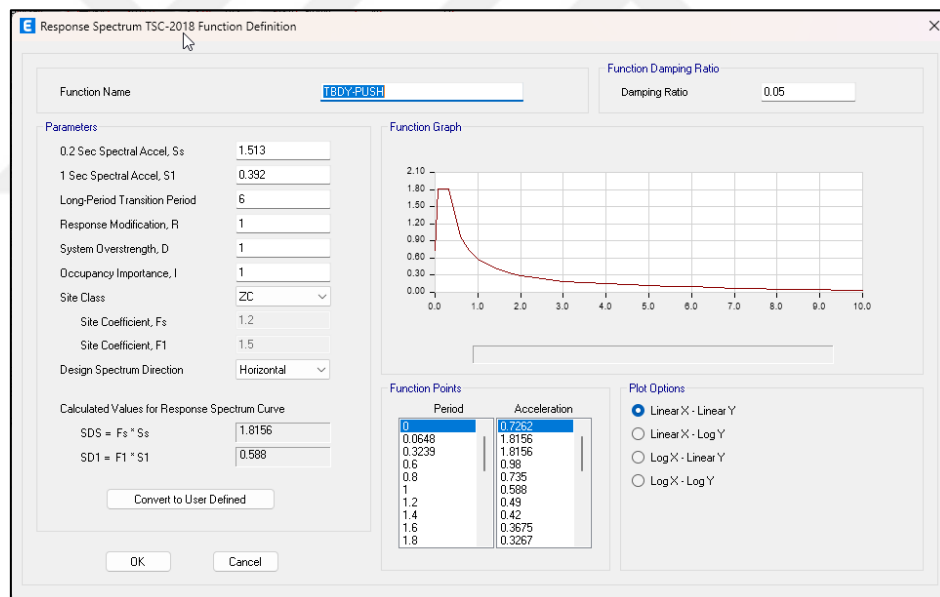


Figure 3.32: Response Spectrum of the Structures calculated by ETABS.

3.2.3. Numerical Model Parameters on ETABS

In this section, non-linear parameters of the structures are given for the structure. Nonlinear material properties of C16 concrete defined in the analysis models given in **Figure 3.33**. For the confined reinforced concrete elements, Mander Material Model has been used, to calculate the nonlinear material properties based on TBEC 2018.

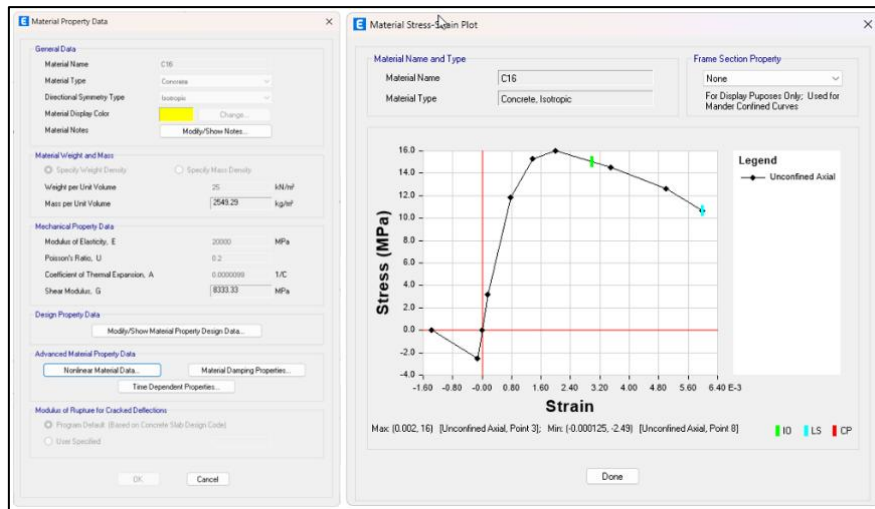


Figure 3.33: Material Properties of C16 Concrete in ETABS.

Figure 3.34 below are the nonlinear material properties of S220 steel reinforcement defined in the analysis models. Nonlinear material properties have been taken from the TBEC 2018 and applied to the system.

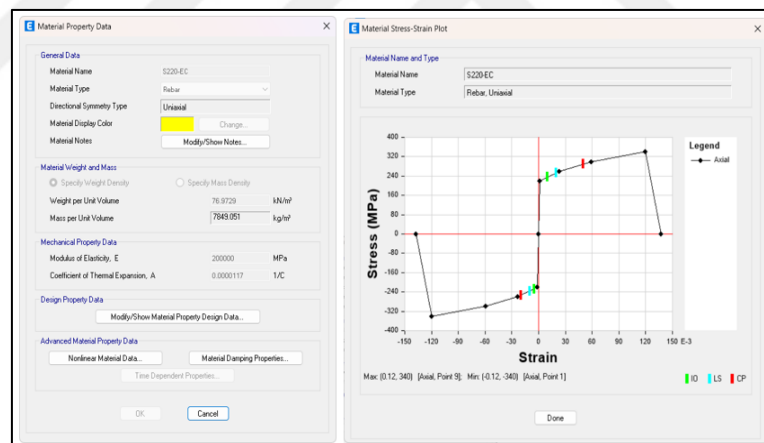


Figure 3.34: Material Properties of S220 Rebar in ETABS.

Below are the properties of the cross section defined as columns in the analysis models. Materials and dimensions of columns are as given below. The columns are 60cmx60cm with $\varnothing 20$ longitudinal S220 grade reinforcement and $\varnothing 10$ S200 grade confinement bars as shown in **Figure 3.35**.

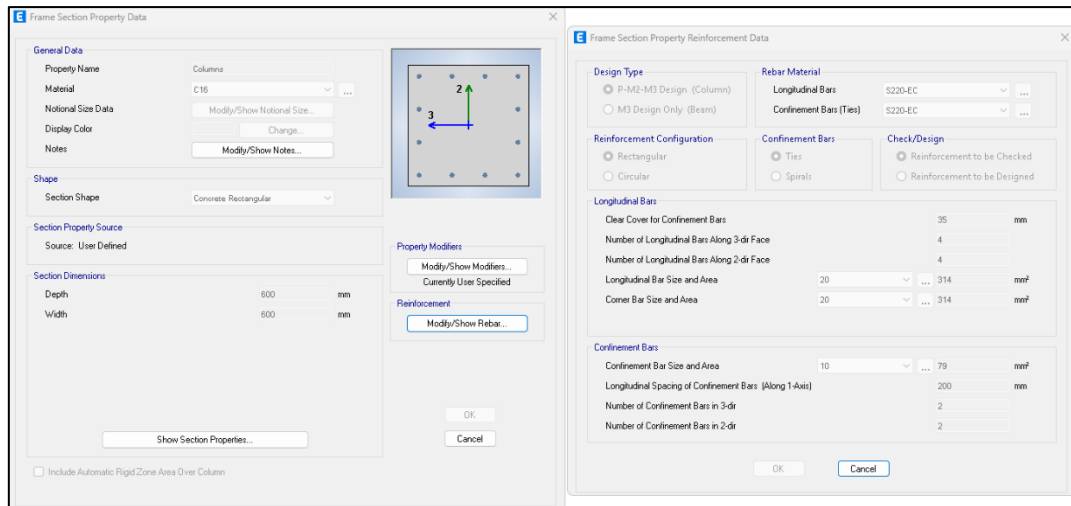


Figure 3.35: Cross-Sectional Properties of Columns in ETABS.

Below are the properties of the cross section defined as beams in the analysis models. Materials and dimensions of beams are as given below. The beams are 25cmx60cm in dimensions (**Figure 3.36**). In the building, 12 cm slabs are used in all floors.

