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Analyzing MSW Landfill Failures: Stability and Reliability Evaluations from Five International Case Studies

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Abstract: This study investigates five cases of municipal solid waste (MSW) landfill slope failures in the USA, China, Sri Lanka, and Greece, with the aim of assessing the safety margins and reliability of these slopes. The stability and reliability of the landfill slopes were evaluated under both static and seismic loading conditions, using pre-failure geometries and geotechnical data, with analyses conducted in accordance with Eurocode 7, employing all three design approaches. Under static loading, the factors of safety were close to unity, and reliability indexes ranged from 1.0 to 2.8, both falling below the recommended values set by Eurocode. The landfill slopes failed to meet the stability criteria in Design Approaches 2 and 3, while in Design Approach 1, four out of five landfills met the criteria. Under seismic conditions, safety factors and reliability indexes were significantly lower than the prescribed criteria in all analyses. Sensitivity analyses revealed that in two cases, unit weight and friction angle were the dominant parameters, while cohesion was the dominant parameter in one case. The findings of this study underscore the importance of establishing minimum design requirements for MSW landfill slope stability to mitigate potential risks to public health and the environment.

Keywords: landfill failure; Eurocode 7; slope stability; geotechnical analysis; environmental engineering

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1. Introduction

Landfills are the most straightforward, cost-effective, and commonly used waste disposal systems worldwide. Despite recent advancements in reuse, recycling, and recovery methods, these efforts have not been able to halt the global expansion of landfills [1]. According to UN projections [2], a significant increase is anticipated in the total mass of waste generated, as well as in the amount of waste deposited in Municipal Solid Waste (MSW) landfills, as illustrated in Figure 1.

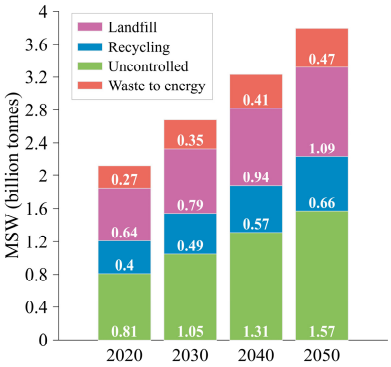


Figure 1. Projections of global municipal solid waste generation in 2030, 2040, and 2050 [2].

From 2.1 billion tonnes in 2023, the generation of MSW is expected to grow to 3.8 billion tonnes by 2050. Of this, the mass of waste in MSW landfills is projected to increase from

0.64 to 1.09 billion tonnes, representing an approximate growth of 70%. While the direct cost of global waste management in 2020 was estimated at USD 252 billion, the inclusion of indirect costs associated with pollution, health impacts, and climate change from poor disposal practices raises this figure to USD 361 billion. The report warns that inaction on waste management could nearly double these costs by 2050, reaching a staggering USD 640.3 billion. These findings highlight the urgent need for improved waste management strategies to mitigate the economic and environmental burdens of MSW [2].

MSW landfills are geotechnical structures; however, unlike traditional geotechnical structures, they are composed of waste rather than soil. According to existing research [3,4], the geotechnical properties of MSW relevant to slope stability are significantly more heterogeneous than those of soil. However, stability analyses often treat them as if they were soil. This approach can result in slopes that are insufficiently stable and robust, where even minor operational deficiencies during the lifespan of MSW landfills can lead to failure, as evidenced by a series of historical catastrophic MSW landfill slope failures. Such events pose significant risks to the environment, public health, and the economy.

An example is the Payatas landfill failure, which occurred on July 10, 2000, in the Philippines, with severe consequences for society and the environment [5]. A total of 13,000–16,000 cubic meters of municipal solid waste (MSW), weighing 15,800–19,400 tons, was involved in the landslide. The causes of the failure were linked to the slope geometry (a slope that was too steep), large amounts of rainfall, and operational deficiencies. A series of MSW landfill failures have occurred worldwide, such as in Sarajevo, Yugoslavia, in 1977 [6]; Bogota, Colombia, in 1997 [7]; and Bandung, Indonesia, in 2005 [8].

Ensuring adequate slope stability in MSW landfills is one of the most critical engineering challenges in landfill operations [9]. Various authors have conducted back-analyses of MSW landfill failures. Zhang et al. [10] analyzed 62 slope failures of MSW landfills, categorizing them into three groups based on the location of the slip surface. In the first group, the entire slip surface lies within the waste pile. In the second group, it passes through the foundation soil, and in the third group, it forms at the interface between the bottom liner and the MSW body. Blight [11] analyzed six large-scale MSW landfill failures that occurred between 1997 and 2005. The study highlights that the causes of failure in the cases reviewed include the absence of engineered designs for landfills, lack of engineering oversight throughout the construction and operation phases, and the most important factor overlooked in all these cases: the influence of both leachate levels and slope angles on the overall stability of the landfills. Various authors have conducted back-analyses of the stability and reliability of MSW landfill slopes using different methods. The most common methods employed are the Limit Equilibrium Method (LEM), the Finite Element Method (FEM), and the Finite Difference Method (FDM).

The Limit Equilibrium Method (LEM) utilizes the concept of static equilibrium, calculating the factor of safety based on the principles of statics by considering force and/or moment equilibrium. This method is widely used in geotechnical engineering practice. However, its major shortcoming is the disregard for strain and displacement compatibility [12]. In contrast, discrete element formulations offer significant advantages when modeling failure and post-failure behavior. They allow individual particles, blocks, or elements to separate, move, and rotate independently, potentially forming new contacts with other blocks. This approach is particularly valuable for analyzing failure mechanisms and large post-failure deformations. However, their drawback is that they do not provide a direct indication of the margin of safety [13].

A study by Vinai et al. [14] demonstrates the application of the Distinct Element Method (DEM) to describe the behavior of geogrid-reinforced embankments under rock impact. The researchers simulate various types of rock impacts on an embankment using Itasca's PFC2D software, version 3.0. The modeling outputs include diagrams that illustrate displacement and damage, such as failures and tension cracks. These results are validated against full-scale impact test data. The study concludes that PFC2D modeling satisfactorily describes the real-world behavior of embankments under rock impact; however, such an

approach does not directly quantify the margin of safety. Medizadeh et al. [1] employ the Finite Difference Method (FDM) in conjunction with the Monte Carlo method to determine the reliability of MSW landfill slopes. In reliability analyses, they select soil unit weight, cohesion, and friction angle as random variables and assume a normal statistical distribution for the safety factor, determined through 2000 simulations. They conclude that this number of simulations is appropriate for assessing the reliability of MSW slopes and that higher coefficients of variation (COV) of random variables result in lower reliability. Chropenova et al. [9] analyze the stability of two MSW landfills near the town of Handlová in Slovakia. They conduct analyses under both static and seismic conditions, with a horizontal acceleration factor of Kh = 0.07 (pseudo-static analyses). These analyses utilize the Bishop and Spencer methods (Limit Equilibrium Methods), assuming both circular and polygonal slip surfaces that pass through the waste body and foundation soil. The Spencer method and the polygonal slip surface result in lower safety factors, ranging from 1.70 to 2.01 under static conditions and from 1.41 to 1.59 under seismic conditions.

Research Purpose

The aim of this study is to quantify the safety margins and reliability of five MSW landfill slopes that have experienced failures by applying Eurocode standards. The following cases were analyzed: Cincinnati, OH, USA [12]; Xiaping, Shenzhen, China [10,15]; Maoershan, Sichuan, China [10]; Meethotamulla, Sri Lanka [10,16,17]; and Xerolakka, Greece [18,19]. Relevant data for conducting stability and reliability analyses were sourced from the literature [10,15–20], where back analyses determined the pre-failure geometry, failure mode, material properties, leachate levels, and other geotechnical parameters. From the literature review, it was determined that in these MSW landfill failures, authors primarily quantified slope stability using the traditional factor of safety, which was around a unit value in all analyzed cases. However, no data were found regarding the stability or reliability of these MSW landfills according to Eurocode 7 or any other building code. The landfills in this study were selected based on the availability of detailed pre-failure geometry and geotechnical data, enabling comprehensive analyses of stability and reliability. Additionally, these cases represent the most common causes of failure, including poor compaction, inadequate foundation soil, high leachate levels, steep slopes, and operational deficiencies. In all the cases considered, the slip surface passes through the waste body, which accounts for 70% of all landfill slope failures [Qian, Translational Failure Analysis of Landfills].

