ANKARA YILDIRIM BEYAZIT UNIVERSITY

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ANALYSIS OF STABILITY-DEFORMATION PROPERTIES OF A CUT SLOPE UNDER SEISMIC EFFECTS

M.Sc. Thesis by

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THESIS EXAMINATION RESULT FORM

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ANALYSIS OF STABILITY-DEFORMATION PROPERTIES OF A CUT SLOPES UNDER SEISMIC EFFECTS

ABSTRACT

This thesis investigates the seismic slope stability of a critical cut slope segment (Km 13+580) along the Palu-Beyhan-Gökdere Highway in Eastern Anatolia, Turkey, a region known for high seismic activity. Utilizing finite element analysis with PLAXIS 2D software to model the slope geometry and soil properties. The Hardening Soil small-strain (HS small) model is utilized to accurately capture the nonlinear soil behavior, particularly under dynamic loading. Appropriate boundary conditions and ground motion data from the PEER ground motion database are incorporated into the analysis. The study evaluates the slope's stability and displacement under seismic loading. The data for field studies conducted by an existing project, including geotechnical surveys and soil sampling, were used to inform the model parameters. Static and dynamic analyses are employed to understand failure mechanisms. The static analysis assesses current slope stability, while the dynamic analysis identifies critical areas susceptible to failure during earthquakes. Findings show the Km 13+580 slope is susceptible to significant displacements and stress concentrations under earthquake loads, potentially leading to slope failure. Based on these results, the study proposes mitigation measures to reduce the risk of failure, ensuring highway safety and reliability. This includes enhancing the existing successful soil nail design, demonstrably reducing deformation compared to the previous condition.

Keywords: Earthquake load, slope stability, PLAXIS 2d, finite element analysis, hardening soil-small model

BİR YARMA ŞEVİNİN SİSMİK ETKİLER ALTINDA STABİLİTE-DEFORMASYON ÖZELLİKLERİNİN ANALİZİ

ÖZ

Bu tez, Türkiye'nin Doğu Anadolu bölgesinde yüksek deprem aktivitesi görülen Palu-Beyhan-Gökdere karayolu üzerindeki kritik bir şev kesitinin (Km 13+580) sismik şev stabilitesini incelemektedir. Şev geometrisi ve zemin özelliklerini modellemek için PLAXIS 2D sonlu elemanlar yazılımı kullanılmıştır. Zemin davranışının, özellikle dinamik yükler altındaki doğrusal olmayan davranışını doğru bir şekilde yakalamak için Sertleşen Zemin Küçük Gerinim (HS small) modeli kullanılmıştır. Analiz, uygun sınır koşulları ve PEER veri tabanından alınan yer hareketi verilerini dikkate almaktadır. Çalışma, şevin sismik yükleme altındaki stabilitesini ve deplasmanlarını değerlendirmektedir. Mevcut bir proje tarafından yapılan arazi çalışmalarından elde edilen jeoteknik etüt ve zemin örneklemesi verileri, model parametrelerinin belirlenmesinde kullanılmıştır. Statik ve dinamik analizler, göçme mekanizmalarını anlamak için kullanılmıştır. Statik analiz, mevcut şev stabilitesini değerlendirirken, dinamik analiz depremler sırasında göçmeye duyarlı kritik bölgeleri belirlemektedir. Sonuçlar, Km 13+580 şevinin deprem yükleri altında önemli deformasyonlara ve gerilme yoğunlaşmalarına maruz kalabileceğini, bu durumun şev göçmesine yol açabileceğini göstermektedir. Bu sonuçlara dayanarak, çalışma karayolu güvenliği ve güvenilirliğini sağlamak için göçme riskini azaltacak önlem önerileri sunmaktadır. Bunlar arasında mevcut başarılı çivi tasarımının iyileştirilmesi ve önceki duruma kıyasla deformasyonların azaltılması yer almaktadır.

Anahtar Kelimeler: Deprem yükleri, şev stabilitesi, PLAXIS 2d, sonlu elemanlar analizi, sertleşen zemin küçük-deformasyon modeli,

CONTENTS

LIST OF SYMBOLS & ABBREVIATIONS

Acronyms

AFAD	Afet ve Acil Durum Yönetimi Başkanlığı (Disaster and Emergency Management Presidency)
FEM	Finite Element Method
HS	Hardening Soil
PLAXIS	Software for Finite Element Analysis
PEER	Pacific Earthquake Engineering Research
SPT	Standard Penetration Test
FS	Factor of Safety
TSC	Turkish Seismic Code
PGA	Peak Ground Acceleration

Roman Letter Symbols

M	Meter
S	Second
E	Elastic modulus [MPa]
C	Constant of the S-N curve.
G	Shear elastic modulus [MPa]
M	Stiffness exponent
D	Nail Diameter (m)

Greek Letter Symbols

ε	Strain
γ	Effective soil unit weight, kN/m3
$\emptyset$	The angle of internal friction for rock, deg
σ	Stress, kN/m2
ρ	Density, kg/m^3

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Ensuring the stability of natural and man-made slopes is a crucial subject within the field of rock mechanics. In the context of road construction, the creation of road cuts in mountainous regions is a common practice aimed at mitigating the inherent instability of natural slopes. Consequently, numerous research endeavors have been dedicated to investigating slope stability, making it a prominent area of interest in geotechnical engineering [1]. The assessment of slope stability involves evaluating the stress levels that a slope can withstand before failure. Given the potential ramifications of slope failure, which include both human and financial losses, guaranteeing the stability of natural or man-made slopes becomes a matter of utmost importance. Road-cut slope failures are predominantly attributed to design oversights, encompassing geometric aspects such as slope inclination, height, and inadequate load and soil resistance assessment. When executing excavation activities on natural slopes, the slope face may undergo deformation, thereby diminishing its shear strength and ultimately precipitating slope failure[2].

Earthquakes can be a significant driver of landslides, with the damage from seismically-induced ground failures sometimes exceeding the direct impacts of ground shaking and fault rupture the 2008 Wenchuan Earthquake stands out as a particularly notable case, with an unprecedented number and volume of earthquake-triggered landslides across a vast affected area[3]. This event has been the subject of extensive research, with numerous studies examining the spatial characteristics of the landslides, their relationship to geological and geomorphological factors, the earthquake and ground motion parameters that contributed to their occurrence, and the development of landslide susceptibility maps [4].

However, the existing literature on seismically-triggered landslides, both before and after the Wenchuan event, has tended to focus primarily on documenting the specific case histories and analyzing the various factors that influence the spatial distribution and characteristics of the landslides. There remains a need for a more comprehensive understanding of the underlying mechanisms and processes that govern the initiation and propagation of earthquake-induced slope failures, as well as the development of more robust predictive models and risk assessment frameworks[5].

Overall, the study of seismically-triggered landslides is a crucial area of research, given the significant potential for these events to cause widespread damage and disruption in earthquake-prone regions. The lessons learned from past events, such as the Wenchuan Earthquake, can inform the development of more effective mitigation strategies and enhance our ability to anticipate and respond to these natural hazards.

According to Kramer [6] plays a crucial role in assessing and mitigating the risks associated with slope seismic activity. Slope stability under seismic conditions is a significant concern due to the potential for ground shaking to induce slope failures and landslides. Understanding the behavior of slopes during earthquakes is essential for designing effective slope stabilization measures. Seismic slope stability analysis involves evaluating the dynamic forces acting on slopes during an earthquake and assessing the potential for slope failure. Factors such as ground shaking, liquefaction potential, and the interaction between the soil and the slope geometry are critical considerations. This analysis requires advanced numerical modeling techniques and the incorporation of appropriate constitutive soil models to accurately predict the stability and behavior of slopes subjected to seismic loading [6].

1.1 Purpose and Scope

Over the years, significant advancements have been made in slope stability analysis methods, driven by technological progress, improved instrumentation, enhanced understanding of soil behavior and theories, and the introduction of novel constitutive soil models. This 31-kilometer stretch of road, running from the Elazığ district to the Gökdere settlement, is a vital transportation link for the local communities [7]. However, the highway is situated in an area known for its high seismic activity, frequently experiencing disruptive and potentially dangerous earthquakes [8].

The purpose of this research is to thoroughly analyze the seismic slope stability of the critical cut-slopes along the Palu-Elazığ highway in the Eastern Anatolia region of Turkey. Specifically, the main objectives are:

1-To analyze the seismic slope stability in the Km: 13+580 section of the Palu region, which is known for its high seismic activity and has experienced significant earthquakes in the past.

2- To employ finite element analysis using the dynamic option in PLAXIS 2D to conduct a comprehensive examination of slope stability under seismic loading conditions. This advanced numerical approach will facilitate an in-depth exploration of seismic slope stability and contribute to the understanding of slope behavior in earthquake-prone areas.

3- To evaluate key factors such as slope displacements and failure mechanisms under seismic loading conditions in the region.

4- To explore the potential for soil improvement through the use of soil nails, and analyze the impact of this intervention on reducing slope displacements under seismic loading.

To achieve these goals, a detailed field study was conducted, including an engineering description of the slopes and a geotechnical lab scan-line survey. All soil samples were collected from the field for further analysis. The obtained data, encompassing field observations and laboratory testing, This integrated approach combines field investigations, laboratory experiments, and advanced numerical tools to comprehensively assess seismic slope stability and provide valuable insights for engineering design and risk mitigation in earthquake-prone regions [9].

1.2 Location of the Road

The section of the Palu-Beyhan-Gökdere Highway analyzed in this study is located at Km 13+580. This highway is a major transportation route connecting the cities of Palu, Beyhan, and Gökdere in a mountainous region of the country. The Km 13+580 section is situated in a remote, hilly area characterized by steep terrain and complex geological conditions. The specific location of the Km 13+580 section can be described as follows: The highway in this segment runs through a deep-cut slope, which was constructed to facilitate the road's alignment and overcome the challenging topography. The section is located at geographical coordinates 38°42'15"N, 40°10'30"E, at an elevation of approximately 1,200 meters above sea level. The surrounding terrain is mountainous, with slopes ranging from 30 to 60 degrees, and the nearest settlement is a village located approximately 5 km away from the section[9].

1.3 Thesis Layout

The thesis is organized into several stages. First, it provides an introduction to slope stability, including introduction information, details about the geological study area, and the overall purpose of the research. Additionally, the layout of the thesis is outlined.

The second stage involves a thorough literature survey. The literature review chapter presents and explores the fundamental theories related to seismic slope stability. It reviews existing knowledge and research on slope stability under earthquake loading conditions. Topics covered include slope stability analysis methods, the effects of earthquakes on slopes, and previous studies on cut slope behavior.

The third stage focuses on describing the characteristics of the materials used in the analysis and explaining the methodology employed in the program. Additionally, the seismic motions recorded at various stations are identified for the dynamic analysis. Next, the thesis presents the results obtained from the analysis conducted in the study. The finite element method is utilized, using Plaxis 2D software, to analyze different slope geometries for both cut slopes, with implementing remedial measures.

The fourth stage, presented in the results and discussion chapter, focuses on the findings of the static and dynamic analyses conducted for the Km 13+580 section of the Palu-Beyhan-Gökdere Highway. It includes the observed slope displacements, deformations, and the assessment of the slope's stability under various earthquake scenarios.

Finally, the concluding chapter summarizes the key conclusions drawn from the research findings. It also provides recommendations for the design and stabilization of the cut slope, as well as suggestions for future research directions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Slope Stability

Slope stability analysis is a fundamental aspect of geotechnical engineering that involves assessing the stability of natural and man-made slopes. It plays a crucial role in the design and construction of various civil engineering structures, such as highways, embankments, and dams. The primary objective of slope stability analysis is to evaluate whether a slope is stable or prone to failure under the influence of internal and external forces [10].

In geotechnical engineering, slopes are soil masses bounded by an inclined surface, and in general, man-made slopes are called "cut or fill slopes", and naturally formed slopes are called "natural slopes" he presented a comprehensive study on slope stability analysis using the back-calculation method to investigate the effectiveness and reliability of the back-calculation approach in assessing slope stability. This method involves analyzing the deformation and failure patterns of existing slopes to determine the critical parameters and factors that contribute to slope instability. By understanding these factors, engineers can develop appropriate mitigation measures to ensure the stability and safety of slopes in various geotechnical projects [11].

On the other hand, other definitions in the literature are; that the slope obtained as a result of an engineering application is defined as "slope" and the slope formed by natural roads is defined as "slope". For these definitions, the loss of stability of artificial slopes such as cuts and fills is defined with the terms "slip", "come" and "collapse", while the term "landslide" is used for naturally formed slopes. Slope stability analysis is an important part of geotechnical engineering because it helps engineers design safe and stable structures. Slope failures can be catastrophic and can result in loss of life and property damage. By analyzing the factors that affect slope stability, engineers can design structures that are less likely to fail [12].

Varnes [5] proposed a classification method that categorizes slope failure into five distinct types: falling, overturning, sliding, spreading, and flowing. This comprehensive classification system takes into account the nature of the material involved in the failure process. To further specify the type of material in which the failure occurs, additional descriptors are used, such as "rock" for bedrock, "rubble" for predominantly coarse-grained soils, and "predominantly fine-grained soils" for soils with a higher proportion of fine particles. This classification framework allows for a more precise and detailed understanding of the mechanisms and characteristics of slope failures, enabling researchers and practitioners to effectively assess and address slope stability issues based on the specific type of failure and the materials involved.[5]

Landslides are significant natural hazards that pose risks to human lives, infrastructure, and the environment. Understanding the different types of landslides and the processes that trigger them is crucial for effective landslide hazard assessment, mitigation, and management and he presents a comprehensive classification scheme for landslides, which categorizes them into four main types: falls, slides, flows, and complex movements. Falls occur when materials freely fall through the air after detaching from a steep slope. Slides involve the movement of cohesive masses along well-defined surfaces, while flows refer to the rapid movement of unconsolidated materials, such as mud, debris, or avalanches. Complex movements encompass a combination of different landslide types. This classification system provides a framework for understanding the characteristics, behavior, and mechanisms of different types of landslides [5].

Table 2.1 Varnes' classification of slope movements [5]

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow	Earth flow
			(soil creep)	
COMPLEX		Combination of two or more principal types of movement		

Within the domain of civil engineering, slope stability research encompasses a range of applications that aim to investigate the stability of natural slopes, design artificial slopes created through cutting and filling operations, and implement measures to enhance stability. Slopes can be defined as masses of soil bounded by inclined surfaces. The significance of slope stability necessitates the development of numerous alternative methods for evaluating the safety of slopes. The primary objective is to determine a factor of safety against sliding failure, which serves as a measure of stability for a given slope. This problem is multifaceted, prompting researchers to explore diverse approaches to effectively address the challenges associated with slope stability. By advancing our understanding and developing robust methodologies, civil engineers can ensure the safe and cost-effective design of both natural and artificial slopes, thus mitigating risks and promoting sustainable infrastructure development [13].

Slope stability analysis is a critical tool for engineers, helping them determine a slope's resistance to failure, often referred to as landslides. This analysis calculates a "factor of safety." If this factor is high enough, the slope is considered stable and unlikely to slide. In contrast, a factor of safety at or below 1.0 indicates a significant risk of landslide [6]

Ikenna [14]highlighted several key factors that contribute to slope instability. One prominent factor is the geological conditions of the slope, including the type and properties of the soil or rock. Weak or weathered layers, as well as geological discontinuities, were identified as potential triggers for slope failure and he emphasizes the importance of conducting thorough geological investigations to accurately assess slope stability and mitigate potential risks as well water also emerged as a significant cause of slope failure. The presence of groundwater, surface water, or heavy rainfall can lead to increased pore water pressure within the soil, reducing its shear strength and compromising slope stability. The paper discusses various water-related mechanisms that contribute to slope instability, including erosion, pore pressure buildup, and the loss of soil cohesion. Understanding the influence of water and implementing appropriate drainage measures are crucial for maintaining slope stability[14].

