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Investigating Stability Problems in Solid Waste Landfills

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Abstract

One of today's most pressing environmental issues is related to waste disposal, especially landfilling. The quality of groundwater has been seriously compromised due to improper storage methods. Problems related to human health and environmental pollution are more common in open dumps. These irregular disposal sites cause many disadvantages and serious health problems. For this reason, cases that caused slope failures in landfills have been examined. This study investigates stability issues related to solid waste landfills, focusing on the assessment of waste stability. The study includes analyses of slope failure cases in various landfills: Hekimbasi, Dona Juana, Gnojna Grora, Hiriya, Payatas, and Xerolakka. Using Plaxis 2D software, the data obtained from these analyses have been rigorously evaluated to determine the most appropriate landfill management strategies. Slope collapses in landfills are generally caused by unsuitable landfill design, lack of daily cover laying and waste compaction, inadequate waste segregation, insufficient leachate drainage and gas discharge, and excessive slope angle and height. The presence of one or more of these conditions can result in a decline in site stability. Instabilities are experienced in these areas where engineering controls are inadequate.

Keywords
Landfill, Slope Stabilitiy, Slope Failure, Back Analysis, Finite Elements Method

Katı Atık Depolama Sahalarındaki Stabilite Sorunlarının Araştırılması

Özet

Günümüzün en acil çevresel sorunlarından biri, atıkların bertarafı, özellikle de düzenli depolama ile ilgilidir. Yanlış depolama yöntemleri nedeniyle yeraltı sularının kalitesi ciddi şekilde tehlikeye girmiştir. Vahşi depolama sahalarında insan sağlığı ve çevre kirliliğiyle ilgili problemler daha yaygındır. Bu düzensiz depolama sahaları birçok dezavantaja ve ciddi sağlık sorunlarına yol açmaktadır. Bu sebeple, daha önce depolama sahalarında meydana gelen şev göçmelerine neden olan vakalar incelenmiştir. Bu çalışmada, atık stabilitesinin değerlendirilmesine odaklanarak katı atık depolama alanlarıyla ilgili stabilite sorunları araştırılmaktadır. Çalışma, Hekimbaşı, Dona Juana, Gnojna Grora, Hiriya, Payatas ve Xerolakka gibi çeşitli düzenli depolama sahalarındaki şev göçmesi vakalarının analizini içermektedir. Plaxis 2D yazılımı kullanılarak, bu analizlerden elde edilen veriler titizlikle değerlendirilmiş ve en uygun düzenli depolama sahası yönetim stratejilerinin belirlenmesi amaçlanmıştır. Düzenli depolama sahalarındaki şev göçmeleri genellikle uygun olmayan depolama sahası tasarımı, günlük örtü serme ve atık sıkıştırma eksikliği, yetersiz atık ayrıştırma, yetersiz sızıntı suyu drenajı ve gaz tahliyesi ile aşırı şev açısı ve yüksekliğinden kaynaklanmaktadır. Bu koşullardan bir veya daha fazlasının varlığı saha stabilitesinde kayba neden olabilir. Mühendislik kontrollerinin yetersiz olduğu bu sahalarda duraysızlıklar yaşanmaktadır.

Anahtar Sözcükler
Depolama Sahası, Şev Stabilitesi, Şev Göçmesi, Geri Analiz, Sonlu Elemanlar Metodu

1. Introduction

The disposal of waste materials is recognized as posing significant environmental risks, with landfills being identified as a central concern. The stability of solid waste landfills is the focus of our research, with critical questions related to their long-term viability being addressed. Specifically, surface rupture incidents within selected landfills are explored, and advanced computational tools are employed for thorough analysis.

Accelerated urbanisation and population growth, coupled with advancements in technology and industrialisation, have intensified the impact of human activities on the global environment. The escalating trend of consumption has led to the generation of waste in quantities and with harmful contents that pose a significant threat to both the environment and human health (Kamer, 2018). One of the most pressing environmental challenges today is waste storage.

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The landfilling of waste is an unavoidable element of all solid waste management systems. It is estimated that around 40% of solid waste worldwide is disposed of using sanitary landfills, while unregulated landfilling remains the primary disposal method in many developing or underdeveloped countries (Kaza et al., 2018).

The selection of an appropriate disposal method for solid waste is contingent upon the planning and management strategies employed. These encompass economic, engineering, land use, landscaping, geographical, and social factors (Kamer, 2018). Solid wastes are composed of numerous components, each with distinct characteristics. Pulat, in his study, encapsulated the challenges faced in determining the engineering properties of municipal solid wastes as follows (Pulat, 2014):

- The inconsistent and heterogeneous composition of municipal solid wastes results in a wide range of engineering parameter values.
- Obtaining samples that adequately represent the natural state of municipal solid waste in the land environment poses a significant challenge.
- The inconsistent and unstable state of solid waste particles complicates sampling and experimentation. Furthermore, there are no specialised standards that define the phases of sampling, sample preparation, and testing for these wastes.
- The characteristics of municipal solid waste vary with time, depth, and location.

The engineering properties of solid wastes, which include porosity, water content, unit volume weight, area capacity, strength, compressibility, and permeability, are outlined (Pulat, 2014).

One of the critical stability issues that may arise at solid waste sites is the stability of the excavated ground. The stability of the stored solid wastes has a direct impact on the stability of the landfill (Pulat, 2014).

This study analysed instances of slope failures in various landfills, including Hekimbasi Landfill (Turkey), Dona Juana Landfill (Colombia), Gnojna Grora Landfill (Poland), Hiriya Landfill (Israel), Payatas Landfill (Philippines), and Xerolakka Landfill (Greece). The back analysis method was employed to predict shear strength. These analyses were conducted using Plaxis 2D software. The data from these analyses were evaluated, and recommendations were made regarding the integration of the landfills.

In their research, Kocasoy and Curi reported that storage operations have been ongoing at the Ümraniye-Hekimbaşı Landfill since 1976. On a daily basis, an average of 1.500 to 2.000 tonnes of solid waste is deposited at the site. Interestingly, their study revealed that no compaction was performed during waste deposition (Kocasoy & Curi, 1995).

Merry et al. conducted an analysis of the Payatas landfill in the Philippines. On July 10, 2000, a slope failure led to the sliding of approximately 1.2 million cubic meters of waste. Remarkably, inadequate compaction during waste placement contributed to the formation of low-density waste (Merry et al., 2005).

In their comprehensive study, Sarihan and Stark meticulously analyzed case studies from Gnojna Grora, Istanbul, Hiriya, and Payatas Landfills. Through rigorous back analysis, they determined shear strength parameters and investigated slope failures. The results of these analyses were meticulously documented. Consequently, considering factors such as landfill location, waste composition, shear strength properties, slope geometry, and soil characteristics, it was concluded that reporting landfill case histories should explicitly address cavity pressure conditions (Sarihan & Stark, 2008).

Blight's investigation focused on six landfills that experienced slope failures spanning the years 1977 to 2005. These sites include Sarajevo (1977), Istanbul (1993), the Philippines (2000), Indonesia (2005), Colombia (1997), and South Africa (1997). Across all these instances, critical factors contributing to the failures were the absence of engineering controls, inadequate landfill design, and deficiencies in operational principles (Blight, 2008).

Caicedo et al. documented a significant event at the Dona Juana Site, where a staggering 800.000 tonnes of solid waste migrated. On September 27, 1997, the slope, with a steepness ratio of 3:1 and a height of 40 meters, experienced a collapse. Initially, the failure initiated in the front portion of Zone 2, but its impact extended throughout the entire waste mass. Caicedo's research attributes the collapse primarily to elevated pore water pressure (Caicedo et al., 2022).

In their study, Fernandez et al. reported that the Dona Juana Site exhibits a migration of 1.5 million tonnes and features a slope ratio of 4.7:1. The analysis led to the conclusion that the site's issues stem from elevated void pressures within the solid waste mass, exacerbated by its highly organic composition. Poorly designed leachate drainage and gas venting systems further contributed to the problem (Fernandez et al., 2005).

According to Athanasopoulos et al., the slope failure that occurred on December 29, 2010, had dimensions of 27 meters in height and 30 meters in width, containing 12.000 tonnes of waste mass. Through reconnaissance studies, field measurements, and stability analyses, it was determined that inadequate storage practices (such as insufficient compaction and daily soil cover), the steep slope of the waste mass, and the rising leachate due to rainfall contributed to the slope collapse rainfall (Athanasopoulos et al., 2013).

Xu et al.'s study documented a catastrophic slope failure on December 20, 2015, at the Hongao landfill site in Guangming New District, Shenzhen, China. The collapsed volume amounted to 2.32 million tonnes, while the pre-collapse volume stood at approximately 6.27 million tonnes. The displaced waste comprised a mixture of silty soil with a water content ranging from 17.3% to 42.4%, along with construction and demolition debris. The primary factors contributing to the slope failure were drainage system malfunction, the total waste volume exceeding design capacity, and elevated pore water pressure (Xu et al., 2017).

Lavigne et al. conducted an extensive investigation into a significant slope failure at the Leuwigajah landfill site in Bandung, Java, Indonesia. This catastrophic event occurred on 21 February 2005 following heavy rainfall. The researchers meticulously examined the collapse preconditions and triggering factors that contributed to this disaster. Additionally, they analyzed the internal structure of the source area to better understand the movement conditions (Lavigne et al., 2014). In a separate study, Fang et al. delved into the Qizishan landfill expansion project. Their focus was on assessing the stability of the landfill. They thoroughly examined the various factors that impact landfill stability (Fang et al., 2011).

2. Materials and Methods

2.1. Assessing Slope Instabilities

Slope stability plays a pivotal role in the field of geotechnical engineering. Analyzing slopes is crucial, especially in the context of natural disasters such as earthquakes, floods, and landslides. Ensuring stability has become a critical engineering challenge, as underscored by Kezer (Kezer, 2019).

One specific area where stability is paramount is in the design of landfills. The stability of a landfill directly impacts its safety and long-term performance. Engineers must carefully consider slope stability during the facility's planning and construction phases. Interestingly, even when dealing with waste materials that have lost their inherent strength and are prone to collapse, slope stability analyses remain applicable (Polat, 2019; Pulat & Yükselen Aksoy, 2017; Qian et al., 2002).

To better understand the causes of slope instabilities, Springman's work, as referenced in Tekin's study (Tekin, 2011), provides valuable insights. Table 1 summarizes these causes, shedding light on the factors that contribute to slope failures.