The research hypothesis posits that in all analyzed cases, the reliability of the MSW landfill slopes is significantly lower than typical values, indicating a much higher probability of failure. By conducting reliability analyses, the risk of failure could have been identified in advance, potentially allowing for the implementation of preventive measures to avert the failures.

In this study, the margins of stability were assessed using the factor of safety (FS) and the over-design factor (ODF), while reliability was quantified using the reliability index calculated by the Monte Carlo method. The study also analyses the influence of seismic loading on slope stability. Additionally, sensitivity analyses were conducted to investigate the effects of individual parameters on the stability of MSW slopes.

The findings of this study indicate that in all analyzed cases, under static loading, the ODF was significantly lower than the prescribed value, failing to meet the criteria set by Eurocode 7. Seismic loading further significantly reduced the ODF value. Reliability analyses indicated insufficient levels of the reliability index in all cases, with values for seismic loading being lower compared to static loading.

2. Materials and Methods

In this study, the slope stability and reliability of five MSW landfills that have experienced failures were analyzed. Table 1 provides a summary of the analyzed cases.

Table 1. A summary of MSW landfill failures was analyzed in this study.

Landfill	Cincinnati, OH, USA, [20]	Xiaping, Shenzen, China, [10,15]	Maoershan, Sichuan, China, [10]	Meethotamulla, Sri Lanka, [10,16,17]	Xerolakka, Greece, [18,19]
Date	9 March 1996	20 December 2015	8 September 2013	14 April 2017	29 December 2010
Cause	Mobilization of a post-peak (residual) shear strength (colluvium)	Rapid filling, inadequate compaction, poor drainage	High landfill leachate level (from rainfall), which reduced shear strength	Low strength of the foundation soil	To steep slopes, inadequate compaction, the absence of daily soil cover, elevated pore pressure
Slope angle	20° (1:2.75)	13° (1:4.33)	14° (1:4.05)	35° (1:1.41)	31° (1:1.17)
Consequences	Environmental	Human casualties, material damage	Unknown	Human casualties, material damage	Waste covered the access road

2.1. Model Geometry and Geotechnical Parameters

The stability analyses in this study consider actual slip surfaces, failure mechanisms, material characteristics, and leachate conditions. These data were obtained from previous studies, where authors determined these factors through back analyses and field observations. In two of the cases analyzed—Maoershan and Xiaping—dams were constructed at the edges of landfills to stabilize the slopes. In the Maoershan landfill, the slip surface intersected both the waste body and a stone slurry dam, leading to the failure of both structures during the event. In contrast, in the Xiaping case, the slip surface was located behind the dam, which remained unaffected by the failure event. The geometry, geotechnical conditions, and relevant properties of waste and foundation soils of the MSW landfills are presented in Figures 2–6 and Tables 2–6. Descriptions of the MSW and soil layers shown in Figures 2–6 are provided in the corresponding Tables 2–6. The calculated factors of safety of analyzed slopes are around unity, which is consistent with the results presented in the reviewed literature [10,17–20].

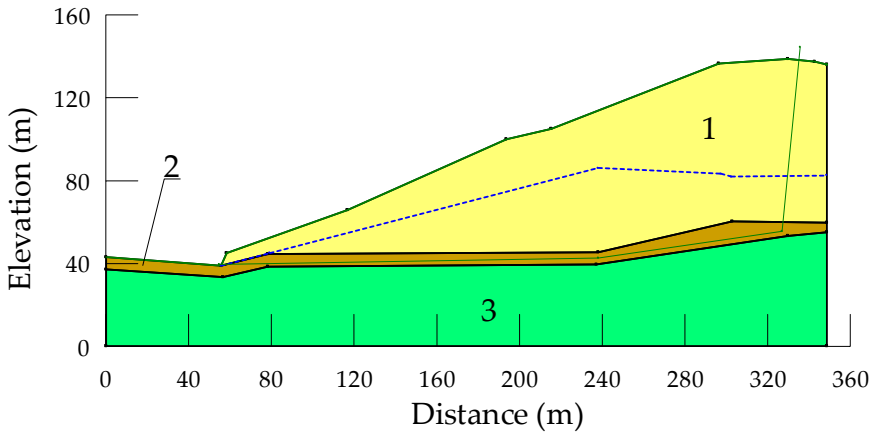


Figure 2. Geometry of the MSW landfill in Cincinnati, Ohio, USA [20].

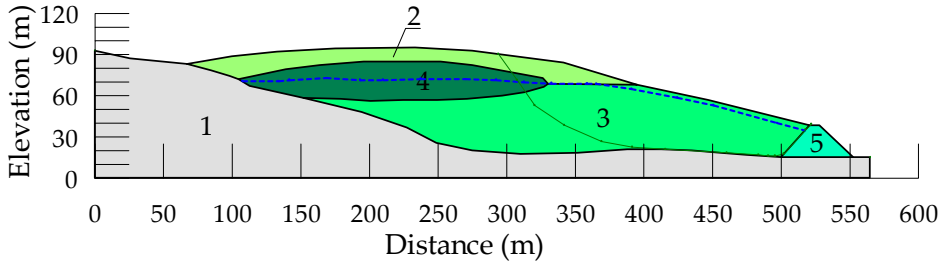


Figure 3. Geometry of the MSW landfill in Xiaping, Shenzen, China [15,21].

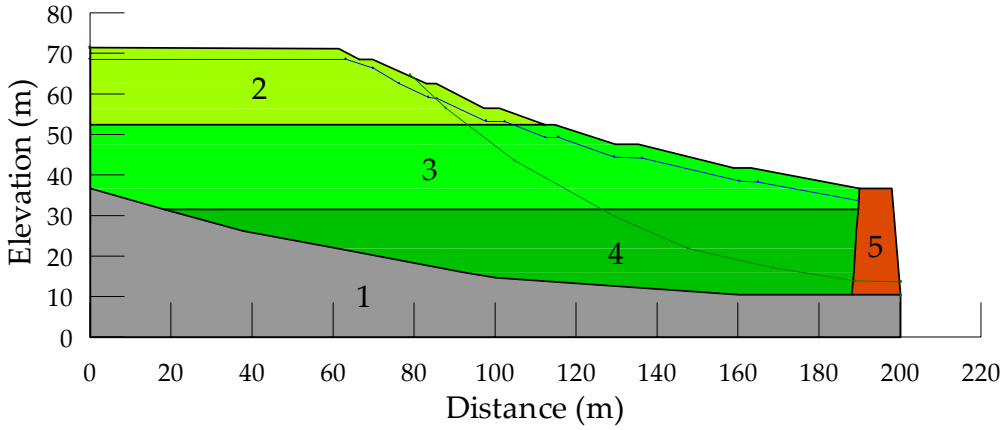


Figure 4. Geometry of the MSW landfill in Maoershan, Sichuan, China [10].

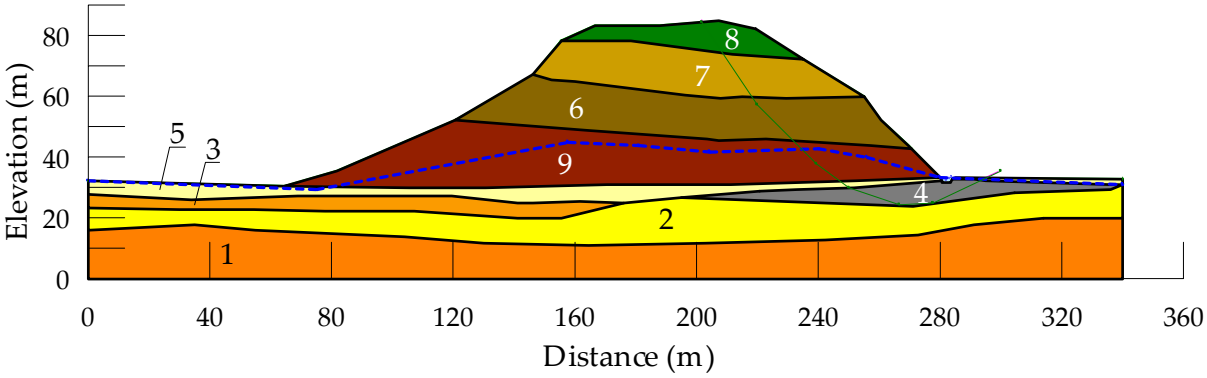


Figure 5. Geometry of the MSW landfill in Meethotamulla, Sri Lanka [16,17].

