

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**STATIC AND DYNAMIC SLOPE STABILITY OF MSW
LANDFILLS**

OĞUZ DAL
A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING

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THESIS SUPERVISOR
PROF. DR. SELÇUK TOPRAK

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2023



YÜKSEK LİSANS JÜRİ ONAY FORMU

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SUMMARY

With population growth, municipal solid waste production has increased, making waste removal and treatment more important. Landfills are the most common method worldwide. Landfills can have problems during and after use. One of the biggest problem is slope stability. Landfill stability depends on many factors like cohesion, internal friction angle and unit weight of wastes, slope angle and height of the landfill, and leachate level in the landfill. Earthquake effects should also be considered for landfills in seismically active areas.

This study aims to create a smart decision tool which can evaluate the slope stability of landfills and help decision makers to improve the stability. The stability decision support system is part of a larger system that also assesses gas and leachate. The smart decision tool is one of the deliverables of the Erasmus+ EU project with the acronym SMARTEnvi. In this study, Bishop, a limit equilibrium approach, was used to analyze the slope stability of landfills with different geometry: slopes of 1:1, 1:2, and 1:3 and heights of 10, 20, 30, 40, 50, and 60 m. A parametric study including waste unit weight, cohesion, internal friction angle, and landfill leachate level were performed. The pseudostatic dynamic stability analyses were executed by using different horizontal (k_h) and vertical (k_v) seismic coefficients representing low and high seismicity zones. Various graphs were generated according to selected factor of safety values for static and dynamic conditions. The results showed how all parameters affected landfill stability and used to develop the smart decision tool.

Key Words: Landfill, Slope Stability, Bishop, Limit Equilibrium Method, Open Dump, Smart Decision Tool.

ÖZET

Nüfus artışıyla birlikte belediye katı atık üretimi artmış, atıkların uzaklaştırılması ve arıtımı daha önemli hale gelmiştir. Düzenli depolama dünya çapında en yaygın yöntemdir. Düzenli depolama alanları, kullanım sırasında ve sonrasında sorun yaşayabilir. En büyük sorunlardan biri şev stabilitesidir. Depolama sahası stabilitesi, kohezyon, içsel sürtünme açısı ve atıkların birim ağırlığı, depolama sahasının eğim açısı ve yüksekliği ve depolama sahasındaki sızıntı suyu seviyesi gibi birçok faktöre bağlıdır. Sismik olarak aktif bölgelerdeki depolama alanları için deprem etkileri de dikkate alınmalıdır.

Bu çalışma, düzenli depolama sahalarının şev stabilitesini değerlendirebilen ve karar vericilerin stabilizeyi iyileştirmesine yardımcı olan akıllı bir karar sistemi oluşturmayı amaçlamaktadır. Stabilite karar destek sistemi, gaz ve sızıntı suyunu da değerlendiren daha büyük bir sistemin parçasıdır. Akıllı karar aracı, SMARTEnvi kısaltmasıyla Erasmus+ AB projesinin çıktılarından biridir. Bu çalışmada, 1:1, 1:2 ve 1:3 eğimlere ve 10, 20, 30, 40, 50 ve 60 m yüksekliklere sahip farklı geometrideki düzenli depolama sahalarının şev stabilitesini analiz etmek için bir limit denge yaklaşımı olan Bishop kullanılmıştır. Atık birim ağırlığı, kohezyon, içsel sürtünme açısı ve depolama sahası sızıntı suyu seviyesini içeren bir parametrik çalışma yapılmıştır. Düşük ve yüksek sismisite bölgelerini temsil eden farklı yatay (k_h) ve düşey (k_v) sismik katsayılar kullanılarak psödostatik dinamik stabilize analizleri yapılmıştır. Statik ve dinamik koşullar için seçilen güvenlik katsayısı değerlerine göre çeşitli grafikler oluşturulmuştur. Sonuçlar, tüm parametrelerin depolama sahası stabilitesini nasıl etkilediğini göstermekte ve akıllı karar aracını geliştirmek için kullanıldı.

Anahtar Kelimeler: Katı Atık Depolama Sahası, Şev Stabilitesi, Bishop, Limit Denge Yöntemi, Vahşi Katı Atık Depolama Sahası, Akıllı Karar Sistemleri.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations</u>	<u>Explanations</u>
<u>and Acronyms</u>	
a_h	: Horizontal pseudostatic (seismic) acceleration
a_v	: Vertical pseudostatic (seismic) acceleration
c	: Cohesion
ϕ	: Internal Friction Angle
f_h	: Horizontal pseudostatic (seismic) force
f_v	: Vertical pseudostatic (seismic) force
k_h	: Horizontal pseudostatic (seismic) coefficient
k_v	: Vertical pseudostatic (seismic) coefficient
τ_d	: Average shear stress of a potential sliding surface
τ_f	: Average shear strength of the soil
W	: Failure mass weight
FE	: Finite Element
FEM	: Finite Element Method
FS	: Factor of Safety
LEM	: Limit Equilibrium Method
MSW	: Municipal Solid Waste
RF	: Reduction factor
TBEC	: Turkish Building Earthquake Code
WSDOT	: Washington State Department of Transportation

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1. INTRODUCTION

1.1. Importance of Research

Rising energy and product demand, along with rising populations and rising living standards, result in substantial amounts of MSW that, if it is not stored or recycled properly, represent significant dangers to the environment. Every year, people throughout the globe produce 2.01 billion tonnes of garbage. The amount of garbage produced by each individual per day varies greatly from 0.11 to 4.54 kilograms around the world, with an average of 0.74 kilos. High-income nations produce around 34% of the world's garbage, or 683 million tonnes, although having just 16% of the world's global population. By 2050, it's predicted that the amount of garbage produced worldwide will reach 3.40 billion tons [Kaza et al., 2018]. Therefore, the importance of waste disposal and treatment methods is increasing day by day. Waste storage methods like landfill and open dumps are used in all countries. Open dumping is widely used in low-income nations, accounting for 93% of garbage disposal, compared to just 2% in high-income ones. In upper-middle-income economies, 54% of trash ends up in landfills. In high-income nations, this ratio falls to 39%, with 35% of trash being diverted to recycling and composting and 22% to incineration [Kaza et al., 2018]. Although the amount of waste is tried to be reduced by waste reduction, reuse and recycling methods, these methods are insufficient, and the landfill method continues to be widely used in the world.

The improper disposal of solid wastes has negative consequences for both the natural environment and human health [Toprak et al., 2021a]. One of the primary concerns in landfill planning and management is ensuring the site's long-term stability. From past to present, many slope failures have occurred in municipal solid waste (MSW) landfills, resulting in damage to people and the environment. Before such events happen, it is important to be aware of the situation regarding the stability of the landfill and to be able to take the necessary precautions early.

There are a lot of studies related to slope stability in landfills. Conventional limit equilibrium analysis for slopes in 2 landfills located in Brazil were done in order to obtain factor of safety values of them and then, the results were compared [Gharabaghi et al., 2008]. Finite element and limit equilibrium method was used for MSW landfills

in geogrid-reinforced and unreinforced conditions. It was concluded that, geogrid can be useful to increase the slope of the landfill and the storage of more MSW is possible [Keskin and Kezer, 2022]. Also, several solutions like berm construction and surface strengthening were discussed to improve the slope stability of landfills and some slope stability analyses were made using Bishop method for a few slopes in Łubna landfill, Poland. Safety coefficients were obtained in the absence and presence of reinforcements and it was understood that reinforcements were beneficial [Koda et. al, 2021]. The seismic activities can also be important for landfill areas located in seismically active fields. There were also some studies related to it. For example, the pseudodynamic method was used in order to assess the urban solid waste landfill seismic stability with translational failure mode [Savoikar and Choudhury, 2012]. Falamaki et al. (2021) assessed not only under construction but also post construction probabilistic seismic and static stability of a landfill in Iran.

1.2. Identification of the Problem

Landfill and open dumps methods are still very common in the world. In general, it is very difficult to find a landfill site for such waste in countries, because no community would like to have such a landfill right next to it that could harm the environment. Therefore, landfills are generally built far from the city center, away from where people live. However, each landfill has a certain capacity. When the capacity is full, the waste areas should be closed in a way that will not harm the environment. Therefore, the new area should be found. Yet, this may not be a preferred method in some cases, both because it will create extra costs and because of the difficulties in finding a new area. In such cases, the slope angle and height of the landfill are increased. Thus, the capacity of the landfill will be increased. However, this approach may not be safe if not properly evaluated. As it can be seen especially in underdeveloped and developing countries, if there are settlements around the landfill, this situation is of great importance for human life because, in the event of a slope failure, the people living there may lose their lives. In addition, if there is gas in the waste, very harmful gases will be released to the environment as a result of this failure, which can harm people, trigger air pollution and global warming. In addition, if there are equipment used for leachate and gas management in the landfill, they may be

damaged as a result of this collapse. In other words, slope failures can cause great damage both socially and financially [Toprak et. al, 2021b]. In the past, many slope failures have occurred for different reasons, and hundreds of people have lost their lives because of this. Today, slope sliding still occurs in municipal solid waste sites. For example, a massive and major landslide happened at a dump site in Russia in October 2022 [Web 1, 2022]. Also, a big rubbish landslide occurred at a dump outside of Bogota, Colombia's capital city in April, 2020. Locals reported being bothered by a terrible odor coming from the dump, which was most likely related to the event [Web 2, 2020]. As long as the landfill is used, the slope stability problem is always one of the main issues to be considered.

1.3. Aim of the Study

Landfills including open dumps are the most widely used waste disposal and treatment method today. Landfills need stability not just during construction and operation, but also after they have been closed. Therefore, the use of a tool that can be used in landfills and open dumps to provide preliminary information about slope stability is of great importance in order to prevent the slope stability problem from harming the environment and people and to take some precautions related to it.

The aims of this study are:

- To characterize the importance of factors that affect the slope stability of landfills,
- To develop relationships about the safety of landfills using these parameters
- To incorporate these relationships into smart decision tool which can assess different conditions and rehabilitations of landfills.

This decision tool is also an output of the SMARTEnvi project [SMARTEnvi, 2023].

To achieve these objectives, slope stability analyses were carried out with the help of GEO5 software by trying different landfill height, slope angle, waste unit weight, cohesion, internal friction angle, horizontal (k_h) and vertical (k_v) pseudostatic (seismic) coefficients and leachate levels. Then, the relationships between these parameters considering factor of safety were developed. Using these slope stability analyses, first order equations related to cohesion and internal friction angle were

obtained for each different case and integrated into MS Excel. Then, these relationships are utilized with the input of the users to present the outputs in Microsoft Excel. Users can also see the effect of different rehabilitation methods via the smart decision tool.



2. OPEN DUMPS AND LANDFILLS

Waste management is of great importance for municipalities and governments. They have to deal with tons of waste every day. There are different waste treatment and disposal techniques. Open dumps, which were used in the past in the developed countries and are still mostly used in underdeveloped or developing countries and landfills, which are more environmentally friendly for the purpose of storing waste, play an important role in the disposal of waste.

2.1. Waste Types

A product or material that is no longer suitable for its intended use is considered waste. Wastes can be classified in different ways. In general, they can be divided into two; hazardous and nonhazardous waste. Hazardous wastes include electronic, radioactive, medical and industrial wastes, while nonhazardous wastes contain municipal solid wastes and other nonhazardous industrial wastes.

2.2. Municipal Solid Waste

Materials such as packaging wastes, organic wastes, metal, glass and plastic wastes can be counted as municipal solid waste. Our homes, schools, and workplaces all contribute to the production of this kind of waste. The composition of MSW changes based on a population's economic level. A population with a low to moderate income creates mostly organic wastes, while a population with a high income generates more waste glasses, paper, and metals.

2.2.1. Comparison of Municipal Solid Waste Generation in Türkiye and in the World

MSW generation in Türkiye and other European countries can be seen in Figure 2.1 [Eurostat, 2022]. In this graph, Türkiye's data for 2020 is obtained from TUIK data [TUIK, 2021]. A comparison of the statistics for 2010 and 2020 shows that for many European countries like Turkey, the changes per capita throughout this period were

insignificant. However, the world's population is increasing day by day resulting in more waste. Therefore, the waste disposal and storage methods used still maintain its importance.

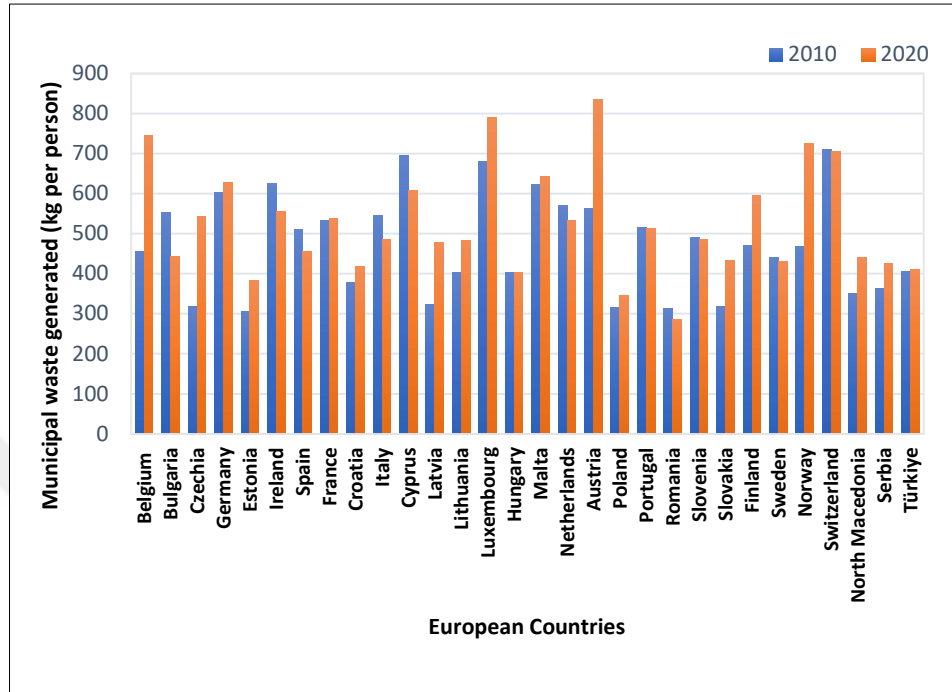


Figure 2.1: MSW generated in European countries.

The annual MSW generation per person in the world is shown in Figure 2.2 [Kaza et al., 2018]. The average daily waste production per person is lower in Asia and Africa in general, while North America and Australia produce more waste. According to TUIK, the estimated daily average for municipal garbage per person in Türkiye in 2020 is 1.13 kg [TUIK, 2021].

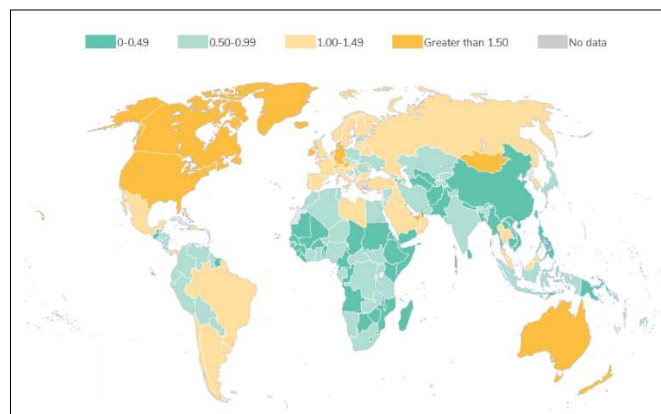


Figure 2.2: Annual generation of MSW per person (kilograms/capita/day).

2.3. Types of Waste Management

Open dumping, incineration, recycling, composting, and landfill are often used methods of waste management.

2.3.1. Open Dumps

Due to a lack of appropriate placement considerations or standards, open dumps are often situated in places that are not suitable for these facilities. The capacity of open dumps is unknown. Waste types and their amounts are not checked, so hazardous waste can also be disposed of in these areas, which has adverse effects on the environment and public health. There is no leachate or gas management. Daily soil cover is rarely used to prevent bad odors. Waste compaction is not applied to these areas. Scavengers can enter these areas and pick up waste. There is a failure to properly close the site after the cessation of activities. The initial cost is low, but the long-term cost is high. Fires can be seen in these areas [UNEP, 2005].

2.3.2. Incineration

Incineration is among the most widely used treatment methods because the volume of the waste may be decreased by as much as 90% and the waste mass can be reduced by as much as %70 [Sirimangkhala et al., 2019]. Ashes, flue gas, and heat are produced during the incineration of waste.

2.3.3. Recycling

The term "recycling" refers to the practice of using previously discarded resources to create something new. Metal, glass, paper and plastic are some examples of recyclable materials. It is possible to save less energy while making product with this method. In addition, it is not necessary to extract raw materials very much because recyclable materials can be used for this purpose.

2.3.4. Composting

The organic waste is decomposed in a controlled environment by a biological process known as composting. Composting has a number of environmental advantages, such as decreasing emissions of greenhouse gases, reducing the effect of droughts, enhancing soil health, as well as recycling nutrients.

2.3.5. Landfill

The conventional and popular way to dispose of waste is in landfills [Zhang et al., 2020]. In many countries, landfills remain the preferred way of disposing of solid waste due to the financial benefits they provide. Sanitary landfills are engineered waste disposal facilities that are built and managed in a way to prevent or reduce adverse effects on the environment and human health. Unlike open dumps, sanitary landfills are carefully planned from the time the site is chosen to the time they are closed and beyond. Figure 2.3 is a schematic illustrating the most important parts of a standard sanitary landfill [UNEP, 2005].

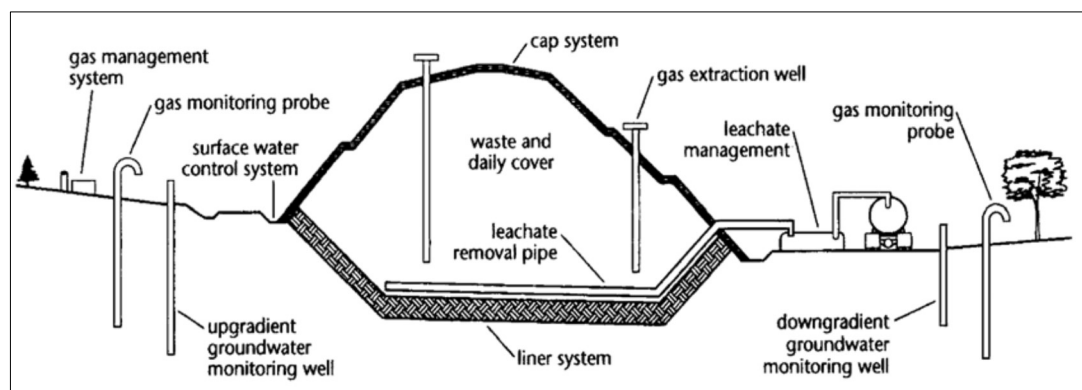


Figure 2.3: Key parts of a standard sanitary landfill.

A cover, leachate collecting system, bottom liner, and natural hydrogeologic setting are the four most important parts of a safe landfill. Wastes' potential to seep into groundwater underneath a landfill may be reduced by carefully selecting the surrounding natural environment. For example, the bottom of the landfill may be a tight rock to prevent waste and leachate from reaching the groundwater. Therefore, it is helpful to keep the geology as impermeable as possible so that it can be estimated

where the waste will go in the event of a leak. Thus, in such a case, the leachate can be caught by the pump by lowering the wells. On the other hand, fractured bedrock is particularly undesirable under a landfill since it makes it difficult to find the leachate.

The bottom liner prevents waste and wastewater (leachate) from mixing with the ground and underground water. Liners can be made of plastic, clay or composite type. The composite type consists of compacted clay and a plastic liner in general.

Water that has been heavily polluted by contact with garbage is called leachate. It sinks to the landfill bottom, where a network of pipes collects it. Leachate is collected when there is accumulation via pipes installed along the bottom. It is called a leachate collection system. At a wastewater treatment facility, the pumped leachate is cleaned, and the particles that are separated out are either sent back into the landfill or delivered to another landfill. Groundwater monitoring wells are also crucial for landfills to check whether leachate has reached and affected the groundwater or not.

To prevent water from entering the dump, a cap or cover is used. It is often made up of many sloped layers, including from bottom to top a membrane or clay liner (to keep rain out), a relatively porous layer of gravelly or sandy soil (to encourage rain drainage), and topsoil where plants may grow (for the stabilization of the underlying cover layers) [Center for Health, Environment and Justice, 2016].

In addition, surface waters may bring about not only water ponding but also scouring and erosion in the final cover. Therefore, drainage management systems are set up within and around the landfill area to reduce the severity of these impacts.

Gas management and monitoring systems are also important for landfills. As long as waste is decomposed, landfill gases like methane and carbon dioxide will be produced. Methane is an explosive gas that may cause damage to closed areas like homes and buildings if it builds up to dangerous levels. Collecting the gas and venting it with a flare, releasing it freely, or recovering it for energy usage may be essential depending on how environmentally sensitive the location is [UNEP, 2005]. To minimize greenhouse gas emissions like carbon dioxide and methane, governments throughout the world are promoting projects that convert landfill gas into power.

MSW landfills are subject to some of the most stringent safety and monitoring regulations. These rules often include restrictions on where the landfill can be put, how it can be lined, how it can be run, how groundwater will be monitored, and how it can be closed.

2.4. Municipal Solid Waste Disposal and Recovery Method Distribution in Türkiye and in the World

The MSW disposal and recovery method distribution in Türkiye in 2018 and in 2020 is illustrated in Figure 2.4 [TUIK, 2021]. According to the figure, MSW is mostly disposed of in controlled landfill sites in Türkiye and its percentage increased from 67.20% to 69.43% between 2018 and 2020. In addition, there are still open dumps in Türkiye, but the use of them is decreasing day by day. The percentage of open dumps use for MSW decreased from 20.24% to 16.99% between the same years. Additionally, between the years 2018 and 2020, the proportion of recovery facilities usage for MSW that includes techniques of composting and recycling climbed from 12.33% to 13.19%. Likewise, other disposal methods also increased from 0.23% to 0.39%.

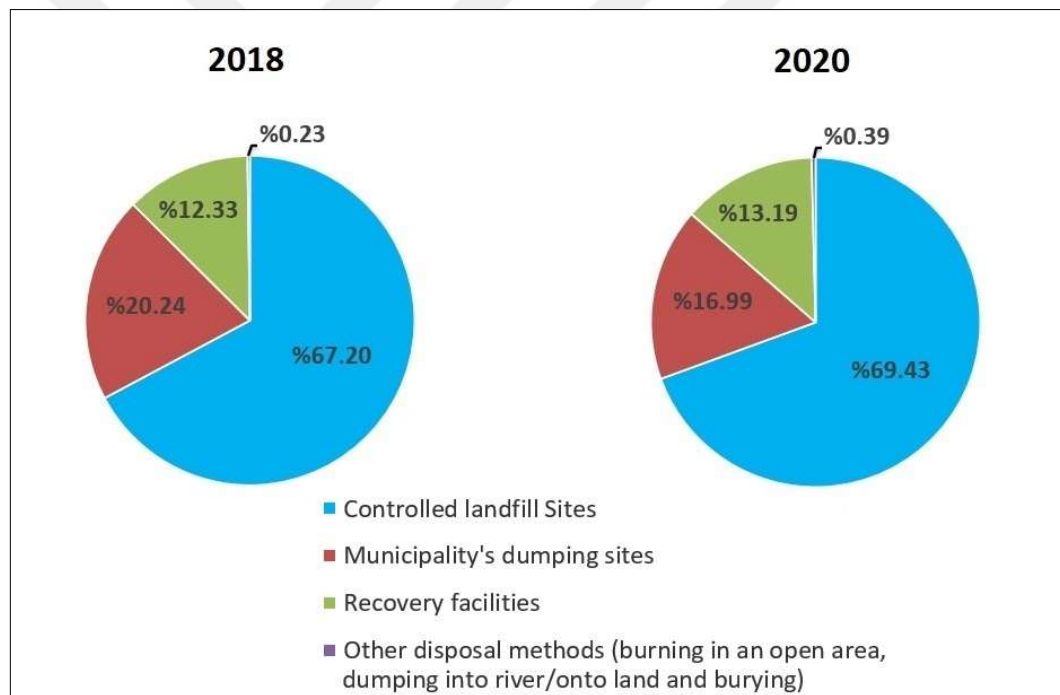


Figure 2.4: The Türkiye's waste treatment and disposal methods.