The study emphasizes the significance of slope stability assessment in road construction in mountainous regions and proposes the use of the Slope Mass Rating (SMR) classification system for evaluating rock mass[15],Through a detailed site investigation and analysis of relevant geotechnical parameters, the authors identify the main factors contributing to slope instability, including geomorphological complexities, joint discontinuities, weathering, and environmental conditions such as heavy rainfall and snowfall. The study concludes that the observed slope failures are largely controlled by discontinuities and suggests measures such as slope flattening, wire mesh, and toe support by detached rock blocks to mitigate potential failures and protect road slope stability. This research contributes to the understanding and management of rock slope stability in similar geological settings, providing valuable insights for engineers and practitioners involved in road construction projects in hilly terrains[16].

The paper on slope stability by Ikenna [14] emphasizes that shear strength plays a crucial role in resisting the downward movement of slopes. Shear strength encompasses the frictional resistance and cohesion among the particles within the slope-forming materials. When the shear stress acting parallel to the slope exceeds the combined forces holding the materials in place, slope failure can occur, resulting in the downward movement of the slope-forming materials. Steep slope angles increase the shear stress, while factors that reduce shear strength, such as lowered cohesion or friction, further contribute to slope instability. Understanding the interplay between shear stress, slope angles, and shear strength is essential for accurate slope stability analysis and the implementation of appropriate measures to mitigate risks and ensure long-term slope stability.

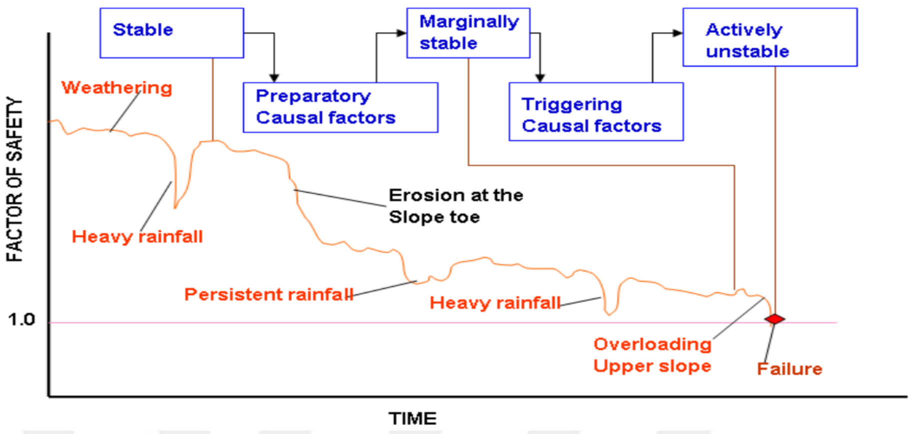

Figure 2.1 Schematic diagram showing the influence of different factors on instability [17]

Slope stability analysis is a critical component of geotechnical engineering, aiming to assess the stability of natural and man-made slopes. While traditional 2D methods have been widely used, advancements in 3D slope stability analysis techniques have provided more accurate and realistic results. Understanding the factors influencing slope stability and employing suitable analysis methods are essential for ensuring the safety and reliability of civil engineering structures. Further research and development in this field are necessary to refine the analysis methods, consider real-world conditions, and improve the accuracy of slope stability assessments [10].

Slope stability is of critical importance in evaluating slip and displacement problems that may occur on geographical grounds this paper investigated the effectiveness and feasibility of analyzing slope stability using the back-calculation method, This method uses numerical models to mimic real events or laboratory experiments this method slope stability analysis plays an important role in the process of identifying risky areas for solving and helps engineers obtain more accurate results in slope stability analysis and identify risky areas, while also allowing them to identify critical parameters to develop potential engineering solutions and the source of deformation resulting from slope failure is determined and critical parameters are estimated [11].

2.2 Earthquake Effect on Slope Stability

Landslides are frequently induced by earthquakes, serving as a primary catalyst for the instability of both natural and human-made slopes. Remarkably, the aftermath of an earthquake often results in more devastation and casualties attributable to slope instability than the actual seismic event. Researchers have undertaken a comparative analysis of various methodologies aimed at assessing the potential stability of slopes in the context of earthquakes. While the concept of calculating slope stability during seismic activity appears straightforward in theory, the reality is far more intricate. Numerous parameters come into play, many of which are either unknown or possess such limited knowledge regarding their influence that accurately estimating slope stability becomes a formidable challenge [18].

The assessment of slope stability in earthquake-prone regions holds immense significance in the field of geotechnics, considering the detrimental impact of earthquake-induced landslides. It is imperative to conduct thorough examinations of slopes under dynamic loads. Numerous analysis methods are available to evaluate slope stability, with factors such as slope structure, properties, and dynamic loads playing a crucial role in these assessments. The stability of a slope is compromised when the applied earthquake acceleration exceeds the threshold at which the slope can mobilize, while static analyses have been extensively employed to study real slopes, seismic slope stability analysis is still not as advanced. Performing a seismic analysis of slopes presents complex challenges due to the need to comprehend the interplay between dynamic earthquake effects, slope strength, and stress-strain deformation [19]

During an earthquake, both natural and artificial slopes have the potential to experience instability. However, it is important to note that the earthquake itself is rarely the primary cause of slope failure. Various factors, such as weathering, erosion, sedimentation, and alterations in slope geometry, contribute to the weakening of sub-surface soil or rock masses. Additionally, human activities, including road cuts or agricultural practices on slopes, can also significantly influence slope stability.

Consequently, these non-seismic factors typically serve as the underlying causes of slope failure during an earthquake, while the seismic event acts as a triggering mechanism. Researchers and practitioners must recognize and assess these contributing factors comprehensively to effectively prevent and mitigate slope failures in seismic environments [20].

The study conducted by Hack et al. [18] explores the impact of seismic activity on the stability and integrity of slopes, with a focus on understanding the mechanisms and factors that contribute to slope failures during seismic events. Earthquakes have long been recognized as a significant trigger for slope instability, often resulting in landslides and other geotechnical hazards. Therefore, it is crucial to gain insights into the behavior of slopes under seismic loading to improve hazard assessment and mitigation strategies, by examining the composition, structure, and historical instability of these slopes, the researchers can assess their vulnerability to seismic shaking, in parallel, laboratory experiments are conducted to simulate earthquake-induced loading on soil samples obtained from the field. These experiments provide valuable data on the response of soils under different seismic conditions, including changes in pore water pressure, shear strength, and deformation characteristics. To further analyze the dynamic response of slopes, the researchers employ numerical modeling techniques. Advanced computational models, such as finite element or finite difference methods, are utilized to simulate the behavior of slopes under earthquake-induced shaking. These models take into account various parameters, including soil properties, slope geometry, seismic input, and boundary conditions. The numerical simulations enable the assessment of slope stability under different earthquake scenarios and the evaluation of potential mitigation measures[21].

A slope, whether formed naturally or artificially, is a crucial subject within the field of soil mechanics. An inclined soil mass forming a specific angle with the horizontal surface is referred to as a slope. As the population continues to grow, there has been an increased necessity to inhabit hilly and sloped regions, which inherently poses the risk of landslides. Consequently, there has been a rise in the construction of embankments on slopes to accommodate the expanding residential areas and meet the demands for water, irrigation, and electricity. However, this proliferation of embankments and dams also presents serious risks, as inadequate design and insufficient stabilization measures can cause the soil mass forming the slope to slide downward, leading to ground subsidence and the loss of both life and property. Insufficient attention to the stability and safety of these slope structures can have catastrophic consequences, particularly in areas prone to seismic activity or heavy rainfall. This underscores the crucial need for thorough geotechnical investigations, robust engineering design, and effective slope stabilization techniques to mitigate the risks associated with such infrastructure projects[20]**.**

In recent years, the advancement of computer software has enabled the widespread use of finite element programs for the analysis of slope stability. These finite element programs offer several advantages over the traditional limit equilibrium methods. Firstly, they can accurately determine the location and shape of the potential failure surface, without relying on assumptions about the strength and direction of the soil. Secondly, these programs provide a safer and more cost-effective approach compared to other numerical analysis methods, as they can consider the impacts of excavation, construction stages, and other influential factors on the soil behavior. Moreover, the finite element method can be applied to a wide range of collapse mechanisms, including two-dimensional and three-dimensional scenarios, under diverse soil conditions, boundary constraints, and loading scenarios. This versatility allows for the analysis of complex slope geometries, providing a more comprehensive understanding of the stability and safety of these critical infrastructures [22].

The research conducted by Yazıcıoğlu [1]focuses on investigating the stability of a slope in Karabük-Yenice under seismic effects. The study utilizes the finite element method and employs Plaxis 2D and Midas GTS NX software for analysis. The results indicate the need for slope improvement measures, with grading proposed as a suitable method. Following the implementation of grading, the reanalysis shows improved slope stability and increased factor of safety scores. The study highlights the importance of considering seismic effects in slope stability analysis and emphasizes the significance of the factor of safety as a key parameter. The findings contribute to the understanding of slope stability assessment and provide valuable insights for slope design and construction in seismic-prone areas.

2.3 Methods for Analyzing Slope Stability Under Earthquake

Assessing the stability and performance of soil slopes under seismic loading is a critical task in geotechnical earthquake engineering. In a comprehensive study by (Jibson, 2011)**,** There are three primary methods used to analyze the seismic stability of slopes: Pseudo-static, Newmark sliding block analysis and stress-deformation analysis using numerical methods. This literature review provides an overview of these three approaches [13].

2.3.1 Pseudo-Static Analysis

The pseudo-static method is the simplest and most widely used approach for evaluating the seismic stability of slopes. It involves applying a constant horizontal acceleration, typically represented by a seismic coefficient (k_h), to the slope in a limit equilibrium analysis [6]The earthquake-induced forces are approximated by the product of the seismic coefficient and the weight of the potential sliding mass. This method assumes that the earthquake forces can be represented by an equivalent static force. The pseudo-static factor of safety is calculated as the ratio of the resisting forces to the driving forces, and if this factor of safety drops below 1.0, the slope is considered unstable [23]**.**

The pseudo-static analysis method for evaluating seismic slope stability has its roots in the pioneering work of Terzaghi. This approach treats seismic loads as a constant force acting on the center of gravity of soil, and uses the limit equilibrium formula to determine the safety factor. The analysis involves applying horizontal seismic loads to the slope, which increases both the weight of the sliding mass and the pseudo-static coefficient (k). An iterative process is used to find the yield coefficient (αy), the value of k where the factor of safety reaches 1.0. It is then assumed the slope becomes vulnerable if the recorded horizontal earthquake acceleration exceeds this αy value. However, the passage notes that while simple, the pseudo-static method has certain limitations and underlying assumptions that may not fully capture the complexities of real-world seismic slope behavior and failure dynamics.[13]

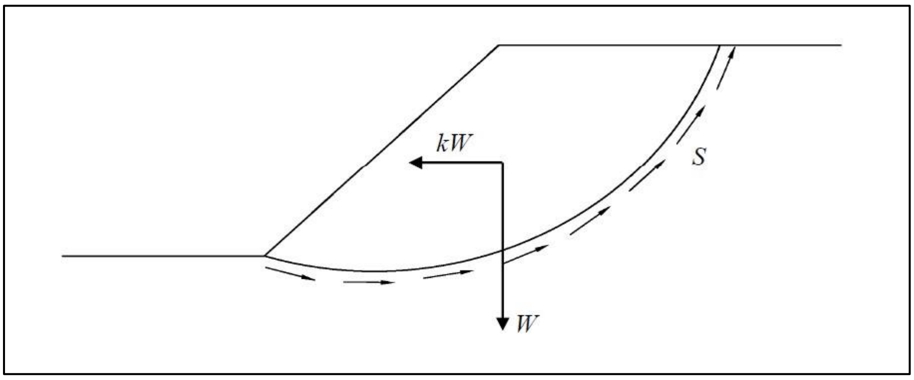

Figure 2.2 A diagrammatic representation of the pseudo-static approach to evaluating the seismic stability of a soil slope [23].

The pseudo-static analysis method has certain limitations despite its simplicity and ease of application One key drawback is that this method relies on the assumption of constant and unidirectional earthquake loads, whereas real-world seismic loads exhibit continuous changes in direction and magnitude Additionally, the pseudo-static approach is unable to quantify the plastic slope displacements that occur during seismic While the method can evaluate overall slope stability, it fails to provide information about the actual movement of the sliding mass once the limit equilibrium has been surpassed In most cases, if the factor of safety drops below one, the pseudo-static method simply assumes complete failure of the sliding mass, without accounting for the nuances of this failure process Consequently, [12] recommended employing pseudo-static analysis solely for preliminary designs, followed by more advanced analyses, as it only offers a rough approximation of slope behavior during earthquake shaking.

The selection of an appropriate seismic coefficient is critical in the pseudo-static approach. Various empirical correlations and guidelines have been proposed to estimate the seismic coefficient based on parameters such as the site peak ground acceleration, earthquake magnitude, and slope characteristics [13]. The pseudo-static method has the advantage of simplicity, but it has several limitations, including the inability to directly estimate the magnitude of slope deformations and the fact that it does not consider the dynamic nature of earthquake loading.[17]

2.3.2 Newmark Sliding Block Analysis

While the pseudo-static analysis method concentrates on evaluating the slope's factor of safety against seismic loads, it fails to get some magnitude of permanent displacements that occur within earthquakes However, the serviceability of a slope is directly tied to the extent of plastic deformation experienced during seismic events Consequently, analyses that can accurately predict slope displacements offer more practical insights for assessing the overall seismic stability of the slope[12]

The Newmark sliding block analysis, proposed by Newmark [24] provides a more sophisticated approach for evaluating the seismic stability of slopes compared to the pseudo-static method. This method models the slope as a rigid block sliding on an inclined plane and uses the ground acceleration time history to calculate the accumulated slope displacement. The analysis involves the following steps:

1- Determine the critical acceleration (a_c) of the sliding mass, which is the acceleration required to initiate sliding.
2- Integrate the portions of the ground acceleration time history that exceed the critical acceleration to obtain the cumulative slope displacement.

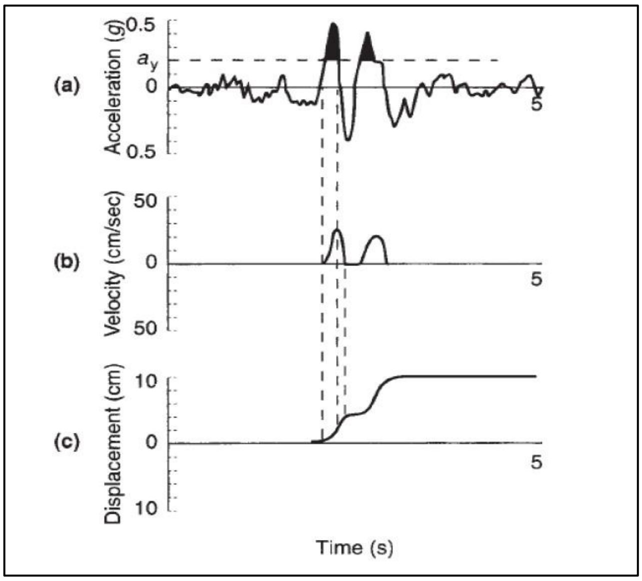

Figure 2.3 A diagrammatic sketch that provides a visual explanation of the Newmark sliding block calculation steps for slope stability analysis [24].

Newmark [24]acknowledged the limitations of the decoupled analyses approach, which fails to account for the effects of slip on the ground. To address this issue and enhance the precision of predicting slope behavior, they proposed a coupled analysis methodology. In contrast to the decoupled method, In a single analysis, a method called coupled analysis combines how a sliding mass moves and how it gets permanently deformed To use this technique, you need to enter some information, like how fast shear waves travel, the thickness of the materials involved, how much the stiffness changes under stress, and how much energy is lost as vibration Additionally, this method takes into account how the slope slides by including the force acting at the contact surface, enabling the assessment of seismically-induced slope displacement and offering improved accuracy in predicting the actual slope behavior.