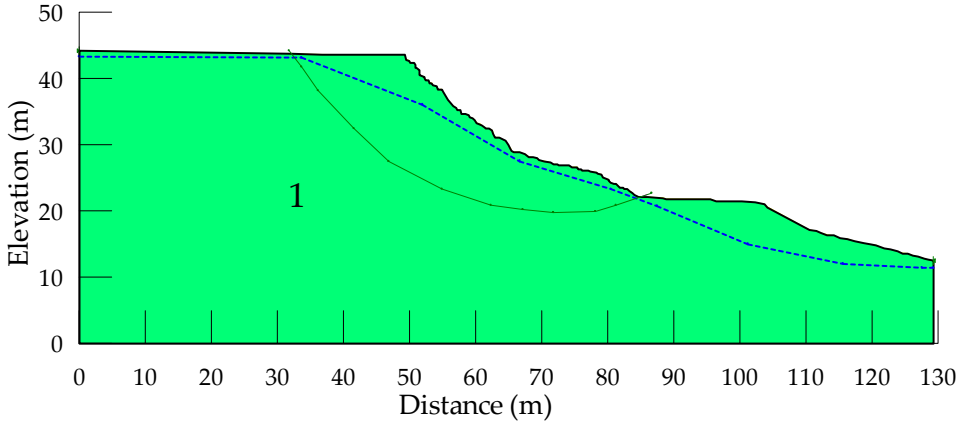


Figure 6. Geometry of the MSW landfill in Xerolakka, Greece [18,19].

Table 2. Geotechnical parameters of the MSW landfill in Cincinnati, Ohio, USA [20].

Nr.	Designation	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)
1	MSW	10.4	4	35
2	Brown native soil	20.1	0	12
3	Shale	23.9	100	45

Table 3. Geotechnical parameters of the MSW landfill in Xiaping, Shenzen, China [10,15].

Nr.	Designation	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)
1	Bedrock	22.0	35.0	50.0
2	Upper waste	8.0	5.0	15.0
3	Lower waste	12.0	8.0	10.0
4	Sludge	15.0	0.0	1.0
5	Dam	25.0	50.0	30.0

Table 4. Geotechnical parameters of the MSW landfill in Maoershan, Sichuan, China [10].

Nr.	Designation	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)
1	Bedrock	22.0	50.0	35.0
2	Upper waste	8.0	8.0	10.0
3	Intermediate waste	10.0	11.0	12.0
4	Lower waste	12.0	15.0	16.0
5	Dam	20.0	27.0	22.0

Table 5. Geotechnical parameters of the MSW landfill in Meethotamulla, Sri Lanka [16,17].

Nr.	Designation	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)
1	Weathered rock	20.0	10.0	38.0
2	Medium dense sandy silt/silty sand	17.0	10.0	30.0
3	Sandy clay	16.0	15.0	25.0
4	Peat	14.0	10.0	20.0
5	Loose silt/sand/gravel	16.0	5.0	28.0
6	Intermediate waste	8.0	20.0	30.0
7	Upper waste	6.5	0.0	38.0
8	Waste fill	5.0	20.0	0.0
9	Lover waste	9.5	20.0	30.0

Table 6. Geotechnical parameters of the MSW landfill in Xerolakka, Greece [18,19].

Nr.	Designation	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)
1	MSW	12.0	15.0	32.0

2.2. Geotechnical Stability Analyses

Geotechnical stability analyses were conducted on simplified numerical and geotechnical models of landfill slopes. GeoStudio software suite, Slope/w module, version 8.15, was employed to conduct the analyses. The stability of the slopes was evaluated using the Spencer method, which was developed by Evert Spencer in 1967 [22]. This method belongs to the Limit Equilibrium Method. It ensures that both horizontal and vertical forces, as well as moments around any point within the model, are in equilibrium, which can be expressed as follows:

$$\sum F_x = 0; \sum F_y = 0; \sum M_0 = 0, \quad (1)$$

where F_x and F_x are forces in the horizontal and vertical directions, respectively, and M_0 is the moment around any point of the model.

The method involves dividing the sliding mass of a slope into a series of vertical slices. For each slice, the method calculates forces acting on the slice, including the weight of the slice, the shear resistance along the potential slip surface, and forces between adjacent slices (interslice forces). The result of the method is the Factor of Safety (FS), which quantifies

slope stability. For values of FS < 1, the slope is unstable, while for FS ≥ 1, the slope is stable. The main features of the Spencer method are:

- Force Equilibrium: The method ensures that the sum of horizontal and vertical forces acting on each slice is in equilibrium. This includes considering the weight of the slice, normal and shear forces on the slip surface, and interslice forces;
- Moment Equilibrium: The method also ensures that moments around any point within the model are balanced;
- Shear and Normal Forces: For each slice, the shear force (resisting force) on the slip surface is calculated based on the shear strength of the material, which is defined by the Mohr–Coulomb failure criterion. The normal force is calculated based on the weight of the slice and the geometry of the slip surface;
- Interslice Forces: The method takes into account forces between adjacent slices, both horizontally and vertically, to ensure overall stability.

Geotechnical Stability Analyses According to Eurocode 7

Eurocode 7 is a design standard that provides guidelines for geotechnical design and investigation work. It emphasizes the interaction between structures and the ground, ensuring their stability and reliability. Key features of Eurocode 7 include the application of the limit state design method and the use of partial factors. These partial factors are calibrated to ensure a sufficient level of reliability for geotechnical structures. Eurocode 7 outlines three design approaches, each differing in the values of partial factors applied to material properties, loads, and resistances [23].

In this study, MSW landfill slopes were analyzed according to all three design approaches. The same partial factors were applied to both MSW and the foundation soil. Design approaches employed in this study are defined as follows [19], where A stands for Action, M for Material property and R for Resistance:

- Design Approach 1, combination 1: A1 '+' M1 '+' R1;
- Design Approach 2: A1 '+' M1 '+' R2;
- Design Approach 3: A2 '+' M2 '+' R3.

The partial factors defined in Eurocode 7 used in this study are presented in Tables 7–9.

Table 7. Partial factors for actions according to Eurocode 7 [24].

Actions		Symbol	Set	
			A1	**A2**
Permanent	Unfavorable	γ_G	1.35	1.0
	Favorable		1.0	1.0
Variable	Unfavorable	γ_Q	1.5	1.3
	Favorable		0	0

Table 8. Partial factors for geotechnical parameters according to Eurocode 7 [24].

Parameter	Symbol	Set	
		M1	**M2**
Friction angle	γ_φ	1.0	1.25
Cohesion	γ_c	1.0	1.25
Unit weight	γ_γ	1.0	1.0

Table 9. Partial factors for resistances according to Eurocode 7 [24].

Parameter	Symbol	Set		
		R1	**R2**	**R3**
Earth resistance	$\gamma_{R,s}$	1.0	1.1	1.0

Stability analyses conducted according to Eurocode 7 result in an Over-Design Factor (ODF), which represents the ratio between the design values of resistances and actions. In contrast, traditional stability analysis yields a Factor of Safety, which represents the ratio of characteristic values of resistance to actions. The ODF is calculated using Spencer's method, as described in Equation (2). The first and second Equations pertain to the equilibrium of horizontal and vertical forces, while the third Equation addresses the equilibrium of moments around any point in the model. The governing value of the ODF is the smallest of the three calculated values, as per Equation (2) [24].

$$ODF = \frac{R_{H,d}}{V_{H,d}};\ ODF = \frac{R_{V,d}}{V_{V,d}};\ ODF = \frac{M_{R,d}}{M_{Sd}}\ , \tag{2}$$

where $R_{H,d}$, $R_{V,d}$, and $M_{R,d}$ are design values of horizontal resistance force to sliding, vertical resistance force to sliding, and moment-resisting sliding, respectively, and $V_{H,d}$, $V_{V,d}$, and M_{Sd} are vertical force contributing to sliding, horizontal force contributing to sliding, and moment contributing to sliding, respectively.