The world's waste treatment and disposal methods are represented in Figure 2.5 [Kaza et al., 2018]. About 37% of garbage is thrown in landfills, 33% is left in open dumps, 19% is recycled or composted, and 11% is incinerated using contemporary technology. As seen in the figure, open dumps and landfills are mostly used around the world. Considering the damage it causes to the environment, the use of open dumps must be reduced as soon as possible, and the used ones must be rehabilitated.

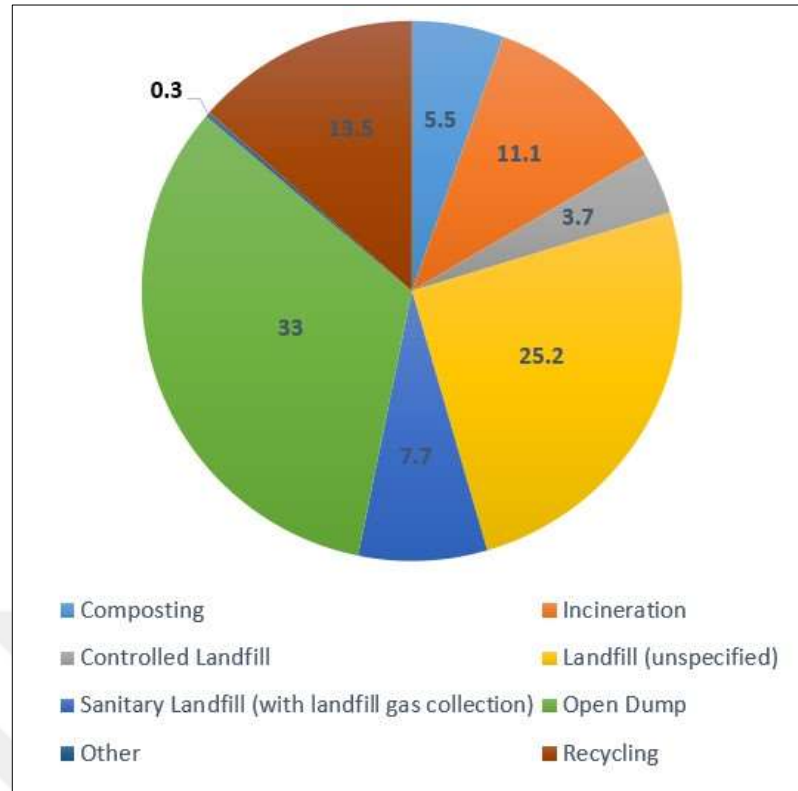


Figure 2.5: The world's waste treatment and disposal methods.

Tons of urban solid waste are generated every day in Turkey and around the world, and the capacity of the landfills is being filled day by day. It is clear that the establishment of new landfills will be difficult considering that it will disturb the environment and people. For this reason, it is preferred to increase the slope and height of landfills in general. However, this situation can create slope stability problems in landfills. Especially in underdeveloped countries, there may be settlements around solid waste sites, and people may lose their lives as a result of slope failures. Therefore, landfills must be monitored and analyzed carefully in terms of slope stability. As another solution, it is very important for our future to reduce the use of waste storage methods like landfills and open dumps and to use other advanced waste recovery techniques such as composting and recycling.

2.5. Types of Failures in Landfills

There may be some failures in the landfill during the active use period, where wastes are accepted continuously, or after the landfill is covered. Instability at a landfill may have disastrous effects on the local ecosystem, endangering human lives and

destroying property. In the past, many people lost their lives due to the instability of landfills, and many other damages occurred in settlements besides landfills.

2.5.1. Slope Failures

One of the failure types that occurs in landfills is slope failure. Past observations showed that the location of the slip surface varies for different landfills. Based on where the sliding surface is located, the landfill instability mode may be classified into three different categories. These categories are shown in Figure 2.6 [Zhang et al., 2020]. The sliding surface can be inside the waste, can cut the subsoil, or can be along the MSW and bottom liner interface. Exploitation mistakes or insufficient geotechnical and geological study of the subsurface generally lead to such failures in general. In the current study, it is assumed that the subsoil under the slope is strong enough to carry the waste. Therefore, in the slope stability analyses carried out within the scope of this thesis, it is thought that the slip surface occurs only in the waste.

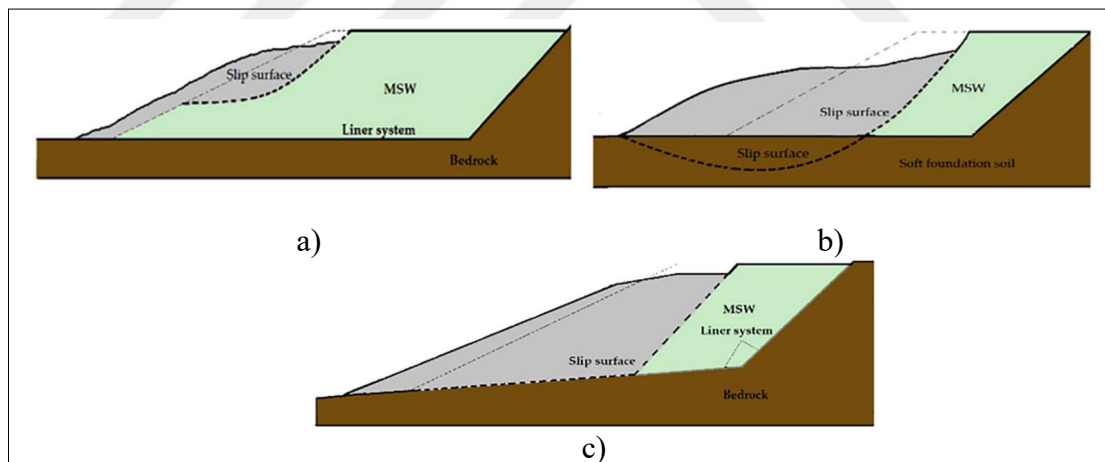


Figure 2.6: a) The formation of a sliding surface in the waste, b) the subsoil is cut through by the sliding surface c) The sliding surface is found where the bottom liner and the MSW meet.

In addition, if the slope angle is too high or too long, the top cover system, which consists of topsoil and protective soil, or the leachate collection system of landfills, is at risk of sliding on the bottom liner system. Extreme weather conditions like torrential rain are a common trigger for these failures.

2.5.2. Explosions

When organic waste is disposed of in a landfill, such as yard waste and food scraps, it is often compacted. The issue is that by doing so, oxygen is removed, which results in anaerobic digestion of the substance. Methane will eventually be produced by this process. Even though methane-rich landfill gas presents a possibility for energy recovery, it can be seen as a danger due to its flammability as well as its ability to generate explosive mixes with air at concentrations of 5 to 15% by volume. There are incidents of fires and explosions occurred in the past because of the methane gas in landfills. For example, Skellingsted landfill in Denmark [Kjeldsen and Fischer, 1995] and Gembloux landfill in Belgium [Lavigne et al., 2014] experienced gas explosions in the past.

2.5.3. Other Failures

Leaks in the leachate collecting systems and in the bottom liner are some other problems in landfills. As a result, leachate may combine with groundwater and contaminate it, as well as potentially polluting the earth.

For example, in less than ten years, leachate collecting systems may get clogged. They malfunction in a number of different ways: they become clogged due to mud or silt; microorganisms grow inside the pipes; minerals precipitate inside the pipes due to a chemical reaction; or the pipes weaken due to a chemical attack from solvents, acids, corrosion, or oxidizing agents, at which point tons of waste may be piled on top of them and crush the pipes [Center for Health, Environment and Justice, 2016].

In addition, some problems can occur with landfill cover. Covers can be damaged by erosion due to weather events such as rain, snow, overextension of plant roots, insects, worms, reptiles such as snakes, and various human activities. In addition, it may cause tears in the membrane or cracks in the clay as a result of the collapse of the cover due to reasons such as the decay of organic wastes [Center for Health, Environment and Justice, 2016].

Landfill settlement may be another problem that can occur during the lifetime of landfills. This settlement can be a differential settlement because of the waste content. If it occurs, it can damage gas and leachate collection systems, drainage systems used

for surface water, underground utilities, and the final cover. Some of the causes of settlement are an increase in void ratio as a result of waste decomposition, consolidation due to waste thickness as well as own weight, waste compaction, small particle motions to larger voids caused by subsurface fire, and physico-chemical and biological changes. Some practices like uniform compaction and sorting can decrease the effect of landfill settlement [Qrenawi, 2006].



3. SLOPE STABILITY OF LANDFILLS

Instability on the slope of a landfill can result in injuries to people, contamination of the surrounding environment, and damage to property. In addition, when a slope failure occurs in a landfill, the gas in the waste (if any) can be released into the environment, which adversely affects the environment. As a result, maintaining the safe functioning of landfills and the stability of landfills is an essential duty for governments and environmental professionals [Toprak et al., 2021a]. It is also important for people who live within a short distance to landfills.

In the past, there have been various slope stability issues in landfill sites. Since open dumps are also referred to as uncontrolled landfill in the literature [Massoud et al., 2022] [Siddiqua et al., 2022] [Ergene Şentürk and Alp., 2016], open dump slope failures are also covered in this section.

In 1993, a total of 1,200,000 cubic meters of solid trash were displaced at the Ümraniye-Hekimbaşı dumpsite in Istanbul. As a result, 39 people passed away. The waste dump had a high slope that exceeds 70 degrees and no compaction was applied to the waste here [Kocasoy and Curi, 1995]. A few hundred people died as a consequence of a slope collapse at the Payatas landfill in the Philippines in 2000 involving an amount of 13,000–16,000 m³ of waste. Near the collapse zone, the landfill's predicted side slopes are 1.5H:1V [Merry et al., 2005]. Another slope failure with a waste volume of 12000 m³ happened in the Xerolakka landfill, in Greece in 2010. The height of the landfill was 30 m and the slopes have an inclination as steep as 1.2H:1V in the top half of the landfill. A number of factors contributed to the collapse, including poor compaction, improper waste disposal procedures, gas and leachate pressure production, and increasing landfill slope steepness. [Athanasopoulos et al., 2013]. Another landslide occurred in 2005 at the Leuwigajah dumpsite, which is situated in Indonesia. This one included the amount of 2,700,000 m³ of garbage. As a consequence of this, 147 people lost their lives [Koelsch et al., 2005]. In Sri Lanka, Meethotamulla open dump collapsed in 2017. 32 people died and dozens of houses were damaged [Jayaweera et al., 2019]. Slope failures can still be observed in landfills today. A significant landslide took place at a landfill on Thursday, October 20, 2022 in the Russian town of Novyi Svet (Нов Свет) in Gatchinsky. Since 2001, the landfill

has been operational. The landslide did not result in any deaths or injuries [Web 1, 2022].

3.1. Slope Stability Analysis Methods

Stability of a slope is often measured in terms of a safety factor (FS). The safety factor of a slope is the ratio of shear strength of soil to shear stress of a potential sliding surface of the slope. Typically, the definition of the safety factor is

$$FS = \frac{\tau_f}{\tau_d} \quad (3.1)$$

In this equation, τ_f is average shear strength of the soil and τ_d is average shear stress of a potential sliding surface.

When landfills are built close to the fault line, it is necessary to pay attention to the earthquake effect while designing and managing the landfill. For earthquake condition, the pseudo-static method is one of the most used methods. This method is also one of the simplest ways to idealize the slope subjected to earthquake. Although the force of an earthquake is dynamic, the main cause of instability may be considered to be the inertial force. The acceleration caused by an earthquake's shaking is viewed as producing inertial forces in the pseudostatic approach. At the centroid of each slice, these pressures operate in both the horizontal and vertical directions. The definition of the forces is

$$f_h = \frac{a_h W}{g} = k_h W \quad (3.2)$$

$$f_v = \frac{a_v W}{g} = k_v W \quad (3.3)$$

where k_v and k_h are dimensionless vertical and horizontal pseudo-static coefficients and W is the failure mass weight. The forces acting on a slope for circular failure surface and linear failure surface can be seen in Figure 3.1 and Figure 3.2.

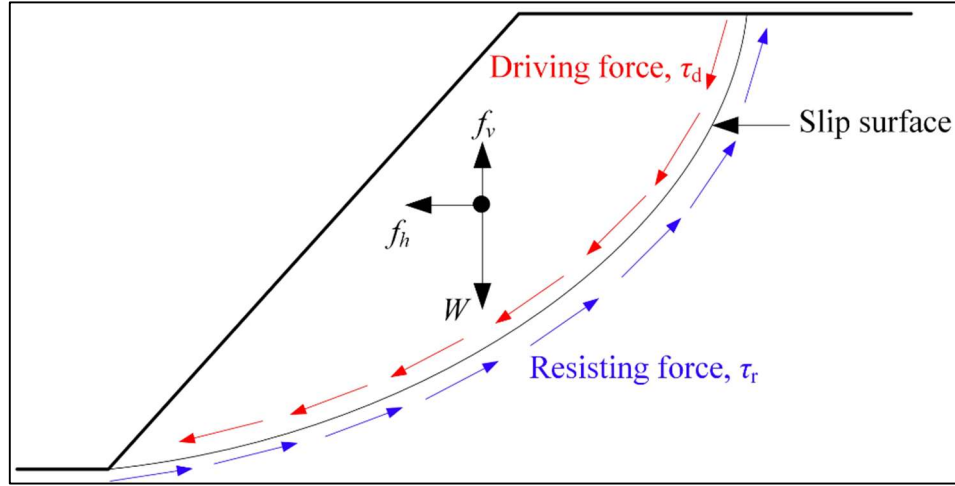


Figure 3.1: Forces acting on a slope in pseudostatic slope stability analysis for circular failure surface.

FS of the slope in Figure 3.2 can be calculated with the following equation:

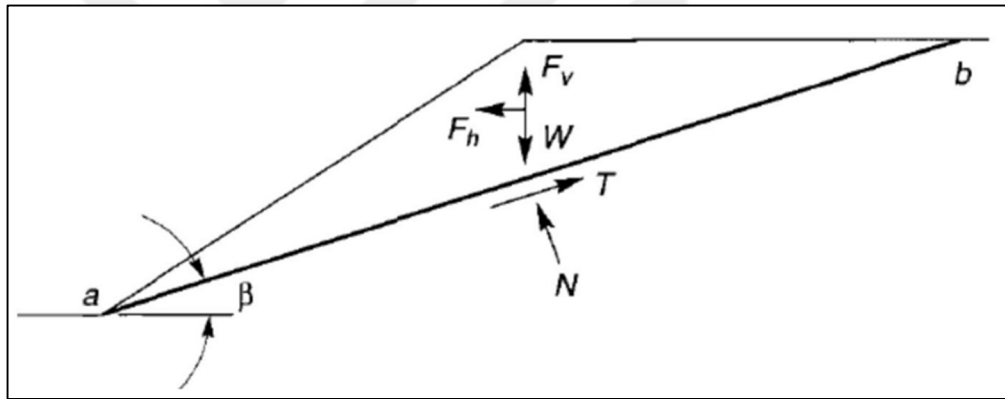


Figure 3.2: Forces acting on a slope in pseudostatic slope stability analysis for linear failure surface.

$$FS = \frac{\text{resisting force}}{\text{driving force}} = \frac{c l_{ab} + [(W - F_v) \cos \beta - F_h \sin \beta] \tan \varphi}{(W - F_v) \sin \beta + F_h \cos \beta} \quad (3.4)$$

As shown in the equation, cohesion (c), internal friction angle (φ), unit weight of waste which effects the sliding weight, k_h and k_v seismic coefficients can affect the results of the formula in the calculation of FS of the slope. Leachate level can also effect the unit weight of waste, so it is also important parameter.

For landfill stability analyses, the limit equilibrium approach is the most commonly used technique [Zhang et al., 2020].

The study of the equilibrium between a rigid body, such as a slope, and a slip surface of any shape like arc of a circle, straight line etc. constitutes the limit equilibrium approach. Shear stresses (τ) are computed from this equilibrium and compared to the available resistance (τ_f) computed using Mohr-failure Coulomb's criterion. This comparison allows to determine the Factor of Safety:

$$FS = \frac{\tau_f}{\tau} \quad (3.5)$$

Available shear strength can be calculated from the following formula:

$$\tau_f = c + \sigma * \tan\varphi \quad (3.6)$$

The rigid body is divided into slices to account for its nonhomogeneity in certain equilibrium approaches (Janbu, Bishop, Fellenius, etc.) as shown in Figure 3.3, whereas in others, the rigid body's global equilibrium is taken into account (Culman).

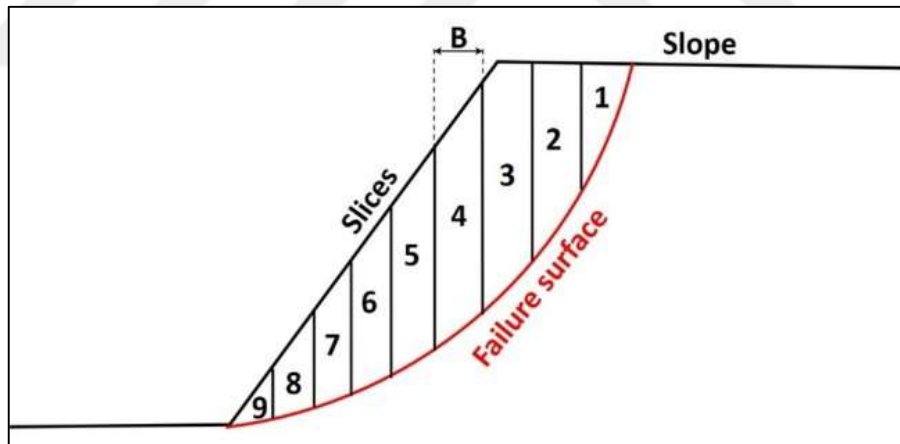


Figure 3.3: Representation of the Method of Slices.

Each slice can be thought of as a distinct body that requires maintaining force and moment equilibrium. Internal forces produced by the interaction between the slices are taken into account by all existing slice methods like Janbu and Bishop methods. Figure 3.4 shows the forces acting on a slice (ignoring external loads). Factor of Safety can be calculated as the following formula:

$$FS = \frac{\sum_i^n \text{Resisting Moments } (i)}{\sum_i^n \text{Driving Moments } (i)} \quad (3.7)$$

Some simplifications must be done about the forces for these slices to calculate FS. That's why a few different methods emerged for method of slices.

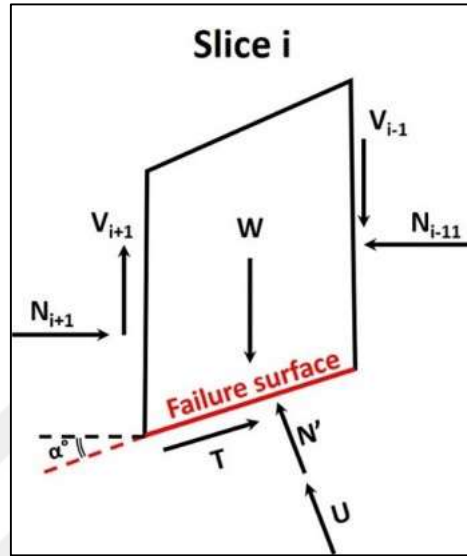


Figure 3.4: Forces acting on a slice.

The limit equilibrium technique of slicing is based only on statics concepts, namely the sum of moments, horizontal forces, and vertical forces. Because the approach says nothing about displacements, stress, or strain, it does not meet displacement compatibility.

The Bishop, Fellenius, Spencer, and Janbu are examples of conventional limit equilibrium approaches.

3.1.1. Simplified Bishop Method

In the simplified Bishop method, slice boundary shear forces are neglected while slice boundary normal forces are taken into account. In addition, it is necessary to look at a number of failure surfaces to find the critical surface that gives the least safety factor. The most popular approach is likely Bishop's simplified version. When used in software, it usually produces desirable results.

3.1.2. Fellenius Method

In the Fellenius (1927) method, the circular slip surface is cut into slices, and the forces acting on each slice are studied. It is assumed that the resultant of the interslice forces is parallel to the slice base. The Swedish slice method, also called the Fellenius method, is based on the idea that the forces on both sides of the slices cancel each other out. It is said that the normal and shear stresses between the slices should not be taken into account in the analyses. This assumption is not likely to be true, so the Swedish slice method gives low numbers for safety.

3.1.3. Spencer Method

Spencer proposed a system that provides both moment and horizontal force balance separately, so it considers the normal and interslice shear forces between slices. The method he developed; accepts the relationship between the normal and interslice shear forces constant. It assumes the ratio (X/E) of the shear force (X) and the normal force (E) between the slices to be constant.

3.1.4. Simplified Janbu Method

While shear force between slices is neglected in this method, normal force between slices is not neglected. Although a force balance in both directions (horizontal and vertical) is supplied by the Janbu approach, no consideration is given to the moment of those forces. Janbu admits that there might be problems with the estimation of the moment in his updated research. So, the horizontal force balance is suggested to be used instead of the moment force balance.

3.1.5. Limit Equilibrium vs. Finite Element Method

Limit equilibrium and finite element methods are commonly used for slope stability analyses. The model is divided into various sections or mesh elements using the FE method. The constitutive rules for materials used in the slope stability model are used to determine stresses and strains. Failure happens naturally in the areas where

the soil's shear strength cannot support the applied shear stresses. In the end, the 'c- ϕ reduction' approach can be used to determine a reduction factor (RF) for finite element methods. With this strategy, the soil strength parameters must be gradually decreased until failure takes place. The FE method's ability to calculate FS (equivalent RF) for slopes is made possible by the shear strength reduction methodology.

Although the limit equilibrium approach requires the use of geometry to find the critical surface, with the finite element approach, the critical surface is determined automatically by different softwares. The displacement can be obtained with this method. In addition, progressive failures may be modeled with this method.

There are many publications comparing the limit equilibrium method (LEM) and finite element method (FEM). Awad-allah (2022) studied the factor of safety values of side slopes at MSW sites and they were assessed in this paper using the limit equilibrium technique and the finite element method. In this study, the modified Bishop method was used. The result can be seen in Figure 3.5.