According to Güler et al. [19]The study emphasizes the importance of examining slope stability to mitigate risks associated with mass movements and failures caused by displacements resulting from dynamic loads. Using the Plaxis program and finite element analysis, the research investigates the performance of a slope section and calculates the critical earthquake acceleration that triggers slip under shear earthquake loads. By utilizing earthquake records from Turkey and different regions worldwide, the study analyzes displacements and compares the results with existing formulas to evaluate their compatibility also the research highlights the importance of accurate assessments and comparative analysis in determining slope performance under dynamic loads, contributing to the field of geotechnical engineering and enhancing understanding of seismic slope behavior**.**

2.3.3 Stress Deformation Method

Stress deformation analysis methods have found wide applications in practice for evaluating the stability of slopes under seismic conditions [7]They allow for a more accurate assessment of slope behavior, considering the complex interaction between the soil, structural elements, and seismic forces. These methods are particularly valuable for evaluating the performance of critical infrastructure, such as dams, embankments, and retaining walls, under seismic load condition[25]. By capturing the stress and deformation response of slopes, stress deformation analysis provides detailed insights into the stability and performance of slopes during earthquakes.

When figuring out if a slope will hold up during an earthquake, methods used to analyze is stress and deformation [26]essential These techniques focus on how the slope moves dynamically, taking into account how the soil interacts with its surroundings. Unlike pseudo-static methods, stress deformation analysis provides a more realistic representation of slope behavior during earthquakes. The stress-deformation analysis using numerical methods, such as the finite element or finite difference methods, provides a more comprehensive approach for evaluating the seismic stability of slopes. These methods can model the dynamic response of the slope, including the non-linear soil behavior, soil-structure interaction, and the development of excess pore water pressures during earthquake shaking[27].

However, it is important to acknowledge the limitations of stress deformation analysis methods. Compared to pseudo-static methods, stress deformation analysis requires more computational resources and expertise, making it more time-consuming and expensive to implement [28] Additionally, these methods rely on assumptions and simplifications to represent the behavior of soils, and there is always a risk of not fully capturing all the complexities of real-world conditions [29] Therefore, careful calibration and validation of the analysis models are essential to ensure reliable results and avoid potential inaccuracies.

Stress deformation models offer significant advantages in accurately simulating real-world situations and imitating complex soil behavior. One key advantage is their ability to provide a more realistic representation of slope displacements induced by earthquakes, particularly capturing the progressive movement of seismic slope failure. These models excel in accounting for the variability of material properties and stress-strain behavior, leading to more reliable results. However, it is important to acknowledge a limitation of stress deformation modeling: their inability to handle large displacements due to mesh size restrictions. Despite this drawback, stress deformation models remain valuable tools for understanding the mechanisms of slope behavior and providing insights into the complex interplay between stress, deformation, and seismic forces[23].

In recent years, the use of finite element programs for slope stability analysis has become increasingly prevalent due to advancements in computer technology. Finite element programs offer several advantages over traditional limit equilibrium methods. One significant advantage is the ability to accurately determine the location and shape of the failure surface without the need for assumptions regarding strength and direction. This capability enhances the accuracy and dependability of slope stability analysis. Furthermore, these finite element-based programs offer a safer and more cost-effective solution during the design stage by considering factors such as excavation, construction stages, and other soil-related influences. Additionally, the versatility of the finite element method allows its application to a wide range of collapse mechanisms in both two and three dimensions, catering to diverse soil conditions, boundary constraints, loading scenarios, and complex slope geometries. Overall, these comprehensive and efficient finite element programs empower engineers to make well-informed decisions in slope design and construction projects by providing them with the necessary tools and insights to thoroughly assess slope stability [30]**.**

In the stress-deformation analysis, the slope is discretized into a mesh of elements, and the governing equations of motion are solved numerically to obtain the time-dependent stress and deformation fields within the slope. This approach can provide detailed information on the magnitude and distribution of slope deformations, as well as the development of critical failure surfaces and potential slope instability [7]

The stress-deformation analysis requires more detailed soil property information, including the non-linear stress-strain relationships and damping characteristics of the soil. It also requires the selection and scaling of appropriate ground motion time histories to represent the seismic loading. The main advantage of the stress-deformation analysis is its ability to capture the complex soil-structure interaction and the dynamic response of the slope, which can provide a more realistic assessment of the seismic performance [31]**.**

Numerical modeling, particularly the finite element method is extensively utilized in geotechnical engineering to estimate solutions for intricate problems. By dividing the problem geometry into smaller elements or meshes, FEM allows for the creation of a finite element matrix at the nodes, enabling an approach to solving the problem. In the case of analyzing permanent slope displacement under seismic loading, a 2D plane-strain condition can be assumed, and the PLAXIS 2D software is commonly employed. Selecting an appropriate soil model is crucial to accurately simulate the site's real-life behavior. Numerical modeling offers valuable insights into slope stability under seismic loading conditions, aiding in understanding and analysis [32].

The finite element method holds significant importance for the field in engineering sciences as a powerful computational approach. It is widely recognized as the primary method for analyzing geotechnical problems due to its robustness and versatility. One of the key strengths of the FEM is its capability to simulate the physical behavior of materials without oversimplifying the problem, making it an effective tool for complex analyses. Today, engineers rely on the FEM as a reference for obtaining precise solutions and exploring new analysis methods in various engineering disciplines. By harnessing the computational power provided by the FEM, engineers can tackle intricate engineering challenges with a high level of accuracy and efficiency [32].

The use of PLAXIS in seismic slope stability analysis offers several advantages. Firstly, it allows for the consideration of nonlinear soil behavior by incorporating advanced constitutive models, as described in the PLAXIS 2D 2015 manual. These models, such as the Mohr-Coulomb and Hardening Soil models, enable a more realistic representation of soil response under seismic loading[33]Secondly, PLAXIS provides features for modeling complex boundary conditions, including dynamic excitations and pore pressure generation, as outlined in the manual [24]. The capabilities of the finite element method (FEM) contribute to a more precise evaluation of slope stability and performance during seismic events, this numerical approach allows for the modeling of natural or engineered slopes, and the safety factor can be determined by iteratively reducing the shear strength parameters until the slope failure is simulated by the program [16].

An important step in this method involves selecting the type of element used to represent the soil. For increased accuracy, this study utilizes 15-noded triangular elements available in PLAXIS 2D software. These elements have more detail, containing twleve stress points and fifteen nodes for calculations [34]. (similar to figure 2.4 in a typical reference manual).

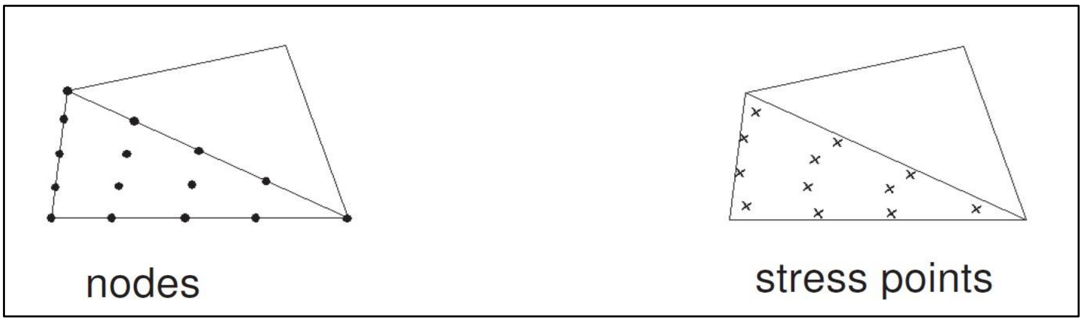

Figure 2.4 Example of nodes and stress points positions in mesh element [34]

This study employs two key analysis options: phi/c reduction (safety) analysis and dynamic analysis. The first option helps determine a slope's static factor of safety, which indicates its stability under static loads. The second option, dynamic analysis, calculates how much a slope might move during an earthquake as the behavior of soil can be complex and non-linear, choosing the right material model is crucial for accurate simulations.[35]

The Hardening Soil Model is a powerful tool for engineers, allowing them to analyze how soil behaves under different loading conditions. Unlike simpler models, it considers the realistic complexities of soil, including how it stiffens, weakens, and permanently deforms under stress. The model uses various parameters, such as initial stiffness, shear resistance, and responsiveness to compression (Poisson's ratio), to accurately reflect how soil reacts to loading forces. A key aspect of this model is its ability to simulate the initial stiffness of soil at low strain levels, which is crucial for precise analysis.[35]

For the paper B.J. Brinkgreve and E. Engin[36] conducted a study to assess the accuracy and reliability of commonly used empirical formulas for estimating model parameters of sandy soils. These formulas are crucial in geotechnical engineering for predicting soil behavior, such as stiffness and strength. The authors thoroughly reviewed existing empirical formulas, highlighting their strengths and limitations, and emphasized the need for rigorous validation. Through a series of laboratory and field tests on different types of sand, they obtained reference values for soil properties and compared them with values derived from the formulas. The results were analyzed, discussing factors influencing formula performance, such as soil type and stress conditions. The study provides valuable insights for engineers and researchers, helping them understand the accuracy and limitations of the empirical formulas and improving the reliability of geotechnical analyses involving sandy soils.

For the authors B.J. Brinkgreve and E. Engin[36] provide an overview of the underlying theories and assumptions of these formulas and discuss their strengths and limitations. They emphasize the need for rigorous validation to ensure the reliability and accuracy of these formulas across different scenarios. To achieve this, the authors conduct a series of laboratory and field tests on various types of sand. They measure and analyze key soil properties, such as particle size distribution, density, and shear strength, to obtain accurate reference values for the model parameters. These measured values are then compared with those derived from the empirical formulas, allowing the authors to evaluate their performance. Overall, this study contributes valuable insights to the field of geotechnical engineering, enabling engineers and researchers to make informed decisions about the use of empirical formulas in deriving model parameters for sands. This study's results hold promise for improving the confidence and precision of geotechnical analyses when dealing with sandy soils.[36]

In research conducted by A. Hamrouni, D. Dias, and B. Sbartai [37] are comprehensive investigation that was undertaken to analyze the stability and ground improvement of structures near tunnels using the finite element program PLAXIS. The primary objective was to assess the deformations induced by surface loads and tunnel lining, ensuring that they remained within acceptable limits. In cases where the deformation values exceeded the acceptable thresholds, various ground improvement techniques were implemented to mitigate the issue. Through these efforts, the study successfully achieved the minimum deformation values by employing suitable ground improvement methods.

According to PLAXIS 2D Material Model Manuals [38] the HSM is well-suited for capturing the non-linear and inelastic behavior of soils, making it effective for simulating both soft and stiff soils under various loading conditions. HSSMALL builds upon this by incorporating the important factor of small-strain stiffness, which is critical for accurate dynamic analysis [39].

CHAPTER 3

METHODOLOGY AND MATERIALS

3.1 Methodology of The Study

Firstly, the data of the slope that is taken into account as geological and geotechnical should be gathered; it entails aspects of soils, geometry of the slope, groundwater, and earthquake. Detailed data is obtained either through site investigation activities like drilling, sampling, or Laboratory testing, and all those are collected by the Ministry of Highway in Turkey [40].

Using the collected data, a finite element model is formulated in PLAXIS 2D after the data has been gathered. The model is the slope geometry including the layers of soil and the condition at the boundary. Accordingly, the suitable material parameters of the soil layers are defined by the gathered data regarding the layers for shear strength, stiffness and the damping coefficients. The other components in the model are the seismic loading parameters within the established model, after which a seismic analysis using the finite element techniques is carried out. This involves dividing the slope into a mesh of interconnected finite or medium elements, each representing a portion of the slope. The equations of motion are solved numerically to obtain the dynamic response of the slope under seismic loading. Regarding the complex structure of the soil-structure interaction, several parameters are taken into account including stress redistribution and possible failure modes. To confirm the essence of the numerical model, the shaking table test which is generally a large-scale experiment is conducted[41].

From the analysis carried out, useful information on the seismic stability of the cut slope is obtained. They can pinpoint out the most sensitive areas that may contain soil to be excavated, determine the safety of slope and also determine the possibility of displacement of the slope or deformation thereof. According to the analysis results, it is possible to formulate the relevant measures to strengthen the stability and safety of the cut slope in the seismic condition.

3.1.1 Introducing Plaxis 2d with a Finite Element Method

Seismic loads affect soils in Geotechnical Engineering and there is substantial research into ponds and how they further respond to the effects of an earthquake. Thus, theoretical and analytical methods, experimentation, statistical and numerical methods have all been used in scientific research in this field. For the last 15 years, various researches using finite element method have been done for analyzing the behavior of dams and slope stability for related structures for seismic loads. By identifying previous works and analyzing their findings, studying the chronology of scientific works in the matter contributes to understanding the progress and development in time-dependent approach of ponds and seismic loads [42].

A two-dimensional finite element simulation was constructed leveraging the PLAXIS 2D software package [43].The specifics of the model utilized for the dynamic analysis are outlined below: The geometric boundaries of the model were positioned at a substantial distance from the area of primary interest, in order to minimize the direct influence of the boundary conditions. Horizontal constraints were imposed along the vertical boundaries, while the bottom boundary of the model was subjected to complete fixity, restricting both horizontal and vertical movements. To emulate the dynamic loading scenario, a predefined displacement was applied at the bottom boundary of the model. Furthermore, standard earthquake boundary conditions were defined on the right and left sides of the model geometry, serving to mitigate the reflection of seismic waves on the model boundaries and prevent associated perturbations[43].

As mentioned previously, Plaxis offers a wide selection of soil constitutive models with varying levels of complexity, ensuring versatility and adaptability in addressing different soil conditions. Within the Plaxis software, users have access to several models including the Mohr-Coulomb model, the Hoek-Brown model, the Hardening Soil model, the Hardening Soil Model with Small-Strain Stiffness, and others notably, among the models above[44]. The Hardening Soil model with Small-Strain Stiffness stands out as the sole one applicable to the soil conditions studied in this thesis.

3.1.2 HS Small Model

The Hardening Soil (HS) model proposed another way of modeling the stiffness of the soil during cyclic loading and unloading. It prescribes an attitude of the ground that is entirely fully deformable within a very small stress range. For instance, the HS Small proposed to overcome such problems concerning high tensile stiffness in the low-rise construction. As it is seen, there are the same set of parameters are involved in both the models, however, the HS Small model incorporates additional parameters to solve this particular scenario. Other parameters consist of the initial or very small Shear stress slip modulus (G0) and second Shear modulus (Gs) which is indicative of 70 percent reduction of G0. Moreover, this model is used in the HS Small model and includes the γ0.7 parameters, stress unit deformation value is indicated. In combination, these parameters give the specific calibration of the HS Small model; the problem of high hardness under tension was solved [34].

It is important that in numerical analysis soils are well described to define stratification the behavior and enter the right parameters into body models. In performing deformation analysis, it is crucial to understand fully the behavior of the soil in each range and the parameter that dictates the range. Soils like clay, silt, sand, gravel, and rocks have their static and dynamic small strain modulus in drained and undrained state, Stiffness of soil decreases with the increase in the strain. As for the stiffness decreases curves, they have the specific S-shape as it is seen in the figure 3.1, depicted on the logarithmic scale[34].

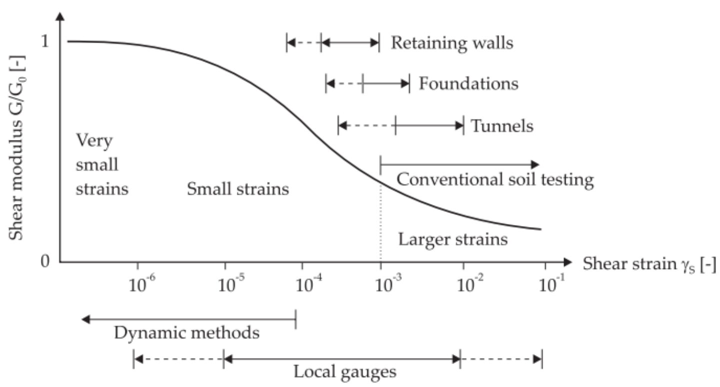

Figure 3.1 Soil hardness Characteristic stiffness-strain behavior curve according to PLAXIS 2D [34]

The stress dependency is expressed by the following formula; first dynamic sliding modulus (Go) is calculated with equation 3.1 based on the Theory of Elasticity: Kempfert, H. G., & Gebreselassie, B.,[45] for Constitutive Soil Models and Soil Parameters

$$G_o=G_0^{ref}\left(\frac{c\cos\varphi-\sigma'_3\sin\varphi}{c\cos\varphi+P^{ref}\sin\varphi}\right)^m \quad \textbf{(3.1)}$$

For PLAXIS 2D Material Models Manual power “m” represents the stress dependency of the soil and it depends type of soil but it’s range in between 0.5and 1 According to Kempfert and Gebreselassie's [45] on soft rocks and weak rocks: for the soft rocks and cemented or structured soil materials, obviously if the ‘m’ exponent which is in the G0 formula has to expect for the common soft rock types reaching from mudstone, siltstone, clay stone or even the highly weathered shale, it have to expect the ‘m’ exponent that is in the G0 formula range from 0 to 0. 5 to 0. 7, the value of ‘m’ will be different for different geotechnical conditions and state of cementation/weathering, as a function of the soft rock material is analyzed for[45].