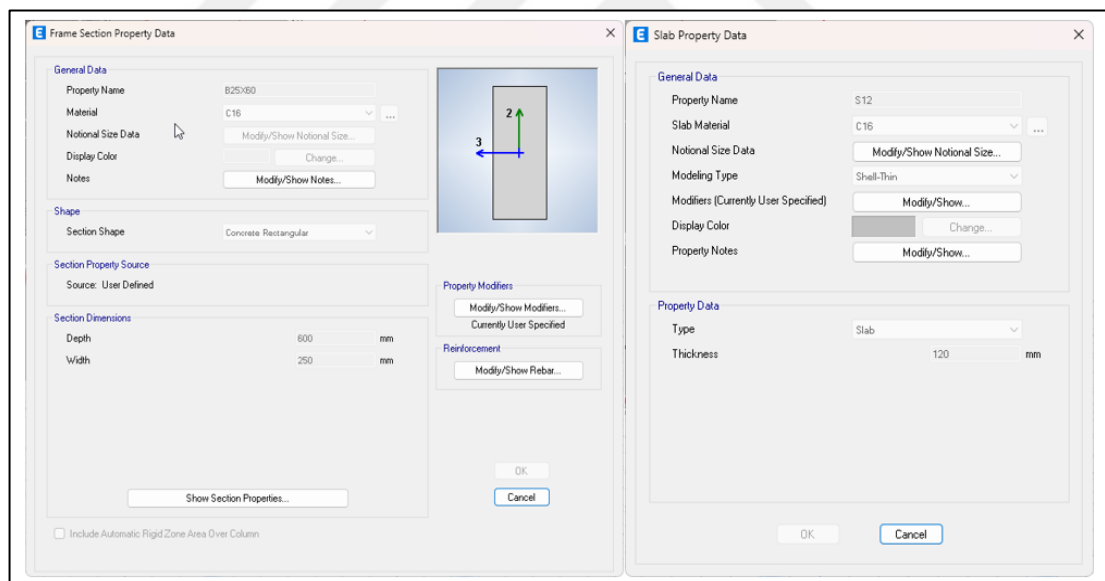


Figure 3.36: Cross-Sectional Properties of Beams and Slabs in ETABS.

Based on TBEC 2018, stiffness modifiers have to be applied to the structural elements. **Figure 3.37** shows the stiffness modifiers applied into the structures based on TBEC 2018. Stiffness modifiers have been applied to the columns, beams and slabs of the structure.

Reinforced Concrete Carrier System Element	Effective Section Stiffness	
Shear Wall – Slab (in plane)	Axial	Shear
Shear Wall	0.5	0.5
Basement Shear Wall	0.8	0.5
Slab	0.25	0.25
Shear Wall – Slab (out of plane)	Flexure	Shear
Shear Wall	0.25	1
Basement Shear Wall	0.5	1
Slab	0.25	1
Bar element	Flexure	Shear
Transverse Beam	0.15	1
Frame Beam	0.35	1
Frame Column	0.7	1
Shear Wall (equivalent bar)	0.5	0.5

Figure 3.37: Stiffness Modifiers based on TBEC 2018.

For the structures, 4 kN/m^2 uniform dead load and 2 kN/m^2 uniform live load have been applied for all the floors of all the structures as schematically given in **Figure 3.38** and **Figure 3.39**.

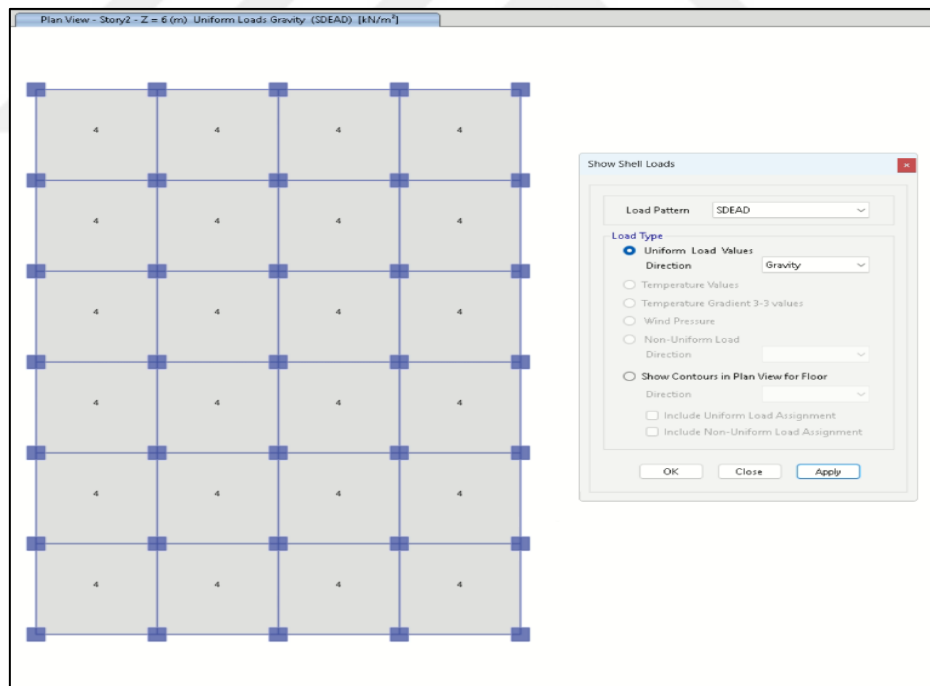


Figure 3.38: SDead Loads on Slabs of the Buildings.

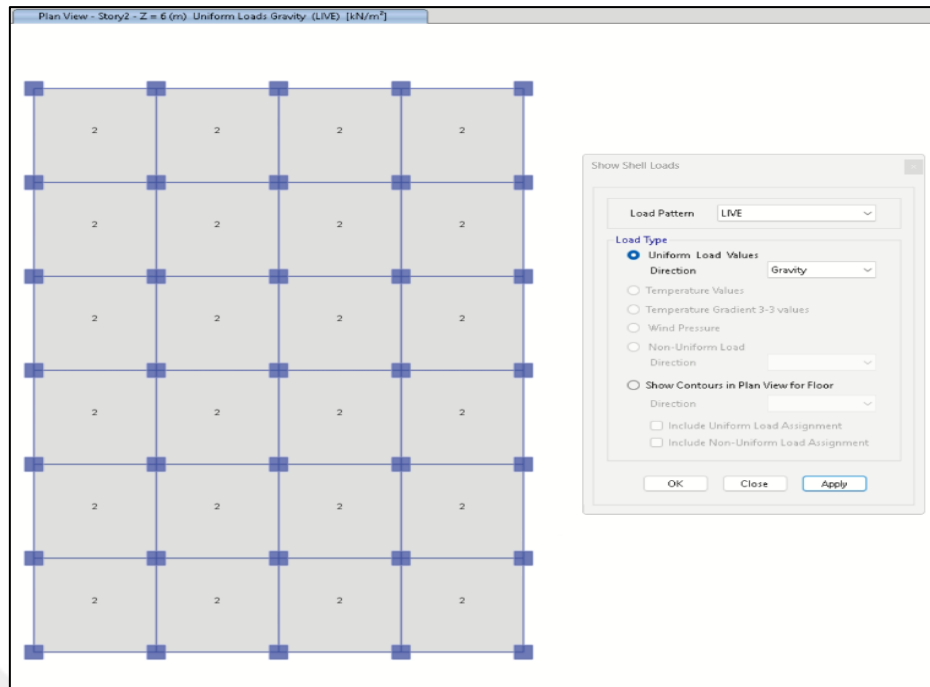


Figure 3.39: Live Loads on Slabs of the Buildings.

Analysis has been carried out based on the single mode nonlinear pushover analysis procedure. Load pattern for G+nQ loading has first applied to the structure (**Figure 3.40**), then pushover analysis in Y-Direction has been carried out (**Figure 3.41**).

