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Reliability of Municipal Solid Waste Landfills within the Eurocode Framework

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Abstract: Municipal solid waste (MSW) landfill slope failures can have significant consequences for the economy, environment, and human health. One potential cause of slope failure is insufficient reliability, resulting from inadequate design. The usual practice in the design of MSW landfills involves utilizing established geotechnical codes, such as Eurocode 7 (EC7), to perform slope stability assessments. Considering the substantial heterogeneity of MSW relative to soil, questions arise regarding the justification of such an approach in the design of MSW landfills. This study examines the suitability of applying EC7 in MSW landfill design, analyzing the stability and reliability of landfill slopes across various heights, front slope angles, design approaches, and consequence classes. This study finds that, in most cases considered, EC7 does not ensure an adequate level of reliability for MSW landfill slopes. Therefore, it is suggested that EC7 should be complemented with specific guidelines for incorporating MSW in geotechnical analyses to achieve the desired structural reliability. Adopting this strategy will not only enhance the reliability of landfill design but also promote the development of solutions that are economically and environmentally sustainable.

Keywords: MSW landfill reliability; stability analysis; MSW shear strength; structural reliability; environmental engineering; landfill sustainability

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1. Introduction

In recent years, the effective handling of increasing volumes of municipal solid waste (MSW) has become a significant issue for geo-environmental experts [1]. Landfills, being the simplest, most cost-effective, and most commonly implemented waste disposal systems globally, continue to expand despite advancements in reuse, recycle, and recovery methods. Environmental challenges, land constraints, and global governmental regulations are prompting engineers to optimize the use of existing landfills and to design new ones with greater volume and height. The increase in landfill capacity highlights the critical importance of their geotechnical performance [2].

Throughout history, there have been many landfill failures caused by their poor geotechnical performance. These failures have often resulted in significant humanitarian, environmental, and economic consequences. For instance, a major landfill failure in Quezon City, Philippines, in 2000, resulted in substantial material damage and human casualties [3]. Another instance is the case of the Xerolakka landfill. This case involved the displacement of approximately 12,000 m^3 of MSW. The main reasons for these failures were the steep slope inclination, inadequate compaction of the waste, and the absence of a daily soil cover. All these factors contributed to elevated pore pressures (gas and leachate), leading to the instability [4]. Additional examples of MSW landfill slope failures and analyses of their causes can be found in [5–9].

In this paper, the geotechnical performance of MSW landfill slopes is assessed through the use of two concepts: stability and reliability. Stability refers to the physical capacity of the landfill slope to withstand failure or collapse. The stability of the slope is determined by analyzing the ratio between forces acting upon the slope and the shear strength of the landfill material along the critical slip surface (Equation (1)). Factors such as the slope angle, mechanical and physical properties of the waste, pore pressure, and compaction can have a significant impact on the slope's stability. The stability of a landfill slope can be expressed through the Factor of Safety (FS) or the Over-Design Factor (ODF). The FS is used in the classical working stress design approach, while the ODF is usually used in analyses conducted according to the limit state design approach, such as Eurocode 7 (EC7) [10]. Higher FS and ODF values indicate a more stable slope, while FS or ODF values less than one represent a potential slope failure.

In their study on the stability analysis of landfill slopes, Qian et al. [11] defined potential failure modes as follows:

(a) Sliding failure along the leachate collection system;
(b) Rotational failure along sidewall slope and base;
(c) Rotational failure through waste, liner, and foundation subsoil;
(d) Rotational failure within the waste mass;
(e) Translational failure due to movement along the underlying liner system.

Analyses of stability and reliability conducted within this study were carried out with the assumption of slope failure mode "(d)", which is explained in more detail later in the text.

In this paper, the term "reliability" refers to the probability of a landfill slope failure occurring, calculated using structural reliability theory. A higher reliability indicates a lower probability of failure. This concept of reliability is quantified using the reliability index, denoted as β.

Different authors have addressed the issue of landfill slope stability and reliability. However, a review of the existing literature reveals a lack of studies that specifically investigate these topics under the Eurocode framework.