In equations; p^{ref} reference stress ($p^{ref} = 100$ kPa) ve K_0^{nc} formula as the normal consolidation coefficient and is calculated according to YASUHARA [43]at which formula:

$$K_o^{nc}=1-\sin\varphi \quad \textbf{(3.2)}$$

Where Go is calculated by this equation for the ratio of unit weight with gravity with shear wave velocity:

$$G_o=\frac{\gamma}{g}.V_s^2 \quad \textbf{(3.3)}$$

After getting G0, we calculated the shear modulus at very small stresses recursive loading in ref account by the equation 3.1 and for calculating the initial modulus of elasticity (Eo) in reference point since νur, which is the Poisson's ratio for discharge, is accepted as a constant, in Equation 3.3 It is calculated as shown.[46]

$$G_o^{ref}=\frac{E_o^{ref}}{2\times(1+v_{ur})} \quad \textbf{(3.4)}$$

In the context of the current model used in the Plaxis 2D software, it is common to have Poisson's ratio equaling to 0. 2 for seismic conditions. When estimating loading and unloading scarios, it reasonable to mention that the unloading-reloading modulus (Eur) is less by 10-15% compared with the initial modulus (E0). In cases where the experimental data is not available at extremely small strain levels, an approximation to E0 can be given by empirical formula of Alpan (1970). This relation, depicted in figure 3.2, offers the possibility of predicting Ed, defined as the dynamic modulus for application to layered media in movement, starting from Es, the so-called static modulus. In the particular case of the HS-Small Strain model, the tool designated by Es refers to the unloading-reloading modulus Eur measured at the engineering strain of the order (10^-3) and the tool designated E0 is equal to the dynamic modulus Ed. This approach is useful in explaining why there is a decrease in the coefficient of elasticity during cyclic loading and unloading[47]

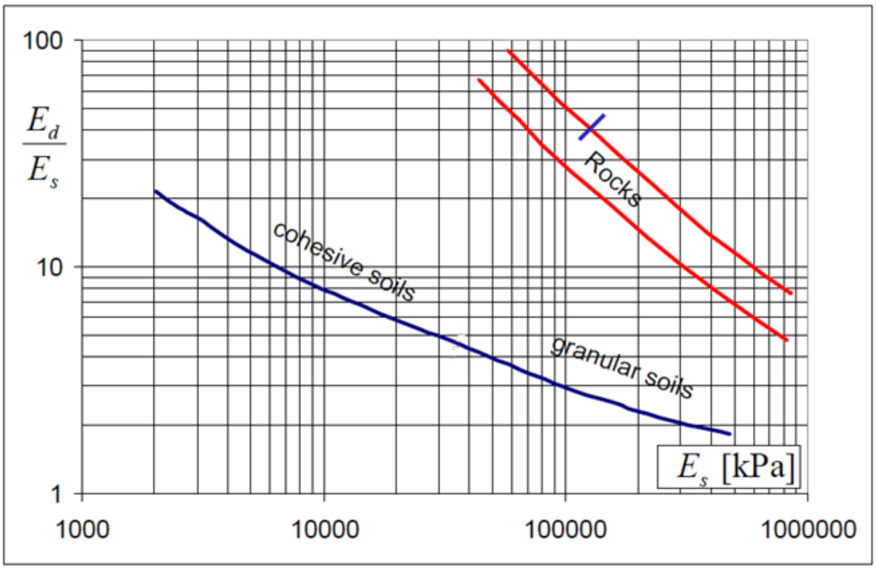

Figure 3.2 Approximative relation between "static" soil stiffness (here Es = Eur) and "dynamic" modulus Ed corresponding to E0 proposed by Alpan (1970) [47]

Therefore, the Eur,ref can be set equal to the "static" modulus Es, which can be estimated by dividing the Ed (or E0) value by the Ed/Es ratio from the Alpan (1970) figure 3.2 and the relationship between E0 and E50 is provided in this equation for

E50 as its shown in equation 3.5 but The Eur/E50 value is decided. Plaxis recommends 3.0 as a default [38].

$$E_{50}=\frac{E_o}{\approx 3.0\text{-}3.5}=\frac{E_o}{3.25} \qquad \textbf{3.5)}$$

In addition to all the parameters determined for the Hardening Soil model, this model also takes into account the increasing stiffness of the soil at small unit deformation stiffness [14]. In the model, HS-small strains calculated as the initial strain history modulus, the small strain shear modulus, and the strain level when the shear modulus decreases by 70% compared to the small strain shear modulus [48].

$$\gamma_{0.7}\approx\frac{1}{9G_o}\left[2c'(1+\cos 2\varphi')-\delta_1'(1+K_o)\sin 2\varphi'\right] \qquad \textbf{(3.6)}$$

Based on the information provided in the Harding and Drnevich [49] research referenced, the typical range for the γ0.7 parameter (the strain level at which the shear modulus decreases by 70% from its small-strain value G0) for mudstone, which is a type of cemented or structured soil/soft rock material and would be between this range 0.00001% to 0.0005%. This is on the lower end of the typical range for soils and rocks, reflecting the higher small-strain stiffness and more brittle behavior of mudstone compared to cohesionless soils or softer clays.

3.2 Project Material and Procedure

3.2.1 Material of The Model

The geotechnical investigation along the Palu highway section at kilometer 13+580 provides valuable insights into the subsurface conditions at the DSK-13+000 location. This analysis integrates the provided information to present a comprehensive understanding of the soil and rock formations encountered in this project area. Beyond the 1.5-meter depth, the soil conditions transition to a rock-dominant formation. From 0-0.3 it’s topsoil 0.30 meters to 10.50 meters, the subsurface is characterized by light brown-beige colored, very weak, weakly durable, very weathered, moderately weathered, fragmented mudstone and spilite. The SPT test results from 1.5 meters to the maximum depth of 20.00 meters consistently show high SPT-N values, ranging from 50/8 to 50/14, indicating the presence of very weak to weak, moderately to highly weathered, and fragmented mudstone and spilite. The soil/rock behavior for this deeper section is classified as Rock (R), before 1.5m it's fill soil on a top and confirming the rock-dominant nature of the subsurface after 1.5-meter depth[9] as it's shown in the figure 3.3 below:

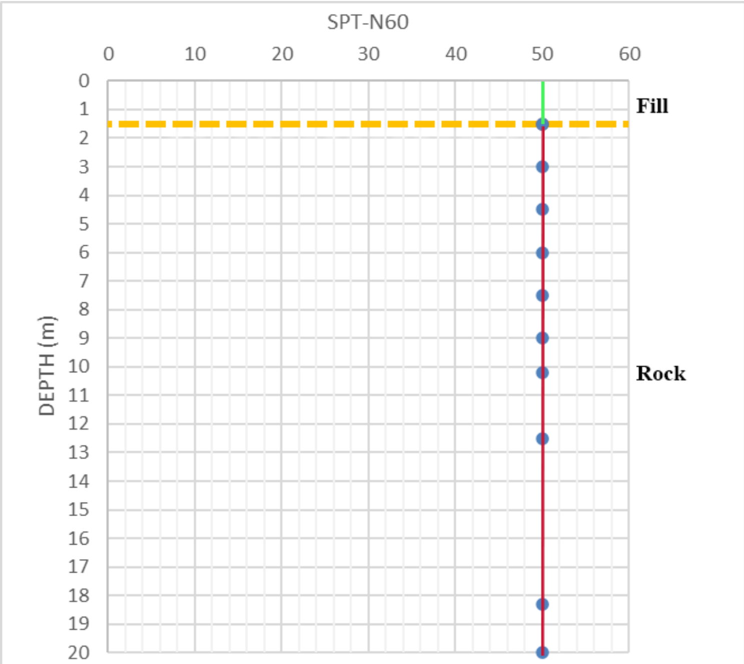

Figure 3.3 Distributions of SPT-N values until 20 m depth

The geological cross-section for Km 13+580 is presented in Figure 3.4:

Figure 3.4 A view of the mudstones of the Yüksekova complex[9]

These examinations were conducted in the earthquake zone of the Palu-Beyhan-Gökdere line which is sensitive to earthquakes in the Eastern Anatolia Region. Based on the scenario which shows that the water table is assumed to be very deep or the soils are considered as dry, the correct drainage state to apply with the Hardening Soil with Small Strain (HS-Small) model in PLAXIS 2D is the drained condition, as the variation of pore water pressure in the soil is insignificant and thus it can be considered to be equal to the atmospheric pressure. This means that no generation and dissipation of excess pore water pressures arise during the time of dynamic loading. The behaviour of the soil is again solely by the stress-strain relation of the effective stress without any interaction of the change in pore water pressure [47].

Soil index parameters and depths were taken from the ground survey published by general Directorate of Highways[9] It's three layers with different value in parameters and depths as shown in table 3.1 but the shear wave velocity is referenced by presumptive or safe bearing capacities obtained from seismic velocities in mudstone (çamurtaşı)with depths [50]. and stiffness parameters required for advanced soil models were calculated with the help of equations 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6 given above. Shear modulus parameters were obtained from the shear wave velocity Vs in the soil and by using by the above equations The soil properties for a representative rock layer, and it's 3 layer each layer have different properties and Hardening soil with small strain (HS_ ss) model for soil parameters outlined in Table 3.2:

Table 3.1 Layers of soil based on analysis of 13+580 critical

Color	Material Name	Depth (m)		Shear wave velocity Vs (m/s)
	Mudstone D=0	0.3	0.3	320
	MudstoneD=0.7	10.5	10.5	540
	Mudstone D=0	20	20	760

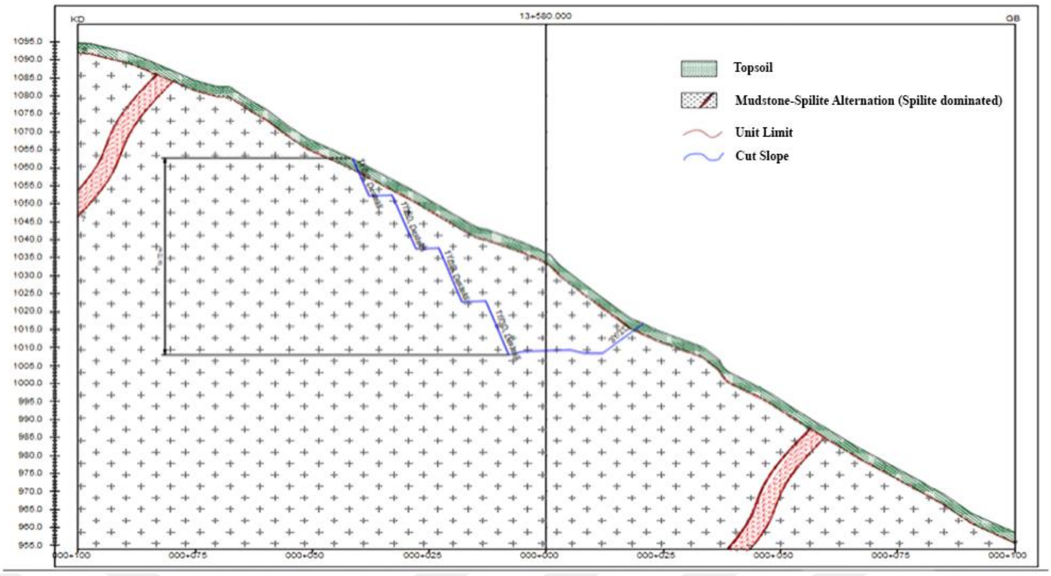

Figure 3.5 Km: 13+580 cross-section, max: 54.7 m

Table 3.2 HS ss model soil parameters

Parameter	**Unit**	**Mudstone D=0**	**Mudstone (Cut) D=0.7**	**Mudstone D=0**
$\gamma_{unsat}/\gamma_{sat}$	[kN/m^3]	22/25	22/25	22/25
E_{50}^{ref}	[kPa]	161000	392000	661000
E_{oed}^{ref}	[kPa]	161000	392000	661000
E_{ur}^{ref}	[[kPa]	484000	1177000	1984000
m	[–]	0.55	0.55	0.55
υ_{ur}	[–]	0 .2	0.2	0.2
c_{ref}	[kPa]	106	61	199
ϕ **ref**	[º]	22	14	29
ψ	[º]	0	0	0
$\gamma_{0.7}$	[–]	1.29.10^{-5}	5.11.10^{-5}	5.175.10^{-5}
G_0^{ref}	[kPa]	310000	7736000	1240000

The calibration of the Rayleigh damping coefficients, which are used to capture the damping behavior of the soil model at different strain levels. To determine the appropriate frequencies, the author Oblak, A [27] proposed a specific approach. The first frequency (f) is set equal to the fundamental frequency of the entire soil layer, which corresponds to the frequency at which the most significant amplification can be expected. The second frequency is set as the closest odd number given by the ratio of the fundamental frequency of the input signal at the bedrock and the fundamental frequency of the whole soil layer [51].

$$F=\frac{V_s}{4H} \tag{3.7}$$

The equation (3.7) gives the relationship between the frequency (f), shear wave velocity (Vs), and depth of the soil layer (H) for the first target frequency, which is set to the fundamental frequency of the whole soil layer. This procedure allows for the appropriate selection of the target damping ratios and frequencies, considering the fundamental characteristics of the soil deposit and the input signal.

Sampling this into the average shear wave velocity of 568m/s and the soil deposit thickness of 30. 8m, the fundamental frequency of the soil deposit is calculated to be 4.61 Hz. Additionally, the Fourier spectrum of the input signal at the bedrock indicates a fundamental frequency of 7.03 Hz. Dividing this bedrock fundamental frequency by the soil layer's fundamental frequency of 4.61 Hz results in a ratio of 1.53 Hz. Based on this, the frequency of Target 2 is set to 3 Hz, as it is the closest odd number to the ratio, while the damping ratios (ξ) is assumed 1-5%. [51]. For the damping ratios and the target frequencies as it's shown on figure 3.5:

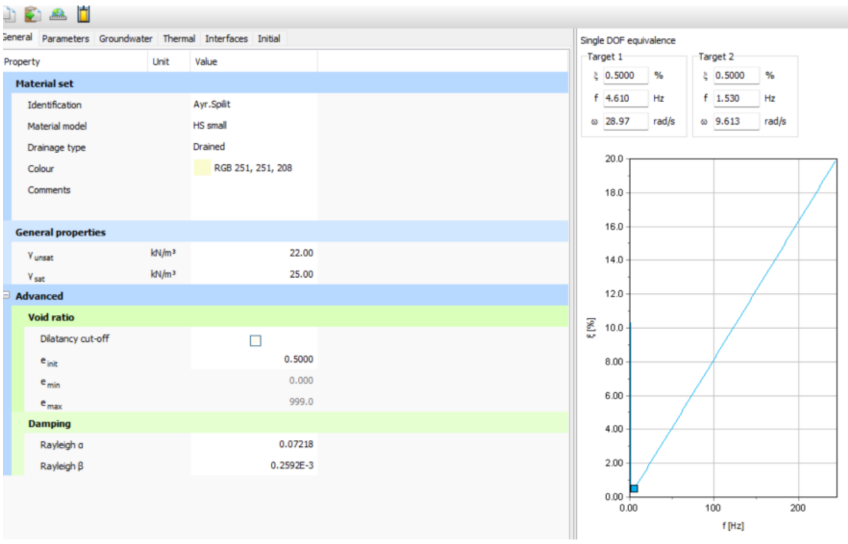

Figure 3.6 Rayleigh damping coefficients

3.2.2 Procedure Analysis for The Model

Firstly, every piece of work to be analyzed on a new project is constructed in two-dimensional software: A geometric model of a three-dimensional problem dimensional representation is made up of two aspects of the full model. Contains Pattern points, lines, and clusters. A geometry model is defined as representation of the ground in the form of subdivision of subsoil into layers, objects of structures, construction phases, and loads. Regarding volume sets, ground layers, and other additional sets of volumes that you, the user, may create, you can select between using 6-node or 15-node triangles for 15-knot triangular element total of 12 stress points and 6-node triangle as seen in Figure 3.7.a. stress point also indicates that the element of the chair has three stress points as shown in the figure 3.7.b. Thus, one can define prior to the test, the locations for the stretch marks as well as the stress points for constructing a stress–strain diagram. [46].