An ODF value less than 1 (ODF < 1) indicates non-compliance with the ultimate limit state criterion according to Eurocode 7, while an ODF value of 1 or greater (ODF $\geq$ 1) represents compliance with this criterion.

2.3. Reliability Analyses of MSW Landfill Slopes

Reliability analyses of MSW landfill slopes were conducted using the Monte Carlo method. The method is a technique for solving deterministic or stochastic mathematical problems that cannot be solved using traditional closed-form techniques. In this method, mathematical problems are solved by applying their statistical analogies, subjecting random numbers to numerical processes [25]. The procedure involves generating random numbers and applying the corresponding cumulative distribution functions of all variables to create combinations of their values. For each combination, the limit state function is evaluated, representing one simulation. This process is repeated a certain number of times, and the probability of failure is determined as the ratio of the number of simulations where the limit state function takes on a negative value to the total number of simulations (Equation (3)) [26].

$$P_f \approx n(G(\hat{x}_i) \leq 0)/N, \tag{3}$$

where P_f is the probability of failure, $n(G(\hat{x}_i) \leq 0)$ is the number of simulations for which the limit state function took a negative value, and N is the total number of simulations.

From the probability of failure, the reliability index can be calculated using the following mathematical Equation [27]:

$$\beta = -\Phi^{-1}\left(P_f\right), \tag{4}$$

where $\Phi^{-1}(.)$ is the inverse standard normal cumulative function, and P_f is the probability of failure.

Eurocode 0 [28] specifies the minimum target values for the reliability index, which depends on the consequence class of the structure and its reference period (Table 10). The consequence classes CC1–CC3 in Eurocode 0 categorize structures based on the potential impact of their failure. CC1 includes structures with a low risk of causing harm to people, the economy, society, or the environment. CC2 encompasses structures with a moderate risk, while CC3 includes structures whose failure could result in significant loss of life or substantial economic, social, or environmental damage. MSW landfills are typically classified into the CC2 and CC3 classes.

Table 10. Target values for reliability index according to Eurocode 0 [28].

Consequence Class	1-Year Reference Period β	50-Year Reference Period β
CC3	5.2	4.3
CC2	4.7	3.8
CC1	4.2	3.3

Similar to Eurocode, the U.S. Army Corps of Engineers [29] classifies structures according to the reliability index and their expected performance level, as shown in Table 11.

Table 11. Target values for reliability index according to the U.S. Army Corps of Engineers [29].

Expected Performance Level	Reliability Index
High	5
Good	4
Above average	3
Below average	2.5
Poor	2.0
Unsatisfactory	1.5
Hazardous	1.0

The reliability indexes calculated in this study were compared to the criteria presented in Tables 10 and 11. These indexes were determined using the Monte Carlo method with 2000 simulations. According to Mehdizadeh et al. [1] and Griffith and Fenton [27], this number of simulations is sufficient to determine the reliability index of a slope with three random variables. The reliability indexes for all slopes in MSW landfills were assessed based on the slip surfaces where the failure occurred.

Random Variables in Reliability Analyses

In the reliability analyses, three geotechnical parameters of MSW were considered as random variables: unit weight, cohesion, and friction angle. Their mean values were selected from Tables 2–6, while the standard deviations and correlation coefficients of cohesion and friction angle were determined based on the study by Petrovic et al. [3]. According to their findings, the coefficients of variation for cohesion and friction angle were $COV_c = 0.72$ and $COV\varphi = 0.34$, respectively. Their results also indicated a lognormal statistical distribution for cohesion and a normal statistical distribution for the friction angle. The correlation coefficient between cohesion and friction angle was found to be −0.41. For the unit weight of MSW, a normal statistical distribution with a coefficient of variation of 0.24 was assumed in accordance with the study by Jahanfar et al. [30].

2.4. Sensitivity Analyses

To determine the effects of each input parameter on the variation of the factor of safety for MSW landfill slopes, sensitivity analyses were conducted. In these analyses, the value of each parameter was varied between predefined minimum and maximum values, while the other parameters were kept at their mean values. The parameters varied in this study were unit weight, cohesion, and friction angle of MSW. The minimum values were determined by subtracting the standard deviation from the mean, while the maximum values were obtained by adding the standard deviation to the mean value of each parameter (Equation (5)).

$$X_{min} = \mu_X - \sigma_X;\ X_{max} = \mu_X + \sigma_X, \quad (5)$$

where X_{min} and X_{max} are minimum and maximum values, μ_x is the mean value, and σ_x is the standard deviation of parameter X.

The mean values of the parameters used in the sensitivity analyses are presented in Tables 2–5. The corresponding standard deviations were calculated using the following equation:

$$\sigma_X = COV_X \cdot \mu_X \quad (6)$$

where COV_X is the coefficient of variation, and μ_x is the mean value of parameter X.

The coefficients of variation for MSW parameters were determined based on the values reported in the literature as follows [3,4,30,31]:

- Cohesion: $COV_{c'} = 0.72$;
- Friction angle: $COV_{\varphi'} = 0.34$;
- Unit weight: $COV_{\gamma} = 0.24$.

2.5. Stability Analysis of MSW Landfill Slopes under Seismic Loading

In addition to the stability analyses of MSW slopes under static loading, pseudo-static analyses were conducted to assess MSW landfill slopes under seismic loading. In these analyses, seismic loading is represented by static forces acting on each slice of the slope. The horizontal and vertical forces are calculated as follows:

$$F_H = k_h W;\ F_V = k_v W \quad (7)$$

where k_h and k_v are the pseudo-static horizontal and vertical seismic coefficients, respectively, and W is the weight of the slice.

The analyses were conducted with values of $k_h = 0.1$ and $k_v = 0.05$, which approximately correspond to an earthquake intensity of VI according to the Modified Mercalli Scale [32].

3. Results and Discussion

A total of 40 stability analyses were conducted for MSW landfills under both static and seismic loading conditions, along with an additional 191 sensitivity analyses. Additionally, ten reliability analyses were performed using the Monte Carlo method, involving a total of 20,000 simulations to determine the reliability index. Both the reliability and stability analyses were conducted for the same predefined slip surfaces where failure had occurred.

3.1. Stability of MSW Landfill Slopes under Static and Seismic Loading

The results of the stability analyses for static loading are presented in Figures 7–12. The Xerolakka MSW landfill exhibits the lowest factor of safety (FS = 0.98), while the highest factor of safety is observed at the Maoershan MSW landfill (FS = 1.08). The higher factor of safety at the Maoershan MSW landfill can be attributed to the retaining structure located at the edge of the slope, which significantly enhances stability due to its shear strength and the gradual slope angle (14°, 1:4.05). Conversely, the lower factor of safety at the Xerolakka MSW landfill is primarily due to the very steep slope angle (31°, 1:1.67) and the very high leachate level, which increases pore pressures, thereby reducing shear strength on the slip surface due to decreased effective stress. The factors of safety for the other analyzed slopes range from 1.01 to 1.03, which are consistent with the observed slope failures in all the analyzed sites. The results of the slope stability analyses in all cases are in good agreement with the results from previous studies [10,15,17–20].

Table 12 presents a summary of the stability analyses conducted under both static and seismic loading conditions. The seismic analyses were performed using horizontal and vertical seismic coefficients of $k_h = 0.1$ and $k_v = 0.05$, respectively, which correspond approximately to an earthquake intensity of VI on the Modified Mercalli Scale. This intensity is characterized by the widespread perception of the earthquake, with many objects falling from shelves, plaster detaching from buildings, broken glass in windows, damaged chimneys, and localized incidents such as landslides, rockfalls, and liquefaction. The results of the analyses conducted under seismic loading indicate that even a relatively low-intensity earthquake is likely to trigger slope failure in the analyzed cases. Due to the

significant reduction in the factor of safety observed across all analyses, no further analyses were conducted with higher seismic loading.