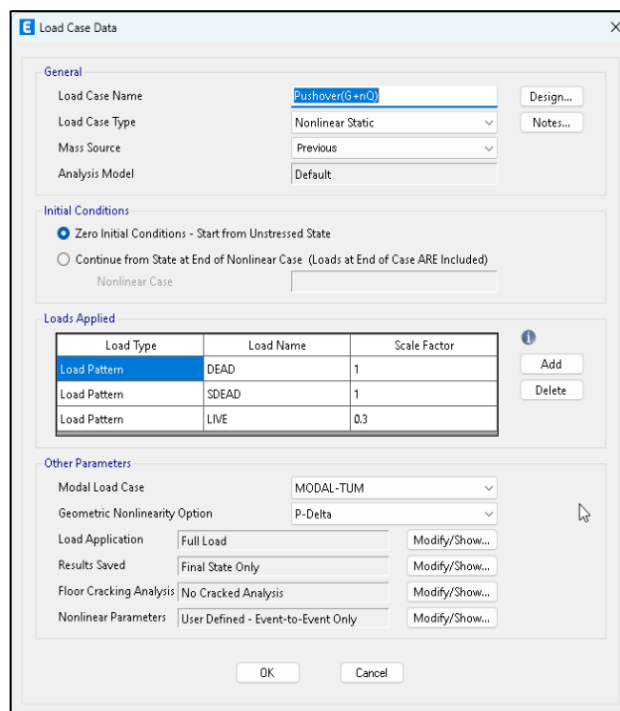


Figure 3.40: Nonlinear Pushover G+nQ Case of Structure.

Load Case Data

General

Load Case Name: Pushover-Y Design...

Load Case Type: Nonlinear Static Notes...

Mass Source: Previous

Analysis Model: Default

Initial Conditions

☐ Zero Initial Conditions - Start from Unstressed State

☒ Continue from State at End of Nonlinear Case (Loads at End of Case ARE Included)

Nonlinear Case: Pushover(G+nQ)

Loads Applied

Load Type	Load Name	Scale Factor
Mode	2	1

Add Delete

Other Parameters

Modal Load Case: MODAL-TUM

Geometric Nonlinearity Option: P-Delta

Load Application: Displacement Control Modify/Show...

Results Saved: Multiple States Modify/Show...

Floor Cracking Analysis: No Cracked Analysis Modify/Show...

Nonlinear Parameters: User Defined - Event-to-Event Only Modify/Show...

OK Cancel

Figure 3.41: Nonlinear Pushover Y-Direction Case of Structure.

Figure 3.42 and **Figure 3.43** are the XTRACT Analysis Report for the beam cross section. Lumped plastic hinges are calculated using the XTRACT software and applied to the analysis models. Properties of the Lump plastic Hinges are given below.

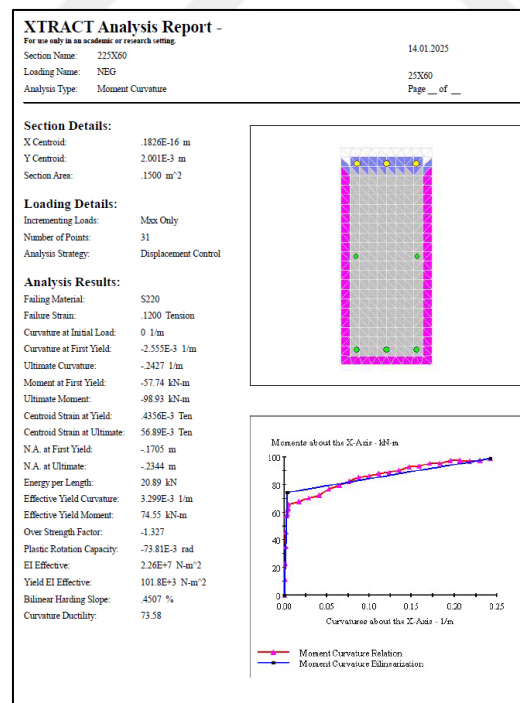


Figure 3.42: Moment Curvature of 25cmx60cm beam Calculated in XTRACT.

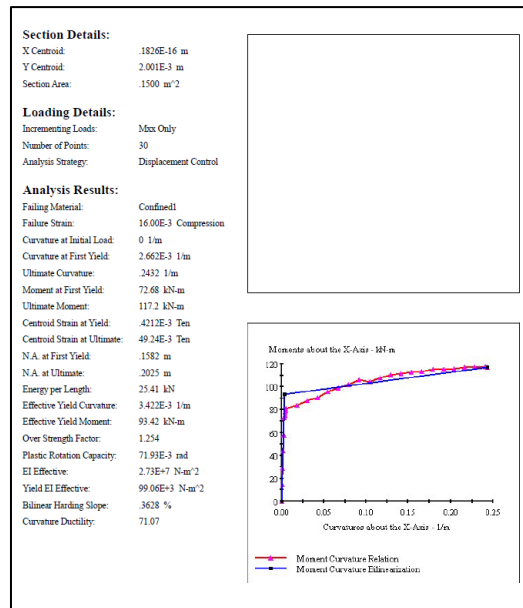


Figure 3.43: Moment Curvature of 25cmx60cm beam Calculated in XTRACT cont.

Properties calculated with the help of XTRACT software have been applied to the system and lumped nonlinear hinges are created and applied to the beams (**Figure 3.44**).

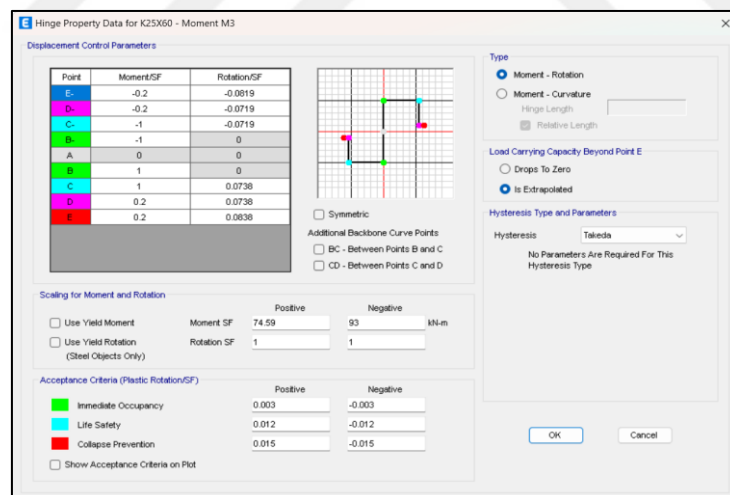


Figure 3.44: Hinge Properties of 25cmx60cm beam.

For columns, fiber hinges are used for analysis models. The properties of fiber hinges of columns are given in **Figure 3.45**.

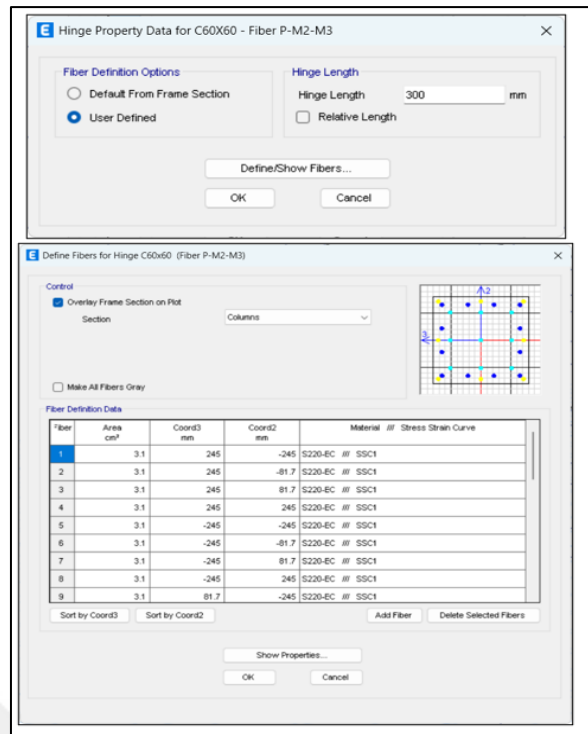


Figure 3.45: Nonlinear Fiber Hinge Properties on Columns.