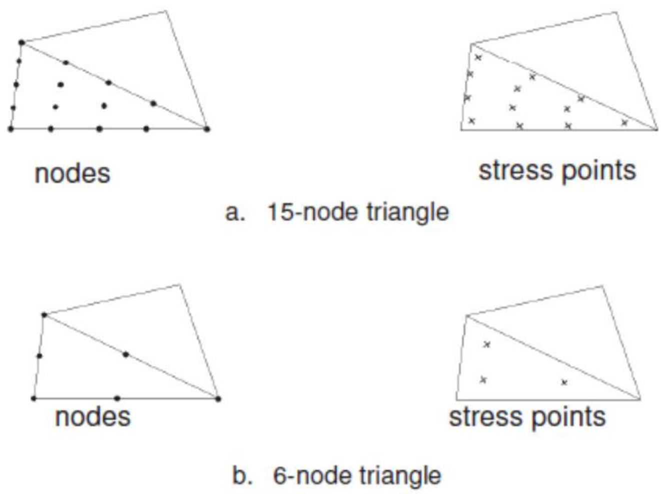

Figure 3.7 Location of nodes and stress areas in soil elements for (a) and (b)[52]

Selecting Plane strain or Axisymmetric results in a two-dimensional finite element model along with two translational degrees of freedom per node This is because, when you select this type of model, the x-axis is the radius of the axisymmetric element and the y axis is the axis of rotation as is depicted in Figure 3.8. This model type is suggested to be used in single source vibration conditions this is because waves behave in an axisymmetric model in the same manner to that of the solid three-dimensional model. This is because of the behavior exhibited by the firm. To better model the damping of waves as they are carried away from the source of the vibration, the axial stress model should be used [13].

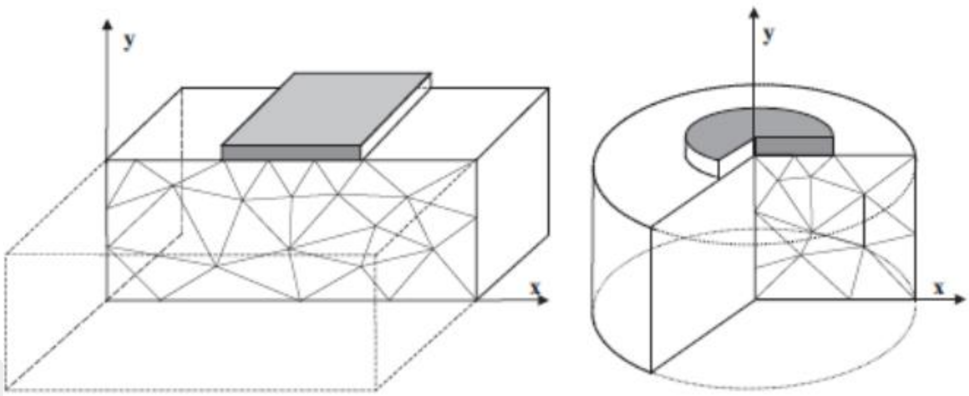

Figure 3.8 Plain strain (left) and axisymmetrical problem (right)

A planar strain model (Figure3.4. left) has a smooth cross-section and refers to the lengths lying perpendicular to the cross-section used in stress state and loading diagrams (z-direction). Forces in the Z direction is assumed to be zero but moderate normal stresses in the Z direction are not fully taken into data base, while in an axisymmetric model (Figure 3.4. right), circular construction has a single radial section on loading around the axis. As for the deformation and stress states they are considered to be the same in all radial directions [51].

After the creation of the geometric model the material properties of the soil and of the structural members, together with the dynamic loads acting on the model and restrained displacements, must be introduced. The choice of most of the soil parameters is done through laboratory tests that are carried for geotechnical characteristics of a soil such as cohesion, angle of friction, poison ratio etc. that are required for the small strain computed by using the formulas that are explained above. The optimization process is regarded as an iterative process in which various model parameters are changed to enhance the model fitness to the laboratory test results while maintaining similarity between the numerical simulations and the actual results for the same constitutive model [42].

Step1: Definition of soil stratigraphy:

Firstly, the Plaxis Input program is used to create a conceptual model that defines the real state of the soils and the structures being analyzed. This involves defining ‘soil stratigraphy’ and ‘water table elevations’ through the development of ‘boreholes’ Boreholes are imaginary points within the drawing area where the position of the soil layers and hence the water level is assumed. What is very crucial to note in this series of tests in that when only one borehole is used, the nature of the employed borehole forms the basis of the model’s soil stratigraphy [48].

Step 2: Definition of Structural Elements

Initially, the soils within the system were identified by surveys, and collection of soil samples for specifying the layers of soils present in the subsurface. After determining the three primary layers of the soil, the geometric models intended for the structural components of the utilized system, such as the soil polygons, plates, lines of displacements, and other structures, were described. Each of the types of structure has specific requirements for parameters and, therefore, data sets, so the Structures mode of the program was used, which made it possible to set and adjust the elements of the structures to the needs of the system. The slope on the other hand was revealed to have three layers in cross-sectional view and this geometry of the slope was successfully input to the Plaxis 2D program with the aim of ascertaining structural response and stability and is graphically depicted in the figure below known as Figure 3.9[48].

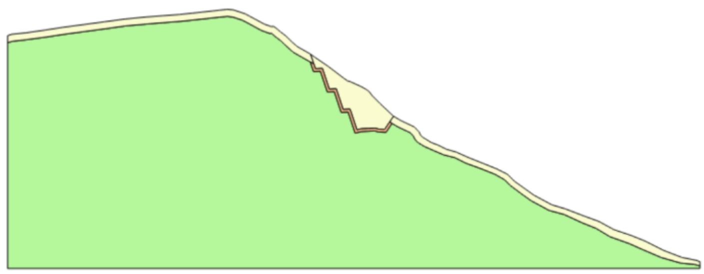

Figure 3.9 Slope cross-section in Plaxis 2d

The identification of material properties and model parameters of the ‘Hardening Soil model with Small-Strain Stiffness’ is significant when trying to model the behavior of soils using Plaxis 2D. To achieve this a holistic approach that comprises laboratory testing and numerical optimization technique using Plaxis software is used. Some other geotechnical properties of the soil are determined in the laboratory to get the cohesion of the soil, angle of friction, poison ratio, and others required for the computation of the small strain by applying certain formulas.

The optimization process is localized on changing the model parameters in a cyclic manner so that the produced numerical simulations could practically model the outcome of the laboratory test. This iterative calibration process allows for the determination of the most appropriate values for the small-strain stiffness.

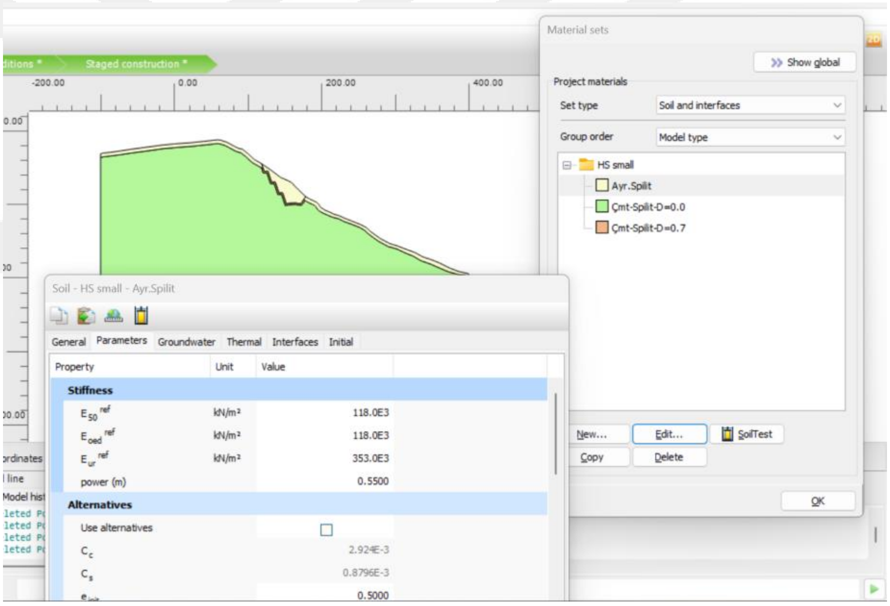

Figure 3.10 Material set up in Plaxis 2d

Step 3: Mesh Generation

With the completion of defining the soil layers and structural element geometries, the Mesh mode in the PLAXIS 2D program was then moved to to generate an automatic mesh generation procedure. During this process, the geometry was split into volume elements and compatible structure elements, offering options of the mesh to a medium level of detail. Before performing the calculations, Gaussian stress points was selected to save calculation data for subsequent analysis. This data would be instrumental in generating relationships between various parameters, such as stress and strain or load and displacement. During the calculation phase, data from each step was saved for these selected stress points. However, even if no points were initially chosen, these important relationships could still be established by specifying the maximum number of step data points to be saved before the calculations commenced [27].

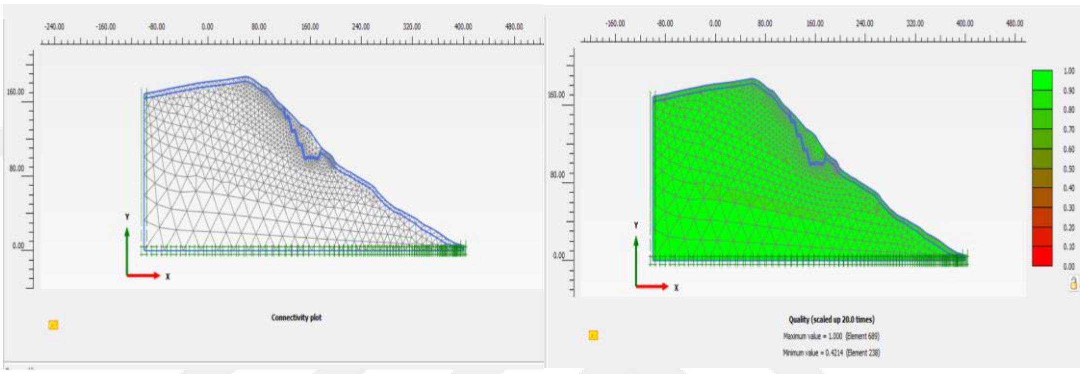

Figure 3.11 Mesh quality for a section in Plaxis 2d

Step 4: Flow condition

In groundwater calculations, the interface elements are handled in a specialized manner. These interface elements possess an active setting for the deformation calculation, which accounts for the soil-structure interaction. Additionally, they have an independent setting for the flow calculation. When the interface elements are active in flow conditions, there is a complete coupling of the pore pressure degrees of freedom. Furthermore, the permeability of the interface is incorporated into the calculations.

Step 5: Staged Construction

Following the meshing process, the calculation stages was then defined, serving various purposes but commonly used to simulate the construction stages. For instance, in the Slope model, calculation stages were set up to represent the initial geometry configuration and the initial stress state, using the Gravity loading option for the finite element calculation on the non-horizontal layers. Another stage was defined for the stability in the plastic phase, where the Pore pressure calculation type was set to the Phreatic option and the Temperature option was ignored for the Thermal calculation type. This was followed by a phase to calculate or observe the factor of safety in a static stage before applying any dynamic loads. Finally, the last phase consisted of the dynamic analysis in the time domain. Each of these calculation stages was critical in accurately modeling the behavior of the system through the various construction and loading conditions.

3.2.2.1 Boundary Conditions for Dynamic Analysis

In dynamic studies, specific types of boundaries other than normal borders should be utilized to represent real-world soil behavior. One of these is the needed borders on the model's right and left sides. To simulate real-life wave propagation, lateral edges are defined as "free field" boundaries. This boundary condition is designed to mimic the propagation of waves as if the model's sides were of infinite extent. In other words, when wave reflections reach the model's borders, they are either attenuated or completely suppressed. These dashpot systems are used to equalize the normal and shear forces produced by the model's mesh elements. Free field boundaries are commonly the preferred choice for earthquake analyses, where the primary input data consists of acceleration-time histories. This particular boundary was documented in the PLAXIS 2D Manual and has been utilized by numerous researchers. [13].

The other type of boundary required for the dynamic analyses is called a ―Complaint base, the compliant base is typically utilized with a line-prescribed displacement. The line prescribed displacement allows the user to specify the input motion as a displacement, velocity, or acceleration history. Internally, the prescribed displacement will be translated into a load history, allowing this boundary condition to apply input motion while also absorbing incoming waves. When employing the free field and/or compliant base boundary conditions, we must generate so-called node pairs along the model's boundary (this requires manually creating an interface along the boundary). A viscous damper is formed between two nodes in a node pair, allowing input and/or free-field motion to be transferred while also absorbing incoming waves [13].

3.2.2.2 Selecting Ground Motions for Peer Source Data

According to Turkish earthquake engineering regulations selecting ground motions for analysis should prioritize historical earthquake data that aligns with the seismic characteristics of the building site. This ensures the analysis considers the most relevant earthquake threats for that specific location. However, if there's a scarcity of suitable historical records, the code permits the use of modified ground motions. Additionally, the code specifies a minimum requirement of eleven ground motions to conduct a response history analysis, which provides a robust assessment of a structure's seismic performance, for that selection of ground motions, a target response spectrum was established for the exact region based on the seismic hazard analysis and the relevant design code requirements[53]. In the Plau region earthquake ground level (Deprem Yer Hareketi Düzeyi) was classified as DD2, and the local ground class (Yerel Zemin Sınıfı) was determined to be ZC, in accordance with the applicable seismic design standards we took the target response spectrum in the Turkish Seismic Hazard map, and selected ground motions to match the target spectrum.

The selection of appropriate ground motions is a critical step in the seismic analysis and assessment of geotechnical structures, such as slopes. For this study, a subset of the Pacific Earthquake Engineering Research (PEER) Center's NGA-West2 (https://ngawest2.berkeley.edu/) ground motion database was adopted to calculate the seismic slope displacements based on a fully coupled sliding mass analysis.

After signing in, the application will guide you to upload a user-defined target spectrum, allowing you to proceed with the ground motion selection process as se Figure 3.12 Following the website instructions, we have uploaded a CSV file containing the compatible spectrum.

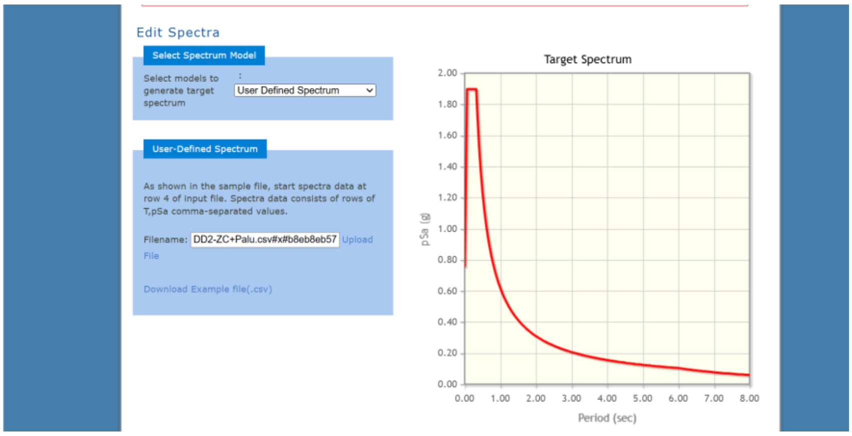

Figure 3.12 Compatible spectrum successfully loaded to the PEER NGA-West 2 application

In earthquake engineering, particularly when selecting ground motions for analysis, various fault mechanisms like normal faults and strike-slip faults play a crucial role. When it comes to building ground motion databases in Turkey, a land prone to destructive earthquakes, strike-slip faults take center stage due to their prevalence. However, it's important to clarify that movement along a strike-slip fault occurs horizontally, not vertically. Imagine two blocks of land shearing past each other sideways, like giant slabs of butter along a countertop. This horizontal displacement is the hallmark of strike-slip faults, and it's the primary driver of the powerful earthquakes they trigger[54].