Table 1: Factors contributing to slope ınstabilities (Tekin, 2011)

1. Long-term effects that reduce stability	**2. Short-term effects leading to loss of equilibrium**
Change in the use or shape of natural or artificial slope,	Water saturation of the soils due to excessive rainfall, snowmelt, inoperability of surface drains,
Geology of the ground (presence of clay or marl type soils),	Seepage pressure, seasonal variations in groundwater levels
Stress history of the soils,	Earthquake loads or externally applied vibrations
Previous failures of the soil that has not been recognised at present,	Change in the loading condition due to a change in geometry or a new structure,
Slip surfaces formed in the soil due to very old tectonic movements,	Change in slope geometry.
The mechanism by which weathering leads to the formation of minerals different from the parent material and softer soils,	
Changes in the slope geometry due to erosion or changes in the internal structure due to water infiltration into the soil and material washout,	
Decrease in soil strength due to surface and groundwater,	
The presence of expansive soils.	

These factors play a crucial role in slope stability and require careful consideration in geoenvironmental engineering projects.

Stability calculation methods are categorized into three based on the shape of the slip plane, whether it is circular or wedge, the desired number of dimensions for analysis, and whether the calculation is done under static or dynamic loads. These methods include the Limit Equilibrium Method, Finite Element Method, and Seismic Analysis (Griffiths & Lane, 2021).

Limit equilibrium analyses have been widely used in solving geotechnical engineering problems for many years. It is assumed that the sliding occurs along a specific surface and the sliding mass is divided into either whole sections or slices. The stresses along the sliding surface are then compared to the shear strength. The Mohr-Coulomb stress criteria (Kezer, 2019; Akçakal, 2009) are employed to seek three main static equilibrium equations of the slope using these analysis methods.

There are three main types of limit equilibrium analyses commonly used in practice: the slice method, wedge method, and infinite slope method (Griffiths & Lane, 2021).

In Kezer's study, the slice method emerges as the predominant limit equilibrium technique for conducting stability assessments of slopes (Kezer, 2019). Widely embraced by geotechnical engineers, this method has spurred the development of numerous computer programs that yield dependable outcomes.

These software solutions facilitate seamless adjustments of shear surfaces, soil properties, and pore-water conditions essential for comprehensive analyses. The finite element method operates on the principle of segmenting a mass into uniform particles and establishing interconnectedness among them (Tekin, 2011).

By employing this methodology, each particle exerts a specific force on its adjacent counterparts, inducing movement. Although in actuality, all elements within a continuous system are interconnected through an infinite number of points, the finite element method simplifies this by assuming connectivity solely at designated nodes. Presently, computer software is extensively employed to conduct finite element analyses. These programs segment the soil into elements and execute computations to ascertain the relationships between them (Aykol, 2008).

In static analyses, gravity serves as the predominant force propelling slope movement. Nevertheless, seismic events introduce both vertical and horizontal accelerations that trigger internal forces within the slope. When performing seismic slope stability assessments, particular attention is paid to the horizontal earthquake acceleration, as it generally induces more severe conditions compared to vertical earthquake acceleration. In many instances, the influence of gravity helps counterbalance the effects of vertical earthquake acceleration (Griffiths & Lane, 2021).

As per the technical guidelines provided by the Environmental Protection Agency (EPA), the recommended factor of safety for slope stability typically ranges from 1.2 to 1.7. In Table 2, values outside the brackets correspond to static calculations, while those inside the brackets relate to calculations considering earthquake loads (Griffiths & Lane, 2021).

In the domain of geotechnical engineering, the assessment of slope stability is recognized as playing a crucial role in reducing the risks associated with natural disasters. Factors of safety (Fs) are provided as a quantitative measure of stability, and the research conducted by Griffiths & Lane (2021) is referred to for precise values.

Table 2: Coefficients of safety (Fs) for slope stability (Griffiths & Lane, 2021)

	The Uncertainty in Soil Strength Parameters	
Risk Assessment of Landslide Failures	Less	More
No danger to human life or the environment	1.25 (1.20)	1.50 (1.30)
Human life or environmental hazards	1.50(1.30)	>2.0(1.70)

In a slope, if the acceleration generated by the earthquake exceeds the yield acceleration of the calculated slope, a slope movement occurs along the plane (Griffiths & Lane, 2021).

When a slope fails, retrospective information can be obtained about the slope conditions at the time of failure. When slope stability is compromised, a safety factor of one (1.0) is obtained. Based on this information, the slope model at the time of collapse can be estimated to closely reflect reality using the appropriate analysis method (Akçakal, 2009; Coşkun, 2021). The location and type of boundary conditions in the model geometry are crucial. If the boundaries are too close to the area of interest, boundary effects may impact the modeling results (Natur, 2018). The following factors play a critical role in the success of a back analysis (Ün & Yıldız, 2021):

- Thorough analysis of the slope geometry both before and after the slope failure.
- Understanding the variations in groundwater levels is essential. In situations where additional loading impacts the slope mass beyond its self-weight, detailed data regarding this loading (distribution, magnitude) should be available.
- Incorporation of field assessments concerning the slope's failure mechanism.
- Selection of a stability analysis method that aligns with determining FS=1, considering the observed failure mechanism in the slope.

During back analysis, the safety factor at the time of collapse is typically assumed to be around “1”. The soil parameters derived from the calculations represent the weighted average shear strength parameters at the sliding surface. The pairs of “c-φ” (c: cohesion, φ: internal friction angle) that meet the condition Fs=1 (Fs: safety factor) are identified through trial and error within the slope model area. In cases where multiple collapses occur on different surfaces of the slope, distinct “c-φ” envelopes are established for various sections. These envelopes are graphed, and the shear strength parameters of the failure surface are determined at the point of intersection (Arıoğlu & Tokgöz, 2022).

3. Conclusions and Recommendations

3.1. Analysis

The Plaxis 2D program, which is based on the finite element method, was utilized for the analyses (Güner, 2022). Within the Plaxis program, the model type was set to "plane strain" prior to initiating the modeling process. This setting ensures that the analysis will be conducted in accordance with the slope geometry. To enhance the precision of the analysis, a 15-node model was chosen, thereby yielding a higher number of nodal points. The boundaries were defined based on the geometry to be created. Once the geometry was established, the input materials were assigned, and meshes were generated using the mesh command.

In the "Staged Construction" section, inputs for the analysis were created in stages, allowing for a safe and systematic analysis. The "Curve" section was used to generate graphs for determining the safety factor. Studies conducted on landfills composed of solid wastes have yielded a broad range of data. As a result, the geotechnical properties of the landfills analyzed in this study were sourced from existing literature (Güner, 2022; Seco e Pinto et al., 1999). In the literature, the modulus of elasticity of the material was found between 3,000 - 25,000 kN/m^2 when modelling solid wastes in the consolidation experiment (Aykol, 2008). Accordingly, the modulus of elasticity was taken as 10,000 kN/m^2 for solid wastes in model analyses using Plaxis (Güner, 2022). In addition, different values of the elastic modulus were also reported in the analyses and it was found that the impact on the safety number was small (Güner, 2022). Poisson's ratio values were found between 0.29 and 0.32 according to the literature (Laman et al., 1999; Akıncı et al., 2010). Accordingly, Poisson's ratio for solid wastes was taken as 0.29 in the model analyses using Plaxis (Güner, 2022). As with the modulus of elasticity, different values were also given for the Poisson's ratio in the analyses. However, it was found to have little effect on the safety factor (Güner, 2022). The engineering properties of these landfills are detailed in Table 3.

Table 3: Engineering properties of landfills composed of solid wastes

Landfill Sites	Hekimbasi	Dona Juana	Gnojna Grora	Payatas	Hiriya	Xerolakka
Unit volume weight, γ (kN/m^3)	11	11	17	12	9	12
Modulus of elasticity, E (kN/m^2)	10.000	10.000	10.000	10.000	10.000	10.000
Poisson 's ratio, ν	0.29	0.29	0.29	0.29	0.29	0.29

The slope geometry of the Hekimbasi landfill was modelled and analysed using the Plaxis (2D CE V20) software, as depicted in Figure 1. The landfill's slope height and angle were measured to be 45 m and 45 degrees, respectively. During the mesh creation process for the modelled landfill, the "Mesh-Medium" option was selected, resulting in a model comprising 262 elements and 2263 nodes. The analysis phase was subsequently carried out, and the resulting deformations were analysed, as shown in Figure 2. When the cohesion value of the waste was set to 0 and the internal friction angle was set to 30º (c=0, ϕ= 30º), the total displacement amounted to 40.09 m. As a result of the analyses performed at the landfill, it was determined that the maximum shear stress was 598.1 kN/m² and the average principal stress was 738.8 kN/m² (Figure 2 and Figure 3). In the event of a slope collapse, a back analysis was performed to retrospectively obtain information about the conditions at the time of the collapse. The safety factor at the time of slope failure is assumed to be 1.0, thereby providing retrospective data on slope conditions and creating a model of the slope at the time of collapse. When the cohesion value of the solid waste was 0 and the internal friction angle was 30º, the safety factor was calculated to be 1.035, as shown in Figure 4. The variation of the cohesion values, the internal friction angle and the safety factor of the model analyses performed are shown in Figure 5. These conditions closely resemble those of the slope at the time of collapse.