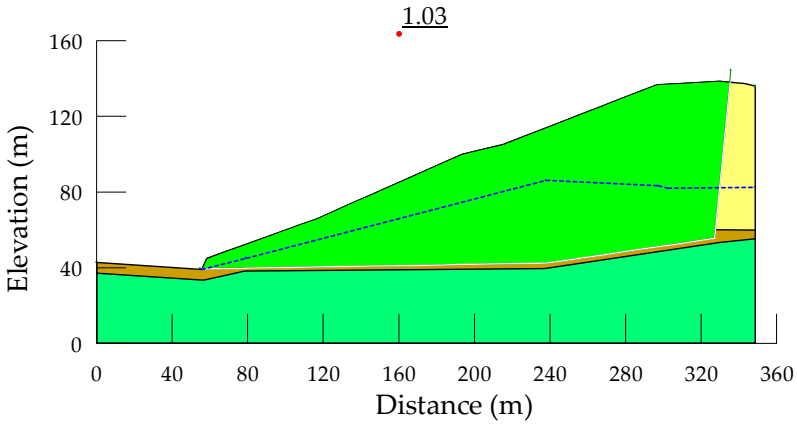


Figure 7. Results of Stability Analysis for MSW Landfill in Cincinnati, USA.

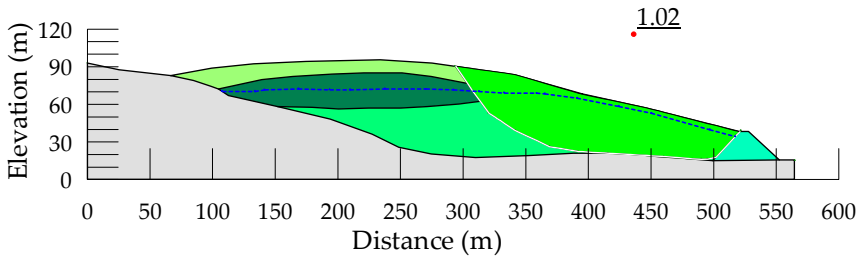


Figure 8. Results of Stability Analysis for MSW Landfill in Xiaping, Shenzen, China.

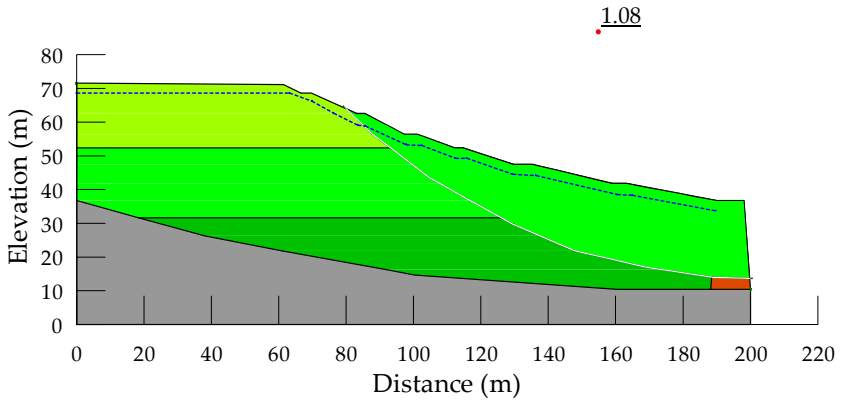


Figure 9. Results of Stability Analysis for MSW Landfill in Maoershan, Sichuan, China.

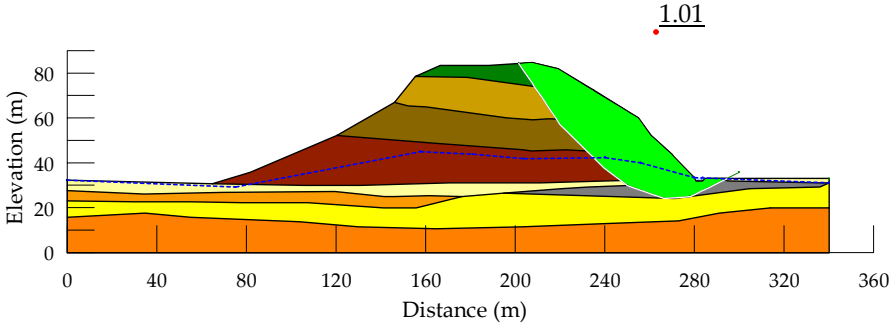


Figure 10. Results of Stability Analysis for MSW Landfill in Meethotamulla, Sri Lanka.

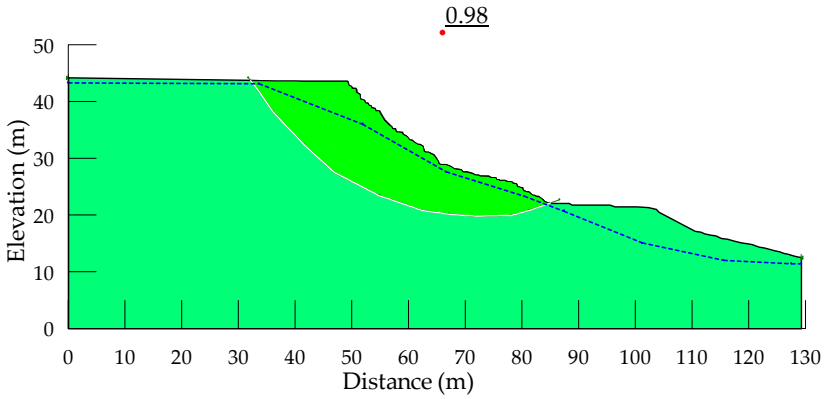


Figure 11. Results of Stability Analysis for MSW Landfill in Xerolakka, Greece.

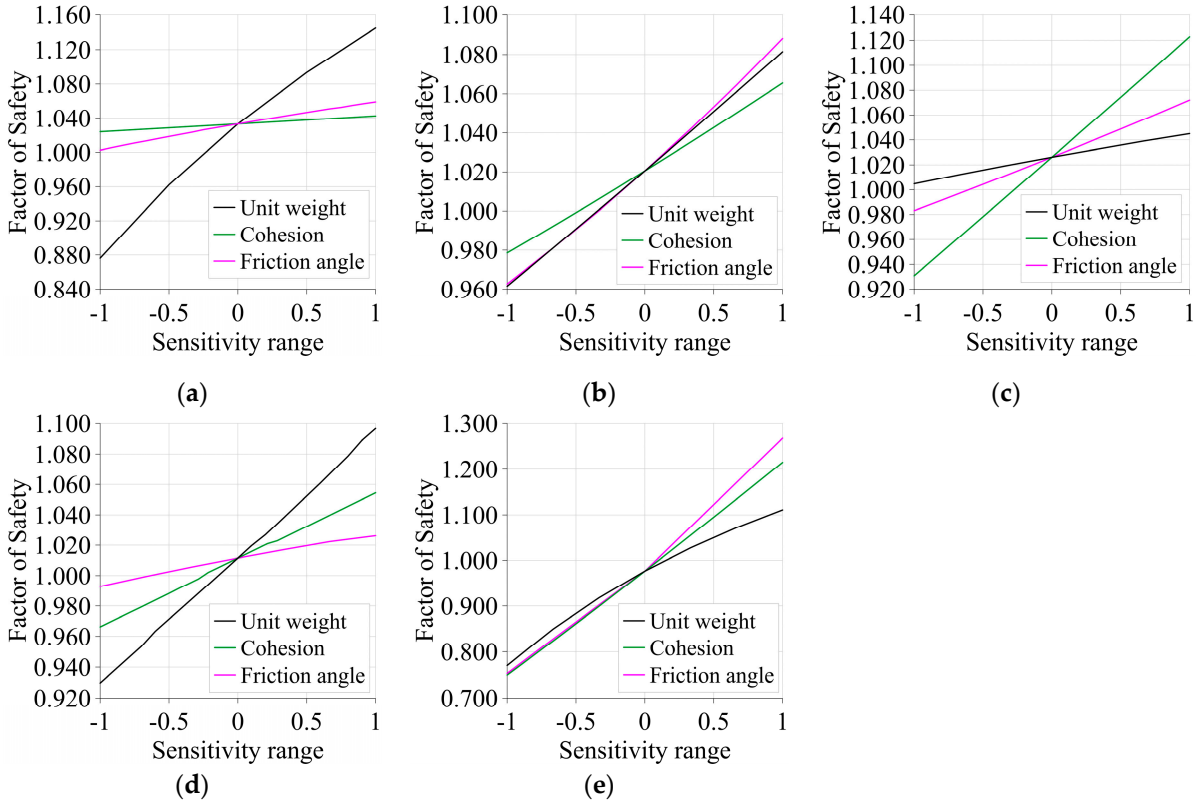


Figure 12. Results of the sensitivity analyses: (**a**) Cincinnati; (**b**) Xiaping; (**c**) Maoershan; (**d**) Meethatomula; (**e**) Xerolakka.