Another key filter applied during database construction is the moment magnitude of the earthquake. Unlike other magnitude scales, moment magnitude offers an objective measure of the total seismic energy released during an earthquake. To ensure the database focuses on potentially impactful events, only ground motions in between 5 and 8 and the second filter was ground motions are chosen from events with an RJB is the selection criterion considers the Joyner-Boore distance in which ranges 0 km and 50 km. This range helps exclude ground motions with extremely close proximity to the fault, which can exhibit unique and potentially misleading characteristics due to near-fault effects with the Vs30 (m/s), input (360, 760) to consider Site Class ZC based on Turkish building code were considered.

Earthquake records according to simple scaling criteria the initial scaling factor criterion it in between 0.5-4.0 for the PEER database where it is selected is 0.5-4.0.

To make the selected records fully compatible with the design spectrum When using SeismoMatch 2023 software[55]; Design spectrum of both 11 recording averages between 0.1-4.0s, Full compliance with was sought and the speed-time and displacement-time graphs of the relevant records were reduced to 0 at the end of the recording. (Hancock et al.,) [56]in software as a full correspondence algorithm the method suggested by was chosen in Figure 3.13:`

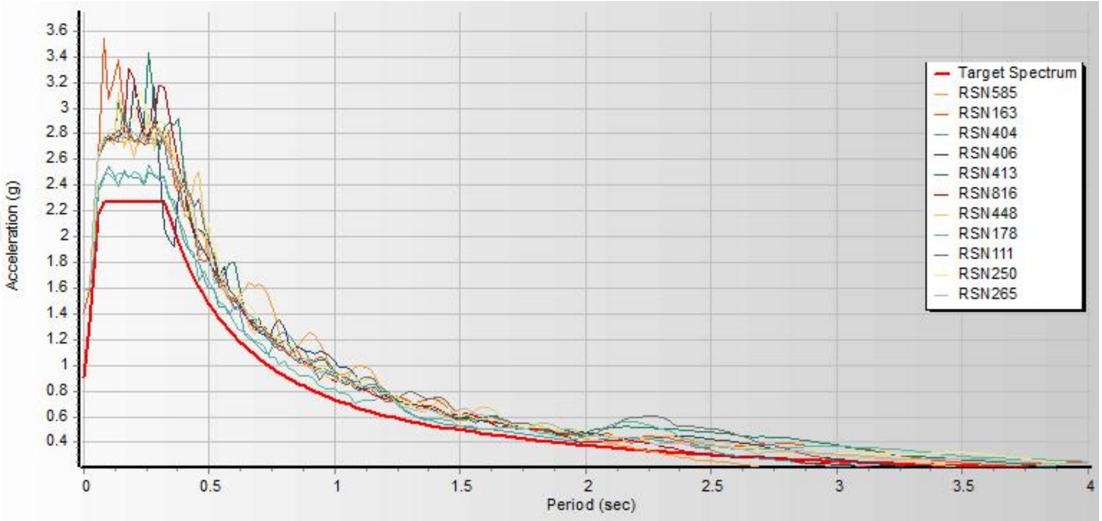

Figure 3.13 DD-2 Spectra of records scaled according to earthquake level and ZC type ground class to the target spectrum

Table 3.3 A summary of the key ground motion

Peer ID	Earthquake Name	Year	Mw	Rjb(km)	Rrup(km)	Vs30(m/sec)
4130	Parkfield-02	2004	6	1.59	2.85	383.9
585	Baja/California	1987	5.5	3.43	4.46	471.53
265	Victoria/Mexico	1980	6.33	13.8	14.37	471.53
250	Mammoth/Lakes	1980	5.94	9.65	16.03	537.16
8166	Duzce_ Turkey	1999	7.14	3.58	3.58	428
448	Morgan Hill		6.19	3.22	3.26	488.77
4065	Chi-Chi/Taiwan	1999	6	1.37	2.85	383.9
4040	Bam_ Iran	2003	5.9	0.05	1.7	487.4
1111	Kobe_ Japan	1999	6.9	3.43	4.46	609
1633	Manjil_ Iran	1990	7.37	12.55	12.55	723.95
1787	Hector Mine	1999	7.13	10.35	11.66	726

Before scaling the motions, we checked the filtration of motions by using seismosignal program[57] to filter out unwanted low and high frequency components to have a ground motion compatible with the Turkish Code, after these filtering process, we scaled the ground motions to match the target response spectra using the seismomatch software for the Palu region, Finally, the scaled ground motions, representing the anticipated seismic loading, were utilized in the nonlinear time history analysis of the model. The process that was used for seismosignal program are baseline correction and bandpass filtering as it's show in figure 3.13 below:

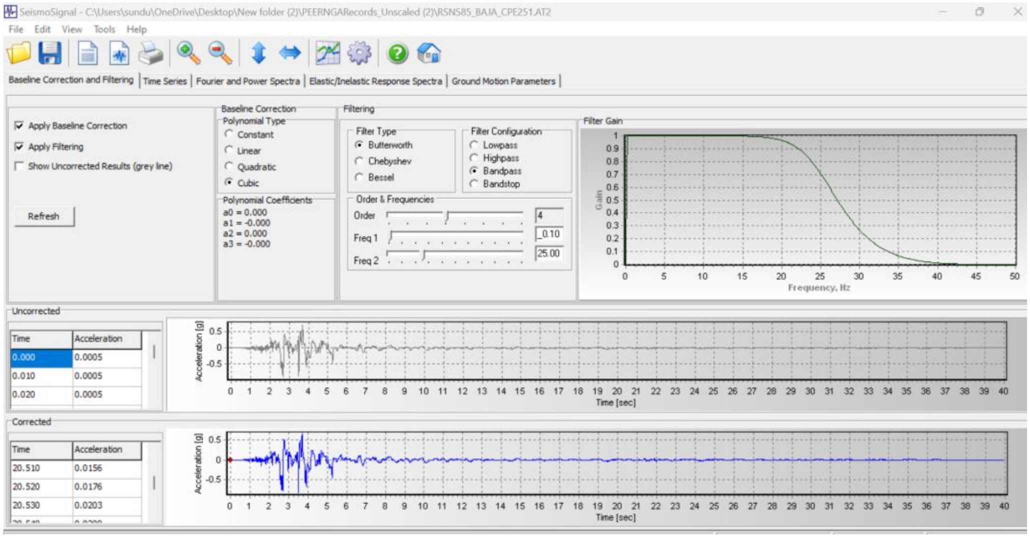

Figure 3.14 Ground motion selection and analysis tool interface[57]

A range of scaling factors were applied to each ground motion record, and the scaled time histories were then evaluated to identify the best match with the target response spectrum, to facilitate the scaling and matching process, the SeismoMatch software was utilized. SeismoMatch is a widely used tool that employs advanced algorithms to modify the ground motion time histories while preserving their essential characteristics, such as the frequency content and duration, The scaled time histories were iteratively adjusted using SeismoMatch until a satisfactory match was achieved between the scaled response spectrum and the target response spectrum[55] as it’s shown figure 3.15

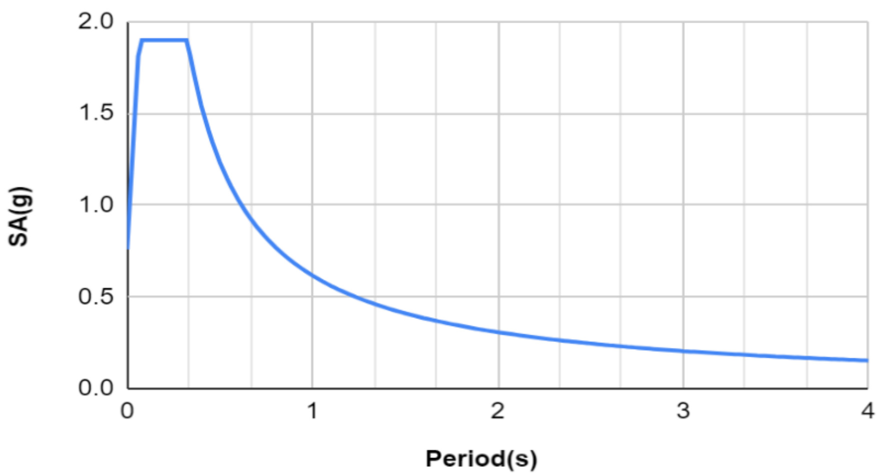

Figure 3.15 Target design spectrum of the region

The next step applied in scaling of ground motion is to determine scaling factors. To ensure the ground motions effectively represent the anticipated earthquake intensity. The code mandates that, after applying these adjustments, the combined response spectra (using the Square Root of the Sum of Squares - SRSS method) must exceed the code-specified elastic spectrum by at least 30%. This ensures the selected ground motions adequately challenge the structure during analysis[54]. One of the examples of scaled motion that used for the analysis is here in figure 3.16:

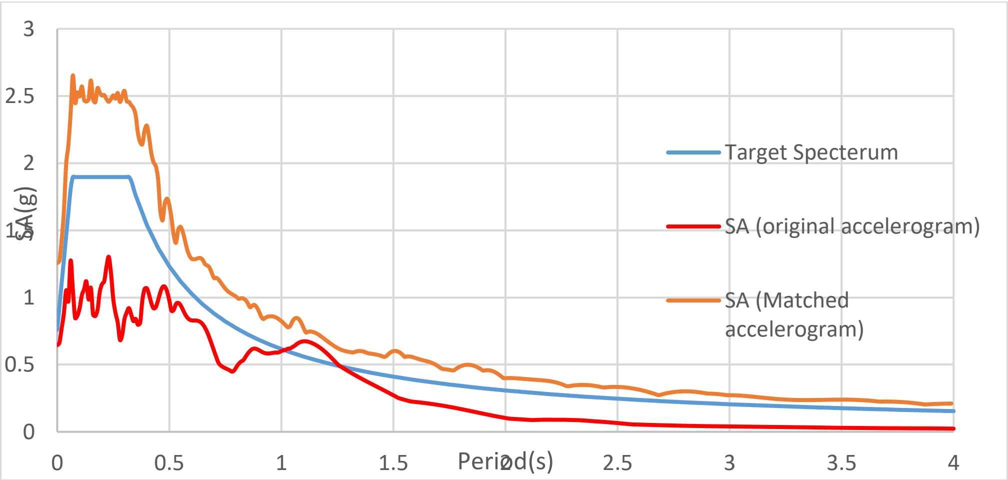

Figure 3.16 Example of a scaled ground motion for the region

By following the method outlined previously, scaling factors for horizontal ground motion are derived for each type of earthquake design from the available databases.

Once the geometry, materials, and mesh have been defined, and the prescribed motion inputs have been specified, the calculation phase can begin. The duration of this phase depends on the size and complexity of the model. To improve the accuracy of the dynamic analysis, it is important to choose a suitable time step. If the chosen time step is too large, the estimated values may be inaccurate and differ from the actual values. To address this, PLAXIS 2D performs key time step calculations to determine the optimal time step value. In other words, the software analyzes the problem and adjusts the time steps accordingly to ensure the wave propagation within an element's minimum dimension per time step. After these preparatory steps are completed, the analysis for the current stage is automatically started.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results and discussion obtained from the finite element analysis of cut slopes subjected to earthquake loading using PLAXIS 2D software. The analysis aims to provide insights into the behavior and stability of slopes when subjected to earthquake motions, emphasizing the influence of seismic loads on deformation patterns. Additionally, the chapter examines the regulatory framework provided by the other guidelines or regulations in which Seismic Code concerning acceptable deformations and stability criteria for slopes.

4.1 Finite Element Model Setup

PLAXIS 2D software was used for the analyses carried out with the finite element approach. The calculation section was created with the parameters and section geometry determined in Chapter 3. The parameters accepted in the calculations of soil layers are provided in detail. Analyses were performed under static and seismic loading conditions for the road cuts within the scope of the existing highway expansion. To examine slope stability in the 13+580 section, which is a critical zone, numerical analyses were conducted. This section, the highest in the study, underwent hardening soil analysis with small strain according to Plaxis's criteria. The slope had a height of 15 m, with a critical cut at 13+580 (hmax = 54.7 m). Once the model geometry was created, the initial result was the mesh quality, as shown in Figure 4.1:

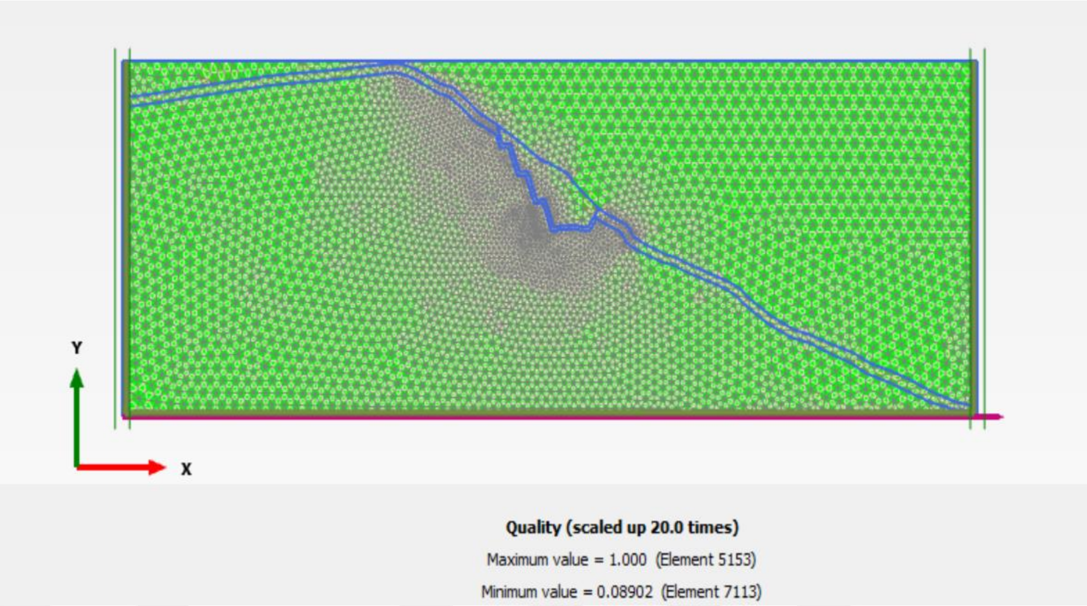

Figure 4.1 Result of geometry in mesh for finite element model**.**

4.2 Interpretation of the Results

4.2.1 Km 13+580 Section Analysis of Static Situation

The displacement contours obtained from the finite element analysis of the critical section (13+580) under static loading conditions, based on the terrain profiles, This section's slopes and hills are generally considered more susceptible to seismic activity and associated hazards like landslides or slope failures during earthquakes. The steeper upper portions near the slope crest are particularly prone to instability and potential sliding or collapse during seismic events. The transition zone between the steeper upper slope and the more gradual lower slope is often a critical area of concern [58].

The stability analysis results for the study area are as follows: Before the first berm, the left bevel (slope height 15m) was supported with a 1H/3V slope, and the right slope with a 3H/2V design. However, in the designed 3H/1V slope area, some deformations were identified through static deformation analysis. The safety factor (FS) for the static situation was calculated to be 1.65. The analysis used the cross-section of the cut in the Km:13+580 section, considering the parameters of the rock, especially in mudstone units encountered in drilling. The critical deformation area was identified through static deformation analysis.

The Turkish General Directorate of Highways, in the stability analysis of road slopes, accepts the factor of safety value of 1.5 and higher values as safe for static situations, while the values higher than 1.1 are considered safe for dynamic situations [59], In order to stay on the safe side in this study, values of 1.2 and higher were accepted as safe.