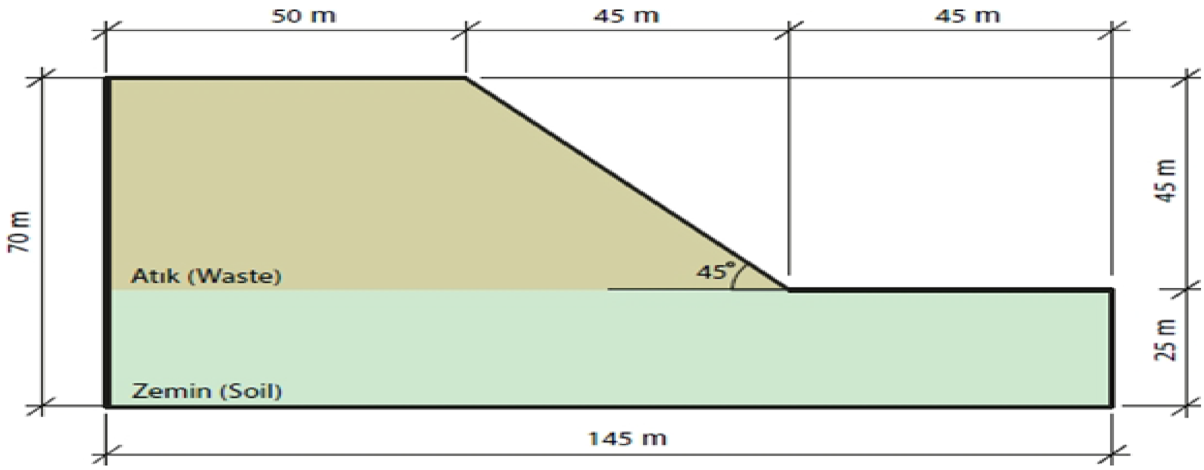

Figure 1: Depiction of the slope geometry of the Hekimbasi landfill

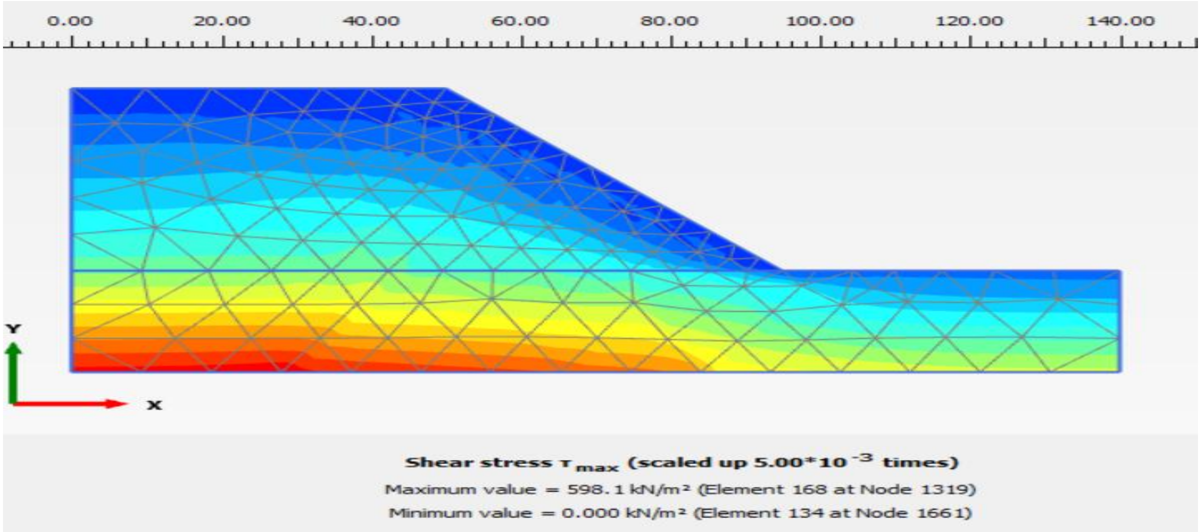

Figure 2: Illustration of the maximum shear stress at the Hekimbasi landfill

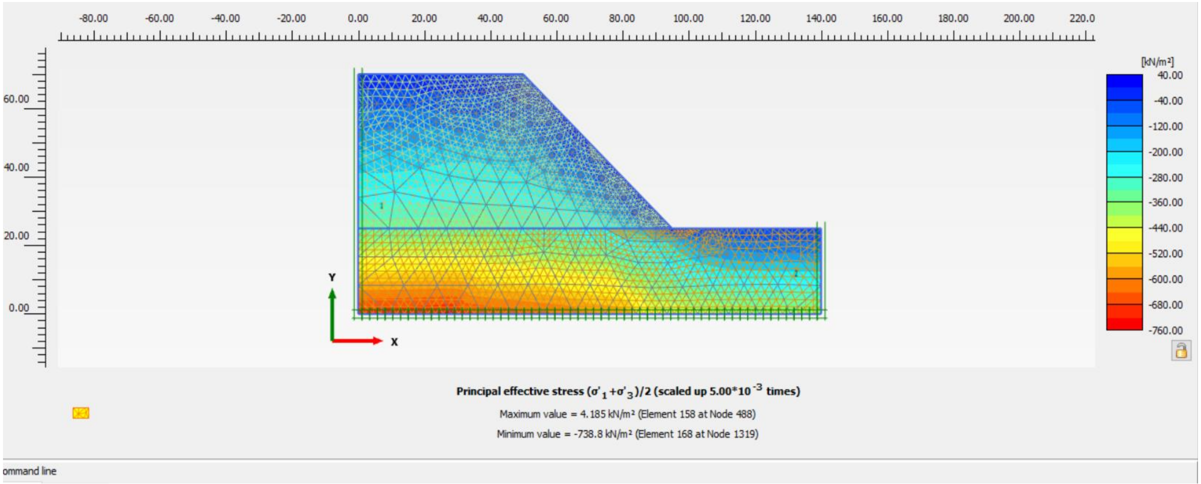

Figure 3: Illustration of the average principal stress at the Hekimbasi landfill

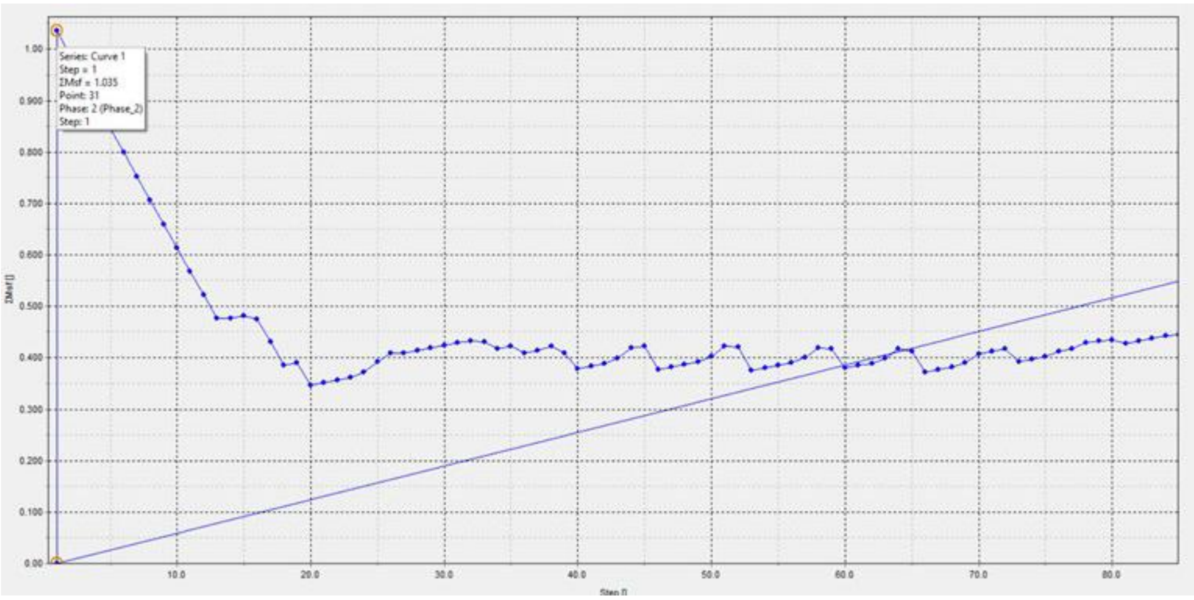

Figure 4: Diagram of the safety number of the Hekimbasi landfill in Plaxis

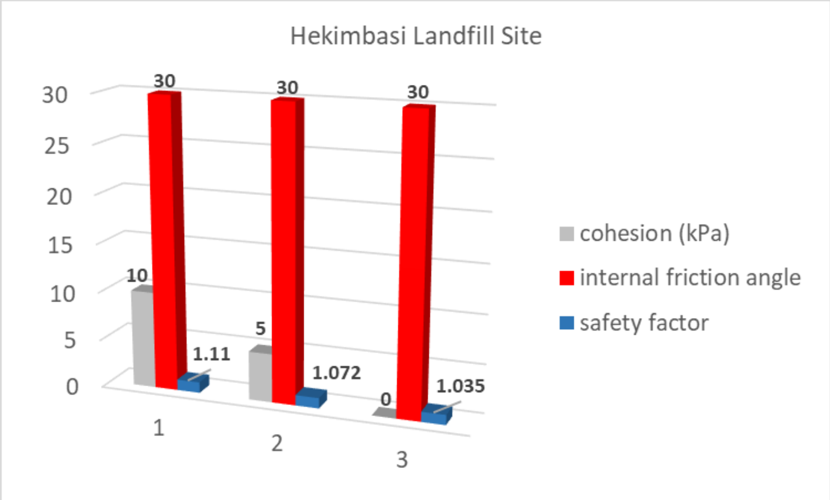

Figure 5: Safety factors as a function of cohesion and internal friction angle for the Hekimbasi landfill

The Dona Juana landfill was modelled and analysed using the Plaxis (2D CE V20) software. The slope geometry of the landfill is depicted in Figure 6, with a slope height of 40 m and a slope angle of 18º. During the mesh creation process in the modelled landfill, the "Mesh-Medium" option was selected, resulting in a model comprising 130 elements and 1137 nodes. Following the analysis, the deformations were examined. When the cohesion value of the waste was set to 0 and the internal friction angle was set to 28º (c=0, ϕ= 28º), the total displacement amounted to 309.2 m (Figure 7). Finite element analyses performed in the storage area showed that the maximum shear stress was 706.8 kN/m² and the average principal stress was 849 kN/m² (Figure 7 and Figure 8). When the safety factor is 1.0, retrospective information about the slope conditions is obtained. In the scenario where the cohesion value of the solid waste in the landfill modelled in Plaxis is 0 and the internal friction angle is 28º, the safety factor is calculated to be 1.109 (Figure 9). The variation of the cohesion values, the internal friction angle and the safety factor of the model analyses performed are shown in Figure 10.