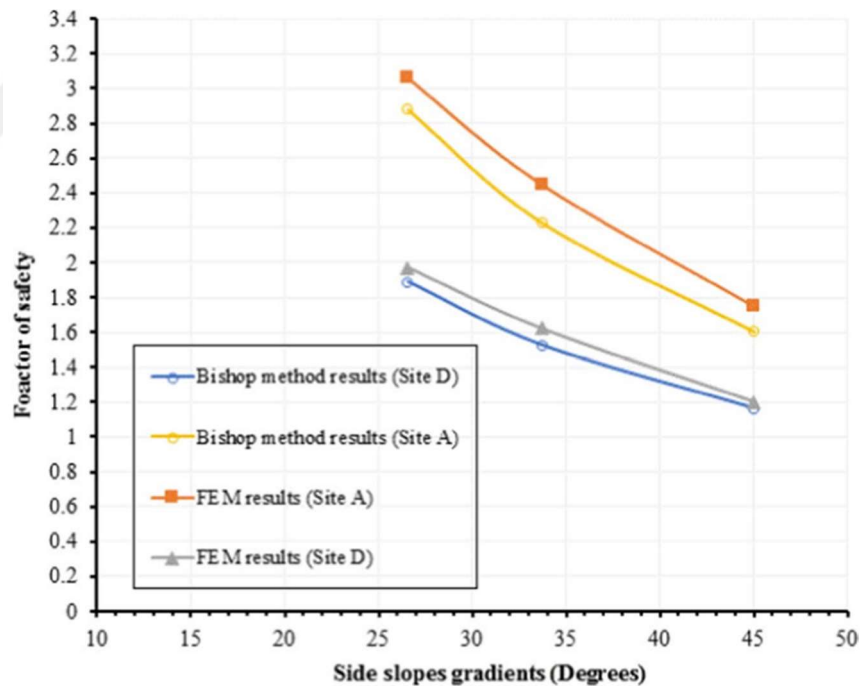


Figure 3.5: The comparison of LEM and FEM on safety factor of different MSW landfills with different slope angles.

As can be clearly seen in the graph, close factor of safety values are obtained for two landfills using both methods. In addition, as the slope angle increases, the safety factor value decreases in both cases. Considering the 1.5 safety factor, it is seen that

the 45-degree slope is not safe for Site D. As the slope increases, the risk of slope slip increases.

Keskin and Kezer (2022) also conducted some slope stability analysis to see the cohesion-FS and internal friction-FS changes with limit equilibrium (Bishop) and finite element analysis. The results are shown in Figure 3.6 and 3.7, respectively.

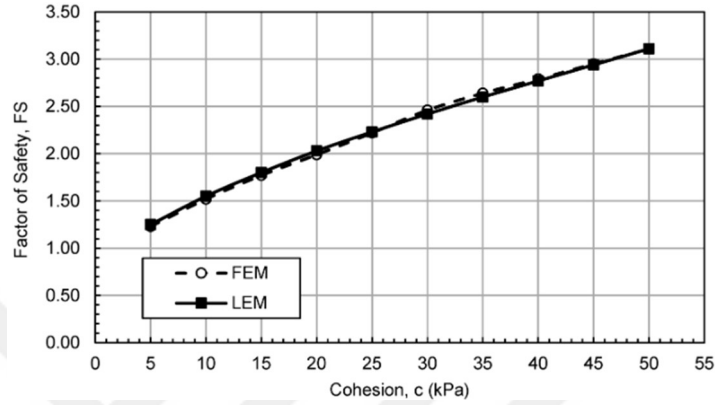


Figure 3.6: Cohesion-FS graph with Limit Equilibrium and Finite Element Methods.

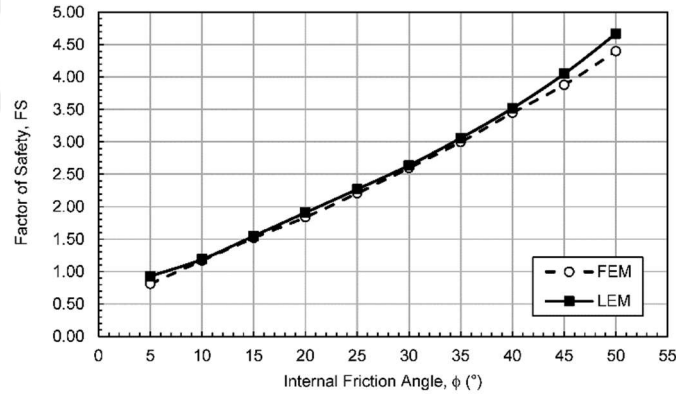


Figure 3.7: Internal Friction Angle-FS graph with Limit Equilibrium and Finite Element Methods.

As shown in graphs, it is seen that the limit equilibrium and finite element methods give very close results. In the analysis for smart decision tool, Bishop method, which is a limit equilibrium method, was used.

3.2. Factors Affecting Landfill Slope Stability

The factors that affect the landfill slope stability are primarily landfill geometry, which includes landfill height and slope angle, unit weight and shear strength of the waste, leachate level in the landfill which can increase because of rainfall or water in waste, and seismicity of the area. Each factor and their characteristic values are discussed below.

3.2.1. Landfill Height

The risk of landslide may increase if the landfill height is increased too much. Toprak and Dal (2022) showed the change of safety coefficients obtained with the change of landfill height for fixed waste characteristics for static and dynamic situations as in Figure 3.8.

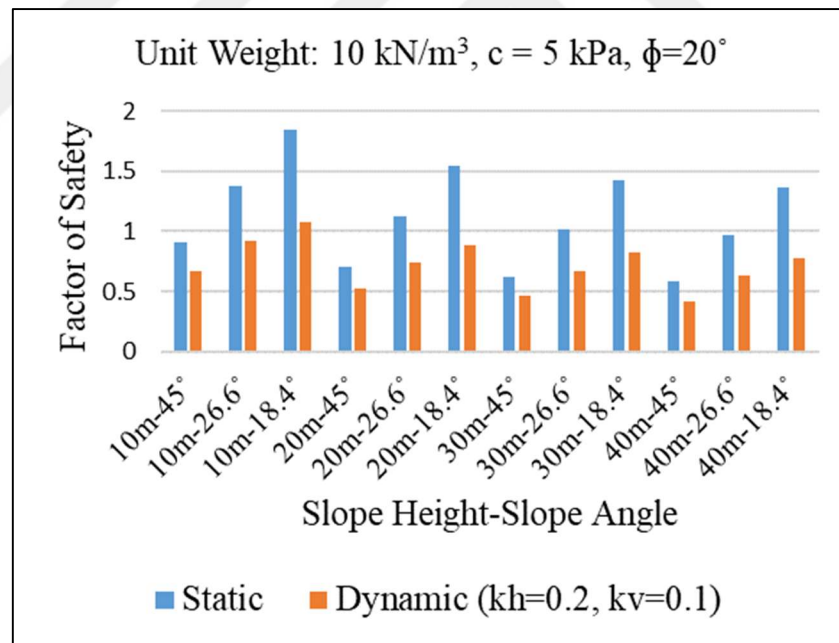


Figure 3.8: Variation of FS values depending on landfill height in static and dynamic conditions.

According to the graph, it is clearly seen that the factor of safety decreases with increasing landfill height for each slope angle.

3.2.2. Slope Angle

Awad-Allah [2022] performed some slope stability analysis in landfill areas for different side slope angles (26.57° , 33.69° and 45°) by using finite element method calculations. Table 3.1 provides a summary of the safety factor data and the corresponding lateral and vertical deformations.

Table 3.1: The safety factor of different landfill slopes.

Slope Angle (°)	Landfill A			Landfill B		
	FS	Lateral displacement (mm)	Vertical Settlement (mm)	FS	Lateral displacement (mm)	Vertical Settlement (mm)
26.57	2.96	26.00	1880	1.97	16.48	1190
33.69	2.35	29.61	1880	1.62	20.20	1200
45	1.67	36.50	1890	1.20	23.30	1200

According to the table, it is seen that the factor of safety decreases as the slope angle in the landfill increases. Furthermore, the change in lateral displacement values is not small as the slope angle increases. However, the slope angle does not have much effect on vertical settlement.

With the amendment made within the scope of the “Regulation on Landfilling of Wastes” used in Turkey, the waste cell and lot slope should be made as 1/3 at most in order to ensure slope stability in the landfill site and to allow the machinery and vehicles in the field to move freely [Official Gazette 1, 2010]. Therefore, the rise in the slope angle increases the risk of slope failure. Accordingly, it is important to keep the slope angle under regular control in the landfill.

3.2.3. Unit Weight and Permeability Coefficient

The unit weight of MSW can vary considerably. One of the reasons for this is the MSW content. The MSW content stored in the landfill can vary from country to country, city to city, and even from one landfill within the city to another landfill. For instance, while there may be more plastic or metal garbage in certain landfills than

others, there may also be more organic waste in some landfills than in others. Another reason for variability is waste decomposition that occurs over time.

In addition, years after the wastes are placed with the landfill, a natural compaction occurs by placing other wastes on it, and changes depending on the depth can be seen in the MSW unit weight.

The dry unit weight and permeability coefficient values of MSW can be seen in Table 3.2 [Yang et al., 2016].

Table 3.2: The dry unit weight and permeability coefficient values for MSW.

Source	Dry Unit Weight (kN/m ³)	Permeability Coefficient (cm/sec)	Test Method
Jang et al. (2002)	7.8-11.8	$1.1 \times 10^{-3} - 2.9 \times 10^{-4}$	Constant Head
Koerner and Eith (2005)	-	$1.2 \times 10^{-2} - 6.9 \times 10^{-2}$	Flow columns
Durmusoglu et al. (2006)	-	$4.7 \times 10^{-4} - 1.2 \times 10^{-2}$	Falling head
Jain et al. (2006)	3-6 m depth	$6.1 \times 10^{-5} - 5.4 \times 10^{-6}$	Borehole permeameter
	6-12 m depth	$2.3 \times 10^{-5} - 5.6 \times 10^{-6}$	
	12-18 m depth	$1.9 \times 10^{-5} - 7.4 \times 10^{-6}$	
Hossain et al. (2009)	6.4-9.3	$1.0 \times 10^{-2} - 8.0 \times 10^{-4}$	Constant Head
Stoltz and Gourc (2010)	3.6-5.9	$1.6 \times 10^{-1} - 4.9 \times 10^{-4}$	-
	4.8-5.9	$1.0 \times 10^{-2} - 1.1 \times 10^{-3}$	

Stark et al (2009) also shared some unit weight values found by different researchers in different locations as shown in Table 3.3.

Table 3.3: The unit weight values of MSW and their location and waste contents.

References	Sample location	Waste constituents and properties	Unit weight (kN/m ³)
Landva and Clark (1990)	Edmonton, Calgary, Mississauga, Waterloo in Canada	20–55% paper products, 5–42% food waste, 4–20% garden waste, 6–15% metal, and 2–15% plastic	10–14
Richardson and Reynolds (1991)	Maine	-	16
Withiam et al. (1995)	Dekorte Park landfill, NJ	Glass, paper, cinders, plastic, metal, and building debris	10.8–12.8
Edinçliler et al. (1996)	Southeastern Wisconsin landfill	Fresh waste	7.5–14.2
Siegel et al. (1990)	California landfill	10–48 years old waste	9.6–17.3
Del Greco and Oggeri (1994); Oweis and Khera (1998)	No information	Baled MSW	5–7
Gabr and Valero (1995); Van Impe (1998)	Pennsylvania landfill	33% ash, soil, and rock; 23% textiles; 13% plastic; 10% metals; etc. 15–30 years old	10–12.1
Mazzucato et al. (1999)	Italy landfill	-	7
Thomas et al. (1999)	Torcy, France	20% plastic, 21% paper, and 11% textile	7.8–16
Pelkey et al. (2001); Pelkey (1997)	Three landfills in Canada	Shredded and unshredded MSW 2–5 year-old waste	10–16
Machado et al. (2002)	Sao Paulo, Brazil	55% soil and organic plastic, 17% plastics, 10% stones, etc. 15 year-old waste	10
Vilar and Carvalho (2004)	Sao Paulo, Brazil	55% soil and organic plastic, 17% plastics, 10% stones, etc. 15 year-old waste	10–12
Gomes et al. (2005)	Portugal	37% plastic, 33% textiles, 11% soil, and 10% metal	11.5
Harris et al. (2006)	Mohawk landfill, NY; Outer Loop landfill, KY	Shredded and processed MSW 2–10 year-old waste	11–7.5
Isenberg (2003)	Hiriya landfill, Israel	Decomposed waste	16
Caicedo et al. (2002a)	Dona Juana landfill, Colombia	48% organic matter; 45% paper, textile, and plastic; and 7% soils, metals, and glass Fresh MSW	10

In addition, Mehdizadeh et al. (2020) obtained literature data from different sources and shared it on MSW unit weight [Babu et al., 2014] [Shariatmadari et al. 2014, 2015] [Jahanfar et al. 2017] [Alidoust et al. 2018] as shown in Table 3.4.

Table 3.4: MSW unit weight data in the literature.

Author	Year	Unit weight (kN/m ³)		Author	Year	Unit weight (kN/m ³)
Landva & Clark	1986	8.08 to 15.4		Kavazanjian et al.	2001	6 to 20
Siegel et al	1990	9.6 to 17.3		Machado et al.	2002	10
Watts and Charles	1990	6 to 8		Caicedo et al.	2002	10
Landva & Clark	1990	10 to 14		Isenberg	2003	16
Del Greco & Oggeri	1994	5 to 7		Vilar & Carvalho	2004	10 to 12
Fassett et al.	1994	8 to 14		Gomes et al.	2005	11.5
Withiam et al.	1995	10.8 to 12.8		Itoh et al.	2005	6 to 7
Gabr & Valero	1995	10 to 12.1		Harris et al.	2006	7.5 to 11
Kavazanjian et al.	1995	3.3 to 12.8		Zekkos et al.	2006	5.5 to 15.5
Manassero et al.	1996	5 to 10		Matasovic et al.	2008	15
Edinçliler et al.	1996	7.5 to 14.2		Zhan et al.	2008	11
Pelkey	1997	10 to 16		Singh et al.	2009	8.8 to 15.8
Mazzucato et al.	1999	7		Yanru et al.	2012	10.22
Thomas et al.	1999	7.8 to 16		Shariatmadari et al.	2014, 2015	6.2 to 13
Stark & Eid	2000	7.3 to 10.3		Feng et al.	2016	7.2 to 12.5
Pelkey et al.	2001	10 to 16		Alidoust et al.	2018	7.5 to 13

Huang and Fan (2016) also searched for MSW physical characteristics as shown in Table 3.5.

Table 3.5: MSW physical characteristics data in the literature.

References	Unit weight (kN/m ³)	Moisture content (%)	Porosity (%)	Hydraulic conductivity (m/s)	Capacity (%)
Tianziling Hangzhou (Zhang et al. 2000)	9.0–12.0	60–110			
The recommendations for partly compaction (Qian and Guo 1998)	9.3–12.4	20–35	40–52	Magnitude 10 ⁻⁵	22.4–55
Oweis et al. (1990)	9.4–14.1 6.3–9.4	10–20	40–50	1.5 x 10 ⁻⁶ 1.1 x 10 ⁻⁵	20–35
Payatas landfill (Jafari et al. 2013)	8–14	82.5		10 ⁻³ –10 ⁻⁵	
Chen et al. (2000)	7.8–13.4	60–110	50–79		
Sto Tirso landfill (Gomes and Lopes 2012)	6–12 (surface) 8–16 (deep)	20–70			

When unit weight values in the literature are checked, unit weight limit values for smart decision tool are determined as 6 and 14 kN/m³. In addition, the variation of unit weight with depth was not taken into account in this study.

According to Turkish Building Earthquake Code (TBEC) (2018), the total stress analysis utilizing undrained shear strength (c_u) for clayey soils and the effective stress analysis for sandy (non-cohesive) soils will be used to determine slope stability in the event of an earthquake. Since its permeability is not as low as clay, effective stress analysis was used for wastes.

3.2.4. Shear Strength Parameters

MSW shear strength characteristics are important for figuring out how stable landfills are and guaranteeing system stability. Researchers have used a variety of methods, including as in-situ testing, large triaxial testing, direct shear testing, and landfill slope analysis, to analyze these parameters. Some of the MSW shear strength

parameters found in the literature can be seen in Table 3.6 [Mehdizadeh et al., 2020] and Table 3.7 [Falamaki et al., 2021].

Several factors, including deterioration age, landfill location, waste composition, testing equipment and methodology, can influence the shear strength values that are computed, therefore results from different studies can vary substantially. As a result, it is crucial to establish these values considering the unique characteristics of each landfill.

Table 3.6: MSW shear strength parameter values.

Author	Type of test	Cohesion (kPa)	Friction angel (°)	Strain (%)
Stoll (1971)	Triaxial test	0	24–42	-
Landva and Clark (1896, 1990)	Direct shear	10–23	24–42	-
Siegel et al. (1990)	Direct shear	-	39–53	10
Golder Associates (1993)	Direct shear	0	41	-
Jessberger and Kockel (1995)	Triaxial test	-	31–49	-
Del Greco and Oggeri (1994)	Direct shear	15.7–22	21–22	-
Houston et al. (1995)	Direct shear	5	33–35	-
Withiam et al. (1995)	Direct shear	10	30	-
Kavazanjian et al. (1995)	Direct shear	43	31	15
Gabr and Valero (1995)	Triaxial test	16.8	34	20
Gabr and Valero (1995)	Direct shear	0–27.5	20.5–39	-
Grisolia et al. (1995)	Triaxial test	2–3	15–20	10–15
Grisolia and Napoleoni (1996)	Triaxial test	70	45	-
Aburatani et al. (1998)	Triaxial test	-	30–35	-
Kavazanjian Jr et al. (1999)	Direct shear	43	31	10
Kavazanjian Jr et al. (1999)	Simple shear	16–30	33–59	10
Mazzucato et al. (1999)	Direct shear	43	31	Peak
Pelkey et al. (2001)	Simple shear	0	26–29.2	Peak
Pelkey et al. (2001)	Direct shear	0–28	16.8–37	5
Caicedo et al. (2002a)	Direct shear	67	23	6.7
Machado et al. (2002)	Triaxial test	0–70	14–28	5–20
Hossain (2002)	Direct shear	0	24–32	-
Caicedo et al. (2002b)	Triaxial test	14	45	-
Vilar and Carvalho (2004)	Triaxial test	23.3–77.4	20–32	10–30
Mahler and De Lamare Netto (2003)	Direct shear	2.5–4	21–36	-
Feng (2005)	Triaxial test	4–55	10–19	5–15
Zekkos et al. (2006)	Triaxial test	0	36–41	-
Zwanenburg et al. (2007)	Triaxial test	0	35–37	-
Zhan et al. (2008)	Triaxial test	0–23	9.9–39	10
Reddy et al. (2008)	Triaxial test	32–38	12–16	15
Dixon & Jones (2005)	Direct shear	0	34	-
Reddy et al. (2009a)	Direct shear	12–63	31–35	15
Reddy et al. (2009b)	Direct shear	31–64	26–30	15
Reddy et al. (2011)	Direct shear	1–40	28–35	15
Reddy et al. (2011)	Triaxial test	18–56	1–11	15
Shariatmadari et al. (2014)	Triaxial test	11–36	10–45	-
Feng et al. (2016)	Direct shear	18–29	15–22	20
Zekkos and Fei (2016)	Simple shear	0	19–24	-

- not reported

Table 3.7: MSW shear strength parameter values and unit weights.

Reference	Unit weight (kN/m ³)	c (kPa)	ϕ (degrees)	Age (years)
Abreu and Vilar (2017)	8–15	0–14	22–34	2–25
Ali et al. (2009)	10	6.63	25.1	10
Bareither et al. (2012)	5.7–8.5	9–22	31–42	0.4
Caicedo et al. (2002)	8.15	78	23	1
Edinçiler et al. (1996)	9.84	27	42	Fresh
Falamaki et al. (2020)	7–11	21–39	25–36	0–10
Gabr and Valero (1995)	11	14	30	15–30
Gotteland et al. (2001)	7.5–10.7	20–55	18.27	> 10 years
Jones et al. (1997)	–	10.5	31	0.3
Kavazanjian Jr et al. (1999)	–	43	31	> 15 years
Miyamoto et al. (2014)	10–12	3.5–6	32–50	–
Pelkey et al. (2001)	11.3	0	29	Fresh
Ramaiah et al. (2017)	7.5–11.5	0–21.3	33–40	2
Reddy et al. (2009)	–	31–64	26–30	Fresh
Singh et al. (2009)	9.5	14	36	> 10 years
Zekkos et al. (2010)	14.5	25	35	0–15 years

According to the results mentioned in the literature, the cohesion limit was determined in the range of 0–80 kPa, and the internal friction angle was determined in the range of 0–50 degrees. Users will not be able to enter any value other than these limits in the smart decision tool.

3.2.5. Seismic Parameters

The horizontal seismic coefficient (k_h) denotes a horizontal seismic force that is directed away from the slope. Therefore, its direction is the failure direction. It is always positive. However, it is possible for the vertical seismic coefficient to be positive or negative. When the vertical seismic coefficient is positive, the seismic force is exerted downwards. When the vertical seismic coefficient is negative, the seismic force is being exerted in an upwards direction.

Toprak and Dal (2022) assessed the effect of k_h and k_v on FS values for open dumps as shown in Figure 3.9. In the analyses to get this graph, it is assumed that the ground is strong enough.

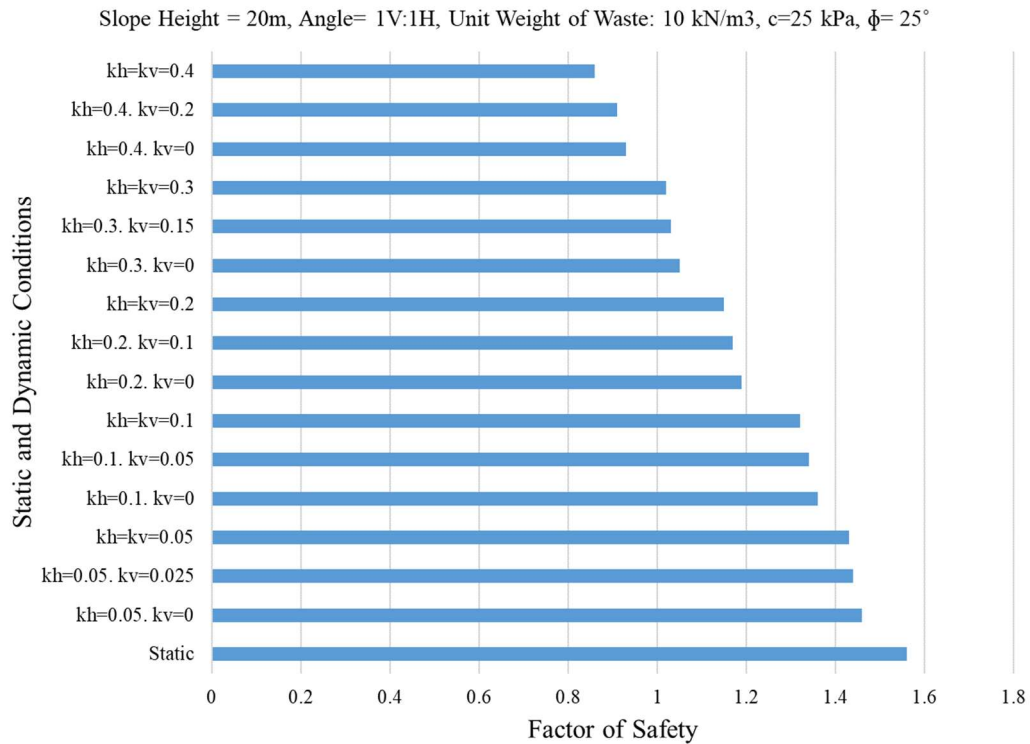


Figure 3.9: The effect of k_h and k_v changes on factor of safety.