Assignment of the nonlinear hinges to the beams and columns are given in the **Figure 3.46** and **Figure 3.47**.

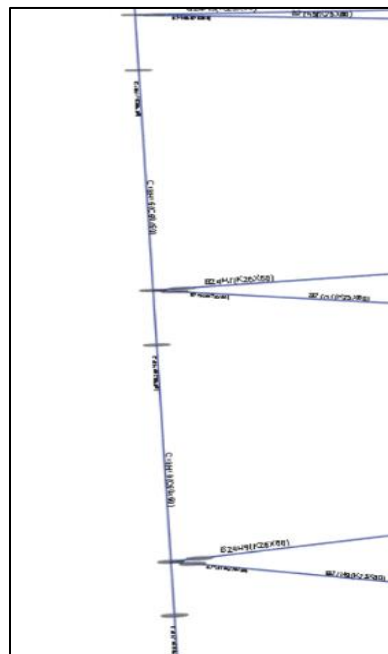


Figure 3.46: Nonlinear Hinge Locations on Frame Members.

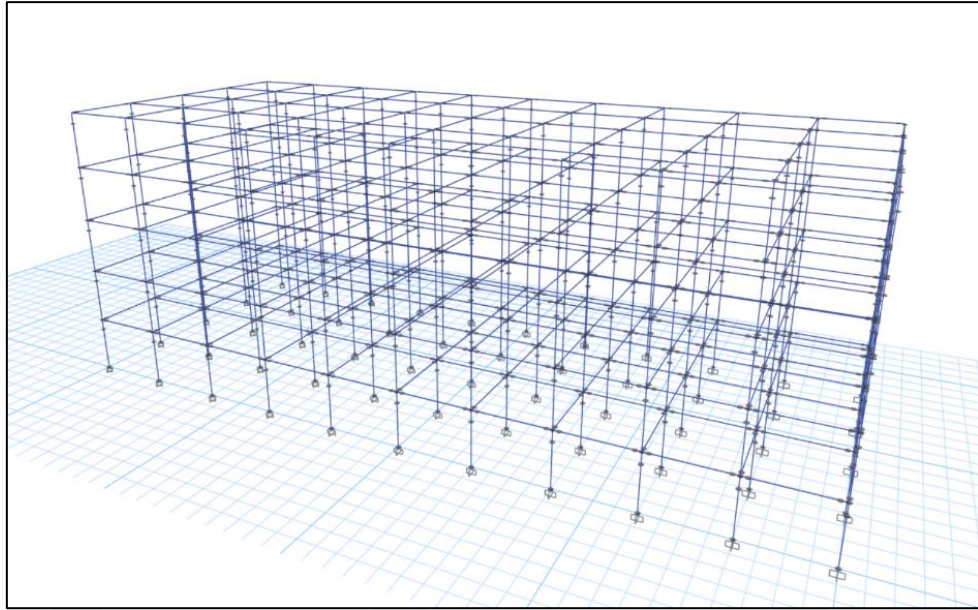


Figure 3.47: Nonlinear Hinge Locations on Structure.

3.2.4. Earthquake Analysis and Results of the Structure Using ETABS

3.2.4.1. Building Earthquake Analysis

For the structural analysis Pushover analysis has been conducted. The Structure is first pushed in the Y-Direction (**Figure 3.49**). After the structure is pushed to the target displacement calculated by NTC 2008 (**Figure 3.48**), a reloading case has been created. The structure is pushed back to the after-earthquake drift level, to represent the residual drift at the structure. Then a tsunami load is applied to the exterior columns of the structure considering the inundation level. After the application of the first level tsunami loads, second level tsunami loads are applied to the 2nd axis of the structure, considering that exterior non load bearing walls and windows will be destroyed during tsunami events.

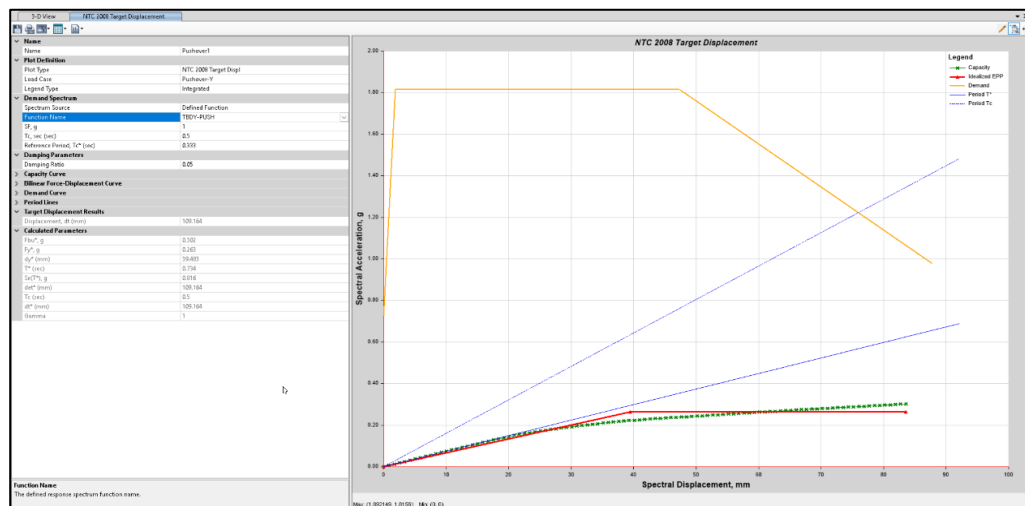


Figure 3.48: Pushover Target for Building.

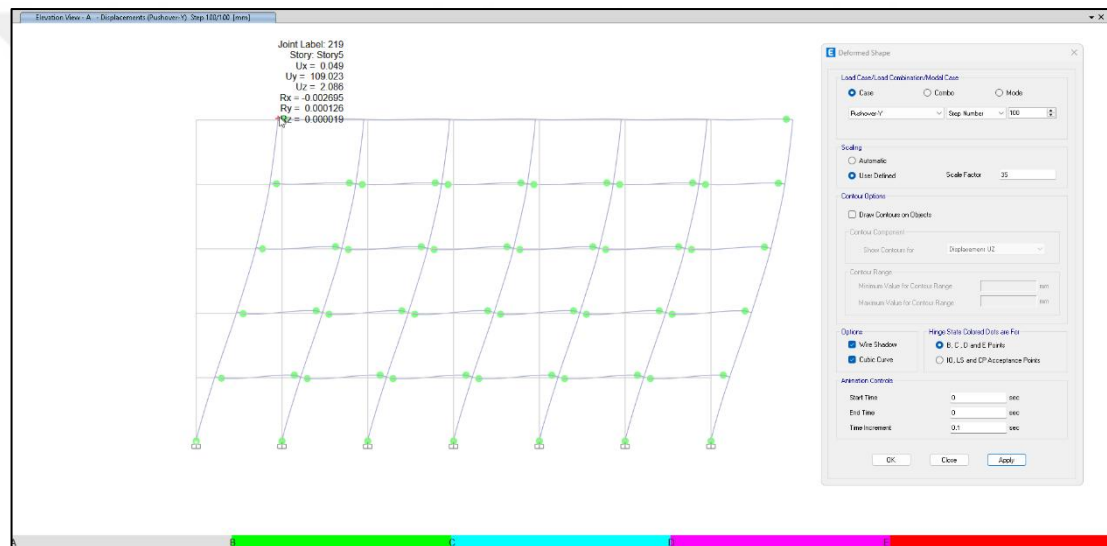


Figure 3.49: Y-Direction Pushover Drifts of Structure.