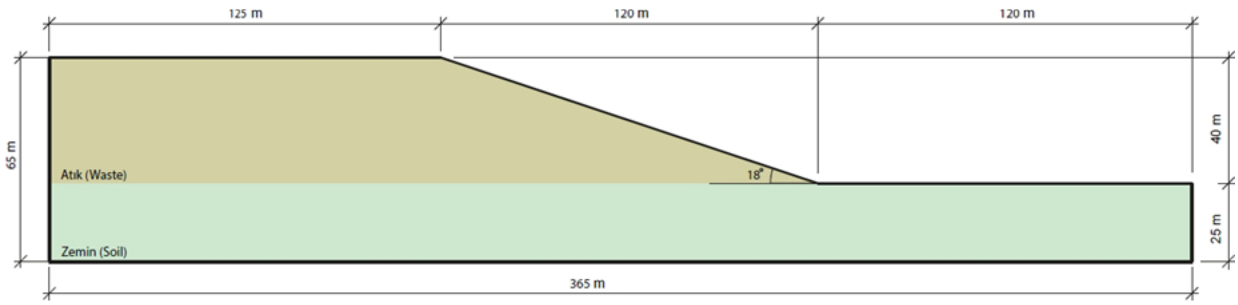

Figure 6: Depiction of the slope geometry of the Dona Juana landfill

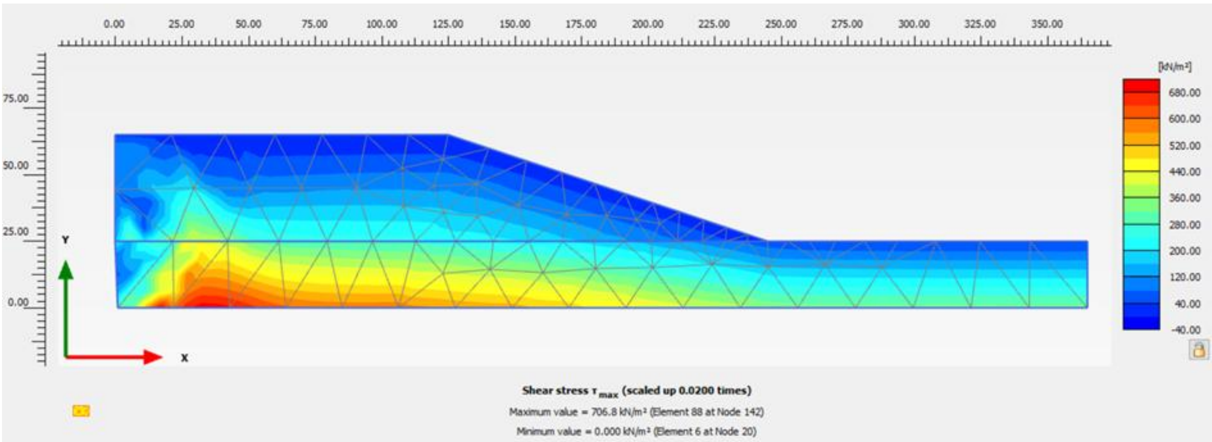

Figure 7: Illustration of the maximum shear stress at the Dona Juana landfill

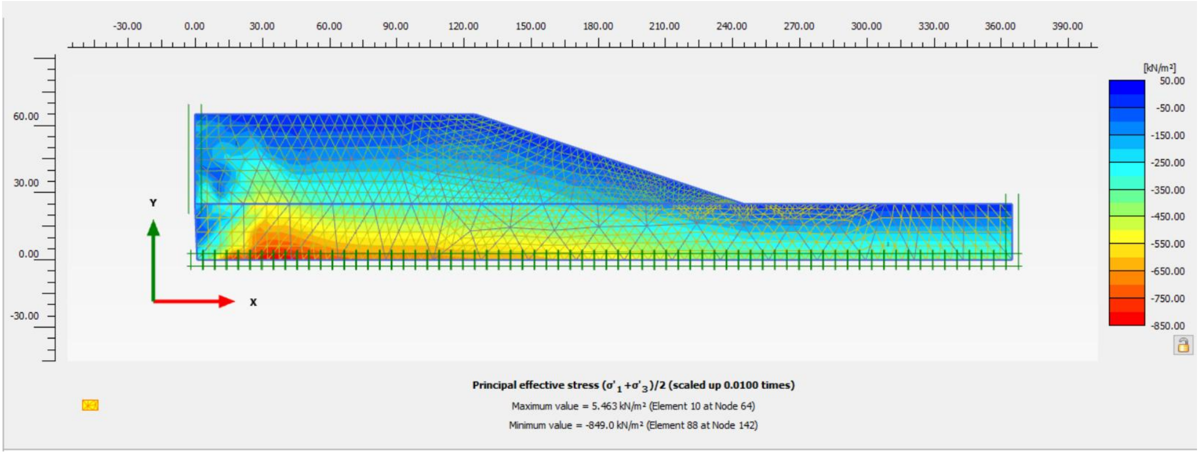

Figure 8: Illustration of the average principal stress at the Dona Juana landfill

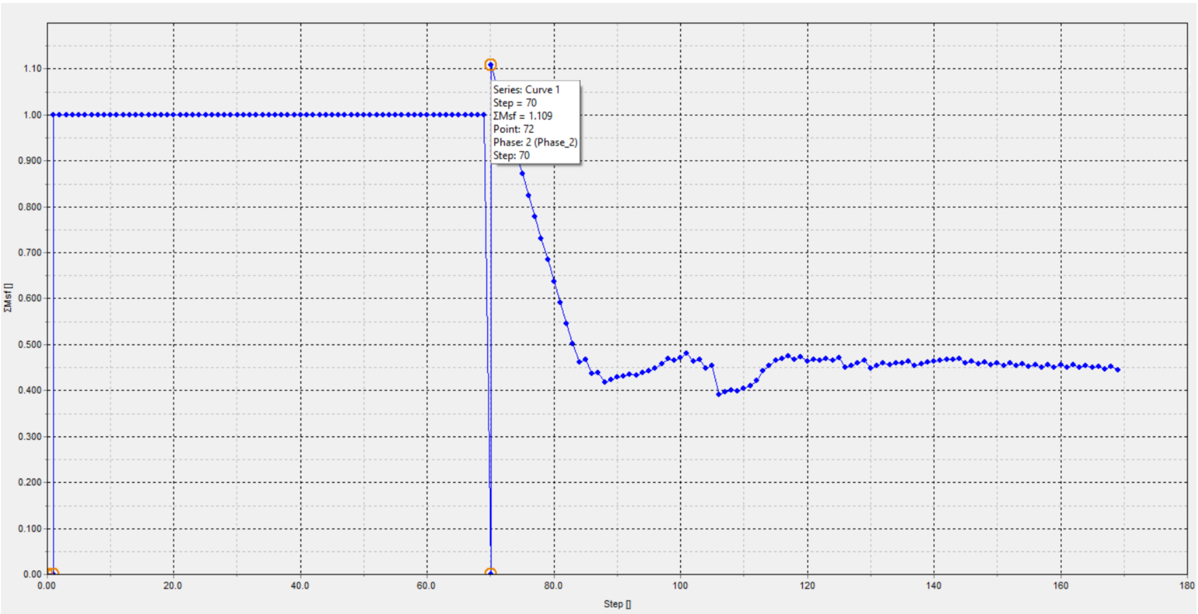

Figure 9: Diagram of the safety number of the Dona Juana landfill in Plaxis

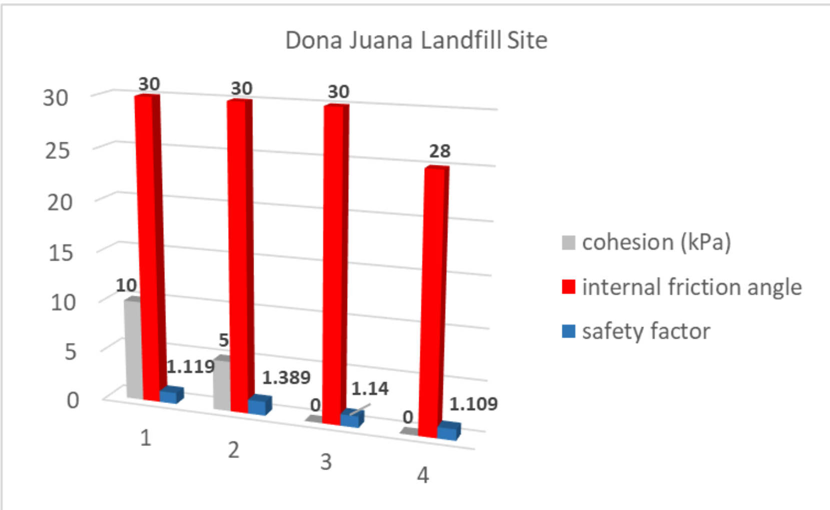

Figure 10: Safety factors as a function of cohesion and internal friction angle for the Dona Juana landfill

The Gnojna Grora landfill site was analyzed using Plaxis (2D CE V20) software to assess the slope stability. The landfill's slope geometry, with a height of 26 m and an angle of 30º, is depicted in Figure 11. Specifically, the slope stability analyses focused on the 1st zone of the landfill, which had steeper slopes. During the modeling process, a “Mesh-Medium” was selected, resulting in 175 elements and 1499 nodes. The deformations in the landfill were examined (Figure 12), revealing a total displacement of 23.09 m at the 239th node (66 elements) when the waste's cohesion value was 0 and the internal friction angle was 21º (Figure 12). The analyses revealed that the maximum shear stress at the landfill was 390.1 kN/m² and the average principal stress was 549.6 kN/m² (Figure 12 and Figure 13). When the cohesion value of the waste was set to 0 and the internal friction angle to 21º, the safety number was calculated to be 1.107 (Figure 14). The variation of the cohesion values, the internal friction angle and the safety factor of the model analyses performed are shown in Figure 15.