According to the figure above, it can be said that the k_h and k_v parameters increase, so the earthquake effect increases and as a result, the safety factor decreases. Also, the effect of the k_h parameter on FS is greater than k_v parameter. In addition, a MSW landfill stable under the static conditions may fail as a result of an earthquake. In this case, a landfill that does not collapse in a static condition may collapse as a result of an earthquake. From this point of view, ignoring the earthquake effect for the landfills in seismic zones can lead to severe consequences.

Different minimum FS values are used in different countries in the seismic situation. Many New Zealand engineers use pseudo-static techniques to represent seismic loading in standard limit-equilibrium analyses in order to evaluate seismic slope stability performance. In New Zealand, these evaluations often use an FS of 1.0 or 1.1 as the minimal level of safety [Gerbrandt, 2015]. Also, Table 3.8 shows how this standard takes into account the uncertainty in the safety analysis methods and input variables [Park et al., 2018].

Table 3.8: Korean safety conditions.

Category	Factor of Safety
Dry season	FS > 1.5
Wet season	FS > 1.2
	FS > 1.3 (when considering rainfall permeation)
In case of earthquake	FS > 1.1

Moreover, the desired safety factor for the pseudo static slope stability study is 1.1 for slope instability caused by earthquakes. It is valid with or without soil strength loss as a consequence of deformation caused by seismic shaking (for example, weakening instability owing to clay strength loss) [WSDOT, 2021].

According to TBEC (2018), a value of 1.10 can be considered as an adequate level of security against slope failure, except in cases involving special risks. For smart decision tool, 1.2 value was used in dynamic state. In some extreme cases where the cohesion is high and the internal friction angle is 0 or close to 0, there can be up to 8% margin of error in the FS value obtained.

3.2.6. Leachate Level and Rainfall

If the water level start to increase, the pore water pressure will be get higher, which will lower effective stress and shear strength. For example, in the slope failure that occurred in Indonesia on February 21, 2005, the failure occurred after 3 days of heavy rain. Also, before Payatas Landfill failure, the weather in Quezon City was very bad. In the 10 days before the failure, 750 mm of rain dropped there [Blight, 2008]. Therefore, leachate collection system is of great importance in landfills. In addition, surface waters must also be removed from the landfill. Open dumps (uncontrolled landfills) that do not have such systems must no longer be used, and those used must be rehabilitated immediately.

3.3. Slope Stability Analyses

Slope stability analyses for landfills were performed using GEO5 software. Bishop method, one of the limit equilibrium methods, was used in the analysis. In limit equilibrium methods, many failure surfaces are analyzed to determine which has the lowest FS.

3.3.1. Parameters used in the Analyses

Slope stability analyses were performed for static and dynamic conditions. In these analyses, the water (leachate) level was considered in three different ways. The first is when there is no leachate in the landfill; the second is when the leachate level is 1/4 of the landfill height; and the last is when the leachate level is 3/4 of the landfill height. The view of a slope stability analysis in GEO5 is shown in Figure 3.10. In the analyses, different values for x distance were taken according to the height of the landfill. Besides, the depth of the subsoil does not affect the analysis results, it only has a visual effect.

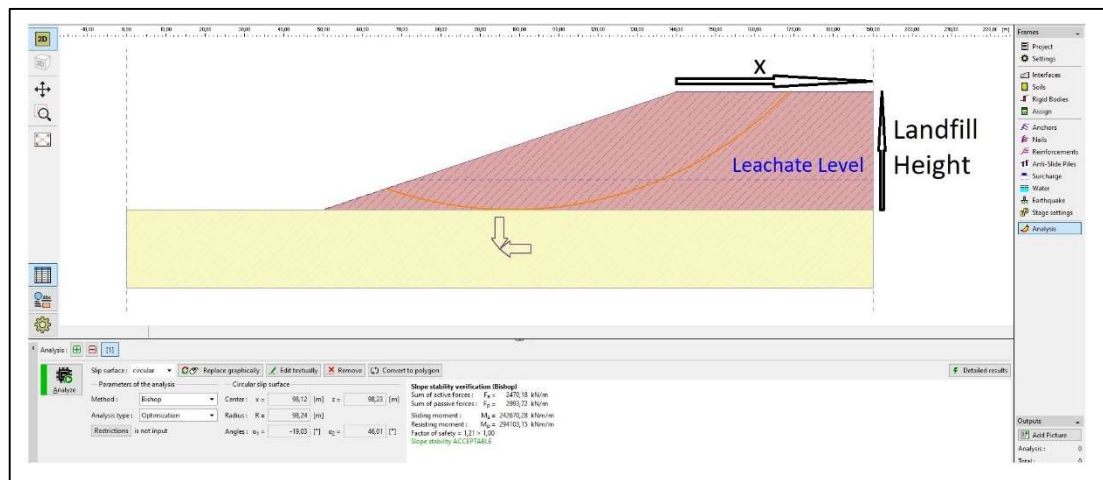


Figure 3.10: The view of a slope stability analysis in GEO5.

In addition, it is aimed to find minimum conditions that meet certain factor of safety (FS) values in static and dynamic conditions in the analyses. The minimum friction angle which provides the stable conditions for a specific landfill height, angle, waste unit weight, waste cohesion, horizontal (k_h) and vertical seismic coefficients (k_v)

has been found to obtain a FS equal to or greater than a predetermined FS in the static and dynamic conditions. While the minimum FS value is taken as 1.6 and 1.1 for static conditions representing different states, it is taken as 1.2 for dynamic conditions.

Slope stability analyses were made according to the safety factor of about 1.6. This approach was chosen to stay on slightly safe side due to some simplifications and other errors that may occur while obtaining the equation for smart decision tool or making the slope stability analysis. According to US Army Corps of Engineers (2003), for slopes, typical minimum allowable values of the factor of safety are 1.5 for typical long-term loading circumstances and approximately 1.3 for multistage and end-of-construction loading. In the smart decision tool, this FS is accepted as equivalent to stable condition which is defined as 1.5 in many design codes and regulations. The following descriptions were used in the smart decision tool for stability conditions.

If the safety factor is greater than 1.5, it is safe. If it is less than 1.5, it is unsafe and detailed evaluation should be made. If it is less than 1.1, it is unsafe and immediate action is required. The value of 1.1 indicates that the slope is very close to the collapse state. It is aimed to minimize the differences that may arise from simplifications or other possible errors in the operations performed for smart decision tool by taking it slightly larger than 1.

In the analysis, it was assumed that the subsoil was strong enough to carry the waste and that the sliding surface did not enter the subsoil.

Unit weight, cohesion and internal friction angle of MSW were determined according to the literature as described previously and used in the analyses. For unit weight, values between 6 and 14 kN/m³ are determined. In case of leachate level in landfill, saturated unit weight of MSW is defined as 7-15 kN/m³. Cohesion values are chosen in the range of 0-80 kPa (0,1,5,10,15,20, ..., 80), and internal friction angle values are between 0-50°. The MSW parameters and values taken into account in the analysis are shown in Table 3.9.

Table 3.9: The parameters used for MSW.

Layer Name	Unit Weight (kN/m ³)	Saturated Unit Weight (kN/m ³)	Cohesion (kPa)	Internal friction angle (°)
MSW	6-14	7-15	0-80	0-50

Besides, the landfill heights and angles used in the analyses are given in Table 3.10. Moreover, horizontal (k_h) and vertical seismic coefficients (k_v) used in the analysis of seismic conditions are provided in Table 3.11. Since the slope stability software does not automatically take the k_v value as positive and negative, the cases of k_v being positive and negative were analyzed separately each time, the friction angle value was obtained according to the k_v , which gives the minimum FS.

Table 3.10: The landfill geometry parameters used in the analysis.

Landfill Height (m)	Landfill Slope (V:Vertical, H:Horizontal)
10, 20, 30, 40, 50, 60	1V:3H, 1V:2H, 1V:1H

Table 3.11: The earthquake parameters used in the analysis.

k_h	k_v
0.05, 0.1, 0.2, 0.3, 0.4	k_h , $k_h/2$, 0

4. RESULTS OF SLOPE STABILITY ANALYSES

This section presents the results of the analyses performed by using the parameters discussed above. In the slope stability analyses, a parametric study with different unit weights, cohesions, and internal friction angles representing the waste and different leachate levels in the landfill were used. The pseudostatic dynamic stability analyses were also performed by using different horizontal (k_h) and vertical (k_v) seismic coefficients.

4.1. The effect of the Parameters Related to Landfill Slope Stability

The effects of the parameters on the landfill slope stability are shown by the graphics drawn considering the data obtained from the analysis. In all graphs, the x-axis represents the cohesion of the waste and the y-axis represents the internal friction angle of the waste.

The analyses can be grouped under 4 main headings according to the earthquake and leachate situation. They are static and dry condition, static with low and high leachate conditions, dynamic and dry condition, dynamic with low and high leachate conditions. In these cases, 3/4 of the landfill height was taken as the high leachate level and 1/4 of the landfill height was taken as the low leachate level.

4.1.1. Static and Dry Conditions

The effect of the parameters like waste shear strength, landfill height, landfill slope angle and unit weight of waste on factor of safety for static and dry condition (no leachate in the waste) can be seen in Figures 4.1 and 4.2. In Figure 4.1, lines show the necessary cohesion and internal friction angle values to represent $FS=1.6$ and no water condition. Each line displays a different unit weight. In these graphs, if cohesion and internal friction angle values of the waste fall below the line shown in the Figure 4.1, the stability of the landfill slope is below 1.6 indicating unsafe condition. In this case, the smart decision tool outputs "NOT SAFE - Detailed reassessment is required". Likewise, Figure 4.2 shows $FS=1.1$ condition. If cohesion and internal friction angle

values of the waste fall below the line shown in the Figure 4.2, the stability of the landfill slope is below 1.1 indicating unsafe condition. In this case, the smart decision tool outputs "NOT SAFE -Immediate action is required".



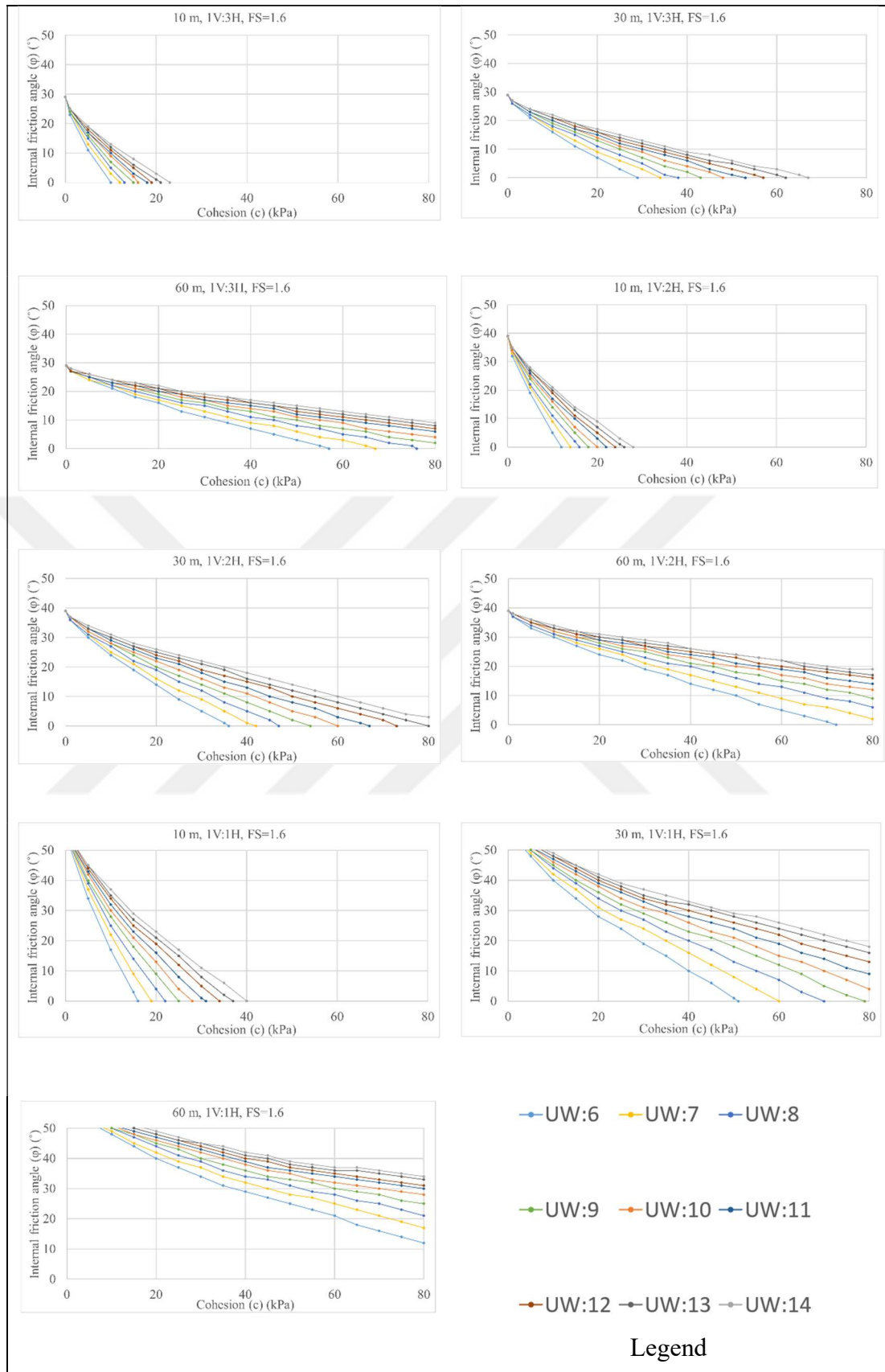


Figure 4.1: The effect of the parameters like unit weight, cohesion and internal friction angle for $FS \geq 1.6$, no water condition and different landfill height and slopes.

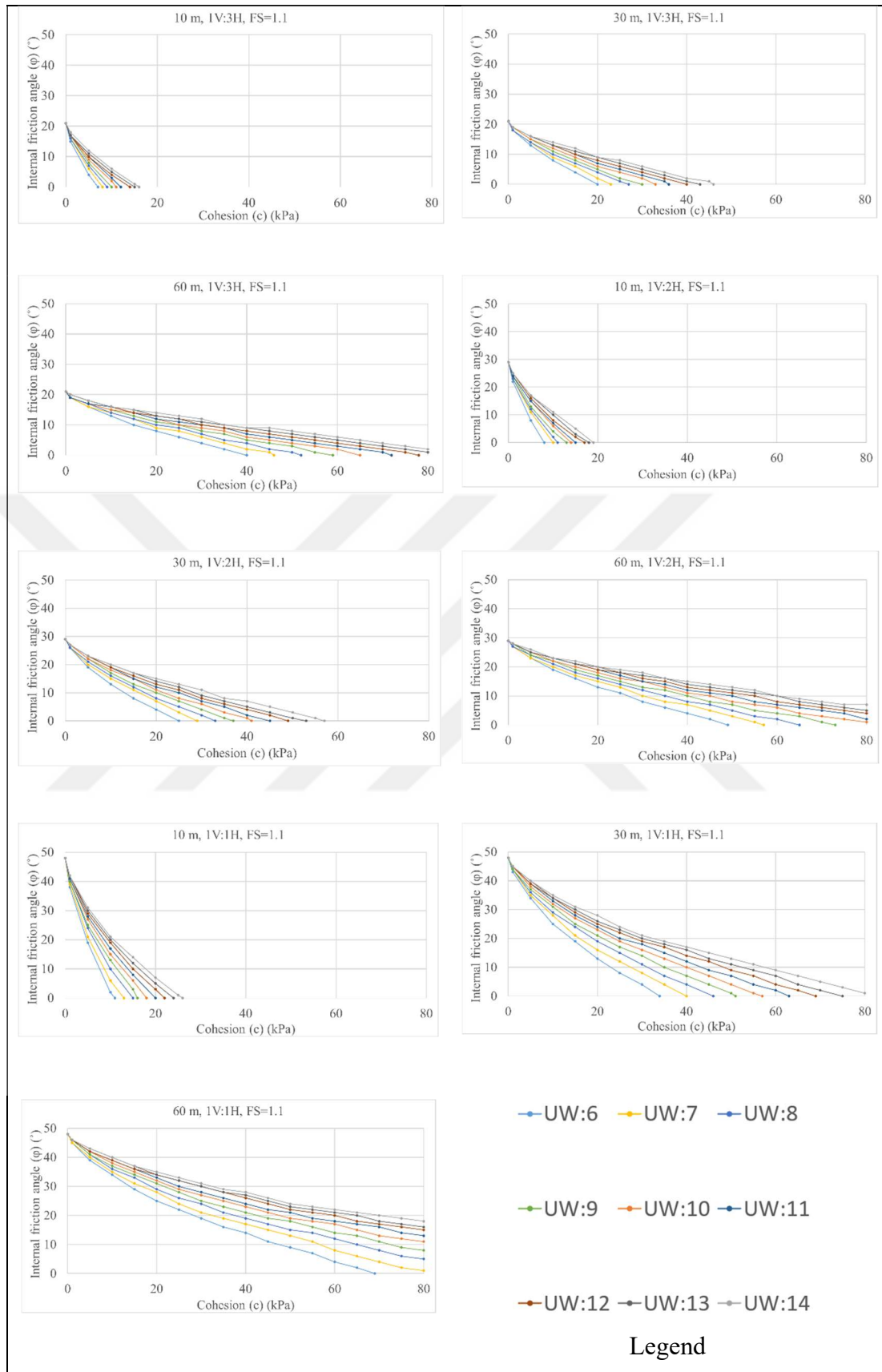


Figure 4.2: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.1$, no water condition and different landfill height and slopes.

According to Figure 4.1 (for FS=1.6), as the height of the landfill increases, the internal friction angle that the waste must have in order to stay on the safe side does not change, while the cohesion value that the waste should have increases approximately 2-3 times for the landfill heights increasing from 10 m to 30 m and from 30 m to 60 m landfill heights.

However, when the height is constant, both the internal friction angle that the waste should have and the cohesion value increase if the slope angle increases. With the change of the angle, the increase for the internal friction angle is around 50%, while the increase for the cohesion is around 25% for the landfill angles increasing from 1V:3H to 1V:2H and from 1V:2H to 1V:1H landfill slope angles.

In every case where the angle and height change, the cohesion and internal friction angle values that the waste should have are lower for the waste with low unit weight, while the cohesion and internal friction angle that the waste should have is higher for the waste with high unit weight. Also, the effect of unit weight changes little with the change of angle and height.

Considering that the waste properties above these lines give values greater than the relevant FS value, it is important to note that at a landfill height of 60 m, high cohesive wastes (at least about 45-50 kPa) must be present in order to remain on the safe side for any angle with a low internal friction angle (<5 degrees). While the waste has a low cohesion value (<5 kPa) at a landfill height of 60 m, a very high internal friction angle is not required at low slope angles (about 25°), while at high slope angles the internal friction angle must be higher than 50° to stay on the safe side. In this case, it is seen that wastes with low cohesion at 60 m landfill height and 45° slope angle will be unsafe under all conditions.

According to Figure 4.2 (for FS=1.1), as the height of the landfill increases, the internal friction angle that the waste must have in order to stay on the safe side does not change, while the cohesion value that the waste should have increases approximately 2-3 times for the landfill heights increasing from 10 m to 30 m and from 30 m to 60 m landfill heights. It is similar to FS=1.6 condition.

However, when the height is constant, both the internal friction angle that the waste should have and the cohesion value increase if the slope angle increases. With the change of the angle, the increase for the internal friction angle is around 50%, while the increase for the cohesion is around 25% for the landfill angles increasing from

1V:3H to 1V:2H and from 1V:2H to 1V:1H landfill slope angles. It is also similar to FS=1.6 condition.

In every case where the angle and height change, the cohesion and internal friction angle values that the waste should have are lower for the waste with low unit weight, while the cohesion and internal friction angle that the waste should have is higher for the waste with high unit weight. Also, the effect of unit weight changes little with the change of angle and height.

Considering that the waste properties above these lines give FS values greater than 1.1, it is important to note that at a landfill height of 60 m, high cohesive wastes (at least about 30 kPa) must be present in order to get FS>1.1 condition for any angle with a low internal friction angle (<5 degrees). While the waste has a low cohesion value (<5 kPa) at a landfill height of 60 m, a very high internal friction angle is not required at low slope angles (about 18°), while at high slope angles the internal friction angle must be higher than 40° to get FS>1.1 condition.

4.1.2. Static with Low and High Leachate Conditions

Figures 4.3-4.6 show the effect of the parameters like waste shear strength, landfill height, landfill slope angle and unit weight of waste on factor of safety for static with low (leachate height is equal to H/4) and high (leachate height is equal to 3H/4) leachate condition.

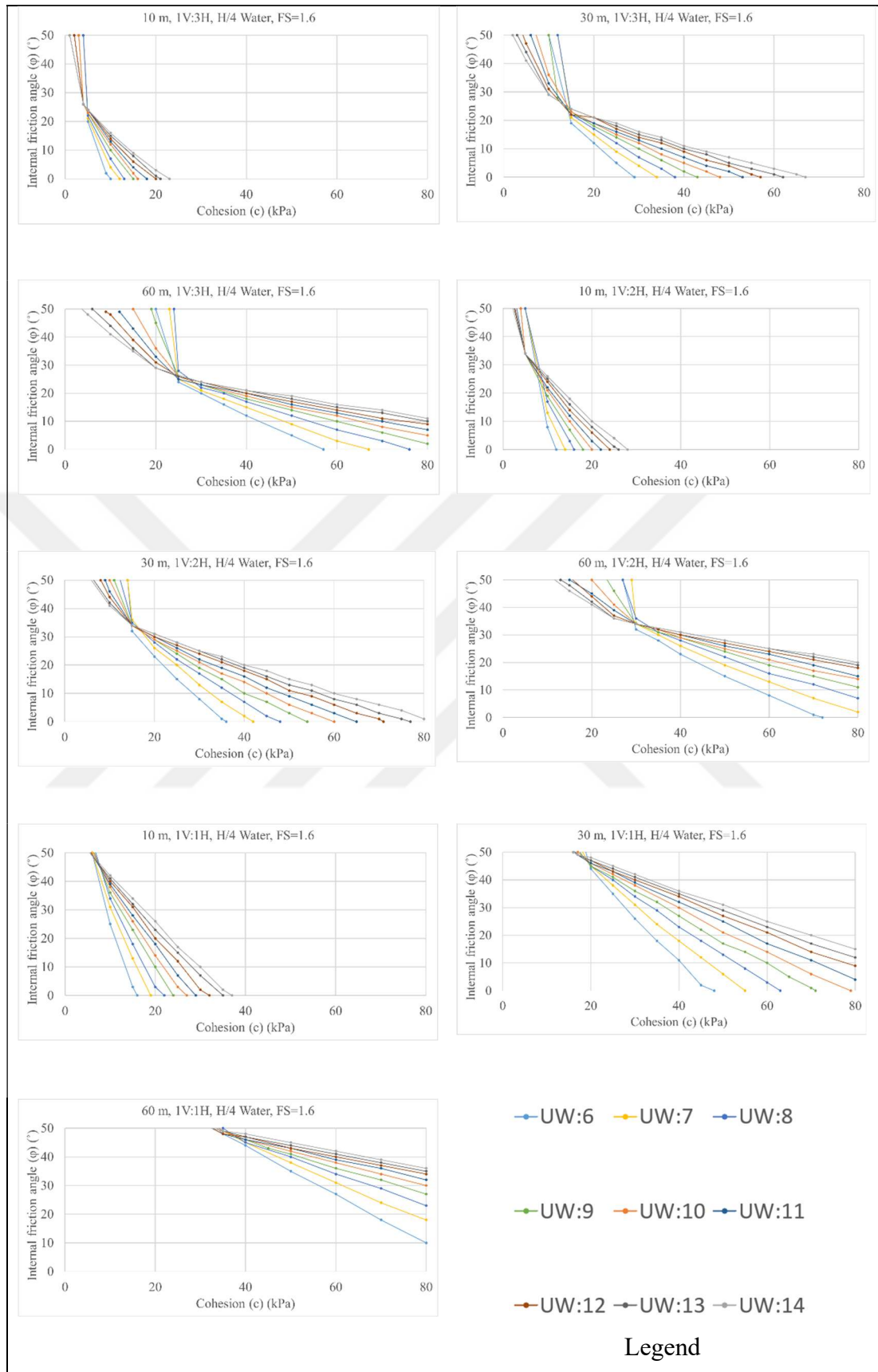


Figure 4.3: The effect of the unit weight, cohesion and internal friction angle for FS ≥ 1.6 , H/4 water condition and different landfill height and slopes.