In the studies reviewed in the literature, the stability of MSW landfill slopes is commonly assessed using the FS, and reliability is evaluated using β. Stability analyses are predominantly conducted using the limit equilibrium method (e.g., the Bishop method), while reliability assessments are performed using simulation-based reliability methods (e.g., the Monte Carlo method) [12–18].

For instance, Gao et al. [14] analyzed the stability of MSW slope landfills at various heights and front slope angles. They assumed a rotational failure within the waste mass and choose an FS of 1.3 as the criterion for ensuring slope stability. They concluded that a smaller front slope angle significantly contributes to the longevity of the landfill. Similarly, Falamaki et al. [18] conducted an examination of the stability and reliability of the Barmshor Landfill in Shiraz City, Iran. In their research, they concentrated on evaluating the landfill's stability across various heights and front slope angles under both static and seismic conditions. They utilized Bishop's method to calculate the FS. Furthermore, they assessed the reliability index using the Monte Carlo method. Juca et al. [17] investigated the stability of the Brasilia sanitary landfill slopes using limit equilibrium methods, assuming rotational failure within the waste mass. They also employed the FS as a measure of stability.

Research Purpose

Within the EU, there are still active MSW landfills. One example is the Prudinec–Jakusevec landfill located in Zagreb, Croatia, where two slope failures occurred in 2023. In accordance with prevailing regulations, the remediation of these slope failures must adhere to the Eurocode.

The Eurocode is a collection of 10 European Standards for the design of buildings and other civil engineering structures, which are mandatory for use within the EU. Eurocode 0 (EC0) and EC7 are integral parts of Eurocode. In addition to various other provisions, EC0 prescribes target reliability levels for structures over different reference periods and consequence classes, while EC7 addresses the design of geotechnical structures, including guidelines for the assessment of slope stability. Table 1 shows target β values for various reference periods and consequence classes as prescribed by EC0 [19].

Table 1. Target values for reliability index β according to Eurocode 0 [19].

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

The reference period refers to the expected lifespan during which a structure is designed to maintain its structural integrity and function effectively. A reference period of one year typically applies to temporary structures, while a duration of fifty years is generally considered for permanent structures.

Consequence classes CC1–CC3 in EC0 categorize structures based on the potential impact of their failure. CC1 represents structures with low risk of human, economic, social, or environmental consequences upon failure. CC2 covers structures with moderate risk and impact, while CC3 includes structures whose failure could lead to significant loss of life or major economic, social, or environmental damage. Consequently, structures within the CC1 category necessitate the minimum level of reliability, whereas those in the CC3 category necessitate the maximum level.

While EC7 provides guidelines on how to incorporate soil parameters into geotechnical analyses, it does not offer similar guidance for MSW. Due to the lack of specific guidelines in EC7 on how to incorporate MSW in geotechnical analyses, it is commonly approached as soil in everyday engineering practices, even though there are notable differences between the two materials.

According to [20,21], for geotechnical structures analyzed according to EC7, there is no clear correlation between measures of stability and reliability. In practice, this implies that a structure may satisfy the criteria for stability but fail to meet the criteria for reliability, or vice versa. This discrepancy is particularly evident in analyses involving materials with high heterogeneity, such as MSW.