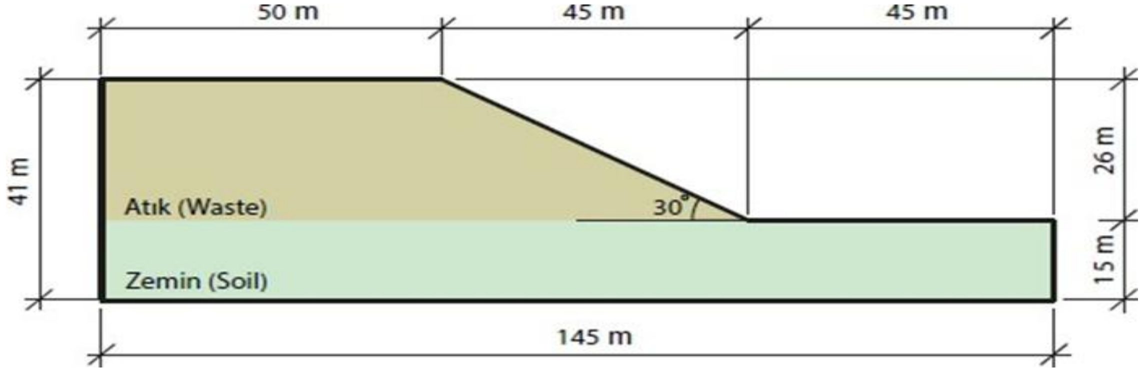

Figure 11: Depiction of the slope geometry of the Gnojna Grora landfill

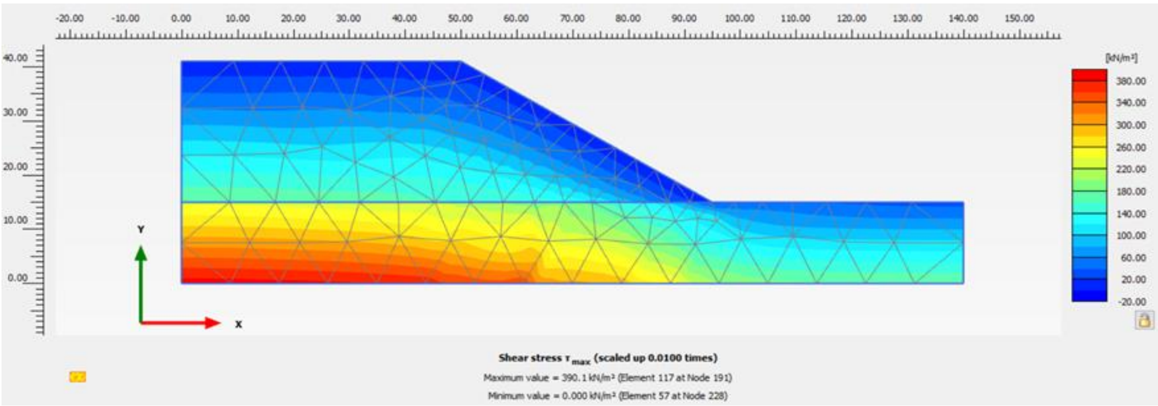

Figure 12: Illustration of the maximum shear stress at the Gnajna Grora landfill

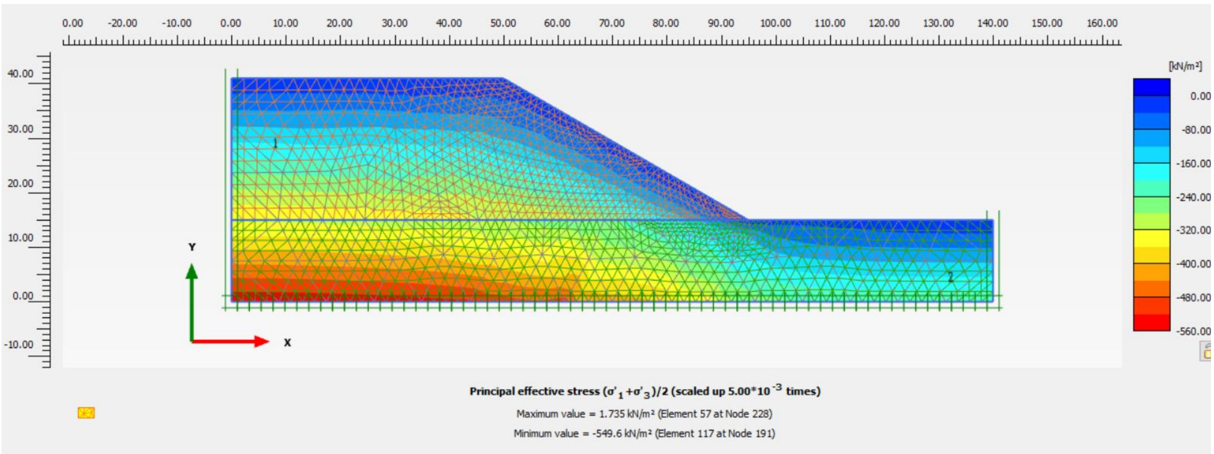

Figure 13: Illustration of the average principal stress at the Gnajna Grora landfill

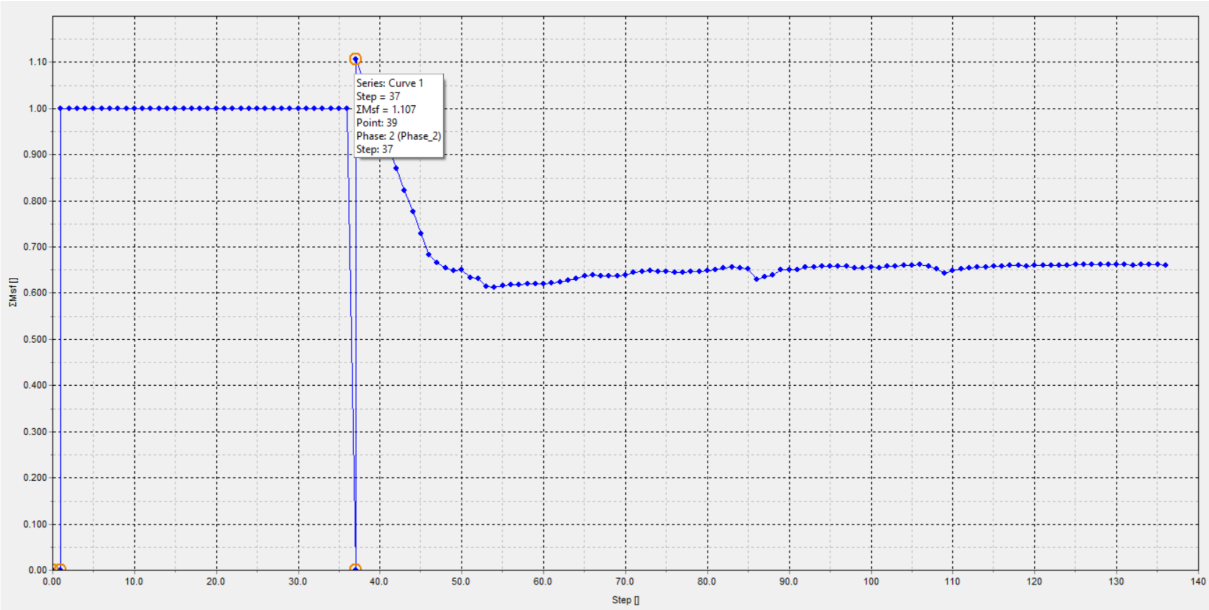

Figure 14: Diagram of the safety number of the Gnajna Grora landfill in Plaxis

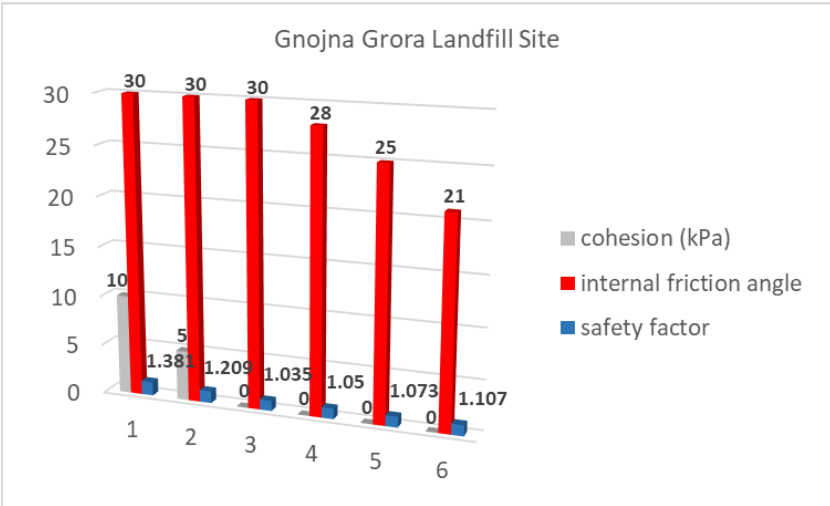

Figure 15: Safety factors as a function of cohesion and internal friction angle for the Gnojna Grora landfill

The Payatas landfill site has been analyzed using Plaxis (2D CE V20) software. The slope at Payatas measures 33 meters in height with a 40-degree angle. The slope geometry of the Payatas landfill is illustrated in Figure 16. During the creation of the landfill model, "Mesh-Medium" was chosen, resulting in 225 elements and 1903 nodes. When the cohesion value of the waste is 0 and the internal friction angle is 28 degrees (c=0, ϕ= 28°), the total displacement is calculated to be 19.42 meters (Figure 17). The investigations conducted at the landfill showed that the maximum shear stress was 431.2 kN/m² and the average principal stress was 575.3 kN/m² (Figure 17 and Figure 18). Furthermore, in the case where the cohesion value of the solid waste in the landfill modeled in Plaxis 2D is 0 and the angle of internal friction is 28 degrees, the safety number is determined to be 1.05 (Figure 19). The variation of the cohesion values, the internal friction angle and the safety factor of the model analyses performed are shown in Figure 20.