With a safety factor of 1.65, the Km:13+580 cross-section is considered to have good static stability and a low risk of failure under normal non-seismic conditions. This indicates the design and construction of that section are adequate from a slope stability perspective. A safety factor of 1.0 represents the bare minimum stability where the resisting and driving forces are balanced. Higher safety factors provide an additional margin of safety to account for uncertainties in soil properties, loading conditions, and analysis methods [60]. Safety factors greater than 1.5 are commonly used in geotechnical engineering as they strike a balance between overly conservative design, which can lead to higher costs, and an acceptable level of risk of failure.

The analysis results indicate a stability problem on the right slope. The analysis showed a horizontally developing deformation of 79.8mm, as seen in Figure 4.2. This indicates a significant deformation issue that needs to be addressed.

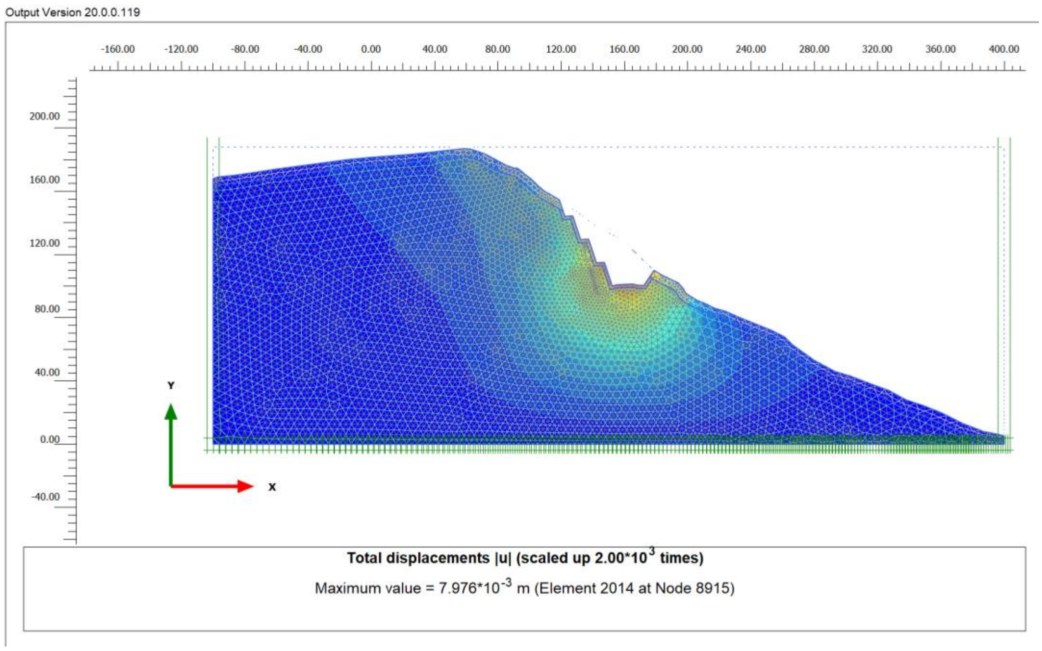

Figure 4.2 Km:13+580 cross-section static state deformation diagram

The safety number obtained from the analysis result in this case is 1.64. Considering the safety numbers criteria for cutting slopes, it is observed that it is safe since FS > 1.50, as shown in Figure 4.3:

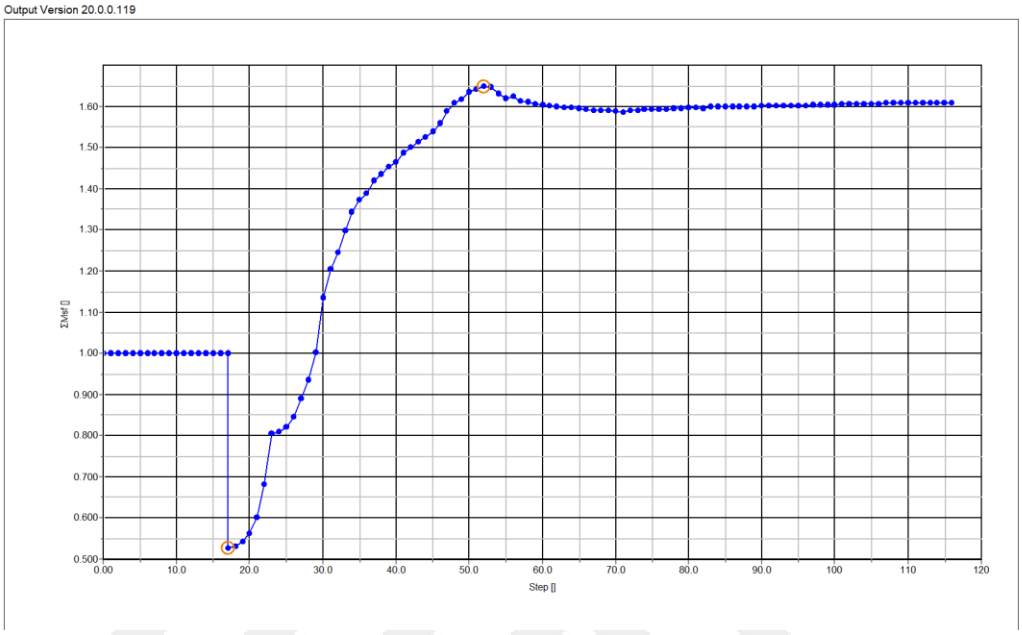

Figure 4.3 Km: 13+580 cross section safety number in static condition

4.3.2 Km:13+580 Section Analyses of Dynamic Situation

Pseudo static analysis:

In addition to the static stability analysis, the study also evaluated the slope's behaviour under earthquake loads. This dynamic analysis was conducted using finite element methods to simulate the slope's response to seismic ground motions.

The dynamic stability of the slope was evaluated using two different analysis approaches - the Pseudo static method and the Stress-Deformation method. The Pseudostatic analysis considers the effects of seismic forces on the slope stability, while the Stress-Deformation method provides a more comprehensive assessment of the slope's behaviour under dynamic loading conditions [60]. For the study area, a peak ground horizantal acceleration (Ao) value determined for the study area in the Turkey Earthquake Hazard Map prepared by AFAD [61] is 0.33g was considered, representing a significant seismic event. By incorporating this seismic coefficient into the analysis of the Km:13+580 cross-section, the engineers were able to assess the slope's performance under dynamic loading conditions.

Through the Pseudo static analysis, the critical slip surface and the corresponding safety factor were determined. This approach helps to quantify the slope's resistance to potential seismic-induced failures. According to the results of the analysis made in the earthquake situation, horizontal deformation of approximately 19 cm was observed, as shown in Figure 4.4:

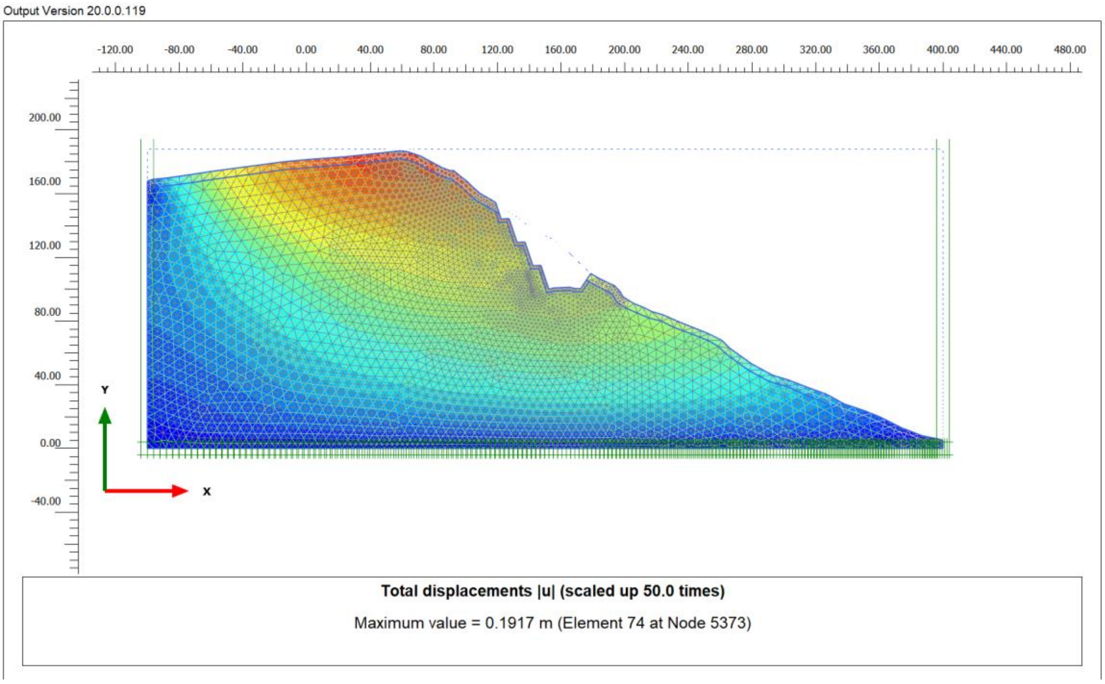

Figure 4.4 Km: 13+580 cross section Pseudo static state deformation diagram

According to established engineering practices, a safety factor greater than 1.10 is generally required for slopes under dynamic loading conditions. The fact that the calculated safety factor for the Km:13+580 cross-section was precisely FS = 1.10 indicates that the slope does not meet the recommended safety criteria for dynamic stability. This dynamic analysis, as shown in Figure 4.5, revealed that the calculated safety factor for the critical slip circle in the earthquake scenario was 1.10. in accordance with General Directorate of highway which is not accepteble [59]. This value represents the ratio of the slope's resistance to the driving forces that could lead to failure during a seismic event.

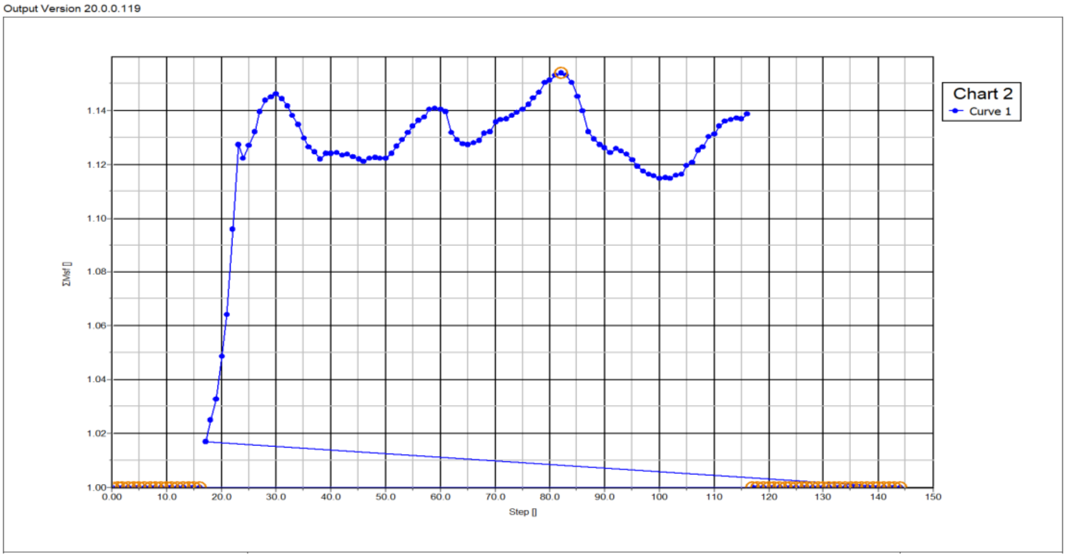

Figure 4.5 Km: 13+580 cross section safety number in dynamic state: FS = 1.1

Stress deformation analysis:

Additionally, the Stress-Deformation analysis was employed to further investigate the slope's response and deformation patterns under dynamic stresses. The combination of these two dynamic analysis methods provides a thorough evaluation of the slope's stability and its ability to withstand the anticipated seismic loads, which is crucial for ensuring the long-term safety and performance of the slope. To gain a deeper understanding of the slope's behavior under dynamic loading, we conducted a series of analyses using 11 different seismic ground motions sourced from the PEER (Pacific Earthquake Engineering Research Center) database[62]. This comprehensive approach allowed for a more robust assessment of the slope's performance, as the use of multiple seismic records helped to capture the variability and uncertainties associated with earthquake-induced ground shaking. The analysis of the slope configurations under the 11 PEER seismic motions provides valuable insights into the slope's potential behavior during an earthquake event. The deformation patterns, characterized by significant horizontal displacements and vertical settlements, highlight the need for comprehensive design considerations and the implementation of appropriate stabilization measures to mitigate the risks associated with seismic events.

This analysis investigated the dynamic response of the component under an earthquake-induced ground motion load. The seismic load was applied as a time-varying ground acceleration input on the bottom right surface of the component, while the remaining surfaces were modelled with a free field boundary condition. The free field boundary allows for the propagation of stress waves through the component, rather than being constrained at the base. This simulates the component being part of a larger structure subjected to earthquake excitation [63].

For the 11 motions in the analysis, the deformation results are crucial for section 13+580 to assess the slope stability, based on the information provided in Table 4.1, the deformation results are indeed crucial for assessing the slope stability and potential failure at Section 13+580. The table presents the maximum horizontal deformation (Ux), vertical deformation (Uy), and total deformation (Ut) in centimeters (cm) for 11 different seismic motion records, and these deformation values indicate the magnitude of slope movements that can occur under seismic loading conditions. The data shows that the slopes with steeper inclinations are more susceptible to larger horizontal and vertical displacements, which can compromise the overall slope stability and increase the risk of failure.

Table 4.1 11 Analyses made under earthquake deformations in (cm)

Peer ID	**Deformation (Ux)**	**Deformation (Uy)**	**Deformation (Ut)**
4130	25.64	3.89	27.51
585	34.68	5.05	38.10
265	47.77	5.82	47.77
250	39.05	5.47cm	40.95cm
8166	32.91	5.11	28.19
448	68.99	6.35	70.72
4065	15.56	3.12	18.97
4040	20.84	2.59	23.20
1111	53.46	7.42	55.75
1633	39.41	12.4	32.41
1787	28.62	6.72	30.81

The deformation plot shown in Figure 4.6 illustrates one of the significant motions under the applied dynamic load. The maximum deformation value is 70.72 cm, occurring at a specific element, indicating the largest displacement experienced by the component. The deformation pattern shows a complex, non-uniform distribution of displacements across the geometry, with the highest values concentrated in the upper-right portion. The deformation is primarily in the horizontal direction, suggesting significant lateral displacements.