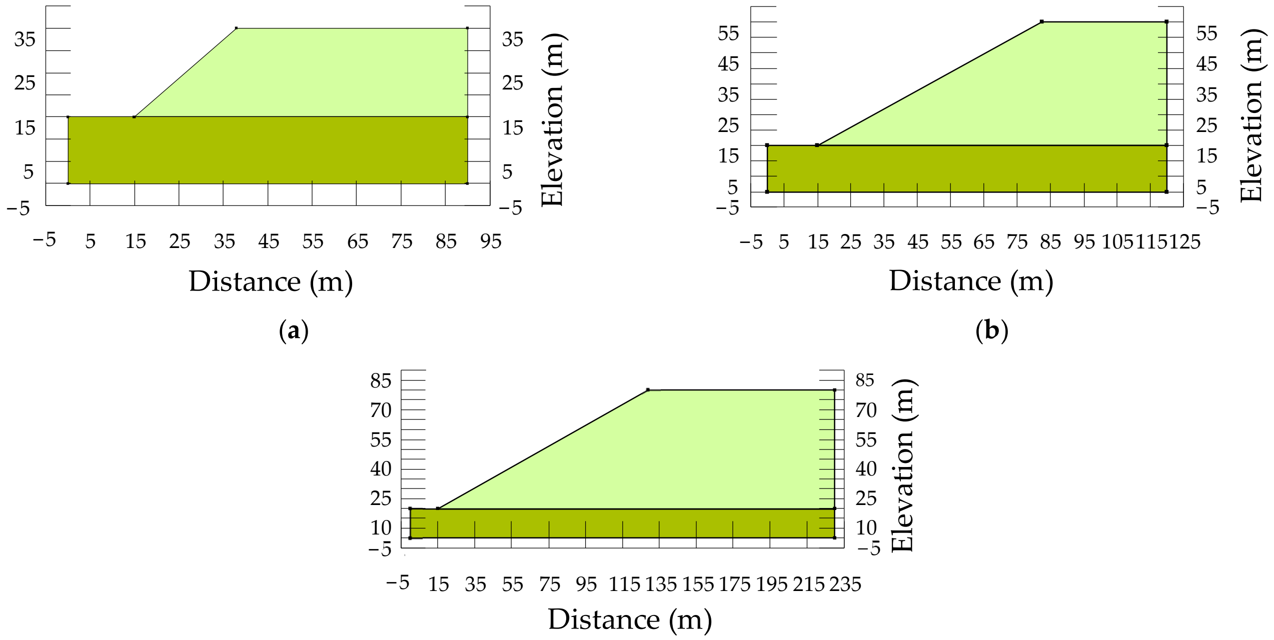
The main goal of this study is to give a broad assessment on whether MSW landfill slopes designed in accordance with EC7 and meeting its stability criteria also meet the target reliability levels prescribed in EC0 (Table 1).

To ensure comparability of the results, all stability and reliability analyses were conducted on MSW landfill slopes for which the ODF equals 1. Stability analyses within this study were conducted utilizing the Bishop method, while reliability was analyzed using the First Order Reliability Method (FORM). Analyses were conducted for all three design approaches according to EC7, and additionally for predefined FS values: FS = 1.3 and FS = 1.5.

The findings of this study indicate that the utilization of EC7 in the design of MSW landfill slopes does not ensure an adequate level of structural reliability, which in practice could lead to a higher number of failures compared to other geotechnical structures. Therefore, it is necessary to implement MSW into EC7 to create a framework for the design of MSW landfills, addressing both safety concerns and broader sustainability goals.

2. Materials and Methods

This study primarily focuses on the theoretical aspects of stability and reliability of MSW landfill slopes. Accordingly, the analyses conducted within this study do not consider constructional and operational issues that may affect the stability or reliability of these slopes. Therefore, various potential operational issues, such as high leachate levels, gas build-ups, and inadequate shear strength at the liner–MSW interface, have not been considered in these analyses. Analyses on simplified models, which include similar assumptions, are also introduced by other authors in studies that explore similar topics [2,12,22]. The model of the MSW landfill slope used in this study is shown in Figure 1.



(**a**) (**b**) (**c**)

Figure 1. Geometry of slope models used in stability and reliability analyses for MSW landfills of different heights: (**a**) H = 20 m, (**b**) H = 40 m, (**c**) H = 60 m.

MSW landfill slope stability was analyzed using all three design approaches according to EC7 [10]:

- Design Approach 1 (DA1): This approach is subdivided into two parts—DA1-CA1 and DA1-CA2. DA1-CA1 is used for persistent and transient design situations, applying different sets of partial factors to actions and materials. DA1-CA2, on the other hand, is utilized for accidental situations, employing a more conservative set of factors to ensure safety under these specific conditions.
- Design Approach 2 (DA2): This approach simplifies the design process by using a single set of partial factors that are applied only to actions. The characteristic values of soil and rock properties are considered as their mean values. DA2 is particularly useful in scenarios where the variability in material properties is not a dominant concern, providing a more streamlined approach.
- Design Approach 3 (DA3): DA3 focuses on applying partial factors to resistances rather than actions. This means that the design values of soil properties are reduced by these factors. This approach is often employed in situations where there is significant uncertainty in ground conditions or where a more conservative design approach is warranted.