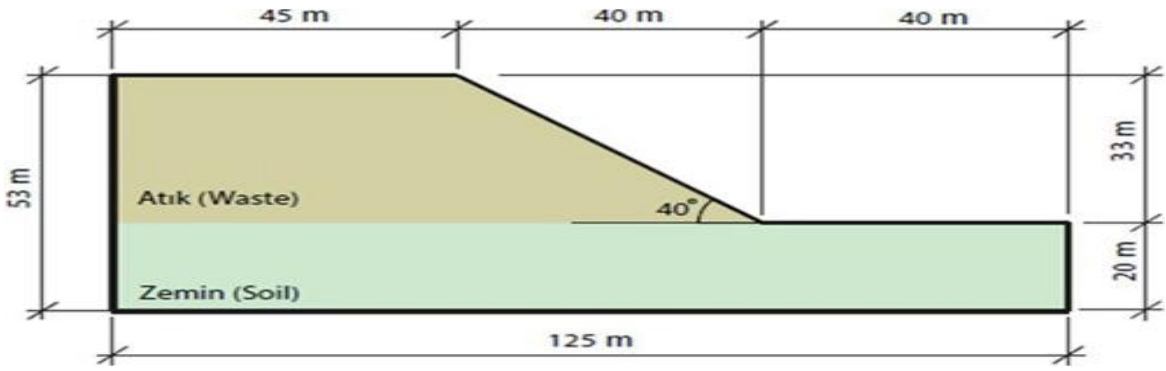

Figure 16: Depiction of the slope geometry of the Payatas landfill

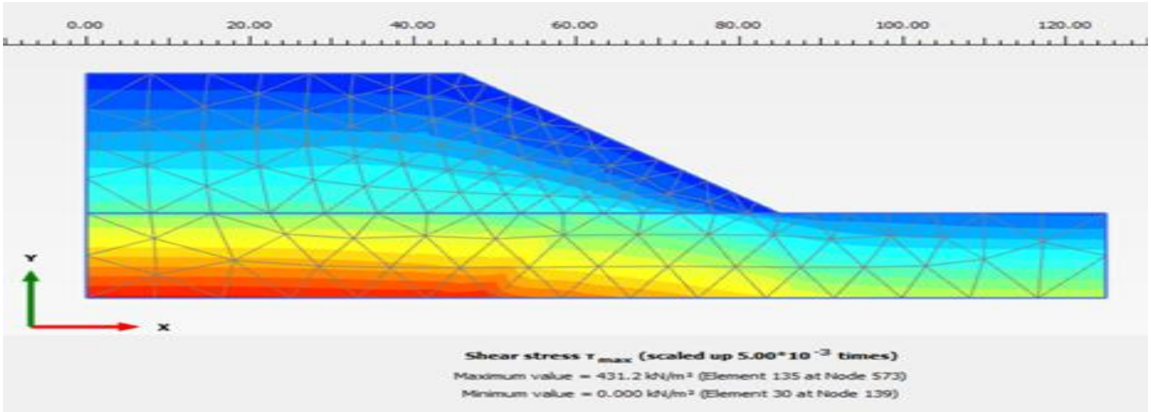

Figure 17: Illustration of the maximum shear stress at the Payatas landfill

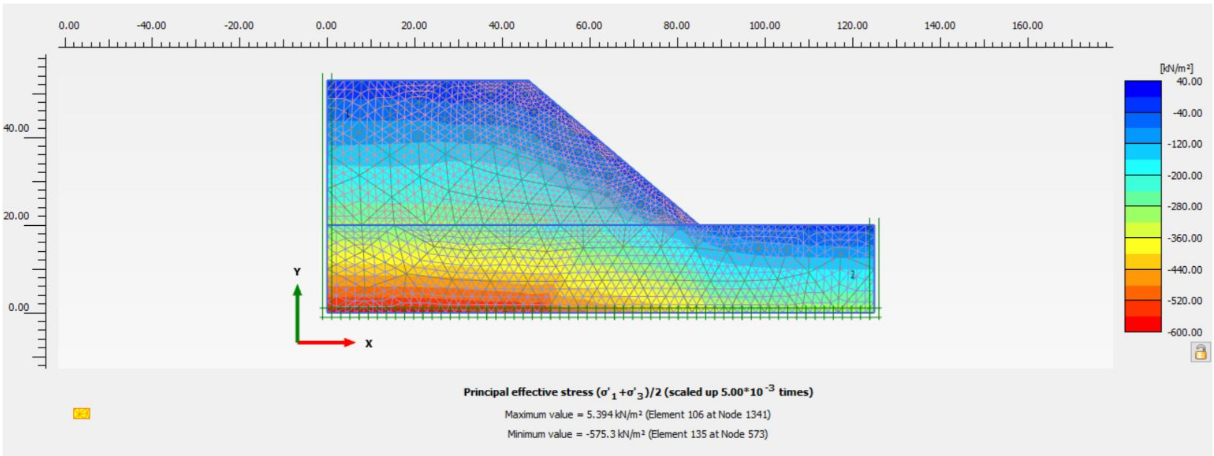

Figure 18: Illustration of the average principal stress at the Payatas landfill

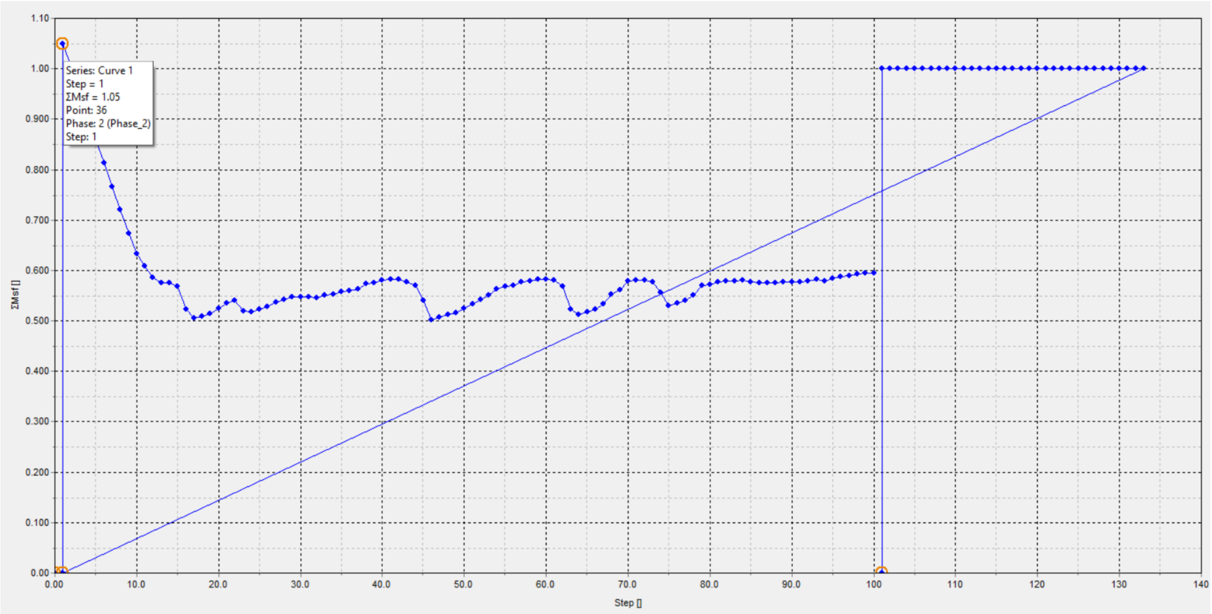

Figure 19: Diagram of the safety number of the Payatas landfill in Plaxis

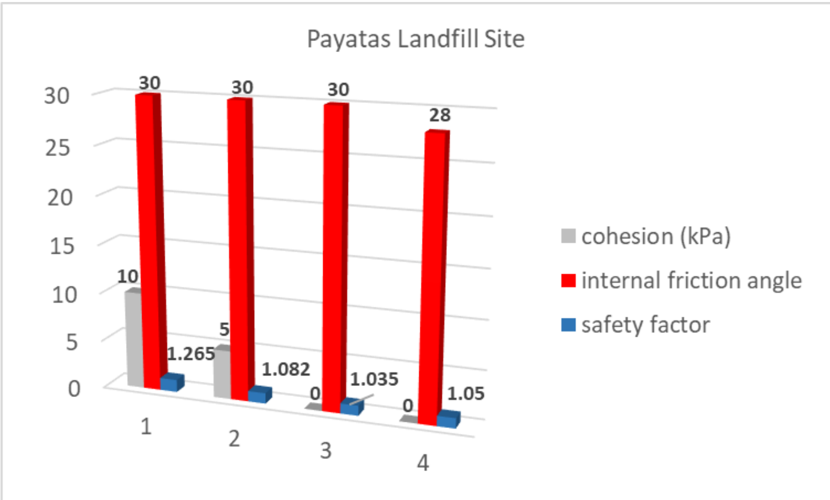

Figure 20: Safety factors as a function of cohesion and internal friction angle for the Payatas landfill

The Plaxis (2D CE V20) program was utilized to conduct an analysis of the Hiriya landfill. The slope geometry of the landfill is illustrated in Figure 21. When designing the slope geometry, a height of 60 meters and an angle of 56 degrees were used. The "Mesh-Medium" option was chosen for creating a mesh in the simulated landfill, resulting in 265 elements and 2227 nodes. Subsequently, the analysis phase was executed, and deformations were examined as shown in Figure 22. With a waste cohesion value of 0 and an internal friction angle of 28 degrees ($c=0$, $\phi= 28^o$), the total displacement was determined to be 184.6 meters. The analyses revealed that the maximum shear stress at the landfill was 861.6 kN/m² and the average principal stress was 865.6 kN/m² (Figure 22 and Figure 23). Furthermore, with a waste cohesion value of 0 and an internal friction angle of 28 degrees, the safety number was calculated to be 1.05, as depicted in Figure 24. The variation of the cohesion values, the internal friction angle and the safety factor of the model analyses performed are shown in Figure 25.