Table 12. Summary of stability analysis results for static and seismic loading.

MSW Landfill	Sliding Mass Area (m^2)	FS * Static Loading	FS * Seismic Loading	Difference (%)
Cincinnati, USA	14,150	1.03	0.81	−21
Xiaping, China	6975	1.02	0.68	−33
Maoershan, China	2067	1.08	0.74	−31
Meethotamulla, Sri Lanka	1834	1.01	0.84	−17
Xerloakka, Greece	490	0.98	0.78	−20

* Factor of Safety.

In all analyzed cases, there is a significant reduction in the factor of safety, ranging from 17% to 33%. The greatest reductions, 33%, and 31%, were observed in the cases of

the Xiaping and Maoershan MSW landfills in China. These cases involve a combination of relatively large sliding mass areas and high leachate levels, which contribute to increased pore pressures. In contrast, the MSW landfill in Cincinnati has the largest sliding mass area among all the cases considered, but its relatively low leachate level results in a smaller reduction in the factor of safety due to seismic loading. In the case of Meethotamula, the low leachate level leads to a smaller reduction in the factor of safety, which is 17%. In the Xerolakka case, the reduction in the factor of safety due to seismic activity is smaller because of the relatively small sliding mass area. The results of the analyses indicate that a combination of a high leachate level and a large sliding mass area leads to the greatest reduction in the factor of safety due to seismic loading.

The significant decrease in the factor of safety under seismic conditions highlights the vulnerability of MSW landfills to earthquake-induced slope failures. These findings underscore the importance of comprehensive seismic hazard assessments and the implementation of risk mitigation measures for MSW landfills, even in regions where only low-intensity earthquakes are expected.

3.2. Stability of MSW Landfill Slopes under Static and Seismic Loading According to Eurocode 7

The summary of slope stability analyses conducted according to Eurocode 7 Design Approach 1, Combination 1 (DA1, C1), Design Approach 2 (DA2), and Design Approach 3 (DA3) for both static and seismic loading is presented in Tables 13–15. Slope stability is quantified by the Over-Design Factor (ODF), which must be greater than or equal to one for the slope to satisfy the ultimate limit state criteria according to Eurocode 7. As shown in Table 13, the stability analysis results for DA1 and C1 fully coincide with those of the classical stability analysis presented in Table 12. This alignment is due to the specific combination of partial factors (Tables 7–9), wherein DA1 and C1, the partial factors for materials and resistances, are set to one. Although the partial factor for external actions is 1.35, since there are no external actions on the slope, the results completely match those of the classical stability analysis.

Table 13. Summary of stability analyses results for static and seismic loading, Eurocode 7, DA1, C1.

DA1, C1 *			
Landfill	**ODF ** Static Loading**	**ODF ** Seismic Loading**	**Difference (%)**
Cincinnati, USA	1.03	0.81	−21
Xiaping, China	1.02	0.68	−33
Maoershan, China	1.08	0.74	−28
Meethotamulla, Sri Lanka	1.01	0.84	−17
Xerloakka, Greece	0.98	0.78	−20

* Design approach 1, Combination 1, ** Over-Design Factor.

Table 14. Summary of stability analyses results for static and seismic loading, Eurocode 7, DA2.

DA2 *			
Landfill	**ODF ** Static Loading**	**ODF ** Seismic Loading**	**Difference (%)**
Cincinnati, USA	0.94	0.73	−22
Xiaping, China	0.93	0.62	−33
Maoershan, China	0.93	0.67	−28
Meethotamulla, Sri Lanka	0.92	0.77	−16
Xerloakka, Greece	0.89	0.71	−20

* Design approach 2, ** Over-Design Factor.

Table 15. Summary results of stability analyses for static and seismic loading, Eurocode 7, DA3.

	DA3 *		
Landfill	**ODF ** Static Loading**	**ODF ** Seismic Loading**	**Difference (%)**
Cincinnati, USA	0.82	0.65	−21
Xiaping, China	0.82	0.55	−33
Maoershan, China	0.82	0.59	−28
Meethotamulla, Sri Lanka	0.81	0.68	−16
Xerloakka, Greece	0.78	0.62	−21

* Design approach 3, ** Over-Design Factor.

Table 14 presents the summary of stability analysis results conducted according to Eurocode 7, Design Approach 2 (DA2). The results indicate that, under both static and seismic loading, none of the MSW landfills meet the ultimate limit state criteria specified by Eurocode 7, DA2. For all analyzed MSW landfills, ODF values are approximately 10% lower under both static and seismic loading compared to those in DA1 and C1. Additionally, the differences between the ODF values for static and seismic loading in DA2 are nearly identical to those observed in the previously analyzed design approach.

Table 15 presents the summary of stability analysis results conducted according to Eurocode 7, Design Approach 3 (DA3). The ODF values are further reduced by approximately 10% compared to DA2, and none of the analyzed MSW landfills meet the ultimate limit state criteria according to DA3. The differences between the ODF values for static and seismic loading are nearly identical to those observed in the previous design approaches.

According to Design Approach 1, Combination 1, all considered MSW landfills, except for the one in Xerolakka, meet the ultimate limit state criteria specified by Eurocode 7. However, none of the MSW landfills meet the ultimate limit state criteria under Design Approach 2 or Design Approach 3. Seismic loading with an intensity of VI on the Modified Mercalli intensity scale reduces the ODF by 16–33% compared to static loading.

The results of the stability analyses conducted in accordance with Eurocode 7 indicate that Design Approach 3 (DA3) yields the most conservative designs. This outcome arises from the application of partial factors from group M2 (Table 8) to the shear strength parameters, whereas the other analyzed design approaches employ values from group M1. Consequently, this results in lower values for resisting forces ($R_{H,d}$, $R_{V,d}$) and moments ($M_{R,d}$), thereby reducing the shear strength of the MSW along the slip surface. In the absence of external actions, identical partial factors are applied to the design values of forces ($V_{H,d}$, $V_{V,d}$) and moments (M_{Sd}), contributing to sliding across all design approaches. This leads to the most conservative ODF value in the case of DA3. Design Approach 2 produces ODF values that are approximately 10% less conservative than those of DA3. This reduction is attributable to the smaller values of partial factors applied to the MSW shear strength parameters from group M2. Although DA2 uses the same partial factors for MSW shear strength parameters as DA1, C1, the ODF values in DA2 are about 10% lower. This difference is because DA2 applies partial factors for resistances from group R2, which are set at 1.1, while DA1, C1 uses values from group R1, set at 1.0. From these analyses, it becomes evident that the application of partial factors for MSW shear strength parameters from group M2 results in a 20% reduction in the ODF value compared to group M1. Similarly, the application of partial factors for resistances from group R2 reduces the ODF value by 10% compared to groups R1 and R3.

Given the potential consequences of MSW landfill slope failure and the significant heterogeneity of MSW, the findings of this study suggest that DA3 provides the safest and most robust designs.

However, a notable limitation of applying Eurocode 7 to the design of MSW landfills is the uniform value of partial factors for unit weight, set at 1.0 for both groups M1 and M2. The results of this study indicate that unit weight significantly influences the stability of MSW landfills. Therefore, it is recommended that further research be conducted to

determine the appropriate values of partial factors for MSW unit weight, which, when used in conjunction with other partial factors, will ensure the desired reliability of MSW landfill structures.

3.3. Reliability of MSW Landfill Slopes under Static and Seismic Loading

Table 16 presents the summary of reliability analysis results.