EC7 permits flexibility in design approaches, allowing different countries to select their preferred methods according to their specific requirements. This variation in design approach is regulated and detailed within the national annexes of each country. Consequently, the implementation of EC7 may vary significantly across European countries, reflecting their distinct geotechnical and regulatory environments.

Additionally to EC7, two cases were analyzed where the values of the safety factors were predefined. Table 2 provides a summary of the selected design approaches used within the scope of this paper.

Table 2. Design approaches for conducting stability and reliability analyses.

Designation	Design Approach	
case 1	EC7	DA1, CA1
case 2		DA1, CA2 and DA3 [1]
case 3		DA2
case 4	Overall factor of safety	FS = 1.3
case 5		FS = 1.5

[1] Both approaches fall under the same category because the partial factors for strength parameters and those for soil resistance to sliding are identical in each design approach.

The height of the landfill has significant influence on the front slope stability. For the given front slope angle, the factor of safety decreases with the increase in the landfill height [14,16]. In this study, three different MSW landfill heights were analyzed: 20 m, 40 m, and 60 m.

The stability of landfill slopes for cases 1–3 was evaluated employing the ODF, while in cases 4 and 5, the FS was utilized. The ODF is defined as follows [23]:

$$ODF = \frac{R_d}{E_d} \tag{1}$$

In Equation (1), E_d represents the design value of the effects of actions, and R_d represents the design value of the resistance to an action. EC7 prescribes that for geotechnical structures, the ODF must be equal to or greater than 1 to satisfy prescribed stability criteria.

The Factor of Safety (FS) in slope stability is a measure used in geotechnical engineering to assess the stability of slopes, such as those in landfills, embankments, or natural terrain. It is defined as follows [24]:

$$FS = \frac{R}{S} \tag{2}$$

In Equation (2), R represents the characteristic value of shear strength of slope material, and S represents the characteristic value of shear stress causing slope failure.

The reliability of the MSW landfill slopes was quantified using the reliability index, determined through the following two-step process:

1. Determination of the maximum MSW landfill slope inclination, based on the following criteria:
    a. Cases 1–3: ODF = 1
    b. Case 4: FS = 1.3
    c. Case 5: FS = 1.5
2. Calculation of reliability indices for the resulting geometries, using the First Order Reliability Method (FORM).

In the analyses of stability and reliability, the following parameters of MSW were employed: cohesion (c'), friction angle (ϕ'), and unit weight (γ). Typically, higher values of cohesion c' and ϕ' increase the stability and reliability of the slope, whereas the influence of unit weight γ is comparatively negligible.

Figure 1 shows the geometry of the models used in the stability and reliability analyses. The bottom layer represents the properly prepared and compacted subsoil. The underlying assumption is that the geotechnical properties of the subsoil are favorable, and the critical sliding surface will be completely contained within the landfill. To verify the validity of this assumption, parametric stability assessments were conducted by varying the geotechnical parameters of the subsoil. Based on these analyses, it was determined that using this assumption is justifiable. The results of these analyses are not shown in the paper. Furthermore, additional justification for the use of this assumption comes from the findings of an extensive study on landfill slope failures, where it was observed that in 69.4% of cases, the entire slip surface was generated within the waste pile [16]. Based on the above, the following geotechnical parameters for the subsoil were selected: $\gamma = 19\ \mathrm{kN/m^3}$, $c = 20$ kPa, $\phi = 25°$.

2.1. Mechanical Properties of MSW

The shear strength parameters of MSW and their statistical characteristics were selected based on the results of extensive statistical analyses of MSW strength parameters presented in [25]. The analysed data were obtained from laboratory and in situ investigations and include MSW of various ages and compositions. The results of this research align well with the recommendations for selecting MSW strength parameters suggested by various authors [6,26,27]. Statistical data for MSW unit weight were determined based on existing research on slope stability using a probabilistic approach conducted by Jahanfar et al. [13]. Based on the findings of that study, the average unit weight of MSW is 13 kN/m^3, accompanied by a standard deviation of 1 kN/m^3, resulting in a coefficient of variation of 0.08.