After the structure is pushed to the target displacement in Y-Direction, the structure is pushed back to the dy point where the residual drifts happen as in **Figure 3.50**.

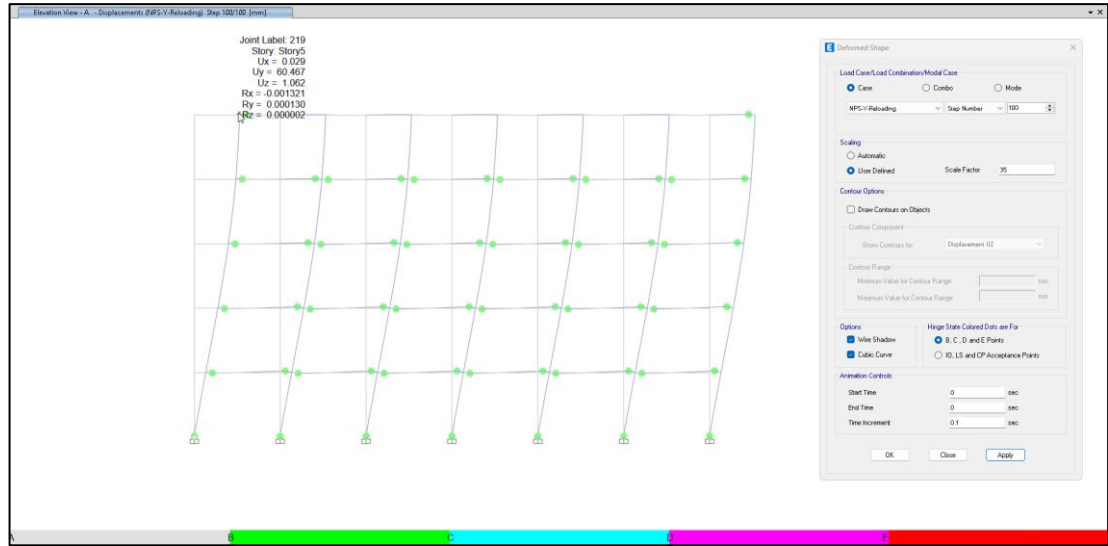


Figure 3.50: Y-Direction Reloading Pushover Drifts of Structure.

3.2.4.2. Building Tsunami Analysis

After the pushover analysis has been made, the structure is subjected to two different tsunami loads. The first load which is applied to the system is the tsunami drag force created by the submarine landslide. Tsunami loads created by the Tuzla landslide and the Prince Island earthquake have been calculated in Section 3.1.2. In this section, these tsunami loads will be applied to the deformed structure.

3.2.4.2.1. Tsunami Loading due to Submarine Landslide

Çınarcık basin with its landslide fans has potential to trigger large submarine landslides. Tsunami loads created by submarine landslides are applied to the structure (**Figure 3.51**). There are two levels of tsunami loadings. First, the loads are applied as drag forces to the exterior columns. Then, the drag forces are applied to the columns on the second axis considering the exterior non-load bearing walls and windows will be destroyed during tsunami inundation.

Figure 3.51: Tsunami Load Case on Structure.

Below are the additional tsunami loads generated by the submarine landslide. The loads are applied to the system as uniform frame loads following the guidance in FEMA P646 (FEMA, 2012) (**Figure 3.52** , **Figure 3.53**). They are applied in accordance with the height of the flow depth calculated as 2.5m in tsunami numerical modeling.

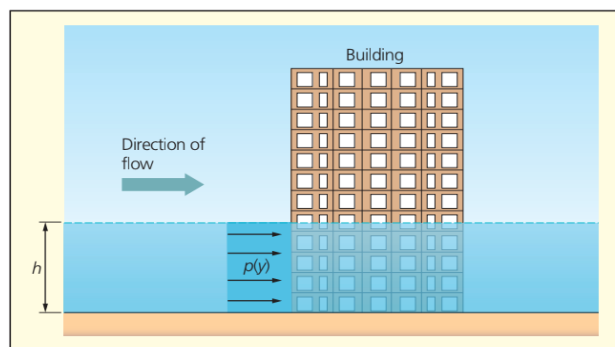


Figure 3.52: Uniformly distributed hydrodynamic loading in front of structures recommended in FEMA P646 (FEMA, 2012).

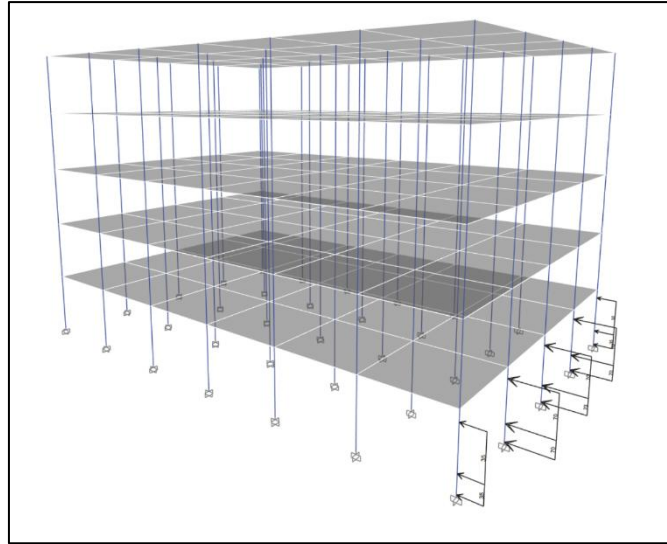


Figure 3.53: Tsunami Drag Forces on Load Bearing System.

Figure 3.54 shows the drifts of the deformed structure under tsunami loads. After the tsunami loads are applied to the structure, exterior non load bearing walls and windows are assumed to be destroyed, thus resulting in the water creating secondary drag force effects. These secondary tsunami loads are applied as drag forces to the system as shown in **Figure 3.55**.

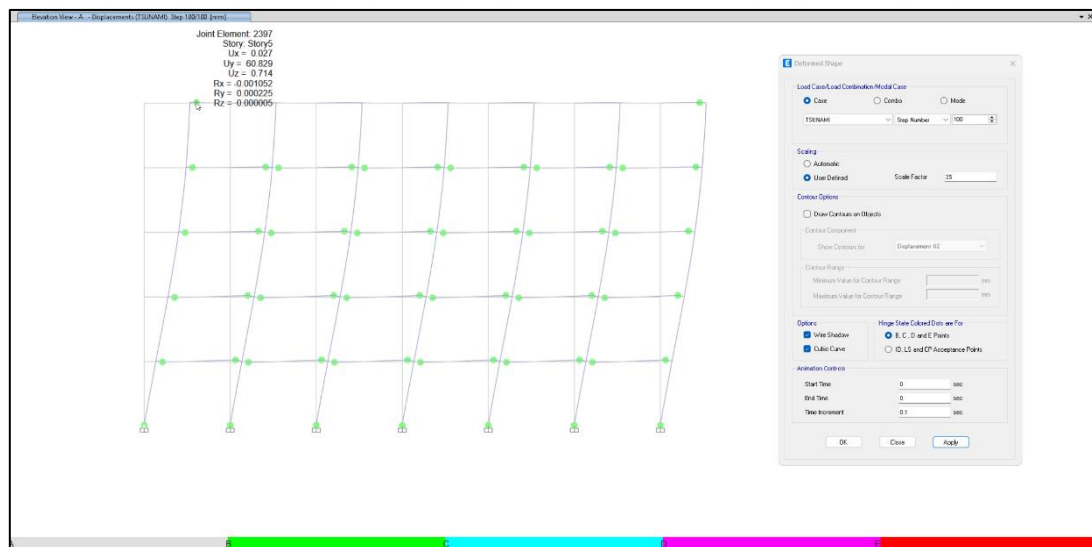


Figure 3.54: Drifts Under Tsunami Loads of the Structure.