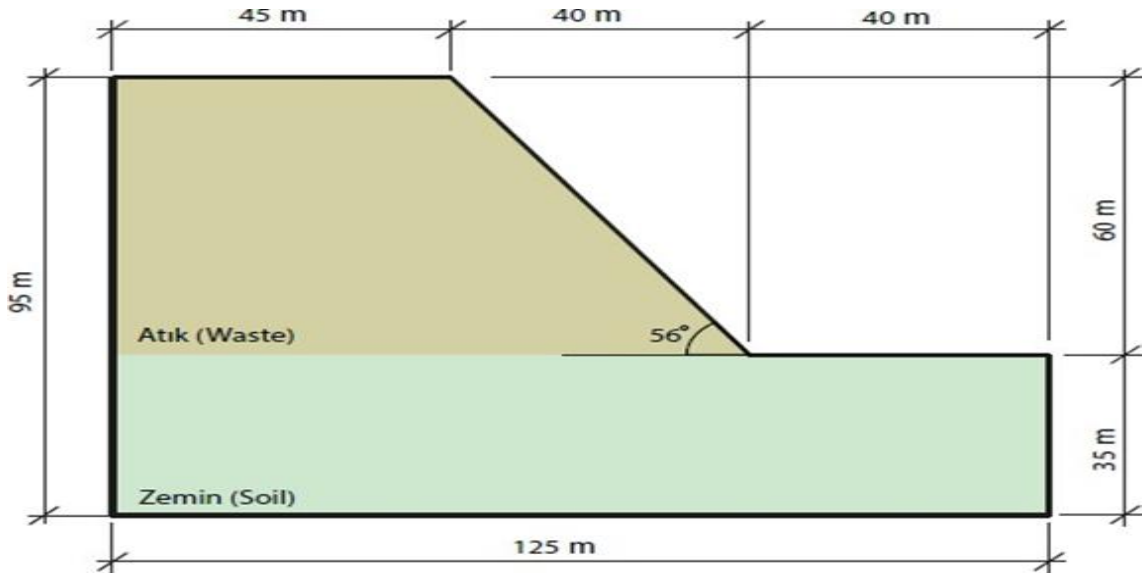

Figure 21: Depiction of the slope geometry of the Hiriya landfill

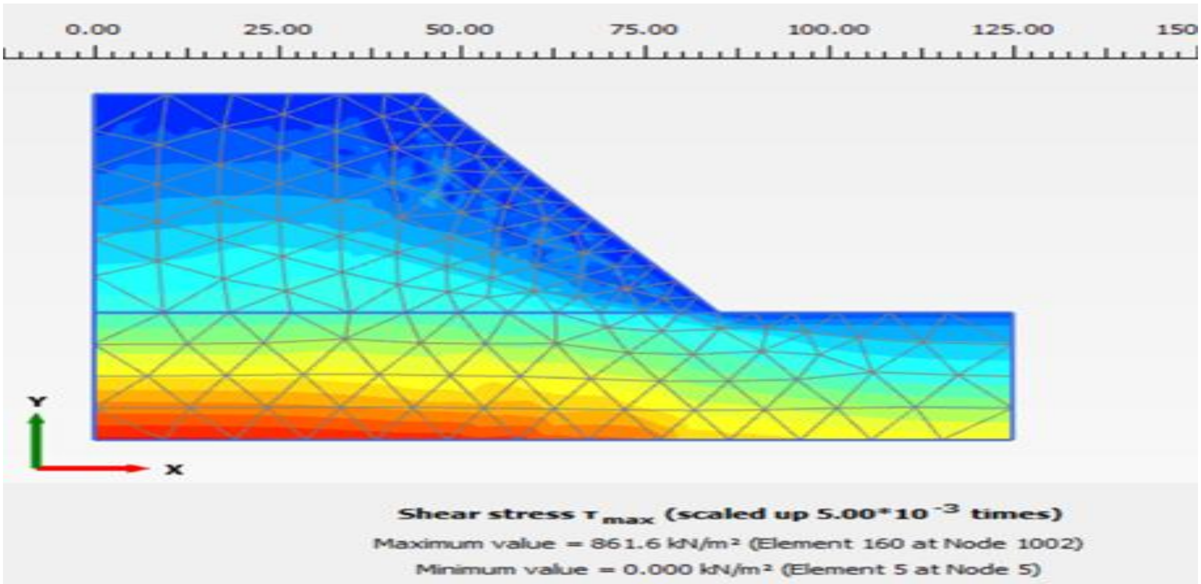

Figure 22: Illustration of the maximum shear stress at the Hiriya landfill

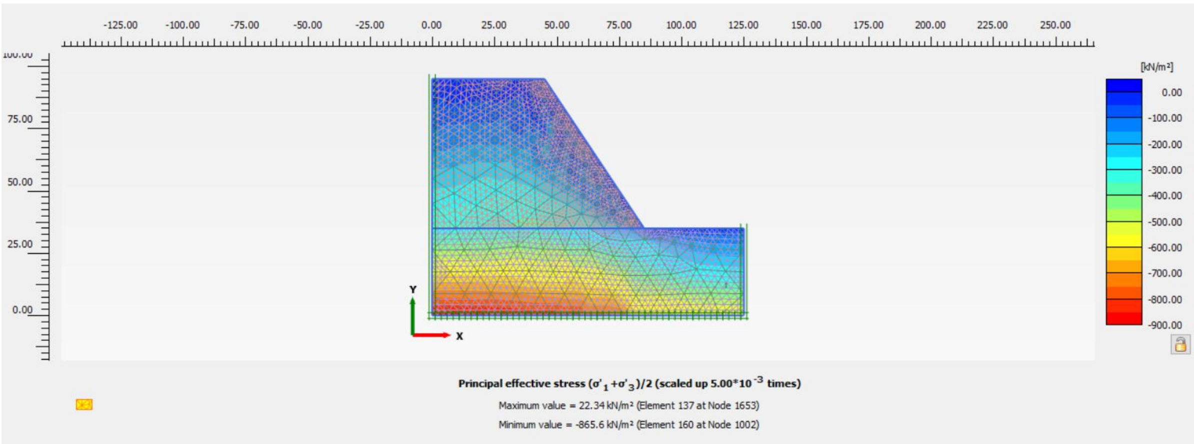

Figure 23: Illustration of the average principal stress at the Hiriya landfill

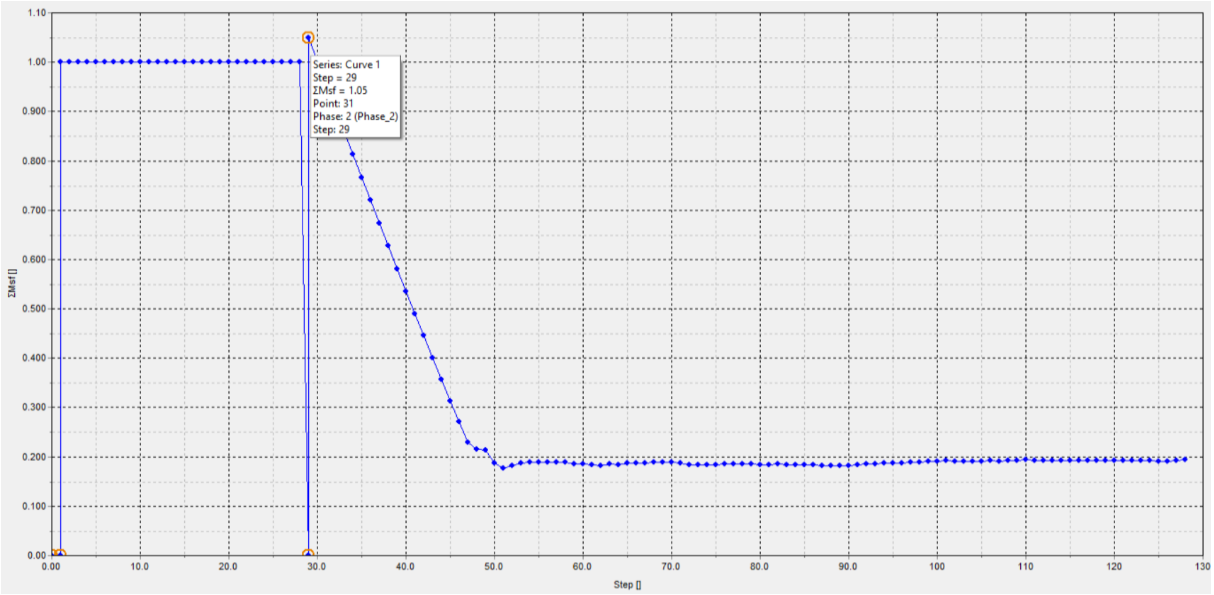

Figure 24: Diagram of the safety number of the Hiriya landfill in Plaxis

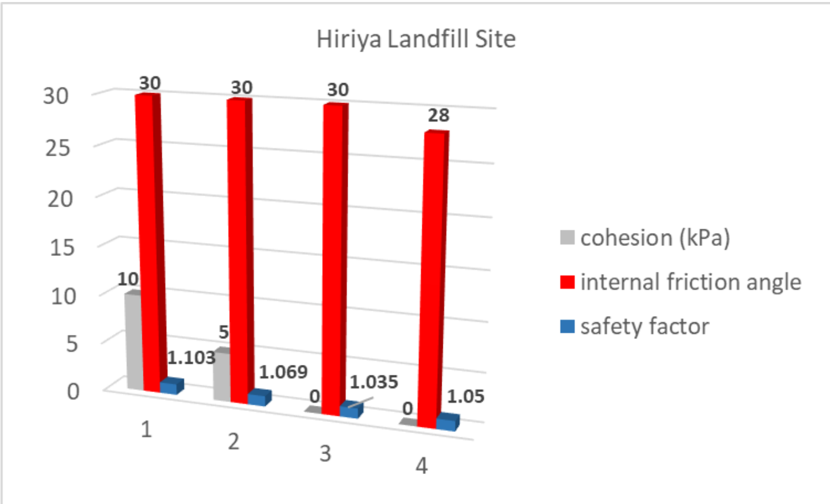

Figure 25: Safety factors as a function of cohesion and internal friction angle for the Hiriya landfill

The analysis of the Xerolakka landfill was conducted using the Plaxis (2D CE V20) program. The geometry of the landfill slope is depicted in Figure 26. The landfill has a slope height of 42 m and an angle of 42 degrees. When creating a mesh in the modelled landfill, the “Mesh-Medium” option was chosen. This resulted in a mesh comprising 216 elements and 1829 nodes. Deformations in the analysed landfill were examined and are illustrated in Figure 27. When the cohesion value of the waste was set to 0 and the internal friction angle was set to 28 degrees (c=0, ϕ= 28 degrees), the total displacement amounted to 14.71 m. Following the examination of total displacements, shear stress was analysed. According to the analysis results, the maximum shear stress at the landfill was determined to be 365.4 kN/m² and the average principal stress was 455.3 kN/m² (Figure 27 and Figure 28). When the cohesion value of the solid waste in the Xerolakka landfill, as modelled in Plaxis 2D, is 0 and the internal friction angle is 28 degrees, the factor of safety is determined to be 1.05, as shown in Figure 29. The variation of the cohesion values, the internal friction angle and the safety factor of the model analyses performed are shown in Figure 30.

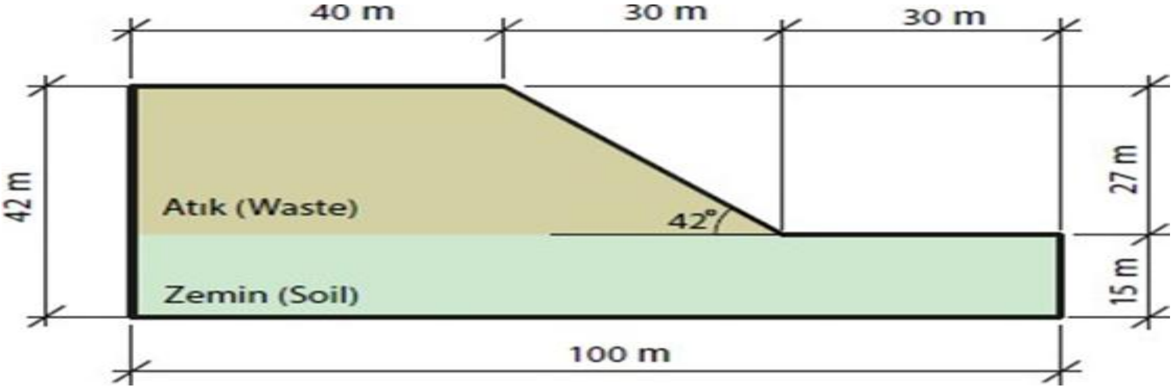

Figure 26: Depiction of the slope geometry of the Xerolakka landfill

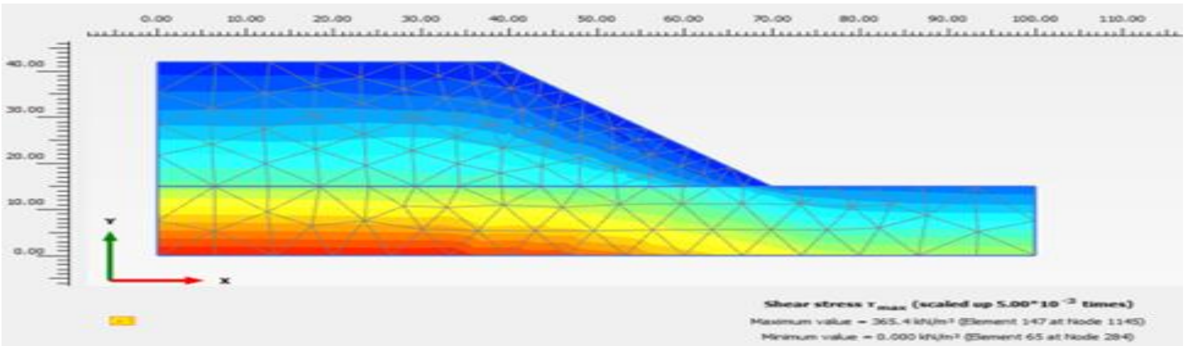

Figure 27: Illustration of the maximum shear stress at the Xerolakka landfill

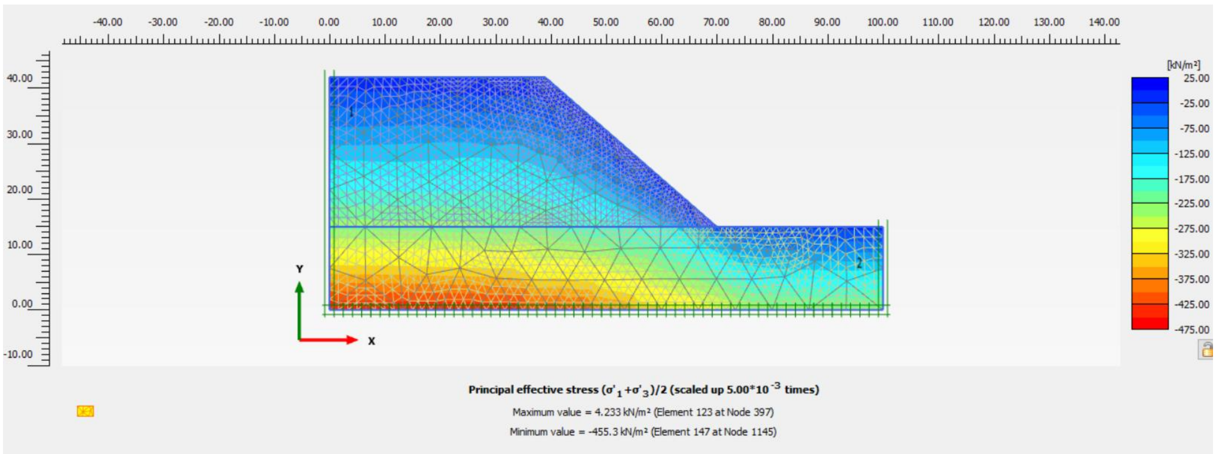

Figure 28: Illustration of the average principal stress at the Xerolakka landfill