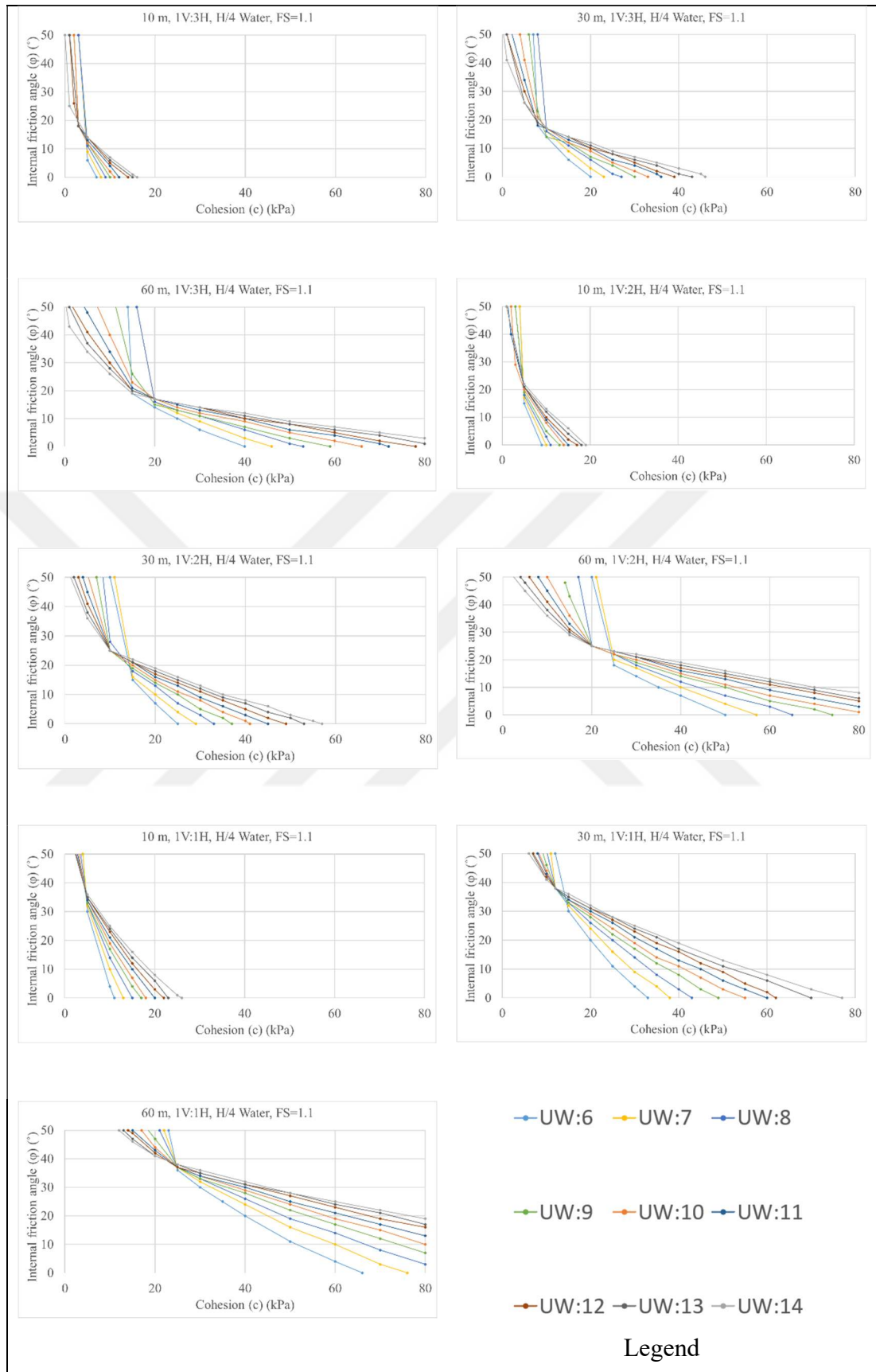


Figure 4.4: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.1$, H/4 water condition and different landfill height and slopes.

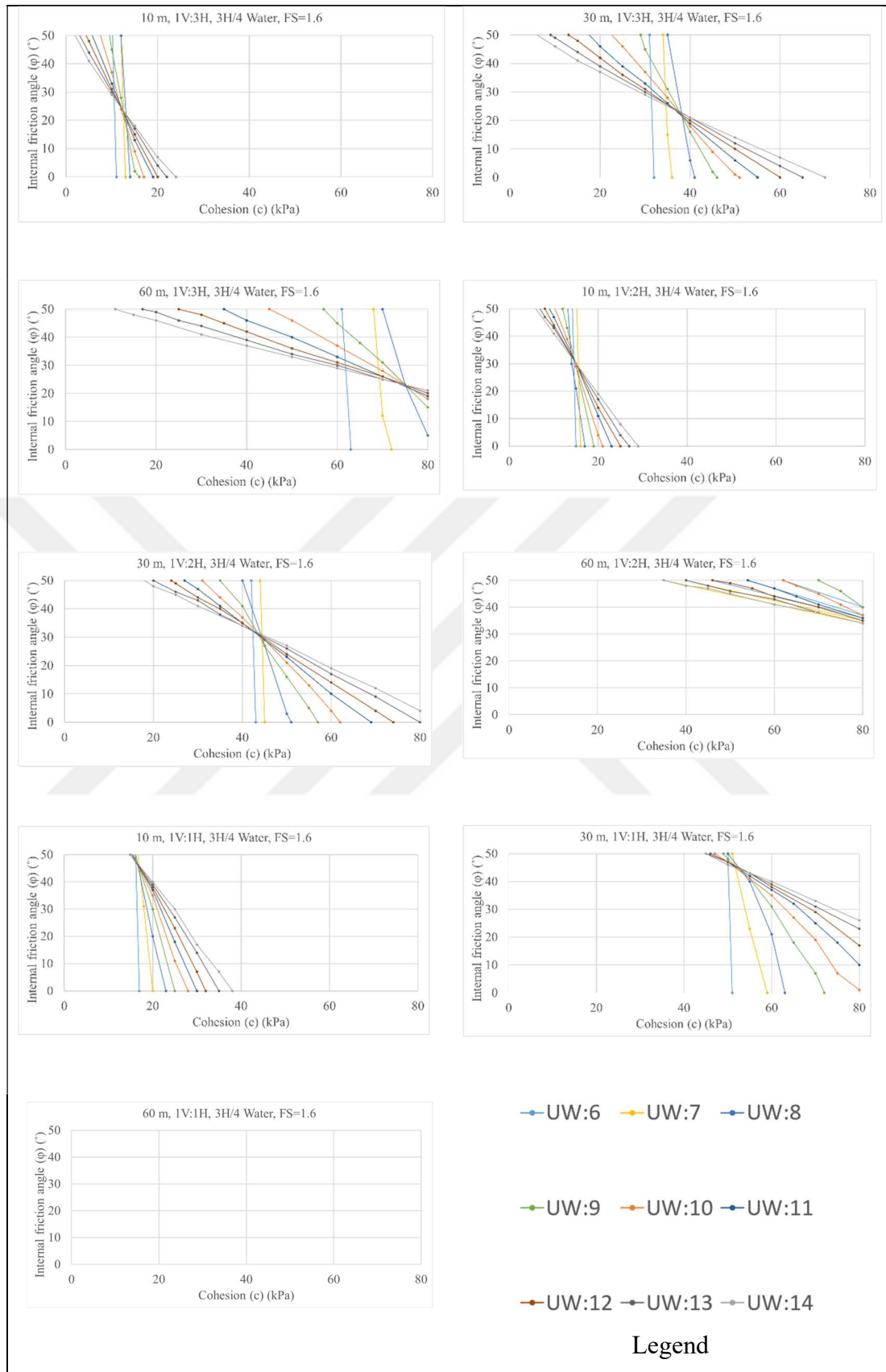


Figure 4.5: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.6$, 3H/4 water condition and different landfill height and slopes.

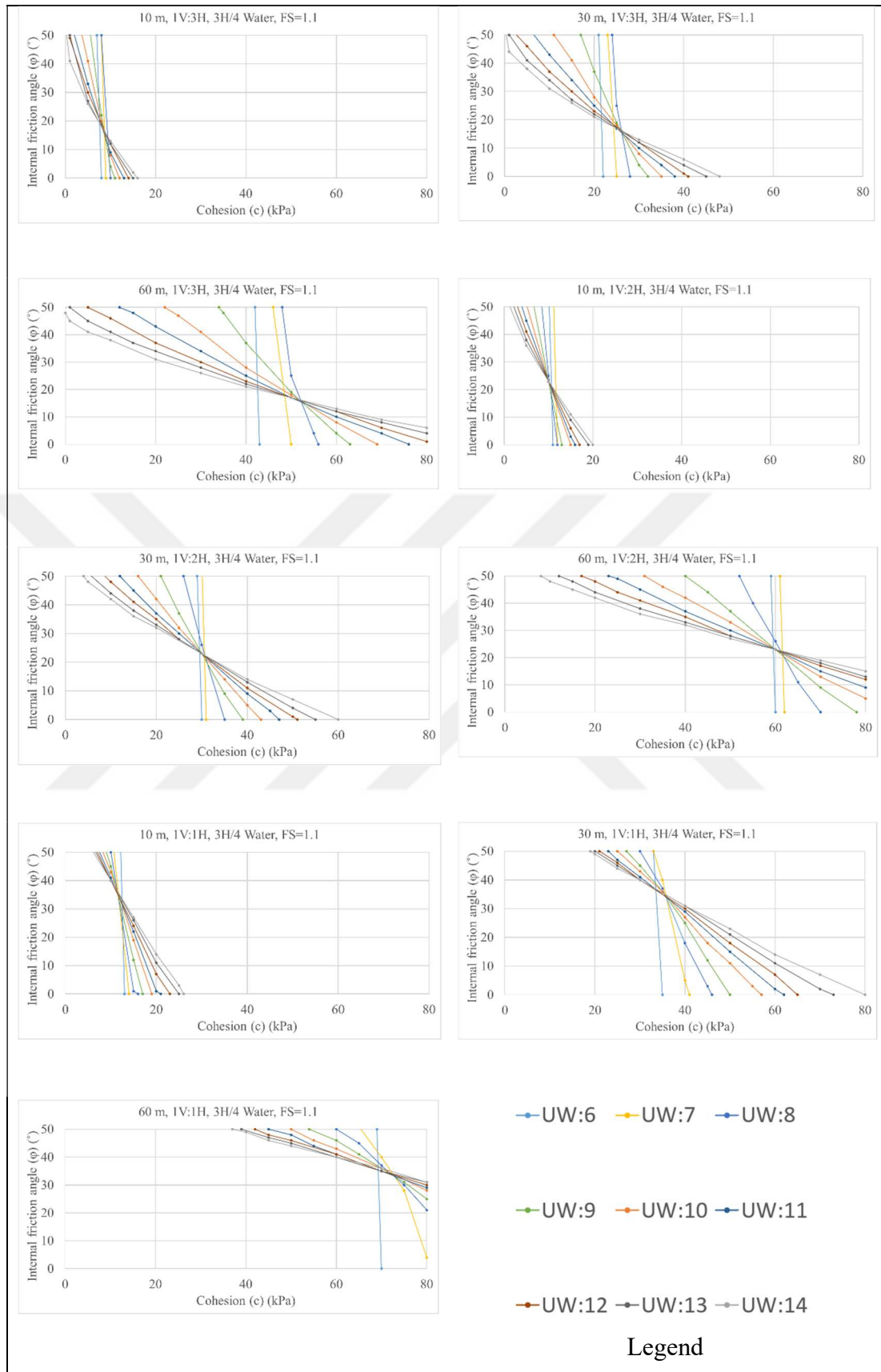


Figure 4.6: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.1$, 3H/4 water condition and different landfill height and slopes.

According to Figure 4.3 (for $FS=1.6$ and leachate height= $H/4$), as the height increases, the waste cohesion value that the waste should have increases approximately 2-3 times if the waste has low internal friction angles. Friction angle of waste must be about 50° when the cohesion of waste is low.

The internal friction angle of wastes for all waste unit weights started from 50° in the figures. The reason for this can be explained with a random example. While the waste cohesion is 4 kPa and the friction angle of waste is 50° , the safety factor cannot exceed 1.6. However, a safe condition is encountered with a FS greater than 1.6 when the cohesion is 5 kPa with the same waste internal friction angle. Therefore, to stay on the safe side, the cohesion is 5 kPa and the internal friction angle is taken as 50° to provide safe condition. In fact, an internal friction angle value of less than 50° while the cohesion is 5 kPa could achieve a safety number of 1.6, but to stay on the safe side, cohesion of 5 kPa and an internal friction angle of 50 degrees were assumed to be safe.

In general, where the angle and height change, the cohesion and internal friction angle values that the waste should have are lower for the waste with low unit weight, while the cohesion and internal friction angle that the waste should have is higher for the waste with high unit weight. Also, the effect of unit weight changes little with the change of angle and height.

Unit weight is very important especially in case of 60 m height and 1V:3H. For example, even if the internal friction angle is 50° , an extra waste cohesion value in the range of 5-25 kPa is required according to the waste unit weight value.

According to Figure 4.4 (for $FS=1.1$ and leachate height= $H/4$), as the height increases, the waste cohesion value that the waste should have increases approximately 2-3 times if the waste has low internal friction angles. Friction angle of waste must be about 50° when the cohesion of waste is low.

The reason for starting directly at 50 degrees, for example, when the cohesion of the waste is 5 kPa, normally lower values of the internal friction angle provide $FS=1.1$, but not the case where the cohesion value of the waste is equal to 4 kPa and the internal friction angle is 50° . Therefore, to stay on the safe side, the cohesion is 5 kPa and the internal friction angle is taken as 50° .

In this condition, all heights and angles shown in the Figure 4.4 have breaking lines. It is related to stay on the safe side as mentioned just before.

In general, where the angle and height change, the cohesion and internal friction angle values that the waste should have are lower for the waste with low unit weight,

while the cohesion and internal friction angle that the waste should have is higher for the waste with high unit weight. Also, the effect of unit weight changes little with the change of angle and height.

Unit weight is also very important especially in case of 60 m height and 1V:3H. For example, even if the internal friction angle is 50° , an extra waste cohesion value in the range of 0-18 kPa is required according to the waste unit weight value.

According to Figure 4.5 (for FS=1.6 and leachate height=3H/4), as the height increases, the waste cohesion value that the waste should have increases approximately 2-3 times if the waste has low internal friction angles. Friction angle of waste must be about 50° when the cohesion of waste is low.

The reason for starting directly at 50 degrees, for example, when the cohesion of the waste is 5 kPa, normally lower values of the internal friction angle provide FS=1.1, but not the case where the cohesion value of the waste is equal to 4 kPa and the internal friction angle is 50° . Therefore, to stay on the safe side, the cohesion is 5 kPa and the internal friction angle is taken as 50° .

There are no breaking lines in this condition. In addition, in the case of 60 m 45 degrees, it is not safe regardless of the characteristics of the waste. Therefore, there is no data in the Figure 4.5i.

In general, where the angle and height change, the cohesion and internal friction angle values that the waste should have are lower for the waste with low unit weight, while the cohesion and internal friction angle that the waste should have is higher for the waste with high unit weight. Also, the effect of unit weight changes little with the change of angle and height.

According to Figure 4.6 (for FS=1.1 and leachate height=3H/4), similar to the conditions before, as the height increases, the waste cohesion value that the waste should have increases approximately 2-3 times if the waste has low internal friction angles. Friction angle of waste must be about 50° when the cohesion of waste is low in general.

In general, where the angle and height change, the cohesion and internal friction angle values that the waste should have are lower for the waste with low unit weight, while the cohesion and internal friction angle that the waste should have is higher for the waste with high unit weight. Also, the effect of unit weight changes little with the change of angle and height. In addition, when the landfill height is 60 m, the slope angle is 1V:1H, the unit weight of waste is 6 kN/m^3 , the line is close to 90° . In fact,

according to the GEO5 analysis, it should be a straight line, even if the internal friction angle changes from 0° to 50° at the same cohesion value, it gives safe results. However, since it is necessary to add an equation based on x (cohesion) for the smart decision tool, the cohesion is increased by one kPa and the value of internal friction angle is decreased 0° in this condition.

4.1.3. Dynamic and Dry Conditions

Figure 4.7-4.9 show the effect of the same parameters with different horizontal and vertical seismic coefficients: $k_h=0.05$, $k_v=0.025$; $k_h=0.2$, $k_v=0.1$ and $k_h=0.4$, $k_v=0.2$.



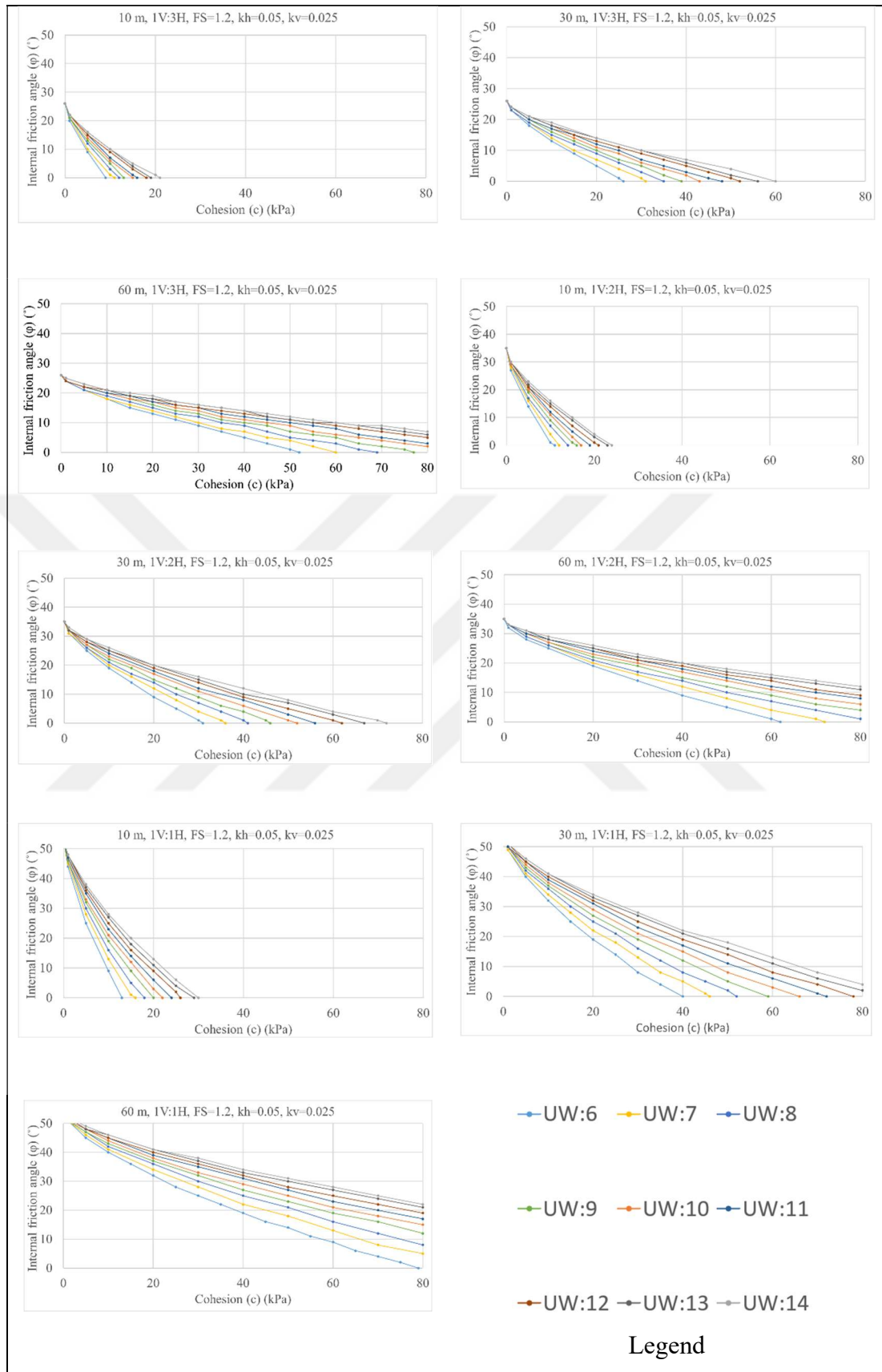


Figure 4.7: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, no water condition, $kh=0.05$, $kv=0.025$ and different landfill height and slopes.

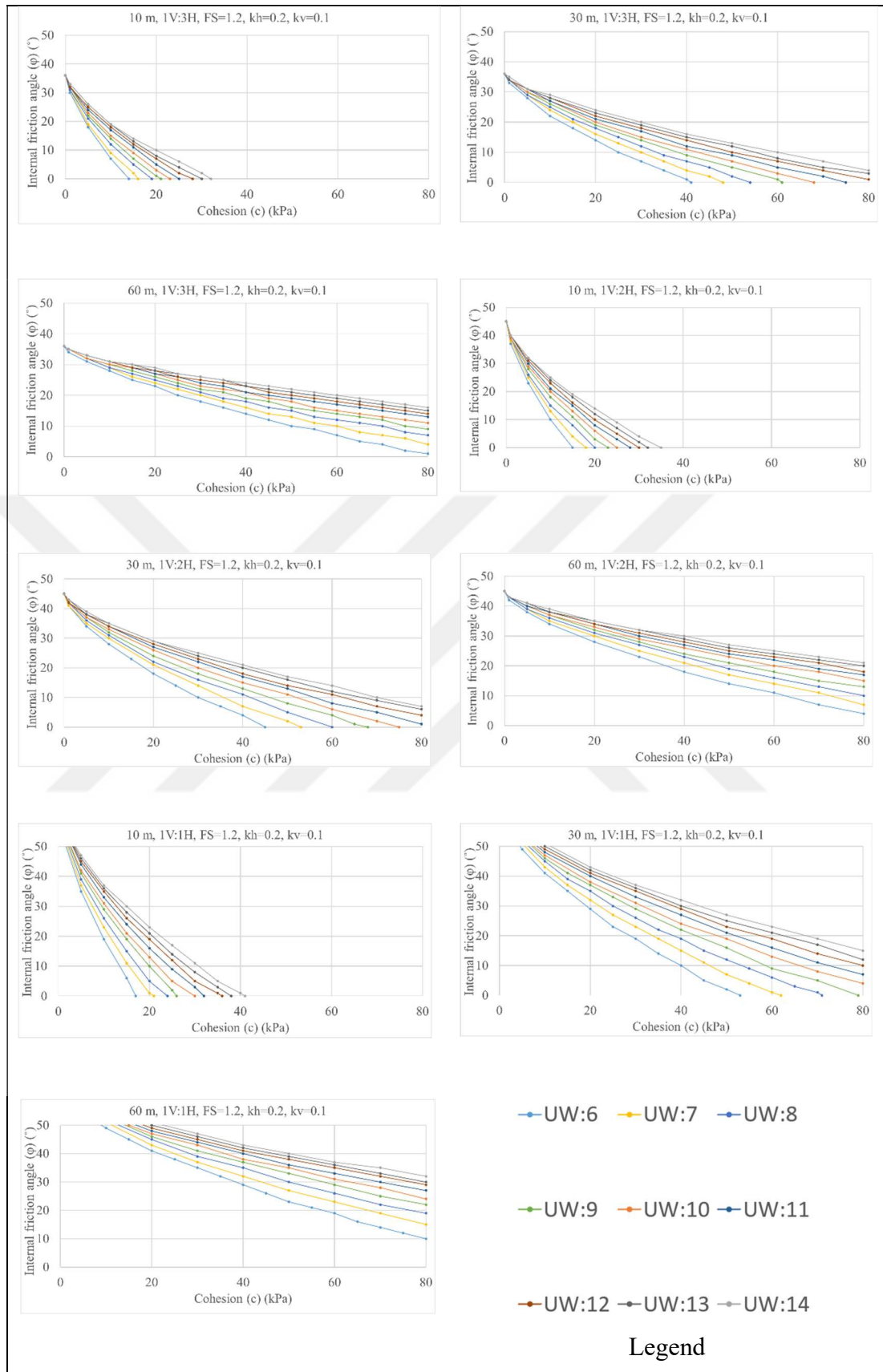


Figure 4.8: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, no water condition, $kh=0.2$, $kv=0.1$ and different landfill height and slopes.