Load Case Data

General

Load Case Name: TSUNAMI-2 [Design...]

Load Case Type: Nonlinear Static [Notes...]

Mass Source: Previous

Analysis Model: Default

Initial Conditions

☐ Zero Initial Conditions - Start from Unstressed State

☒ Continue from State at End of Nonlinear Case (Loads at End of Case ARE Included)

Nonlinear Case: TSUNAMI

Loads Applied

Load Type	Load Name	Scale Factor
Load Pattern	DRAG2	1

[Add] [Delete]

Other Parameters

Modal Load Case: MODAL-TUM

Geometric Nonlinearity Option: None

Load Application: Full Load [Modify/Show...]

Results Saved: Multiple States [Modify/Show...]

Floor Cracking Analysis: No Cracked Analysis [Modify/Show...]

Nonlinear Parameters: User Defined - Event-to-Event Only [Modify/Show...]

[OK] [Cancel]

Figure 3.55: Secondary Tsunami Loads Load Case.

Figure 3.56 gives the secondary tsunami loads generated by the submarine landslide. The loads are applied to the system as uniform frame loads. They are applied in accordance with the height of the flow. **Figure 3.57** shows the drifts of the deformed structure under secondary tsunami loads. Fiber hinge status of columns based on the tsunami loading are given in **Table 3.5** and **Table 3.6**.

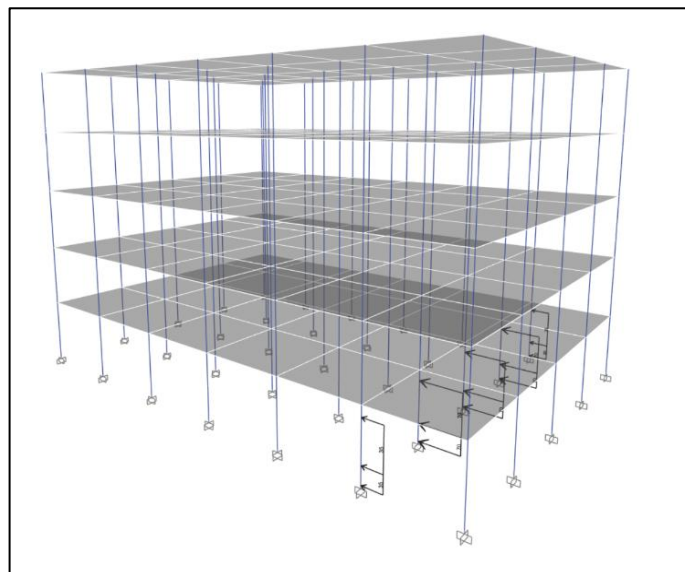


Figure 3.56: Secondary Tsunami Drag Forces on Load Bearing System

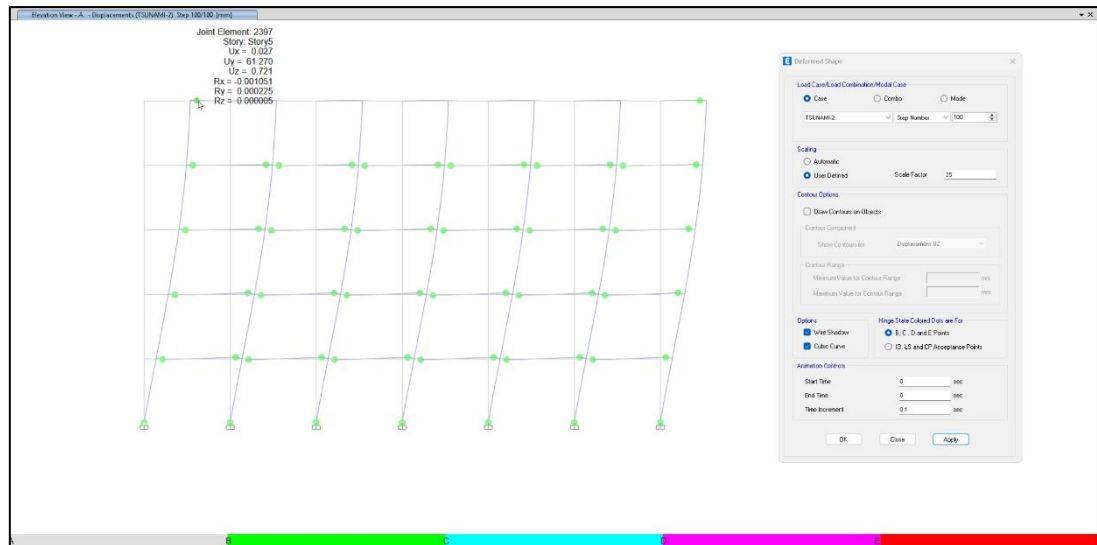


Figure 3.57: Drifts Under Tsunami Loads of the Structure.

Table 3.5: First story columns fiber strains for Pushover Y

PUSHOVER FIBER HINGE FIBER STATES OF COLUMNS FOR PUSHOVER Y				
Story	Frame	Hinge	Generated Hinge	Fiber Strain
Story1	C1	C60x60	C1H1	0,012404
Story1	C49	C60x60	C49H1	0,010811
Story1	C2	C60x60	C2H1	0,012047
Story1	C14	C60x60	C14H1	0,010275
Story1	C27	C60x60	C27H1	0,012035
Story1	C58	C60x60	C58H1	0,010263
Story1	C64	C60x60	C64H1	0,012047
Story1	C68	C60x60	C68H1	0,010275
Story1	C71	C60x60	C71H1	0,012404
Story1	C75	C60x60	C75H1	0,010811
Story1	C78	C60x60	C78H1	0,010842
Story1	C79	C60x60	C79H1	0,010296
Story1	C80	C60x60	C80H1	0,010283
Story1	C81	C60x60	C81H1	0,010296
Story1	C94	C60x60	C94H1	0,009967
Story1	C95	C60x60	C95H1	0,009495
Story1	C96	C60x60	C96H1	0,00948
Story1	C97	C60x60	C97H1	0,009495
Story1	C102	C60x60	C102H1	0,010842
Story1	C106	C60x60	C106H1	0,009967
Story1	C108	C60x60	C108H1	0,01084
Story1	C109	C60x60	C109H1	0,010294
Story1	C110	C60x60	C110H1	0,010282
Story1	C111	C60x60	C111H1	0,010294
Story1	C128	C60x60	C128H1	0,01084
Story1	C133	C60x60	C133H1	0,01083
Story1	C134	C60x60	C134H1	0,010284
Story1	C135	C60x60	C135H1	0,010271
Story1	C136	C60x60	C136H1	0,010284
Story1	C149	C60x60	C149H1	0,01083
Story1	C153	C60x60	C153H1	0,010816
Story1	C154	C60x60	C154H1	0,01027
Story1	C155	C60x60	C155H1	0,010258
Story1	C156	C60x60	C156H1	0,01027
Story1	C165	C60x60	C165H1	0,010816