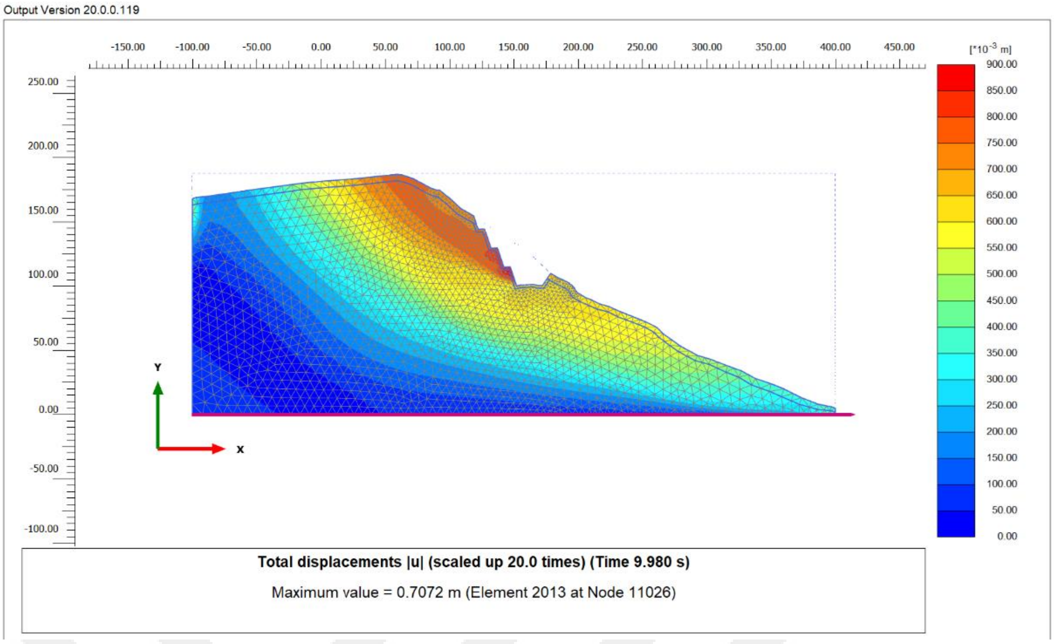

Figure 4.6 A significance of maximum total displacement in earthquake motion

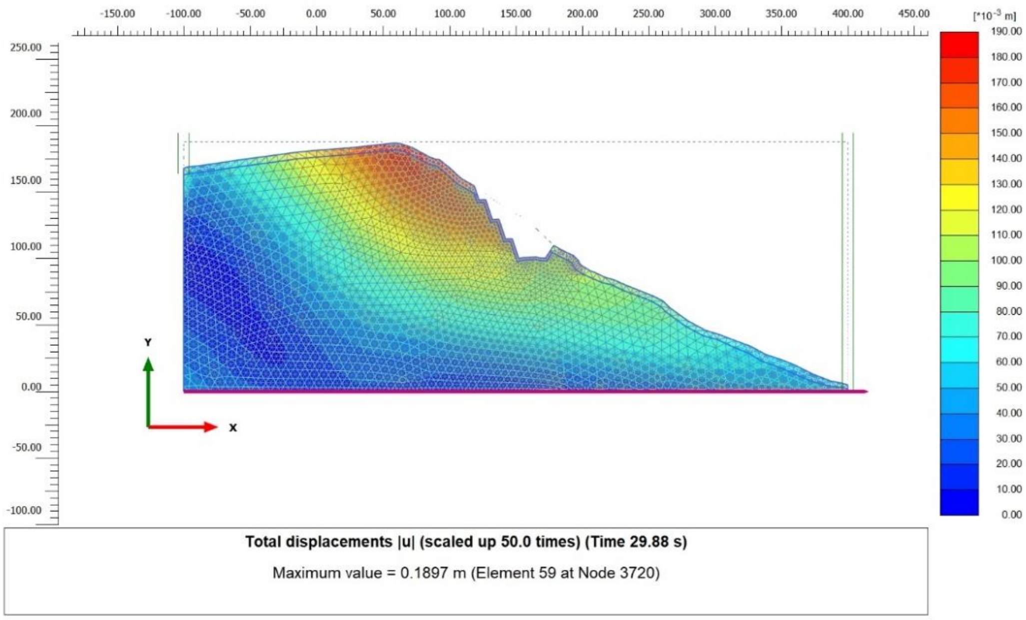

Figure 4.7 Minimum total displacement in earthquake motion

When material is excavated from a slope, it can create steep, unsupported faces that are inherently less stable. The steepness resulting from the excavation might have reached a critical angle where the material cannot support itself, especially under dynamic loads. Dynamic forces, such as those from seismic activity, further exacerbate the instability by introducing additional stresses and cyclic loading, which can weaken the soil or rock mass and lead to progressive failure. This combination of a steeper slope angle and dynamic loading conditions often results in localized failures, as shown in the analysis.

The displacement analysis for the excavated slope reveals a concerning profile. Figure 4.8 shows significant downward displacement, particularly in the upper portion of the slope, indicating a high potential for instability. The maximum displacement value is reported as 65.5cm, which is a substantial deformation that could compromise the slope's overall stability. This displacement pattern suggests that the excavation has created inherently unstable conditions with steep, unsupported faces that are vulnerable to failure.

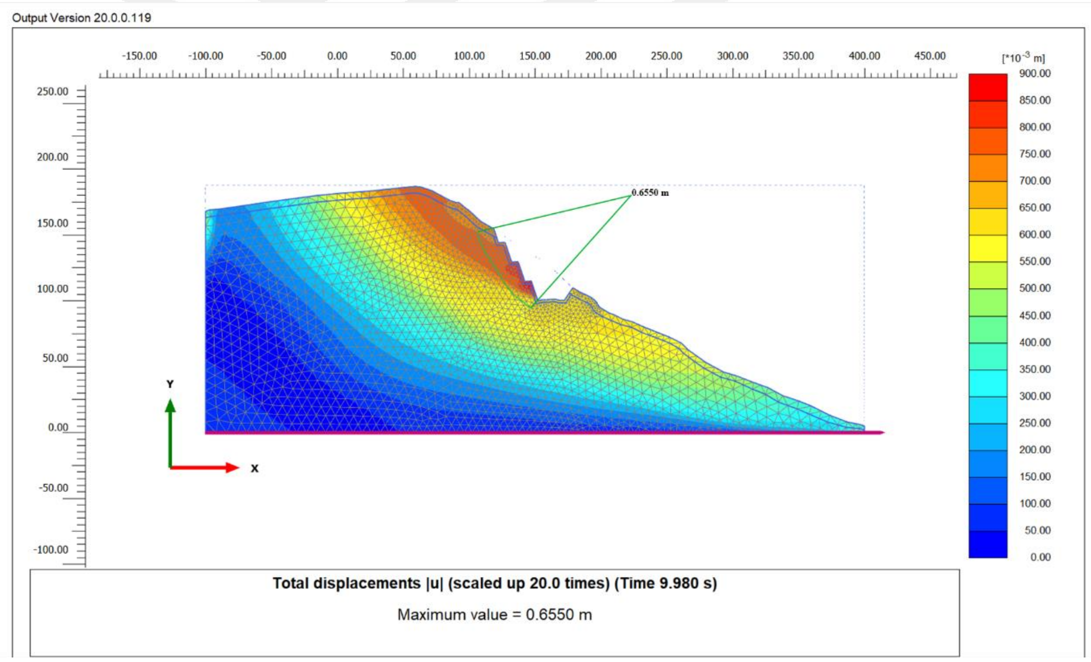

Figure 4.8 Significance total displacement in excavation slope of earthquake motion

Furthermore, the quality of the finite element mesh and the specific material properties assigned to the excavated region can influence the results. If the excavated material is modeled as weaker or more deformable compared to the surrounding intact slope, this discrepancy will be highlighted under dynamic analysis. The stress concentration around the excavation site, combined with dynamic loads, can lead to exaggerated deformations and potential failure mechanisms. To mitigate such issues, careful planning and reinforcement measures should be implemented during excavation to maintain slope stability, especially in seismic-prone areas [26]. The analysis conducted for the Km: 13+580 excavation section has revealed a concerning issue with the slope stability. The initial slope ratio of 2/3 (H/V) was found to be unstable, necessitating the implementation of additional stabilization measures to ensure the long-term safety and integrity of the site.

In section Km:13+580, the left slope cutting geotechnical design by soil nails in PLAXIS 2D and the design for that cross-section with soil nails and shotcrete is presented as follows: The soil nailing process for slope stabilization and excavation support involves several key steps. First, the slope is excavated at a steep inclined angle that allows it to stand upright without additional support, but with the nails installed at a non-vertical angle. Next, a layer of shotcrete with reinforcing mesh is immediately applied to the exposed ground surface to maintain soil integrity. Then, soil nails are installed by drilling holes at a specific slope and length, placing the nails, and injecting cement grout to secure them. Finally, the installed nails undergo a small amount of pre-stressing to activate the nails and engage the surrounding soil, creating a stable reinforced structure. This carefully sequenced process makes soil nailing an effective technique for addressing a variety of geotechnical challenges [2]

Soil nailing is done in the following order:

1. The ground is excavated steeply and inclined enough to stand upright without support, but the nails should not be vertical.

2. Shotcrete is immediately applied to the ground surface with mesh steel.

3. A soil nail of a certain slope and length is driven into the ground, or a hole is drilled.

4. After the nail is placed inside, it is covered with cement injection.

5. The nail is subjected to an extremely small amount of pre-stressing to activate it and engage the surrounding soil.

The design of the soil nails for the section at 13+580 incorporates several key elements to achieve effective slope stabilization. The 10-meter-long soil nails, with a 28-millimeter diameter, are arranged in a 2-meter by 3-meter pattern. This layout helps distribute the reinforcement throughout the slope, providing uniform support. The soil nails are further reinforced with a 20-centimeter-thick shotcrete facing, which adds additional structural integrity to the system. Unlike ground anchors, soil nailing is a specialized technique that works to stabilize slopes or steep cuts by preventing displacements and limiting lateral pressure during and after the excavation process. Based on the provided information, the soil nail design has been successful in reducing deformation compared to the previous condition, indicating it is an effective solution for stabilizing this slope. As shown in Figure 4.9, limiting displacements is critical to maintaining the stability and integrity of the slope over the long term. Overall, the design details illustrate how soil nailing can be an efficient and reliable approach for stabilizing challenging slope geometries.

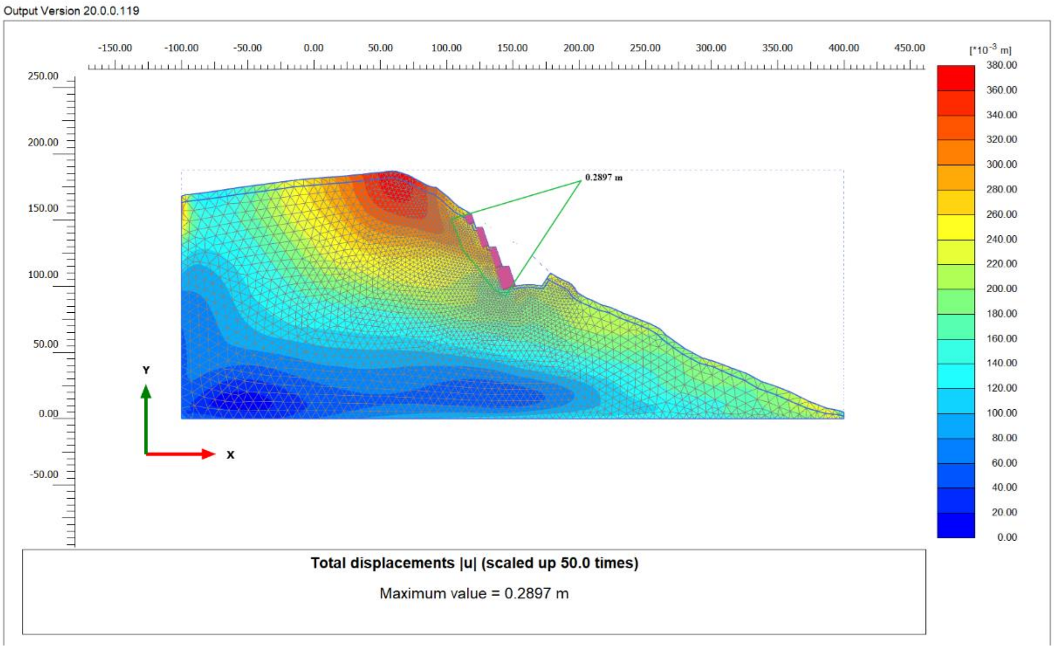

Figure 4.9 After installing soil nails, maximum displacement observed

4.5 Compliance with Deformation Criteria

The results of the finite element analysis are evaluated against the deformation limits specified by the Turkish Seismic Code:

Maximum Allowable Displacement: According to the code, allowable displacements for critical infrastructure slopes are not explicitly defined with quantitative thresholds. This is likely because the acceptable deformation can vary depending on specific project requirements, slope geometry, soil/rock conditions, and the consequences of failure.

The initial problem statement did not provide any specific information about acceptable deformation limits for the slope. Typically, the evaluation of slope stability focuses on the safety factor against failure, rather than quantifying allowable deformations. However, in general engineering practice, some guidelines and specifications do provide criteria for acceptable slope deformations, according to the Federal Highway Administration (FHWA) guidelines:[64]

For static (non-seismic) conditions:

- Typically, total slope deformations less than 6 inches (150 mm) are considered acceptable for most transportation facilities.
- For critical structures or slopes, a more stringent limit of 1-3 inches (25-75 mm) of total deformation may be appropriate.

For seismic (earthquake) conditions:

Allowable deformations depend on the importance of the structure and the consequences of failure.

- For critical slopes, total deformations less than 12 inches (300 mm) are generally considered acceptable.
- For less critical slopes, up to 24 inches (600 mm) of deformation may be tolerated, provided the slope remains stable.

Comparing the deformation values in acceptable limit deformation for the cut section at 13+580 under seismic loading, as per the FHWA guidelines, was originally 65.5 cm. However, after the installation of soil nails, this acceptable deformation limit has been significantly reduced to 28.97 cm. This substantial decrease in the allowable deformation is a clear indication that the soil nail design and installation have successfully addressed the seismic vulnerability of the cut section, provided robust reinforcement and effectively distributed the stresses. The deformation of 28.97 cm, which is well within the FHWA guidelines, should give greater confidence in the long-term stability and safety of the infrastructure under seismic loading conditions, demonstrating the effectiveness of the soil nail system in enhancing the overall seismic resilience.

CHAPTER 5

CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusion

The numerical results obtained in this study led to the following conclusions;

- The finite element analysis using the Plaxis 2D software was an effective tool for evaluating the stability of the cut slope at Km 13+580 of the Palu-Beyhan-Gökdere highway under static and seismic conditions. The HS small model within Plaxis provided This constitutive model is specifically designed to account for the high stiffness of soils at very small strain levels, as well as the non-linear stress-strain behavior of geotechnical materials. The discussion includes the formulations and parameters used in the HS Small model, such as the initial shear modulus (G0), and the stress-dependent exponent (m). These model refinements aim to improve the accuracy of the numerical simulations and better capture the complex behavior of soils under seismic loading conditions to get accurate predictions of the slope's deformation and failure mechanisms.

- For the rock class candidate ground motions are selected from the PEER NGAWest2 ground motion database (https://ngawest2.berkeley.edu/). The ground motions are selected such that their fault mechanism is strike-slip, their moment magnitude is greater than 5.0 and RJB distances are between 0 km and 50 km. Afterward, by using the target spectra, ground motions for each target spectrum are selected. The selected ground motions are scaled with the SeismoMatach scaling methods.

- Under static conditions, the cut slope was found to be stable with a safety factor of 1.645, indicating an acceptable level of stability. However, the seismic analysis revealed that the slope would experience significant deformations and potential failure during a strong earthquake event.

- The pseudo-static analysis using a horizontal seismic coefficient of 0.33g showed that the safety factor decreased to 1.15, which is below the recommended minimum value of 1.2 for seismic conditions. This suggests that the cut slope would be vulnerable to failure during a moderate to strong earthquake.

- The stress-deformation analysis using the Plaxis 2D dynamic module demonstrated the development of critical shear strains and the formation of potential failure surfaces within the slope during the simulated earthquake loading. This highlights the need for appropriate seismic design and mitigation measures to ensure the long-term stability of the cut slope.

- The original acceptable deformation limit for the cut section at 13+580 under seismic loading was 65.5 cm. However, after the installation of soil nails, this deformation limit has been significantly reduced to 28.97 cm, which is a 44.23% decrease and less than the acceptable deformation required under the FHWA guidelines. This substantial decrease in the allowable deformation is a clear indication that the soil nail design and installation have successfully addressed the seismic vulnerability of the cut section, provided robust reinforcement, and effectively distributed the stresses. The lower acceptable deformation of 28.97 cm, should give greater confidence in the long-term stability and safety of the infrastructure under seismic loading conditions, demonstrating the effectiveness of the soil nail system in enhancing the overall seismic resilience.

5.2 Recommendations

- Conduct Regular Monitoring and Maintenance: Implement a comprehensive monitoring and maintenance program for the critical slope section to detect any changes or signs of instability early on. This could include regular visual inspections, inclinometer measurements, and other geotechnical monitoring techniques.
- Explore Additional Stabilization Measures: Investigate the feasibility of implementing additional stabilization measures, such as anchored retaining

walls, drainage systems, or other slope reinforcement techniques, to further improve the slope's stability and reduce the risk of failure under seismic conditions.

- Improve Seismic Design Inputs: Ensure that the seismic design inputs, such as ground motion data and soil parameters, are regularly updated and aligned with the latest available information and standards. This will help to accurately capture the site-specific seismic hazards and soil behavior.
- Incorporate seismic resilience in future highway design: The findings of this study should be considered in the design and planning of future highway projects in the region, ensuring that seismic slope stability is a key consideration in the overall infrastructure design and construction.

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- Geotechnical Engineering
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