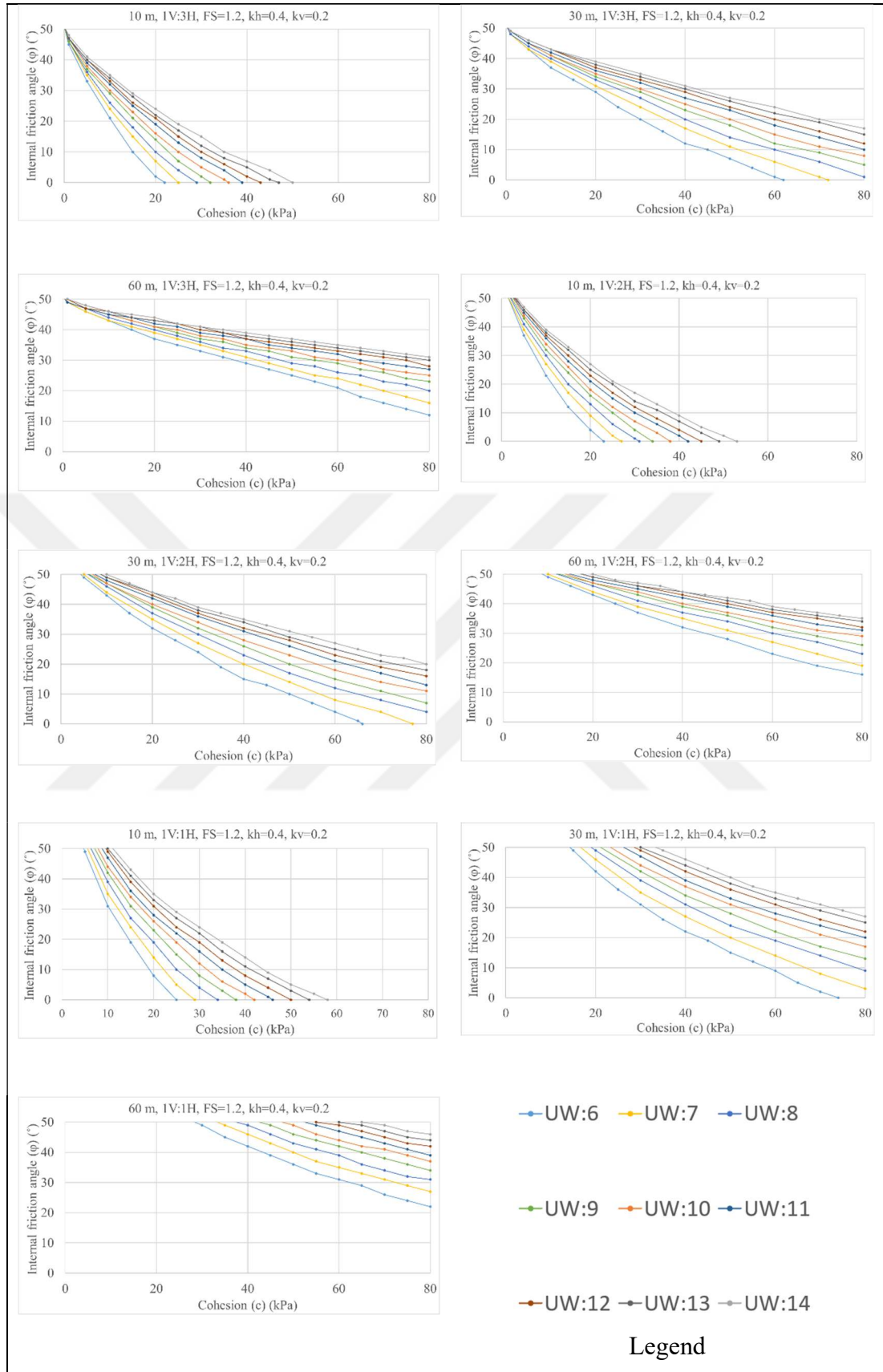


Figure 4.9: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, no water condition, $kh=0.4$, $kv=0.2$ and different landfill height and slopes.

According to Figure 4.7 (for $FS=1.2$, $k_h=0.05$, $k_v=0.025$), as the height of the landfill increases, the internal friction angle that the waste must have in order to stay on the safe side does not change, while the cohesion value that the waste should have increases approximately 2-3 times for the landfill heights increasing from 10 m to 30 m and from 30 m to 60 m landfill heights.

However, when the height is constant, both the internal friction angle that the waste should have and the cohesion value increase if the slope angle increases. With the change of the angle, the increase for the internal friction angle is around 20%, while the increase for the cohesion is around 20-25% for the landfill angles increasing from 1V:3H to 1V:2H and from 1V:2H to 1V:1H landfill slope angles.

In every case where the angle and height change, the cohesion and internal friction angle values that the waste should have are lower for the waste with low unit weight, while the cohesion and internal friction angle that the waste should have is higher for the waste with high unit weight. Also, the effect of unit weight changes little with the change of angle and height.

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In Figure 4.9, at 60 m landfill height and 45° landfill slope angle, the waste must have very high waste cohesion and internal friction angle when the earthquake intensity acting on the slope is large, although there is no water in the waste. Therefore, the earthquake effect should not be ignored, especially in the MSW sites located in the earthquake zone.

The effect of the earthquake can be seen more clearly in Figure 4.10. This result is valid for 10 m landfill height and 1V:3H slope angle.

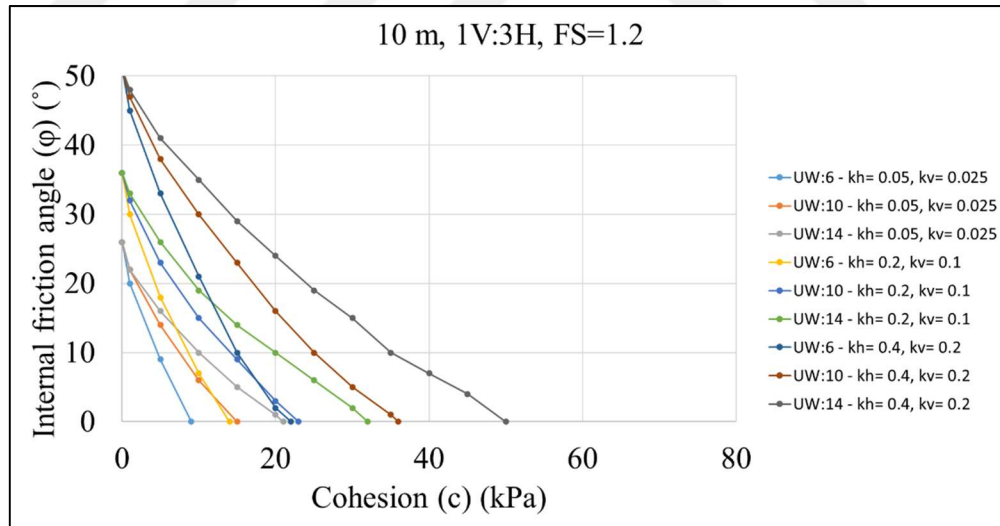


Figure 4.10: The effect of k_h , k_v on the safety factor and strength parameters with 1V:3H slope angle.

According to the figure, it can be said that the necessary cohesion and internal friction angle are increasing if the earthquake effect increases. Due to its low angle and low height, even in very severe earthquakes, these landfills can be safe if enough strengthful waste is available.

The same graph for 1V:1H slope can be seen in Figure 4.11.

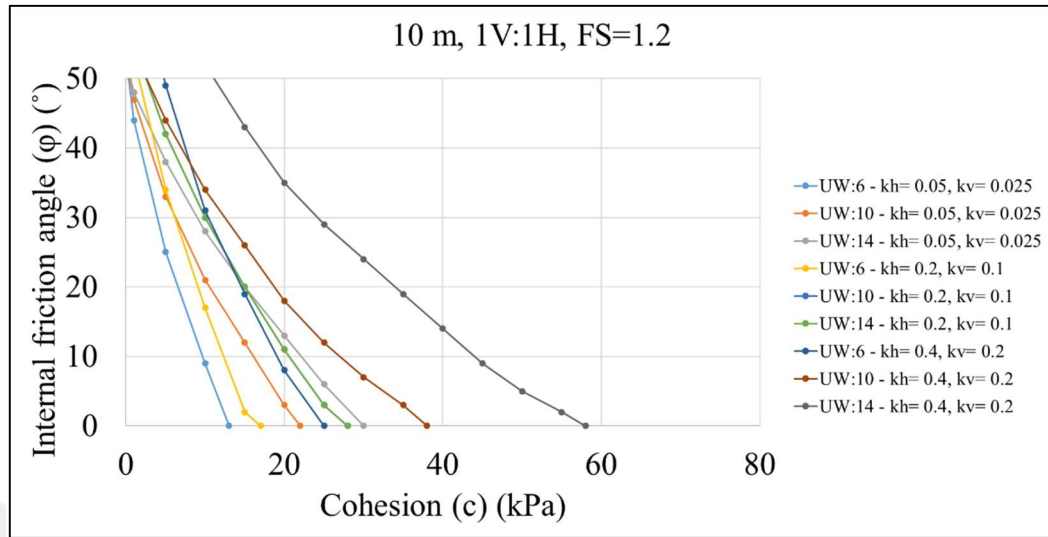


Figure 4.11: The effect of k_h , k_v on the safety factor and strength parameters with 1V:1H slope angle.

As shown in the figure, in 1V:1H slope condition, the friction angle of waste must be at least 50° to stay safe in dynamic condition when cohesion of waste is close to zero. If it is compared with Figure 4.10, it can be said that, with high slope angle, the increase in k_h and k_v values indicate that a higher internal friction angle is required for waste to stay in safe. For $FS = 1.2$, the minimum waste cohesion value did not change much to be safe seismically.

4.1.4. Dynamic with Low and High Leachate Conditions

The effect of leachate level for can be seen in Figure 4.12-4.17. According to these figures, it is seen that with the increase of leachate level, higher strength waste is required compared to the dehydrated state in general. In cases where the earthquake intensity is slightly higher, landfills with 30 and 60 meters high with high slopes are in any case unsafe when the leachate level is $3/4$ of the landfill height. When the earthquake and leachate effect are combined, it is understood that very high-strength wastes are required and quite problematic situations arise as these wastes are difficult to obtain in the field.

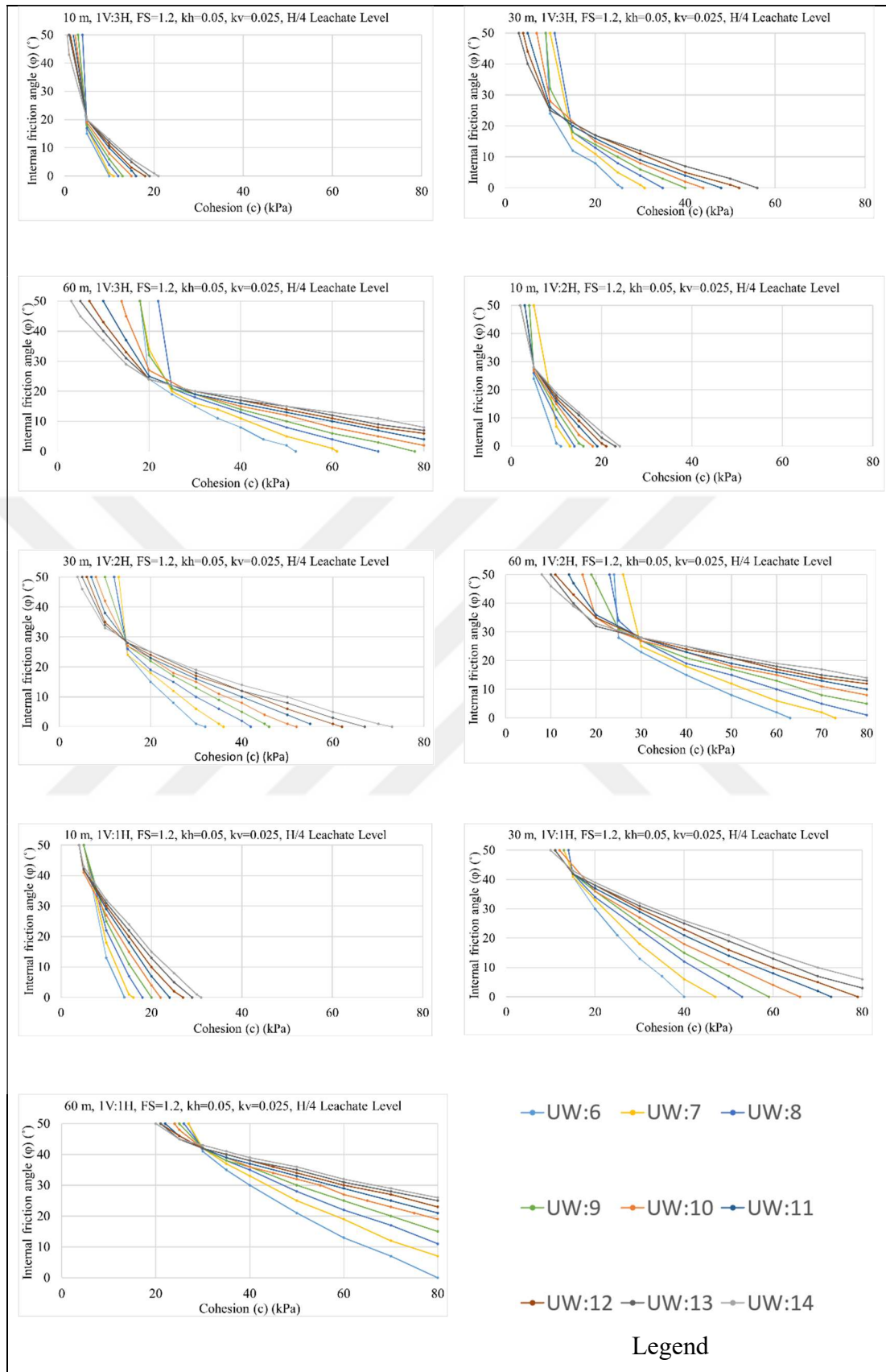


Figure 4.12: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, $H/4$ water condition, $kh=0.05$, $kv=0.025$ and different landfill height and slopes.

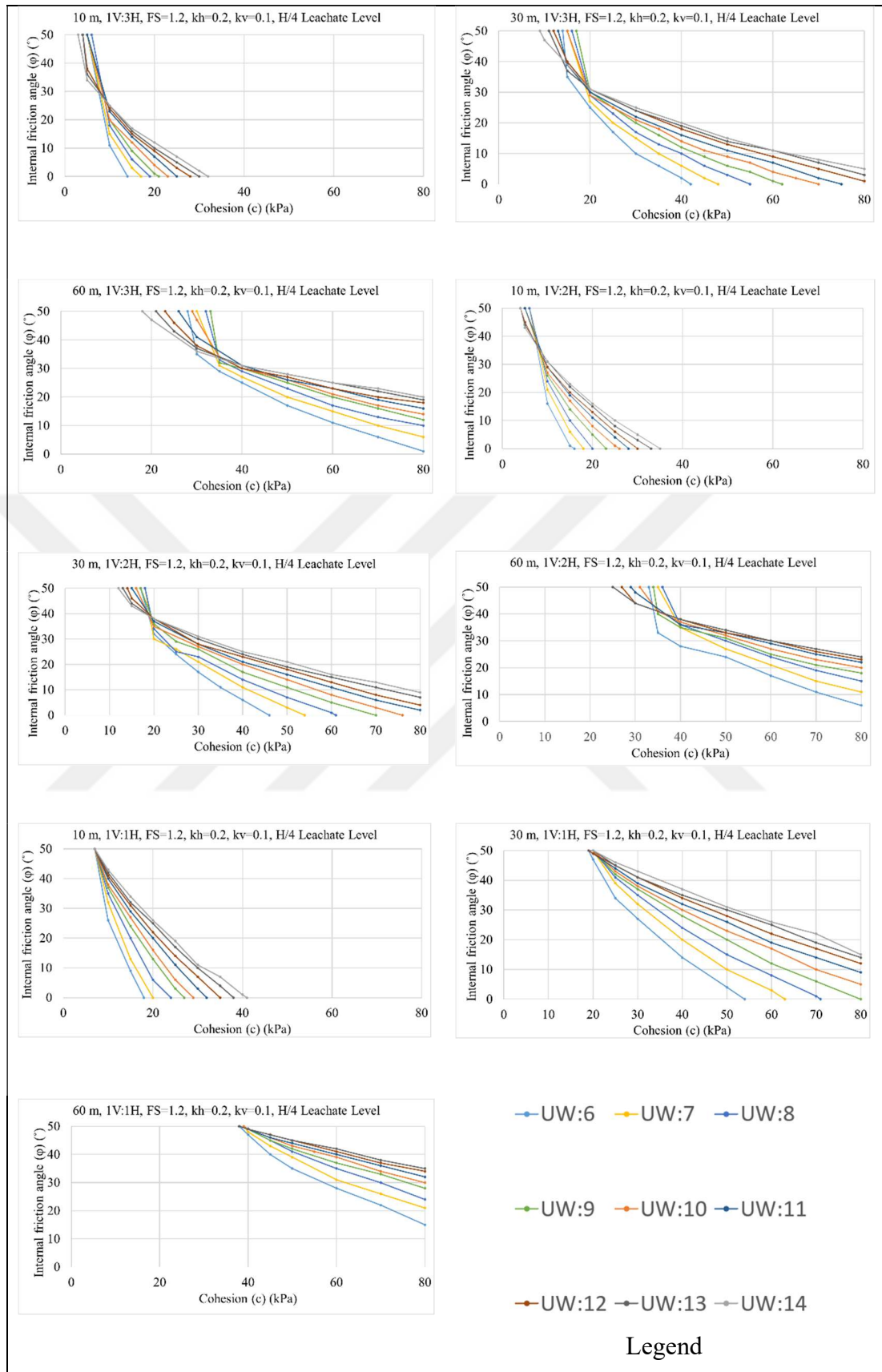


Figure 4.13: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, $H/4$ water condition, $kh=0.2$, $kv=0.1$ and different landfill height and slopes.

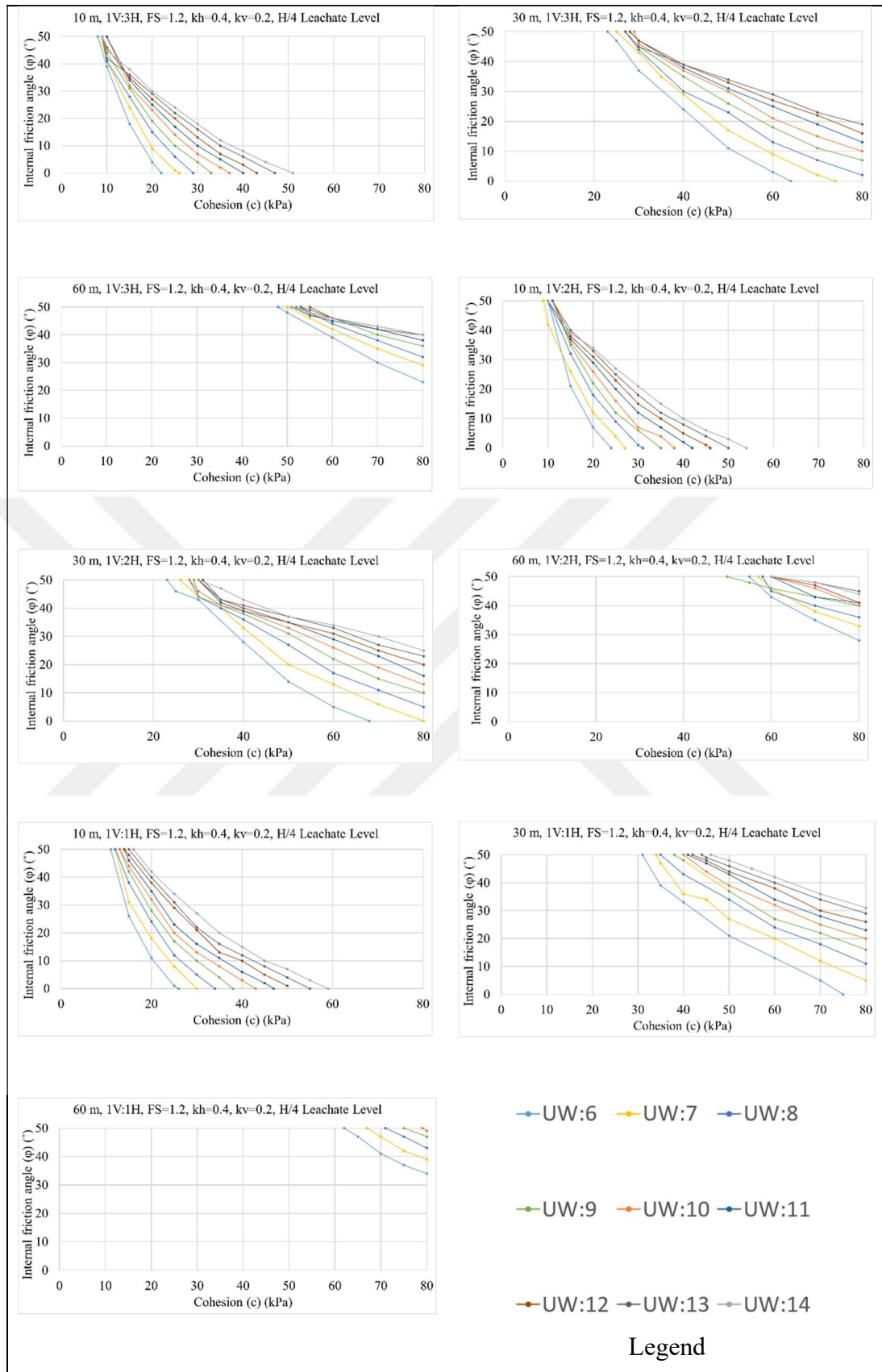


Figure 4.14: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, H/4 water condition, $kh=0.4$, $kv=0.2$ and different landfill height and slopes.