Table 16. Summary results of reliability analyses for static and seismic loading.

Landfill	β * Static Loading	P_f ** Static Loading	β * Seismic Loading	P_f ** Seismic Loading	Δβ (%)
Cincinnati, USA	1.9	2.9×10^{-2}	0.5	3.1×10^{-1}	74
Xiaping, China	1	1.6×10^{-1}	0.7	2.4×10^{-1}	30
Maoershan, China	2.8	2.6×10^{-3}	0.8	2.1×10^{-1}	71
Meethotamulla, Sri Lanka	2.6	4.7×10^{-3}	1.5	6.7×10^{-2}	42
Xerloakka, Greece	1	1.6×10^{-1}	0.8	2.1×10^{-1}	20

* Reliability Index, ** Failure Probability.

The Monte Carlo method converged after 2000 simulations, which is consistent with the findings of other studies [1,27]. Reliability is quantified by the reliability index (β) and failure probability (Pf). For static loading, the Xiaping and Xerolakka landfills have the lowest reliability index values, β = 1, while Maoershan has the highest, β = 2.8. The reliability index values for the Cincinnati and Meethotamula landfills fall between these two extremes. The minimum target reliability index values according to Eurocode 7 for a reference period of 50 years are 3.8 for consequence class CC2 and 4.3 for CC3 (Table 10), corresponding to failure probabilities of 7.23×10^{-5} and 8.54×10^{-6}, respectively. Table 16 shows that the reliability indexes and failure probabilities of all analyzed MSW landfills do not meet the minimum target values for consequence classes CC2 and CC3, which are typically applied to MSW landfills. According to the US Army Corps of Engineers (Table 11), the expected performance level for the Maoershan landfill under static loading is below average; for Meethotamula it is poor, and for Cincinnati, Xiaping, and Xerolakka it is unsatisfactory. For seismic loading, the expected performance level is hazardous for all analyzed MSW landfills.

Based on the conducted analyses, it can be concluded that the calculated reliability of the slopes for all analyzed MSW landfills is significantly below the levels prescribed by Eurocode and the U.S. Army Corps of Engineers. As a result, slope failure could have been considered a plausible outcome for these landfills.

From Tables 12–16, it can be observed that in the considered cases, there is no correlation between the safety factors of the ODF and the reliability index. This outcome is expected and is due to the fact that the results of reliability analyses predominantly depend on the statistical characteristics (coefficient of variation, statistical distribution) of the strength parameters, while these characteristics have less impact on the results of stability analyses [33]. The lack of correlation between the ODF and the reliability index suggests that traditional stability analyses may not fully capture the risk associated with landfill slope stability. While ODF provides a measure of safety based on deterministic factors, the reliability index offers a probabilistic assessment that considers the inherent variability and uncertainty in material properties. This discrepancy underscores the importance of incorporating reliability-based approaches in the design and evaluation of MSW landfills to better account for the potential for failure under varying conditions.

3.4. Sensitivity Analyses Results

Figure 12 shows the results of the sensitivity analyses. The vertical axis represents the factor of safety, while the horizontal axis represents the sensitivity range, which reflects the minimum and maximum values of the input parameters considered in the analysis. These minimum and maximum values are determined according to Equation (5). In all

cases, there is a positive correlation between increases in unit weight, cohesion, friction angle, and the factor of safety. For the Xiaping and Xerolakka landfills, the friction angle has the greatest influence on the factor of safety, while cohesion has the greatest impact in the case of the Maoershan landfill. In the Cincinnati and Maoershan landfills, unit weight is the most significant factor influencing the safety factor.

The results of the sensitivity analyses are consistent with expectations for shear strength parameters (cohesion and friction angle). In contrast to slopes constructed in soil, where soil unit weight has a negligible effect on the factor of safety, sensitivity analyses conducted in this study show that unit weight has a more significant impact on the stability of MSW landfill slopes. This is attributed to the relatively high coefficient of variation of MSW unit weight compared to that of soil, as well as the significantly lower value of the unit weight of MSW relative to soil unit weight. Therefore, in designing safe and reliable MSW landfill slopes, it is crucial to pay particular attention to accurately determining the characteristic values of both the strength parameters and the unit weight of MSW.

The findings from these sensitivity analyses underscore the importance of accounting for the variability in MSW properties during the design phase. The significant influence of unit weight on slope stability suggests that even small errors in estimating MSW unit weight could lead to considerable differences in the predicted safety factor.

These observations also point to the potential benefits of incorporating probabilistic methods into the design and analysis of MSW landfills. By considering the variability and uncertainty of MSW properties in a more structured way, engineers can better anticipate the range of possible outcomes and design more resilient structures.

3.5. Limitations and Implications for Future Research

The stability and reliability analyses conducted in this study were performed on simplified two-dimensional geotechnical models using the Spencer method, which is part of the limit equilibrium methods group. This method was chosen because it considers both moment equilibrium and force equilibrium. However, a limitation of the limit equilibrium method is that it is based solely on the principles of statics, neglecting strains and displacements. Despite this drawback, its main advantage is that it quantifies the safety margin of the slope and is routinely used in geotechnical engineering practice [13], making it a suitable choice for this study. Another possible limitation of this study is the omission of the potential impact of geosynthetics on the stability and reliability of MSW landfill slopes. The analyses were based on literature data, which did not provide information on the influence of geosynthetics on MSW slope failures. Additionally, the literature lacks details on whether the design of these slopes was conducted according to any specific building codes.

The study revealed that the safety and reliability margins of all analyzed landfills are significantly lower than those prescribed by Eurocode 7. Although Eurocode 7 is primarily intended for the design of geotechnical structures involving soil, it is also applied to structures involving MSW based on the authors' experience. Further research is needed to adapt Eurocode 7 for the design of structures involving MSW, particularly in terms of calibrating partial factors for loads, material properties, and resistances. According to the results of the sensitivity analyses, special attention should be given to the unit weight of MSW, as its impact on the stability of MSW landfill slopes is significant.

4. Conclusions

In this study, stability and reliability analyses were conducted on the slopes of five MSW landfills that experienced failures. Actual slip surfaces, failure modes, material properties, and leachate levels were obtained from the literature. As there were no available data on geosynthetics used in these MSW landfills, their influence on stability was not considered. The main factors leading to failure included high leachate levels due to inadequate drainage systems, poor MSW compaction, and overly steep slopes. The factors

of safety for the analyzed slopes are around unity, which is expected given that slope failures occurred.

The primary goal of the study was to assess the safety and reliability margins of these slopes and compare them with the values prescribed in Eurocode. Additionally, the slopes of the considered MSW landfills were classified according to the US Army Corps of Engineers based on the reliability index. The study found that reliability indexes in all considered cases for static and seismic loading did not meet the target values for consequence classes CC2 and CC3 as prescribed in Eurocode 0. According to the U.S. Army Corps of Engineers classification, the expected performance level is below average for the Maoershan landfill, poor for Meethotamulla, and unsatisfactory for Cincinnati, Xiaping, and Xerolakka. For seismic loading, the expected performance level is hazardous for all analyzed MSW landfills. The results of the reliability analysis indicate an increased probability of failure in all the cases considered.

The study showed that the safety margins for the ultimate limit state of all considered MSW landfill slopes are below those prescribed in Eurocode 7, Design Approaches 2 and 3. In the case of Design Approach 1, Combination 1, 4 out of 5 analyzed landfills meet these criteria. Therefore, it can be concluded that the application of Design Approach 1, Combination 1, for the design of MSW landfill slopes can result in potentially unstable slopes. Design Approach 3 produces the most conservative designs, while Design Approach 2 results in designs that are 10–15% less conservative.

Seismic loading, equivalent to an earthquake of intensity VI according to the Modified Mercalli intensity scale, reduced the FS and ODF values by 10% in all considered cases. In contrast, the reduction in the reliability index was more pronounced, ranging from 20% to 74%. Based on these findings, it can be concluded that seismic loading is a critical factor to consider in the design of MSW landfill slopes, as it can significantly influence their stability.

The sensitivity analysis results showed that, in addition to the shear strength parameters of MSW, unit weight has a significant influence on the stability of MSW landfill slopes, which is not typically the case for slopes constructed in soil. Therefore, it is essential to accurately determine the characteristic values of MSW unit weight in the design process, which can be achieved, for example, by applying statistical methods.