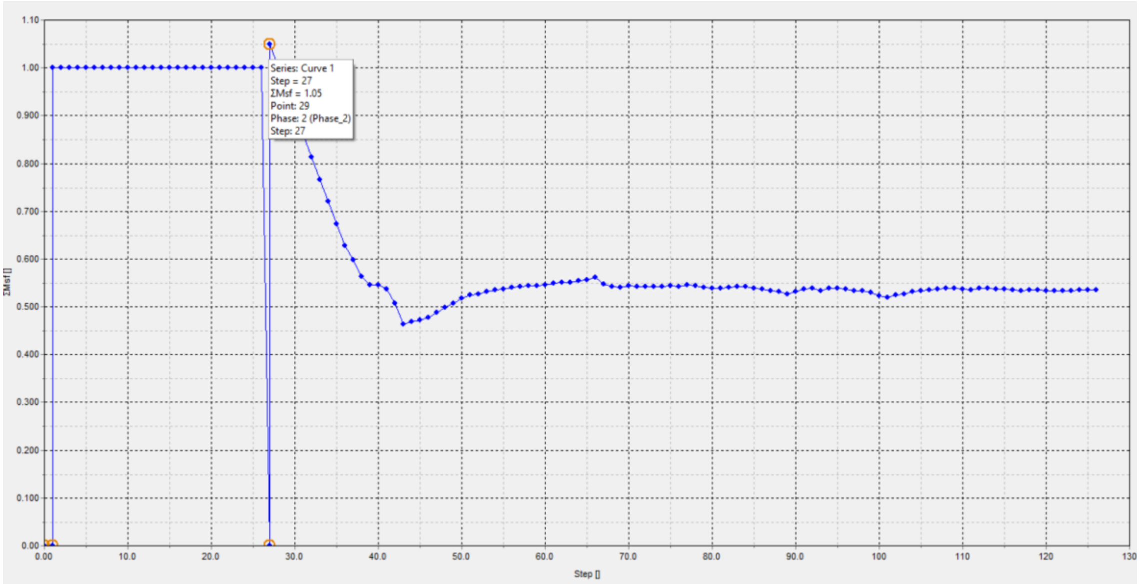

Figure 29: Diagram of the safety number of the Xerolakka landfill in Plaxis

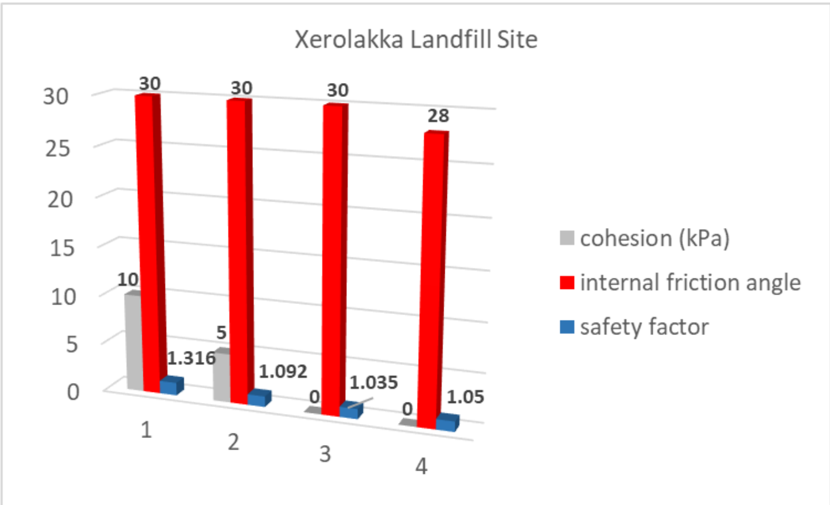

Figure 30: Safety factors as a function of cohesion and internal friction angle for the Xerolakka landfill

Table 4 presents the results of the landfill analyses, including shear stress, safety factor, and total displacement values obtained from the evaluated landfills.

Table 4: Results of landfill analyses

Landfill Site	Hekimbasi	Dona Juana	Gnoja Grora	Hiriya	Payatas	Xerolakka
Cohesion (kN/m²)	0	0	0	0	0	0
Internal friction angle (°)	30	28	21	28	28	28
Total displacement (m)	40,09	309,2	23,09	184,6	19,42	14,71
Shear stress (kN/m²)	598,1	706,8	390,1	861,6	431,2	365,4
Safety factors	1,035	1,109	1,107	1,05	1,05	1,05

In this study, the results of finite element analyses conducted for six irregular storage sites where collapse events occurred are presented. The maximum shear stress values (half the difference between the maximum and minimum principal stresses) and the average principal stress values (the average of the maximum and minimum principal stresses) shown in the figures are summarized collectively in Table 5. Using the maximum shear stress values and the average principal stress values, the maximum and minimum principal stress values for these six irregular storage sites were easily calculated.

Table 5: Stress and shear stress parameters in landfill areas

Landfill	Shear Stress Failure Value (kN/m²)	Average Normal Stress (kN/m²)	Maximum Principal Stress (kN/m²)	Minimum Principal Stress (kN/m²)
Hekimbaşı	598.1	738.8	1441.91	35.69
Dona Juana	706.8	849	1673.38	24.62
Gnojna Grora	390.1	549.6	1026.65	72.55
Hiriya	431.2	575.3	1093.64	56.96
Payatas	861.6	865.6	1830.43	-99.23
Xerolakka	365.4	455.3	886.03	24.57

These results indicate that the material in each landfill site is subjected to different stress conditions, significantly affecting its mechanical strength and deformation behavior. Therefore, stress analyses are critical parameters that must be considered in design and engineering processes to ensure the safe and long-term use of the material. Understanding how the material behaves under different stress conditions and how these conditions impact its strength is vital for designing safer and more durable structures.

3.2. Results

This study presents a comparative analysis of six distinct landfill sites: Hekimbasi, Dona Juana, Gnoja Grora, Hiriya, Payatas, and Xerolakka. The evaluation parameters for each site encompass cohesion, internal friction angle, total displacement, shear stress, and safety factors.

The landfill materials at all sites exhibit zero cohesion (kN/m²), indicating that the materials are granular with no inherent or natural binding property. The internal friction angle, a measure of the shear strength of the landfill material, varies across the sites. Gnoja Grora has the lowest value of 21º, suggesting that the material at this site is likely to shear or deform under less stress compared to the other sites, which have values around 28-30º.

In terms of total displacement (m), Dona Juana and Hiriya show significantly higher values (309.2 m and 184.6 m respectively) compared to the other sites. This could indicate more significant settlement or movement of the landfill mass at these sites, possibly due to factors such as load, composition of the waste, or underlying soil conditions.

The shear stress (kN/m²), a measure of the force that causes layers or parts to slide upon each other in opposite directions, also varies across the sites. Hiriya exhibits the highest shear stress of 861.6 kN/m², while Xerolakka shows the lowest at 365.4 kN/m². This suggests that the landfill material at Hiriya is subjected to higher forces that could lead to deformation or failure.

The safety factors for all sites are slightly above 1, indicating that the landfills are designed to withstand the applied stresses. However, these values are quite close to 1, suggesting that there may be little room for error or unexpected increases in stress.

While all the landfill sites share some common characteristics, there are notable differences in their geotechnical properties and behavior. These differences could have significant implications for the stability and long-term management of these sites. Further investigation and monitoring would be beneficial to understand the causes of these variations and to develop appropriate mitigation strategies.

The significant findings from the analysis are encapsulated in this section, and practical recommendations grounded in these insights are offered.

The selection of a suitable site is paramount in the establishment of solid waste landfills. It is vital that the selected site adheres to all relevant regulations prior to the installation of a storage facility. The main contributors to slope failures include deficiencies in engineering control, substandard landfill design, and a lack of comprehension of design principles and operation. Consequently, it is imperative that engineering controls are comprehensively implemented in line with the landfill design.

Several characteristics can lead to stability issues in municipal solid waste sites. These include the inhomogeneity of the solid waste, inconsistent compaction, differential settlement across the site, inherent instability of the garbage, and the development of pore water pressures.

Slope collapses in landfills are frequently caused by unsuitable landfill design, lack of daily cover laying and waste compaction, inadequate waste segregation, insufficient leachate drainage and gas discharge, and excessive slope angle and height. The presence of one or more of these conditions can result in a decline in site stability. In certain instances, adverse groundwater conditions and weather conditions can intensify these issues, leading to slope failures. This was particularly observed in the Hiriya and Payatas landfills.

It was observed that the impacts of groundwater elevation and slope angle on stability were not sufficiently considered in the landfill sites. Additionally, it is essential to collect and remove any leachate that may occur in the landfill.

The surge in waste production, economic growth, and rapid population increase, particularly in developing countries, has escalated the demand for landfills. Given the financial constraints, landfills constructed as a rule have been unable to be maintained due to the lack of natural reduction measures, such as leachate collection systems and lining materials. The subsequent year witnessed a significant amount of environmental contamination. Furthermore, it is believed that weak layers in the landfill, caused by sporadic or various factors or inadequately compacted soil layers, may have contributed to failures.

The most crucial conclusion is that landfill owners and managers, whether they operate dumpsites or construct structured landfills, should employ prepared and skilled personnel to manage their landfills. Likewise, administrative or control specialists should be adequately trained. Measures for controlling and enhancing capacity should be implemented, if not already in place. The disposal of MSW by uncompacted dumping should be phased out as soon as possible. Where this is impractical, steep, hilly regions, especially sites intersected by streams or other watercourses, or located in marshes or lakes, should be avoided.

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