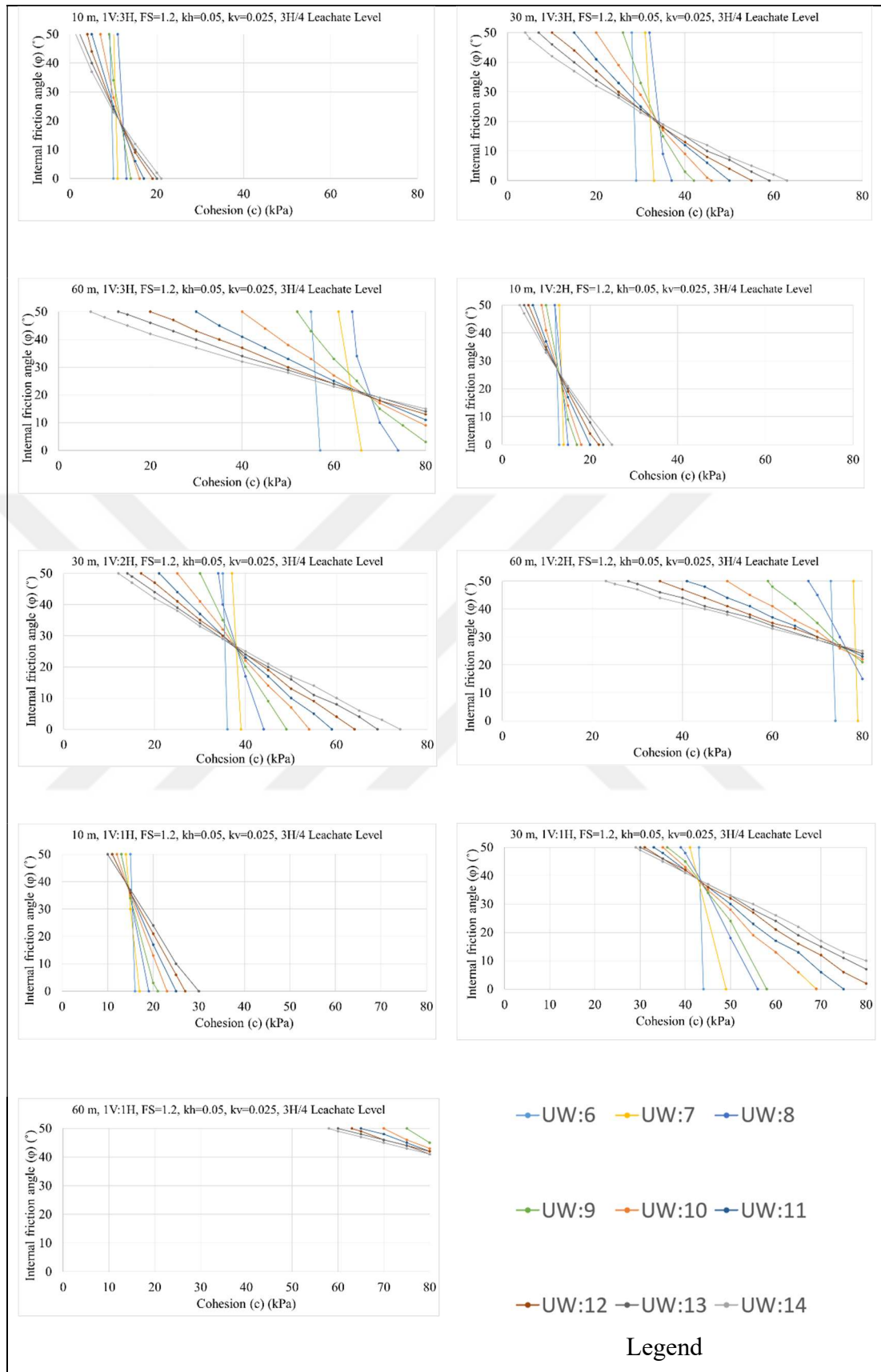


Figure 4.15: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, 3H/4 water condition, $kh=0.05$, $kv=0.025$ and different landfill height and slopes.

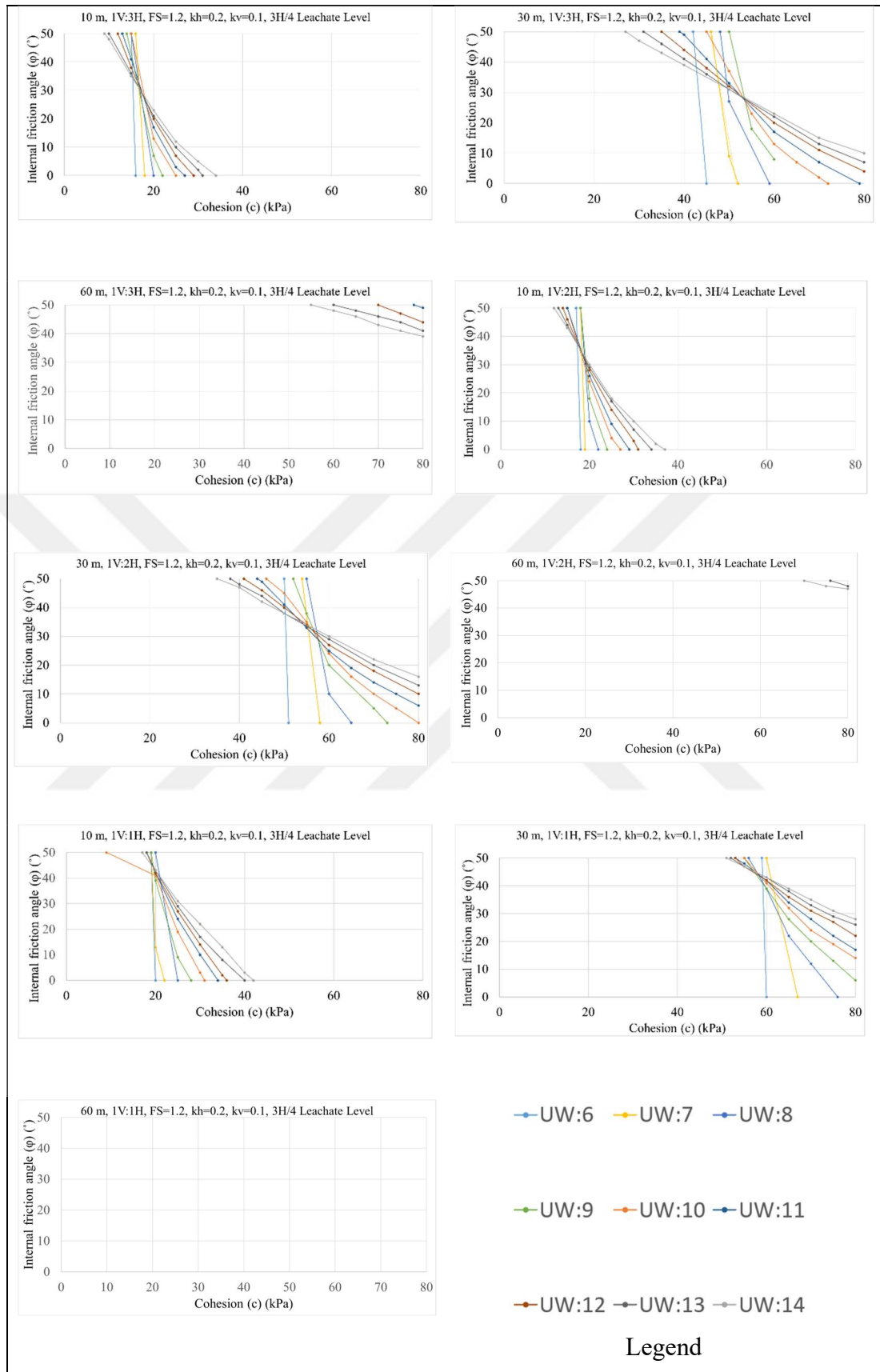


Figure 4.16: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, 3H/4 water condition, $kh=0.2$, $k_v=0.1$ and different landfill height and slopes.

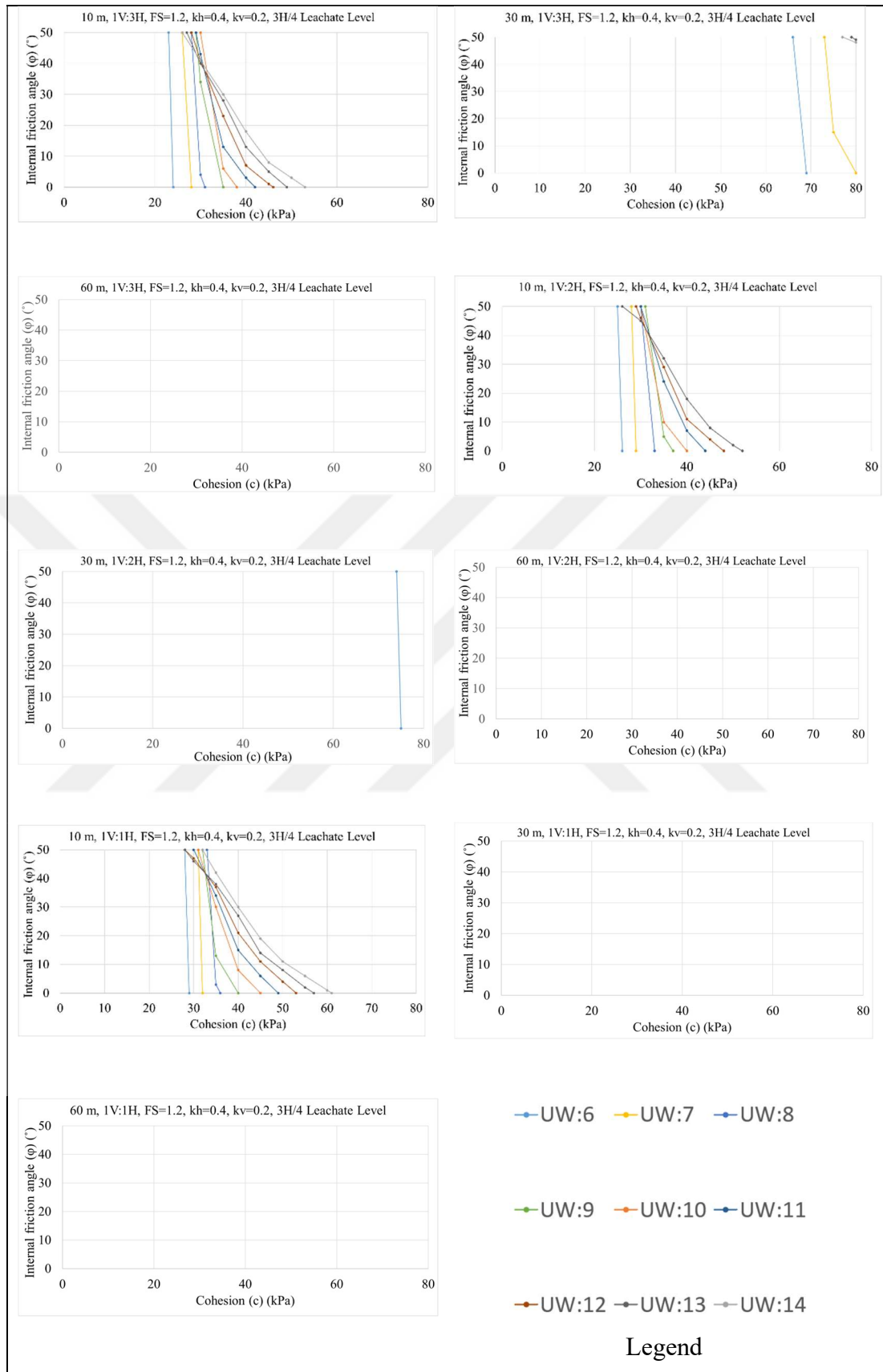


Figure 4.17: The effect of the unit weight, cohesion and internal friction angle for $FS \geq 1.2$, 3H/4 water condition, $kh=0.4$, $kv=0.2$ and different landfill height and slopes.

The effect of leachate level can be seen in Figure 4.18, Figure 4.19 and Figure 4.20.

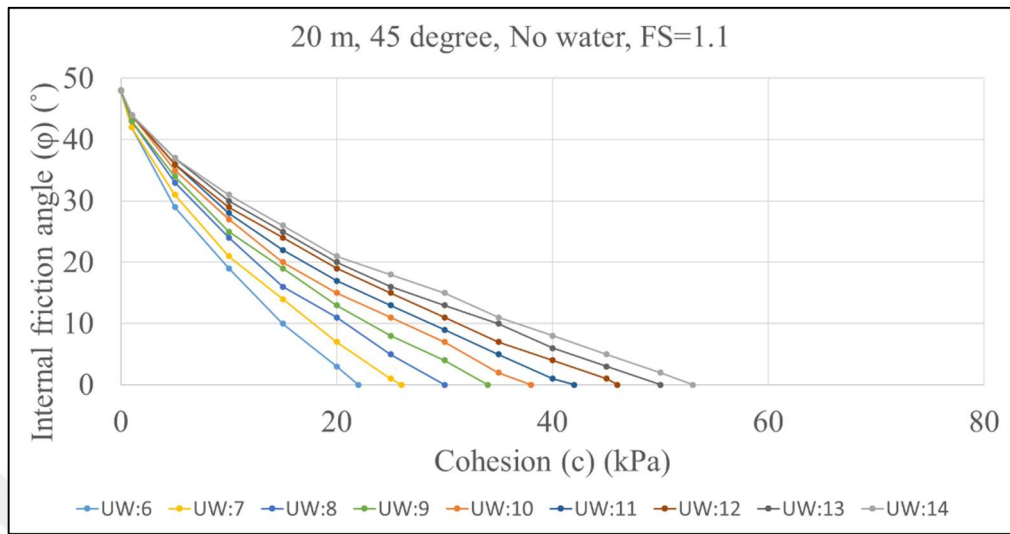


Figure 4.18: 20 m landfill height, 45° slope angle, no water condition.

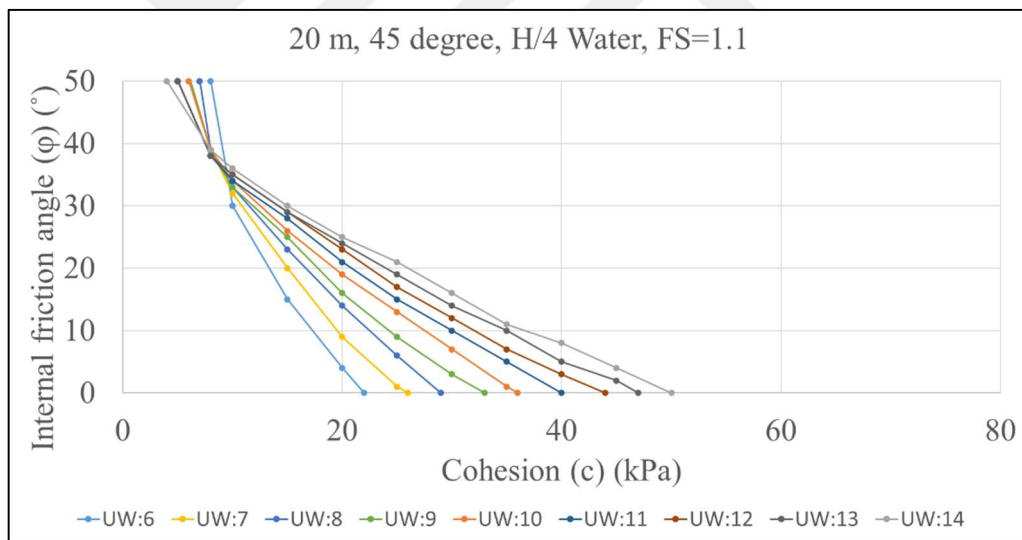


Figure 4.19: 20 m landfill height, 45° slope angle, 1/4H water condition.

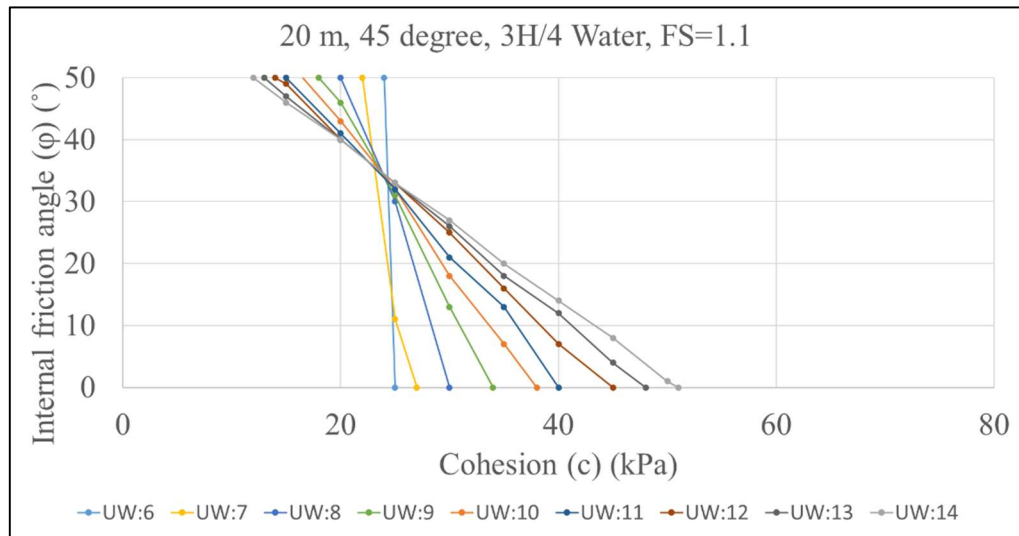


Figure 4.20: 20 m landfill height, 45° slope angle, 3/4H water condition.

As seen in the figures, the cohesion-internal friction angle graphs get steeper as the water level increases. While the internal friction angle was 0, there was little change in the required cohesion values. However, at low cohesion values, quite large changes were observed in the required internal friction angle. In this case, it is beneficial to provide at least 20 kPa of cohesion value in wet soils in the case of 20m 45 degrees.

4.2. Smart Decision Tool for Stability Part

Smart Decision Tool is one of the project outputs within the scope of Erasmus+ project. This tool includes gas, leachate and stability parts. The study in this thesis constitutes the stability part of this tool. This tool was prepared using Microsoft Excel software.

In the stability part, the input parameters that the user must enter are shown in Table 4.1. As shown in the figure, first of all, the user must select the landfill geometry. The landfill height can be set to any value between 10 and 60 meters. Slope angle options are 3H:1V, 2H:1V and 1H:1V. The waste unit weight, cohesion and internal friction angle values can be entered as an integer between 6 and 14, 0 and 80 and 0 and 50, respectively. Besides, the leachate level can be selected as 0, 0.25 or 0.75 depending on the landfill height. As seismic conditions, the user must determine k_h and k_v values. If these values are given 0, it indicates the static condition. 0, 0.05, 0.1, 0.2, 0.3 and 0.4 can be selected for k_h , while k_h , $k_h/2$ and 0 can be selected for k_v .

There are three options in the rehabilitation section to increase the safety factor of the landfill slope and get it in safe condition. Firstly, the slope angle of the landfill can be decreased. Secondly, the landfill height may be reduced. The last choice is to reduce the leachate (water) level in landfill waste. The user can change any or all of the values in these options according to his/her own opinion.

Table 4.1: Input parameters in the stability part of the smart decision tool.

Input data		
LANDFILL GEOMETRY		
Landfill Height (10-60)	10	m
Slope Angle (1/3, 1/2, 1/1)	1V/3H	vertical/horizontal
WASTE CHARACTERISTICS		
Unit Weight of waste (γ) (6-14)	7	kN/m ³
Cohesion of waste (c) (0-80)	6	kPa
Internal Friction Angle of waste (ϕ) (0-50)	20	°
LEACHATE LEVEL		
water (leachate) level above ground/landfill height (0,0.25, 0.75)	0.75	-
SEISMIC CONDITIONS		
kh (horizontal pseudostatic coefficient) (0,0.05, 0.1, 0.2, 0.3, 0.4)	0	-
kv (vertical pseudostatic coefficient) (0, kh/2, kh)	0	-
Rehabilitation		
decrease the slope angle, enter the new angle (1/3, 1/2, 1/1)	1V/3H	vertical/horizontal
decrease the landfill height, enter the new height (10-60)	10	m
reduce the water (or leachate) level above ground, enter the new water (leachate) level above ground/landfill height (0, 1/4, 3/4)	0	-

Right after the input data is entered, in the Calculation Results section shown in Table 4.2, the results are given about the safety coefficient of the slope in normal and rehabilitation situations, and in these cases, it is stated whether the slope of the landfill is safe or not. The possible outputs in the Calculation Results part can be seen in Table 4.3.

Table 4.2: Calculation results in the stability part of the smart decision tool.

Calculation results	value
Factor of Safety against stability	<1.2
Safety Condition	NOT SAFE
AFTER REHABILITATION OF ONLY THE SLOPE ANGLE	
Factor of Safety against stability	<1.2
Safety Condition after rehabilitation of only the slope angle	NOT SAFE
AFTER REHABILITATION OF ONLY THE LANDFILL HEIGHT	
Factor of Safety against stability	>1.2
Safety Condition	SAFE
AFTER REHABILITATION OF ONLY THE WATER (OR LEACHATE) LEVEL	
Factor of Safety against stability	<1.2
Safety Condition	NOT SAFE
AFTER REHABILITATION OF THE SLOPE ANGLE, LANDFILL HEIGHT AND WATER (OR LEACHATE) LEVEL	
Factor of Safety against stability	>1.2
Safety Condition	SAFE

Table 4.3: Possible outputs in the Calculation Results section.

Condition	FS against stability	Safety Condition
Static ($k_h=0$, $k_v=0$)	>1.5	SAFE
	1.1-1.5	NOT SAFE - Detailed reassessment is required
	<1.1	NOT SAFE - Immediate action is required
Dynamic ($k_h \neq 0$)	>1.2	SAFE
	<1.2	NOT SAFE

4.2.1. Background Calculations

There are thousands of equations in the background of the smart decision tool. To obtain these equations, hundreds of cohesion-internal friction angle graphs are drawn for each water (leachate) level, landfill height, landfill slope angle, minimum FS boundary, and earthquake status (k_h , k_v). For example, for 10 m landfill height, 45° (1V:1H) slope angle, $FS \geq 1.6$, water level at 1/4 of the landfill height and static ($k_h=0$) conditions, the resulting graph is shown in Figure 4.21.