To enhance the design of MSW landfill slopes, it is recommended to develop a comprehensive design framework that incorporates both traditional and advanced analytical methods. This framework could include stability analyses for both static and seismic loading conditions, reliability-based design, and sensitivity analyses. Implementing such a framework will facilitate the construction of more robust MSW landfill designs, capable of withstanding potential operational issues, such as drainage system blockages, inadequate material compaction, and other deficiencies.

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References

1. Mehdizadeh, M.J.; Shariatmadari, N.; Karimpour-Fard, M. Effects of anisotropy in correlation structure on reliability-based slope stability analysis of a landfill. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2021**, *39*, 795–805. [CrossRef] [PubMed]
2. Lenkiewicz, Z. *Global Waste Management Outlook 2024—Beyond an Age of Waste: Turning Rubbish into a Resource*; United Nations Environment Programme: New York, NY, USA, 2024. [CrossRef]

3. Petrovic, I.; Hip, I.; Fredlund, M.D. Application of continuous normal–lognormal bivariate density functions in a sensitivity analysis of municipal solid waste landfill. *Waste Manag.* **2016**, *55*, 141–153. [CrossRef] [PubMed]
4. Daciolo, L.V.P.; Correia, N.d.S.; Boscov, M.E.G. Extensive database of MSW shear strength parameters obtained from laboratorial direct shear tests: Proposal for data classification. *Waste Manag.* **2022**, *140*, 245–259. [CrossRef] [PubMed]
5. Merry, S.M.; Kavazanjian, E.; Fritz, W.U. Reconnaissance of the July 10, 2000, Payatas Landfill Failure. *J. Perform. Constr. Facil.* **2005**, *19*, 100–107. [CrossRef]
6. Gandolla, M.; Grabner, E.; Leoni, R. Stabilitäts probleme beinicht verdichteten Deponien am Beispiel Sarajevo (Jugoslawien) (stability problems with an uncompacted waste deposit). *ISWA J.* **1979**, *28*, 5–11.
7. Hendron, D.M. Large Landslide Risks in Solid Waste Facilities. . . Geotechnical Fundamentals Count. *Geo-Strat. Geo Inst. ASCE* **2006**, *6*, 32–34.
8. Koelsch, F.; Fricke, K.J.; Mahler, C.F. Stability of Landfills—The Bandung. In Proceedings of the Tenth International Waste Management and Landfill Symposium, Cagliari, Italy, 3 October 2005.
9. Chropeňová, D.; Slávik, I.; Hruštinec, Ľ. Stability Analysis of Waste Landfills on Potentially Unstable Territory. *Civ. Environ. Eng.* **2024**, *20*, 283–292. [CrossRef]
10. Zhang, Z.; Wang, Y.; Fang, Y.; Pan, X.; Zhang, J.; Xu, H. Global study on slope instability modes based on 62 municipal solid waste landfills. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2020**, *38*, 1389–1404. [CrossRef] [PubMed]
11. Blight, G. Slope failures in municipal solid waste dumps and landfills: A review. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2008**, *26*, 448–463. [CrossRef] [PubMed]
12. Huang, Y.H. *Slope Stability Analysis by the Limit Equilibrium Method*; ASCE Press: Reston, VA, USA, 2014. [CrossRef]
13. Krahn, J. The 2001 R.M. Hardy Lecture: The limits of limit equilibrium analyses. *Can. Geotech. J.* **2003**, *40*, 643–660. [CrossRef]
14. Vinai, R.; Ronco, C.; Oggeri, C. Validation of numerical D.E.M. modelling of geogrid reinforced embankments for rockfall protection. *Geam. Geoing. Ambient. Mineraria* **2021**, *58*, 36–45.
15. Zhao, S.Y.; Ke, H.; Lan, S.Z.; Zhang, S.; Hu, J. Stability Analysis of the Refuse Dam in Xiaping MSW Landfill, China. In Proceedings of the 8th International Congress on Environmental Geotechnics, Hangzhou, China, 28 October–1 November 2018; pp. 453–460. [CrossRef]
16. Munwar Basha, B.; Raviteja, K.V.N.S. Meethotamulla Landfill Failure Analysis: A Probabilistic Approach. In *Geotechnics for Natural and Engineered Sustainable Technologies*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 341–351. [CrossRef]
17. Karunawardena, W. *Geotechnical Assessment on the Failure at Meethotamulla Waste Fill*; National Building Research Organisation, Ministry of Disaster Management: Colombo, Sri Lanka, 2017; Volume 5.
18. Zekkos, D.; Vlachakis, V.S.; Athanasopoulos, G.A. The 2010 Xerolakka landfill slope instability. *Environ. Geotech.* **2014**, *1*, 56–65. [CrossRef]
19. Athanasopoulos, G.; Vlachakis, V.; Zekkos, D.; Spiliotopoulos, G. The December 29th 2010 Xerolakka Municipal Solid Waste landfill failure. In *Challenges and Innovations in Geotechnics: Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France, 2–6 September 2013*; Delage, P., Desrues, J., Frank, R., Puech, A., Schlosser, F., Eds.; Presses des Ponts: Paris, France, 2013; Volume 1, pp. 309–312.
20. Chugh, A.K.; Stark, T.D.; DeJong, K.A. Reanalysis of a municipal landfill slope failure near Cincinnati, Ohio, USA. *Can. Geotech. J.* **2007**, *44*, 33–53. [CrossRef]
21. Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M.; Tarantola, S. *Global Sensitivity Analysis. The Primer*; John Wiley & Sons, Ltd.: London, UK, 2008; pp. 1–292. [CrossRef]
22. Spencer, E. A Method of analysis of the Stability of Embankments Assuming Parallel Inter-Slice Forces. *Géotechnique* **1967**, *17*, 11–26. [CrossRef]
23. Orr, T.L.L.; Farrell, E.R. *Geotechnical Design to Eurocode 7*; Springer: Dordrecht, The Netherlands, 1999. [CrossRef]
24. *EN 1997-1:2004*; Eurocode 7: Geotechnical Design—Part 1: General Rules. European Committee for Standardization: Brussels, Belgium, 2004.
25. Marks, R.E. Monte Carlo. In *The Palgrave Encyclopedia of Strategic Management*; Palgrave Macmillan: London, UK, 2016; pp. 1–4. [CrossRef]
26. Pirić, K. *Reliability Analysis in Ship Structural Concept Design*; Unpublished Doctoral Thesis; University of Zagreb: Zagreb, Croatia, 2014.
27. Fenton, G.A.; Griffiths, D.V. Reliability-Based Geotechnical Engineering. In Proceedings of the GeoFlorida 2010: Advances in Analysis, Modeling & Design, West Palm Beach, FL, USA, 20–24 February 2010; Volume 9, pp. 76–99.
28. *EN 1990:2002+A1:2005+A1:2005/AC:2010*; Eurocode: Basis of Structural Design. European Committee for Standardization: Brussels, Belgium, 2011.
29. U.S. Army Corps of Engineers. *Introduction to Probability and Reliability Methods for Using in Geotechnical Engineering*; U.S. Army Corps of Engineers: Washington, DC, USA, 1997.
30. Jahanfar, A.; Amirmojahedi, M.; Gharabaghi, B.; Dubey, B.; McBean, E.; Kumar, D. A novel risk assessment method for landfill slope failure: Case study application for Bhalswa Dumpsite, India. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2017**, *35*, 220–227. [CrossRef] [PubMed]
31. Raviteja, K.V.N.S.; Basha, B.M. Characterization of Variability of Unit Weight and Shear Parameters of Municipal Solid Waste. *J. Hazard Toxic Radioact. Waste* **2021**, *25*, 04020077. [CrossRef]

32. Båth, M. *CF Richter, Elementary Seismology*; W. H. Freeman and Co.: New York, NY, USA, 1959; Volume 11, pp. 257–258. [CrossRef]
33. Baecher, G.B.; Christian, J.T. *Reliability and Statistics in Geotechnical Engineering*, 1st ed.; Wiley: Chichester, UK, 2003.

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