Table 3.6: First story columns fiber strains for tsunami analysis

PUSHOVER FIBER HINGE FIBER STATES OF COLUMNS FOR TSUNAMI ANALYSIS				
Story	Frame	Hinge	Generated Hinge	Fiber Strain
Story1	C1	C60x60	C1H1	0,008662
Story1	C49	C60x60	C49H1	0,007381
Story1	C2	C60x60	C2H1	0,008373
Story1	C14	C60x60	C14H1	0,006844
Story1	C27	C60x60	C27H1	0,00836
Story1	C58	C60x60	C58H1	0,006829
Story1	C64	C60x60	C64H1	0,008373
Story1	C68	C60x60	C68H1	0,006844
Story1	C71	C60x60	C71H1	0,008662
Story1	C75	C60x60	C75H1	0,007381
Story1	C78	C60x60	C78H1	0,007414
Story1	C79	C60x60	C79H1	0,006873
Story1	C80	C60x60	C80H1	0,006859
Story1	C81	C60x60	C81H1	0,006873
Story1	C94	C60x60	C94H1	0,007353
Story1	C95	C60x60	C95H1	0,006889
Story1	C96	C60x60	C96H1	0,006873
Story1	C97	C60x60	C97H1	0,006889
Story1	C102	C60x60	C102H1	0,007414
Story1	C106	C60x60	C106H1	0,007353
Story1	C108	C60x60	C108H1	0,007404
Story1	C109	C60x60	C109H1	0,006863
Story1	C110	C60x60	C110H1	0,006848
Story1	C111	C60x60	C111H1	0,006863
Story1	C128	C60x60	C128H1	0,007404
Story1	C133	C60x60	C133H1	0,007397
Story1	C134	C60x60	C134H1	0,006854
Story1	C135	C60x60	C135H1	0,006839
Story1	C136	C60x60	C136H1	0,006854
Story1	C149	C60x60	C149H1	0,007397
Story1	C153	C60x60	C153H1	0,007391
Story1	C154	C60x60	C154H1	0,006848
Story1	C155	C60x60	C155H1	0,006833
Story1	C156	C60x60	C156H1	0,006848
Story1	C165	C60x60	C165H1	0,007391

3.2.4.2.2. Tsunami Loading due to Prince Islands Earthquake

Prince Island Earthquake has potential to trigger small scale tsunamis due to the small vertical component of fault displacement. Hence, the tsunami inundation in Çınarcık is lower than the levels estimated due to Tuzla landslide, with the flow depth calculated in front of the building as 0.5m. Tsunami loads created by the Prince Island earthquake are applied to the structure as given in **Figure 3.58**.

Load Case Data

General

Load Case Name: TSUNAMI [Design...]

Load Case Type: Nonlinear Static [Notes...]

Mass Source: Previous

Analysis Model: Default

Initial Conditions

☐ Zero Initial Conditions - Start from Unstressed State

☒ Continue from State at End of Nonlinear Case (Loads at End of Case ARE Included)

Nonlinear Case: NPS-Y-Reloading

Loads Applied

Load Type	Load Name	Scale Factor
Load Pattern	DRAG	1

[Add] [Delete]

Other Parameters

Modal Load Case: MODAL-TUM

Geometric Nonlinearity Option: None

Load Application: Full Load [Modify/Show...]

Results Saved: Multiple States [Modify/Show...]

Floor Cracking Analysis: No Cracked Analysis [Modify/Show...]

Nonlinear Parameters: User Defined - Event-to-Event Only [Modify/Show...]

[OK] [Cancel]

Figure 3.58: Tsunami Loads Load Case.

Figure 3.59 shows the additional tsunami loads generated by the Prince Island Earthquake. The loads are applied to the system as uniform frame loads. They are applied in accordance with the height of the flow. **Figure 3.60** gives the drifts of the deformed structure under tsunami loads.

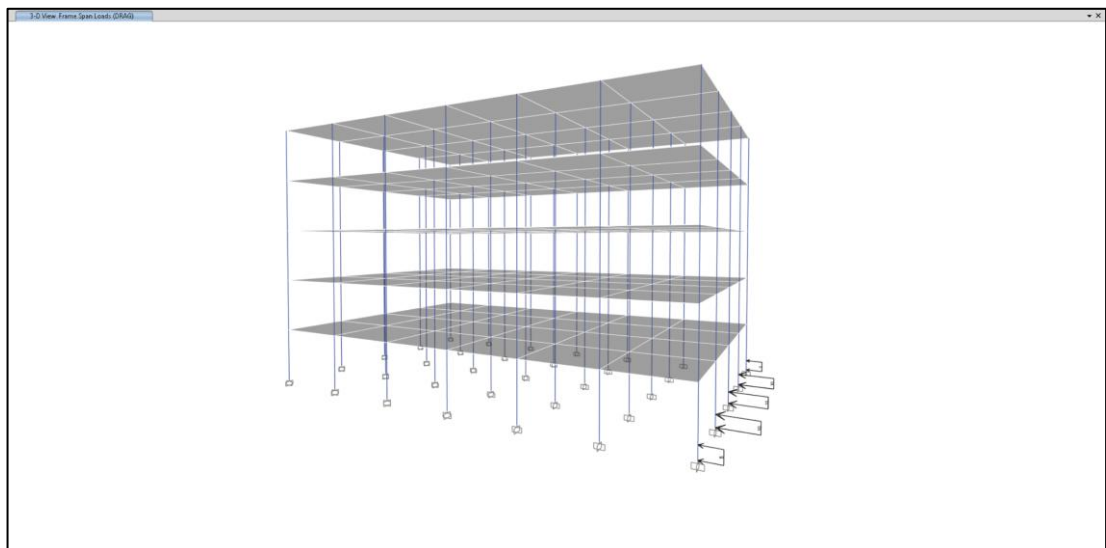


Figure 3.59: Tsunami Drag Forces on Load Bearing System.

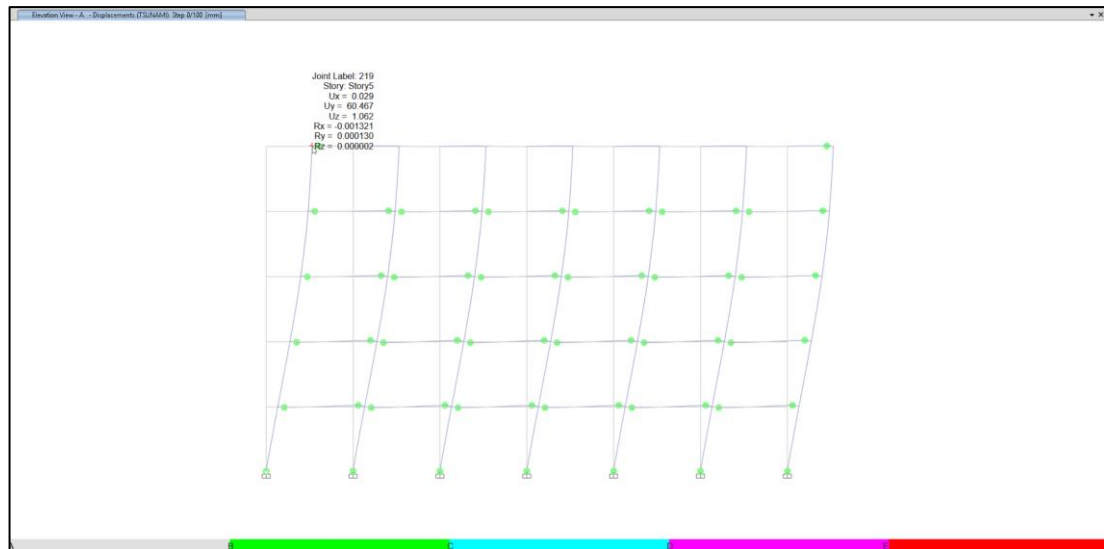


Figure 3.60: Drifts Under Tsunami Loads of the Structure.

For PI earthquake scenario, it is assumed that the tsunami load cannot destroy the exterior non-load bearing walls and windows. Therefore, tsunami loading is applied only to the exterior columns.

Figure 3.61 summarizes the drifts calculated on the building after earthquake and tsunami loading. According to the earthquake loading of the building, 110mm drift and 60 mm residual drift is calculated for the structure, which corresponds to 0.73% and 0.4% compared with the height of the building. This value does not exceed to 2% target story drift which is not likely to have significant structural damage. The tsunami loading due to submarine landslide is applied on the structure after the earthquake drift and it causes a building drift of 62mm that corresponds to 0.41%. The effect of tsunami generated by the earthquake is creating additional drift on the building.