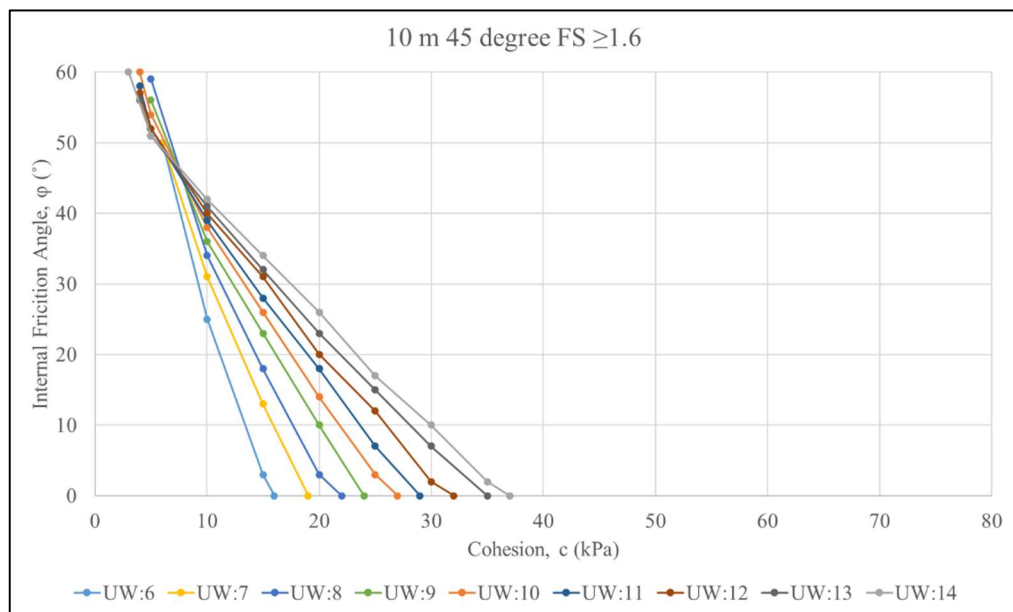


Figure 4.21: Cohesion-internal friction angle graph for 10 m landfill height, 45° (1V:1H) slope angle, $FS \geq 1.6$, water level at 1/4 of the landfill height and static ($k_h=0$) conditions.

In this graph, each line represents a unit weight value. The points on the lines are the cohesion and internal friction angle values obtained from the slope stability analysis results, giving a minimum FS value of 1.6. By combining these points, these lines are obtained. Then, linear trend lines were drawn for each unit weight with the help of Microsoft Excel and the equations of these trend lines were obtained. The trend line obtained for 14 kN/m³ unit weight in the same situation can be seen in Figure 4.22. In the obtained equation, the x value represents the cohesion, and the y value represents the internal friction angle. This equation appears to be very close to reality and is acceptable. In this way, thousands of equations were obtained for each different case.

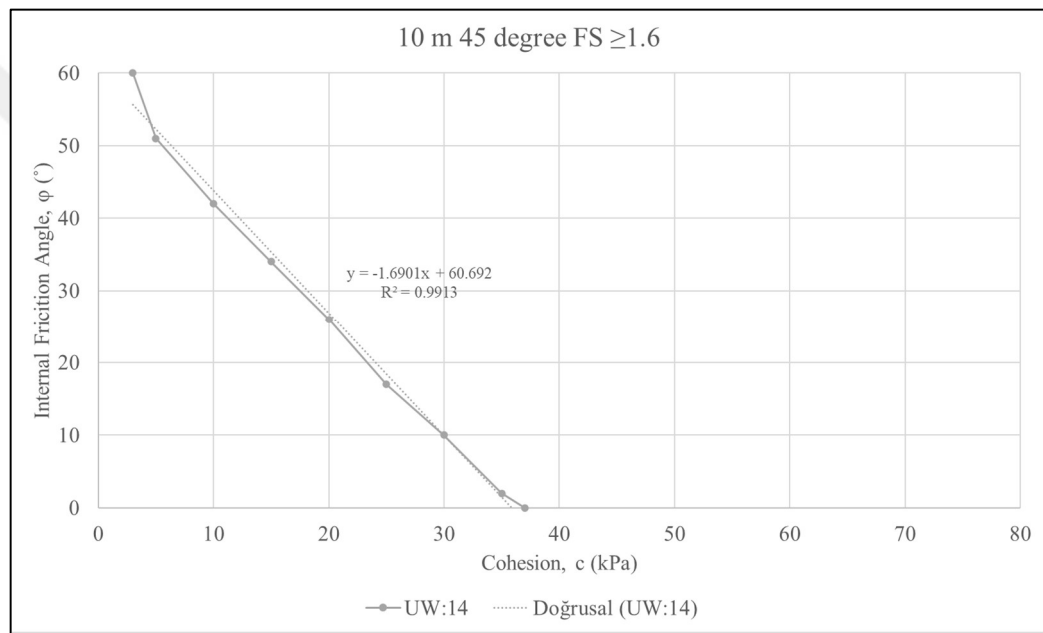


Figure 4.22: The trend line obtained for 14 kN/m³ unit weight, 10 m landfill height, 45° (1V:1H) slope angle, FS≥1.6, water level at 1/4 of the landfill height and static (k_h=0) conditions.

In static and dynamic analysis performed in case of a water level and the slope angles of 18.4349° (1V:3H) and 26.5651° (1V:2H) degrees, the linear trendline is not generally close enough to the slope stability analysis results obtained by GEO5 software. For example, for 10 m landfill height, 18.4349° (1V:3H) slope angle, FS≥1.6, water level at 1/4 of the landfill height and static (k_h=0) conditions, the resulting graph is shown in Figure 4.23. The trend line obtained for 14 kN/m³ unit weight in the same situation can be seen in Figure 4.24.

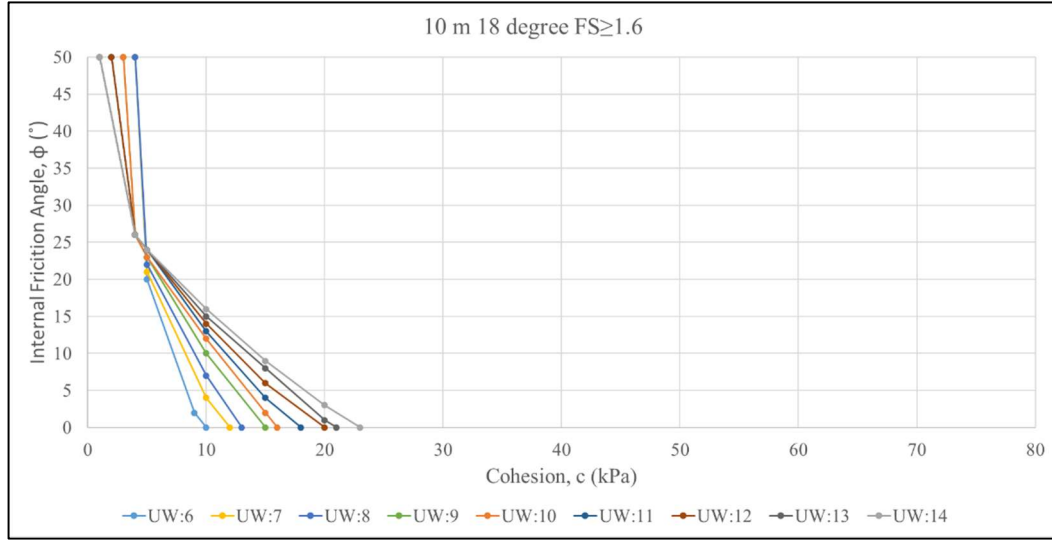


Figure 4.23: Cohesion-internal friction angle graph for 10 m landfill height, 18.4349° (1V:3H) slope angle, $FS \geq 1.6$, water level at 1/4 of the landfill height and static ($k_h=0$) conditions.

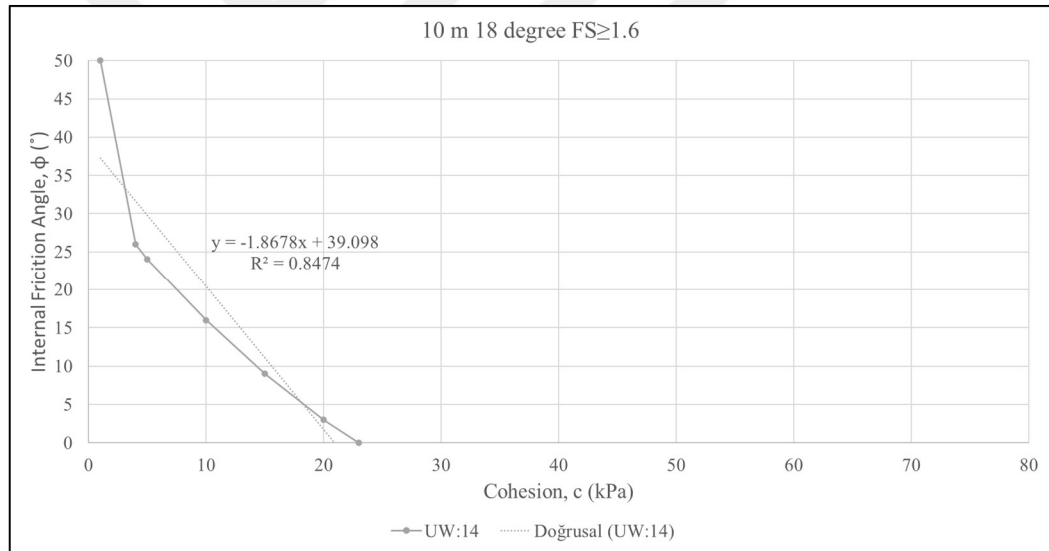


Figure 4.24: The trend line obtained for 14 kN/m³ unit weight, 10 m landfill height, 18.4349° (1V:3H) slope angle, $FS \geq 1.6$, water level at 1/4 of the landfill height and static ($k_h=0$) conditions.

As shown in Figure 4.24, the linear trend line is considered not close enough to the analysis results. Therefore, 2 linear trendlines are drawn in these cases. Accordingly, an equation will be used up to a certain border cohesion value, and a different equation will be used for cohesion values greater than that. Two trend lines obtained for 14 kN/m³ unit weight in the same situation can be seen in Figure 4.25.

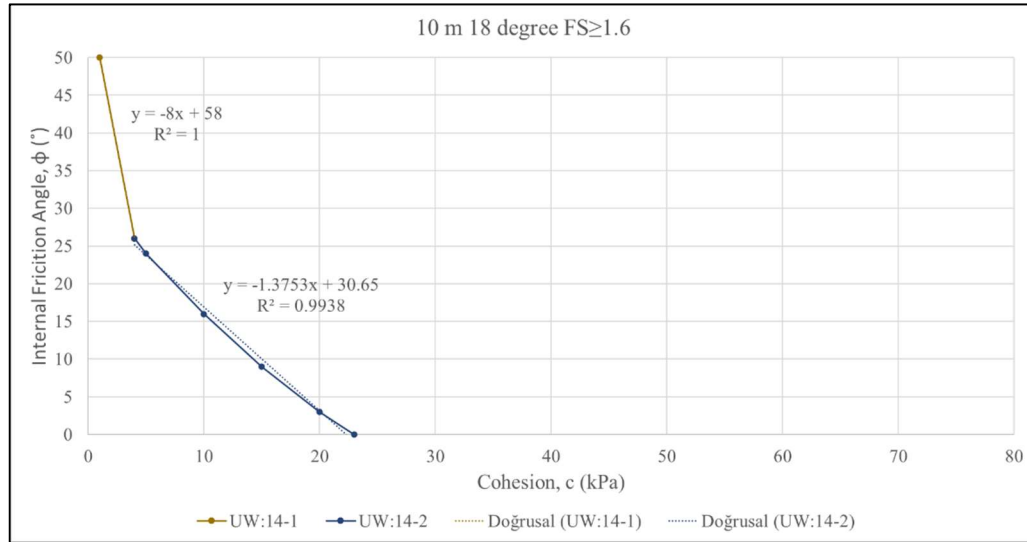


Figure 4.25: Two trend lines obtained for 14 kN/m³ unit weight, 10 m landfill height, 18.4349° (1V:3H) slope angle, FS≥1.6, water level at 1/4 of the landfill height and static ($k_h=0$) conditions.

As can be seen in Figure 4.25, linear equations that are much closer to the analysis results are obtained with this method. In this way, all the different cases are expressed by one or, if necessary, two equations. Later, these data were saved in a new worksheet in Microsoft Excel as shown in Table 4.4. In the table, landfill height, slope angle, unit weight of waste, seismic coefficients (k_h and k_v), equations obtained by graphs, some parameters related to equations and border cohesion are included. In the figure, there is no equation 2 because it was not necessary for the condition with 0 leachate level (no water condition). Therefore, border cohesion was not meaningful, so a random constant value is assigned for each condition for no leachate level. At the bottom of the table, there are also cases where the leachate level is different from 0 where both equations are written. In these cases, the border cohesion value becomes important. When the user enters a value less than the border cohesion value as input data, the first equation is activated, and when a greater value is entered, the second equation is activated. There are 2 more tables for FS=1.1 in static condition and for FS=1.2 in dynamic condition.

Table 4.4: Table in which the equations obtained for each case are recorded.

L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
Condition	Landfill Height	Slope Angle	Unit Weight of waste	kh	kv	Leachate Level	Equation	Rkare	m	a	Equation2	Rkare	m2	a2	Border Cohesion
>=1.6	m	°	kN/m ³	-	-	-	-	-	-	-	-	-	-	-	-
10	1V/3H	6	0	0	0	0	= -2.8065x + 26.97	0.9791	-2.8065	26.976	0	0	0	0	10000
11	1V/3H	6	0	0	0	0	-	-	-2.673	26.97	0	0	0	0	10000
12	1V/3H	6	0	0	0	0	-	-	-2.539	26.96	0	0	0	0	10000
13	1V/3H	6	0	0	0	0	-	-	-2.405	26.95	0	0	0	0	10000
14	1V/3H	6	0	0	0	0	-	-	-2.271	26.94	0	0	0	0	10000
15	1V/3H	6	0	0	0	0	-	-	-2.137	26.94	0	0	0	0	10000
16	1V/3H	6	0	0	0	0	-	-	-2.003	26.93	0	0	0	0	10000
17	1V/3H	6	0	0	0	0	-	-	-1.869	26.92	0	0	0	0	10000
18	1V/3H	6	0	0	0	0	-	-	-1.735	26.91	0	0	0	0	10000
19	1V/3H	6	0	0	0	0	-	-	-1.601	26.9	0	0	0	0	10000
20	1V/3H	6	0	0	0	0	y = -1.4673x + 26.8	0.9853	-1.4673	26.894	0	0	0	0	10000
21	1V/3H	6	0	0	0	0	-	-	-1.417	26.89	0	0	0	0	10000
22	1V/3H	6	0	0	0	0	-	-	-1.367	26.88	0	0	0	0	10000
23	1V/3H	6	0	0	0	0	-	-	-1.318	26.88	0	0	0	0	10000
24	1V/3H	6	0	0	0	0	-	-	-1.268	26.87	0	0	0	0	10000
25	1V/3H	6	0	0	0	0	-	-	-1.218	26.86	0	0	0	0	10000
26	1V/3H	6	0	0	0	0	-	-	-1.168	26.86	0	0	0	0	10000
27	1V/3H	6	0	0	0	0	-	-	-1.118	26.85	0	0	0	0	10000
28	1V/3H	6	0	0	0	0	-	-	-1.068	26.84	0	0	0	0	10000
29	1V/3H	6	0	0	0	0	-	-	-1.018	26.84	0	0	0	0	10000
30	1V/3H	6	0	0	0	0	y = -0.9681x + 26.8	0.9866	-0.9681	26.831	0	0	0	0	10000
31	1V/3H	6	0	0	0	0	-	-	-0.943	26.8	0	0	0	0	10000
32	1V/3H	6	0	0	0	0	-	-	-0.918	26.76	0	0	0	0	10000
33	1V/3H	6	0	0	0	0	-	-	-0.894	26.73	0	0	0	0	10000
34	1V/3H	6	0	0	0	0	-	-	-0.869	26.69	0	0	0	0	10000
35	1V/3H	6	0	0	0	0	-	-	-0.844	26.66	0	0	0	0	10000
36	1V/3H	6	0	0	0	0	-	-	-0.819	26.63	0	0	0	0	10000
37	1V/3H	6	0	0	0	0	-	-	-0.794	26.59	0	0	0	0	10000
38	1V/3H	6	0	0	0	0	-	-	-0.77	26.56	0	0	0	0	10000
39	1V/3H	6	0	0	0	0	-	-	-0.745	26.52	0	0	0	0	10000
40	1V/3H	6	0	0	0	0	-	-	-0.72	26.48	0	0	0	0	10000

Moreover, slope stability analyses with GEO5 were made only in conditions where the landfill height value was 10, 20, 30, 40, 50 and 60 m and related equations were obtained via graphics. The necessary equations between these heights were found by interpolation method using the coefficients (m and a) of these equations.

At the end of each table, there are some calculations related to safety conditions. At the bottom of the table, the landfill height, slope angle, unit weight of waste, k_h , k_v , leachate level conditions entered by the user as input data are written side by side. Then, m and a values corresponding to these data are obtained from the table by using some functions in Microsoft Excel and noted in different cells. After that, the cohesion and internal friction angle values are noted from the values entered by the user. Using the m, a coefficients obtained, the waste cohesion (c) and internal friction angle (ϕ) values entered by the user, the following equation must be true to ensure FS>1.5 and SAFE condition:

$$\phi - (a + m * c) > 0 \quad (4.1)$$

In summary, by using user inputs, the equation related to the relevant situation is obtained from the table, and the m and a coefficients are obtained, and thus the equation to be used for this situation is obtained. Then, a friction angle value is found by putting the cohesion value from the user instead of x variable in the equation. This value is the friction angle value that provides the FS=1.5 condition. If the friction angle

entered by the user is more than this value, that is, if the above equation is greater than 0, it means that this situation is achieved. If there is a second equation for the case of the parameters entered by the user, the calculation is made using the same formula (only m and a values belong to the second equation).

Finally, for the two equations, the values obtained as a result of the calculation made according to the above formula are prioritized according to the border cohesion. That is, the first equality result for the cohesion values entered as data by the user, which is smaller than the border cohesion, and the second equality result for the cohesion values greater than or equal to the border cohesion are taken into account. With the help of if-else functions, this situation was applied in excel and as a result, a single result was obtained. This result is different for each different value entered by the user.

The same is applied for the static state table where $FS=1.1$ and the dynamic state table where $FS=1.2$. If the result of the calculation made with the equations obtained for $FS=1.1$ is again greater than zero, it shows that the FS value is greater than 1.1 for the relevant case. Likewise, if the result of the calculations made with the equations obtained for $FS=1.2$ gives a number greater than zero, this indicates that $FS>1.2$ and the dynamically relevant slope condition is safe.

As a result, when a user enters input data, 3 different values are obtained from a total of 3 different tables related to 3 different situations ($FS=1.5$ and $FS=1.1$ in static condition, $FS=1.2$ in dynamic condition) in the background. As stated in the calculation result section, using the data in the rehabilitation section, 5 different FS and safety condition values are output to the user. One of them shows the results without rehabilitation, while the other 4 different situations show the results obtained with the application of different rehabilitations. So, the same calculations were done for 4 different rehabilitation conditions. 3 different results for $FS=1.5$ and $FS=1.1$ in static condition, $FS=1.2$ in dynamic condition were obtained for each rehabilitation situation. For example, the outputs for 5 different calculation results for $FS=1.5$ condition can be seen in Table 4.5. The output of the first line shows the result when there is no rehabilitation. The second, third, fourth and fifth lines show results after rehabilitation of only the slope angle, only the landfill height, only the water (leachate) level and after rehabilitation of all of them, respectively. So, it can be said that if the output is greater than 0, its FS is more than 1.5 and it is SAFE. Otherwise, it is less

than 1.5. The same operations were performed for the other FS=1.1 static case and FS=1.2 dynamic case.

Table 4.5: Calculation table at the end of FS=1.5 table.

m	a	Cohesion	Internal Friction Angle	>1.6	m2	a2	Border Cohesion	>1.6	Output
-0.2219	52.89	40	35	-9.014	0	0	10000	35	-9.014
-0.2158	26.405	40	35	17.227	0	0	10000	35	17.227
-1.4023	53.381	40	35	37.711	0	0	10000	35	37.711
-0.2219	52.89	40	35	-9.014	0	0	10000	35	-9.014
-1.1963	26.504	40	35	56.348	0	0	10000	35	56.348

Finally, at the Calculation Results part, if the user enters k_h as 0, outputs for FS=1.5 and FS=1.1 in the background are automatically taken into account. For FS=1.5, if the output value is greater than 0, FS>1.5 and "SAFE" are output. If it is less than 0, this time FS=1.1 output value is checked. If it is greater than 0, FS=1.1-1.5 and "NOT SAFE - Detailed reassessment is required" are output. If it is less than 0, FS<1.1 and "NOT SAFE -Immediate action is required" are output. The same thing is done for 4 different rehabilitated situations, too. As a result, 5 different FS and safety condition values are obtained for 5 different situations. The user sees these outputs. However, all the processes described in this section are done in the background.

5. CONCLUSION

Domestic solid waste production is rising daily as a result of the world's growing population. Despite increased efforts to limit waste through reducing, reusing, and recycling methods, waste storage remains the world's most popular form of trash disposal. Landfills need stability not just during construction and operation, but also after they have been closed. Therefore, the use of a tool that can be used in landfills and open dumps to provide preliminary information about slope stability is of great importance in order to prevent the slope stability problem from harming the environment and people and to take some precautions related to it.

Within the scope of this thesis, several parameters affecting the stability of the slopes in landfills are evaluated. These parameters are mainly unit weight, cohesion and internal friction angle of waste, landfill height and slope angle, k_h and k_v seismic parameters for earthquake condition, and leachate level. The shear strength properties (cohesion and internal friction angle) and the unit weight of the waste can be very variable since the waste is generally heterogeneous and the waste is generally not homogeneously distributed in the landfill. It is very difficult to control or limit the variation of these parameters in landfill. Among the parameters taken into account in the current study, especially the landfill slope angle and height parameters are the most important of the controllable parameters. In landfills, it is possible to control the slope angle and height when necessary. In addition, if the landfill is built in an earthquake zone, then the slopes in the landfill must also be evaluated seismically. In some cases, the slope that is safe in static condition may be unsafe in dynamic condition depending on the intensity of the earthquake. There are many cases in the literature showing the collapse of landfill slopes which affects the environment and people adversely. Moreover, the leachate (water) level can also have a significant effect on slope stability. In this respect, leachate collection systems in landfills gain great importance. If there is an increase in the leachate level after heavy rainfall in solid waste sites located in regions where precipitation is intense in certain periods, it is important that these leachate waters are collected and removed from the site as soon as possible. In uncontrolled landfills (e.g., open dumps) that do not have a leachate collection system, it is very difficult to prevent this situation. Therefore, the rehabilitation of such landfills is very important for the environment and human health.

As one of the intellectual outputs of the international SMARTEnvi project, it is anticipated that the findings will be used to the creation of smart decision-making systems, which will help with the design of solid waste sites and solid waste management.

The relationships and tool developed in this study can be useful for the responsible engineers and managers at municipalities to decide about the safety of landfills. In addition, the results can help taking decisions about rehabilitation of landfills.

Some future studies related to the topics covered herein can be as follows. In this study, the variation of the waste unit weight value with depth was not examined. Integrating it into slope stability calculations by taking into account the variation with depth in the future will allow a more detailed examination of the effect of the waste unit weight on the safety coefficient. In addition, in this study, it is assumed that the failure surface in the landfill passes through the waste considering that the subsoil under the waste is strong enough. In future studies, the subsoil variability and stability can be integrated in the decision tool to cover more general conditions.

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BIOGRAPHY

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APPENDICES

Appendix A: Publications Within the Scope of Thesis Study

Dal O., Toprak S., (2022), “Static and Dynamic Response of Open Dumps”, 6th GTU Graduate Research Symposium, Kocaeli, Türkiye.

Toprak S., Dal O., (2022), “Katı Atık Depolama Sahalarında Şev Stabilesini Etkileyen Faktörler”, Zemin Mekaniği ve Geoteknik Mühendisliği 18. Ulusal Konferansı, Kayseri, Türkiye.