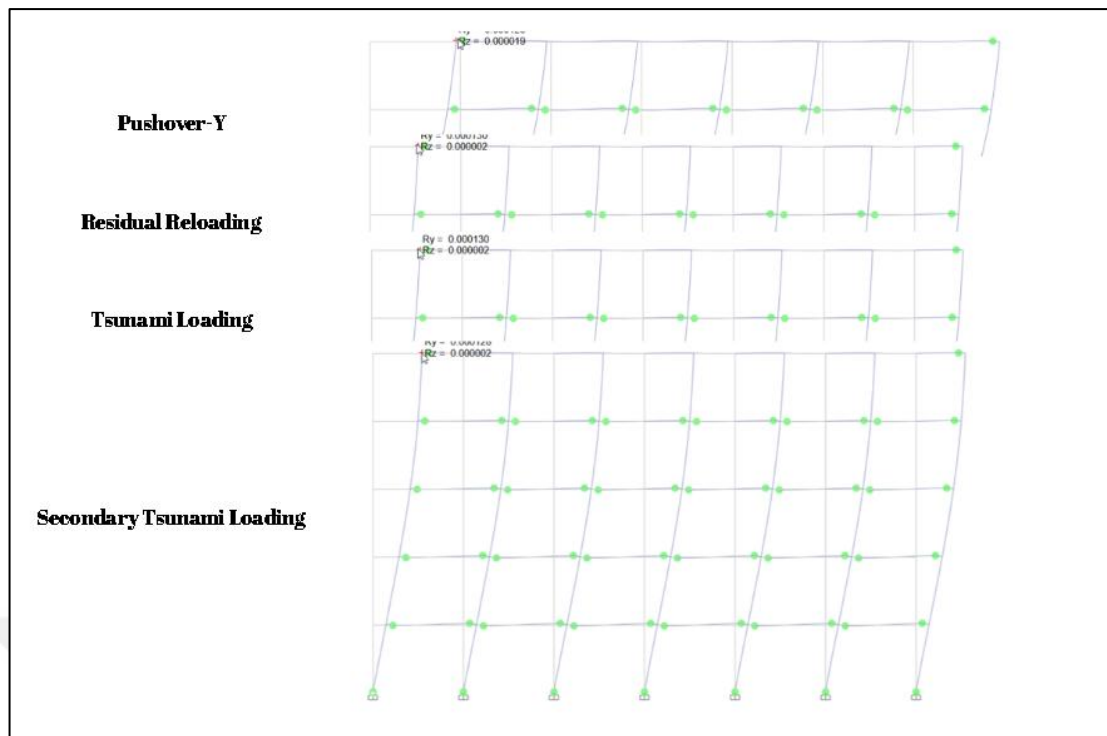


Figure 3.61: Drifts Under Different Loadings.

4. CONCLUSION

Within the scope of this study, cascading earthquake and tsunami hazard has been investigated in the pilot area Çınarcık town, Yalova, Türkiye. A 5-story reinforced concrete structure located in the middle coast of Çınarcık is selected, and earthquake and tsunami loading is calculated.

Two scenarios are investigated in this study as a major earthquake with a magnitude of Mw7.3 offshore Prince Islands and a submarine landslide occurred in Çınarcık Basin offshore Tuzla with a slump volume of 0.8 km³. In order to investigate the effects of a DD2 level earthquake in Marmara Sea and cascading tsunami hazard triggered by submarine landslide zones in Çınarcık Basin, pushover analysis and secondary loading of tsunami force on the building has been conducted. The summary of the outcomes is listed below:

- Bathymetric and topographic data has been processed and the detailed study domain of Çınarcık town has been prepared including the corner coordinates and heights of buildings, coastline as well as coastal defense structures.
- Tsunami simulations have been performed for two scenarios using NAMIDANCE numerical model by solving 2D nonlinear shallow water equations. The calculations have been done in two steps as static input and dynamic input analysis. The initial tsunami wave amplitudes for Mw7.3 earthquake are calculated as 0.27m and -0.94m. The maximum initial wave amplitude generated by the Tuzla landslide is calculated using the empirical equations depending on the volume of slump and initial submergence. The calculated maximum initial wave amplitude due to landslide is 7.2m with a wavelength of about 4.3km.
- The maximum water surface elevation occurred due to the Mw7.3 earthquake in the entire Marmara Sea is calculated as 3.22m while the maximum negative water surface elevation is computed as -3.56m. The time series of water surface fluctuations at the northern border of finest-gridded domain, Domain E, have the maximum value of 0.2m and this fluctuation is used as dynamic input for the calculation of tsunami inundation at Çınarcık. The maximum inundation

depth at Çınarcık is calculated as 0.87m, which has the value of 0.6m in front of the selected building.

- The maximum water surface elevation occurred due to the Tuzla landslide is calculated as 15.5m while the maximum negative water surface elevation is computed as -8.7m in the entire Marmara Sea. The water surface fluctuations used as dynamic input at the northern border of finest-gridded domain, Domain E, have the maximum value of 1.8m. The maximum inundation depth at Çınarcık is calculated as 6.1m, while the value in front of the building is corresponding to 2.5m with a current velocity of 4.7 m/s.
- Tsunami loads in front of the building is calculated both for earthquake and submarine landslide scenarios using ASCE 7-22 with the inundation depth and current velocity of dynamic input analysis at Domain E. According to the results of numerical modeling, the exerted tsunami load due to earthquake is calculated as 53.7 kN. The tsunami load applied to the building due to the submarine landslide is computed as 695 kN.
- The numerical earthquake analysis for DD2 level is conducted using ETABS software referring to the Turkish Earthquake Code (2018). The pushover analysis due to DD2 earthquake provides a structural residual drift of 60mm that corresponds to 0.4% drift. This value does not exceed the structural story drift limit of 2%. This means the structural elements of the building needs to be investigated in a nonlinear manner.
- The secondary loading of building by tsunami loads due to Mw7.3 earthquake shows that structure stays in the same drift level. This scenario also assumes the windows and exterior non-load bearing walls are not collapsed and the tsunami cannot penetrate inside the building. Therefore, there is not tsunami loading for the interior axes of the building.
- The secondary loading of building by tsunami loads due to Tuzla landslide gives a structural drift of 62mm. It is assumed that the windows and exterior non-load bearing walls collapsed with the effect of tsunami inundation and can penetrate inside the structure. Thus, the interior axes of building are also loaded accordingly. The structural drift of 62mm means that the tsunami load creates additional structural drift. However, it is not as significant as the earthquake loading. It is important to highlight that the tsunami load is calculated using the

maximum inundation depth and current velocity in front of the building and only the drag force is taken as the hydrodynamic force.

It is important to note that in this study, only the maximum inundation depth and current velocity is used in front of a single structure. For the study, also only the hydrodynamic drag forces are considered, while hydrostatic forces and buoyant forces are not loaded on the selected structure as the instant loads without making time series analysis. Besides, only two scenarios have been used for tsunami simulations as secondary loading on the building.

It is necessary to highlight that this study uses a submarine landslide scenario based on a slump volume that is half of the eastern slump area among three different landslide scenarios in the referred literature. There are larger slump volumes that may be less likely to occur but still should be taken into account for tsunami hazard assessment in Çınarcık town. Thus, it means the submarine landslide scenario used in this study is not the worst-case scenario but can be said as more likely to occur. Therefore, other larger slump volumes can be used to prepare more comprehensive scenarios and can be analyzed for larger-scale hazard assessment.

For future studies, the forces acting on the structure can be applied as time series loads, and analyses of more structures can enable to have the evaluation of cascading effect in urban scales and help develop more accurate hazard prevention mechanisms. Furthermore, the collapse pattern of buildings can be determined in the pushover analyses and the blockage of roads and evacuation routes can be evaluated more comprehensively.

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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