Characteristic values of MSW parameters shown in Table 3 were determined according to the formula proposed by Schneider [28]:

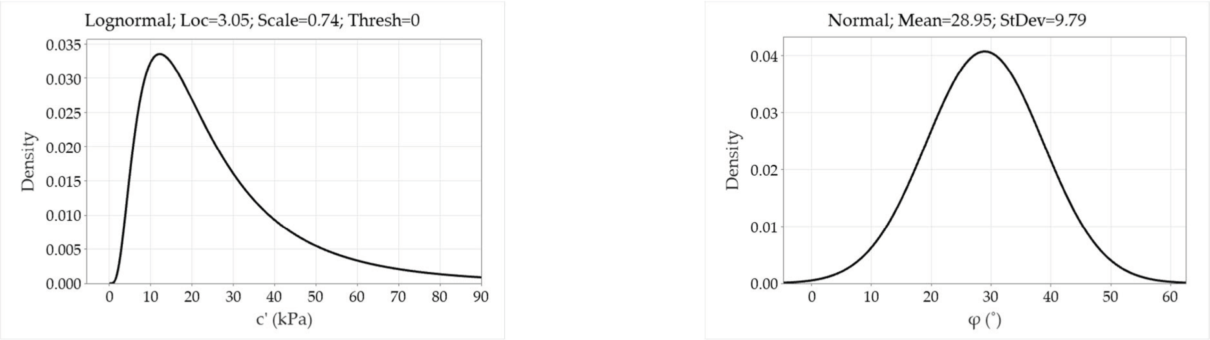
$$X_k = X_m \cdot (1 - 0.5 \cdot COV_X), \tag{3}$$

where X_m is the mean value of the property and COV_X is the coefficient of variation in the property.

Table 3. Geotechnical properties of MSW employed in stability analysis.

Property	Symbol	Units	Mean Value	Characteristic Value
Unit weigth	γ	kN/m^3	13.00	12.48
Cohesion	c'	kPa	27.19	17.4
Friction angle	ϕ'	$^\circ$	28.95	24.0

In structural reliability analyses, variables with a larger coefficient of variation exert a greater impact on the outcomes, whereas variables with a smaller coefficient of variation have a lesser impact [2,29]. Consistent with this principle, in the reliability analyses conducted within this study, both the friction angle and cohesion are treated as random variables, and the MSW unit weight is considered a constant. An additional reason for considering the MSW unit weight as a constant is its negligible influence on the value of the limit state function in slope stability analyses [30]. The probability density functions of the random variables are shown in Figure 2. Table 4 presents an overview of the statistical parameters utilized in reliability analyses.



(**a**) (**b**)

Figure 2. Probability density functions of cohesion (**a**) and friction angle (**b**) of MSW [25] for conducting reliability analysis.

Table 4. Random variables used in reliability analyses.

Random Variable	Distribution	Mean Values	Standard Deviation	Coefficient of Variation
Cohesion	Lognormal	27.19	19.58	0.72
Friction angle	Normal	28.95	9.79	0.34

Since the cohesion and friction angle are correlated, the correlation matrix has been defined for the purpose of determining the reliability integral. The correlation matrix provides a quantitative measure of the relationships between different variables: the friction angle and cohesion, in this case. According to [25], the correlation matrix for the purpose of reliability analyses of municipal solid waste (MSW) landfill slopes can be defined as follows:

$$C = \begin{vmatrix} 1.0 & -0.36 \\ 0.36 & 1.0 \end{vmatrix}$$

The coefficients of variation for soil strength parameters according to [31] range from 0.1 to 0.5% for cohesion, and for the friction angle, they range from 0.05 to 0.2% [20,29]. For MSW, these values are significantly higher, as shown in Table 4. Given that the coefficient of variation has a substantial impact on the outcomes of reliability analyses, it is assumed that the MSW landfill slope exhibits lower reliability index values compared to the target values prescribed in Eurocode.

2.2. MSW Slope Stability and Reliability Analyses

Stability analyses were carried out using the Slope/W application, part of the GeoStudio 2012 software suite, version 8.15. To calculate the factor of safety, Bishop's method was employed (Equation (4)):

$$FS = \frac{\sum_1^n c_i l_i + (W_i - u_i l_i) tan\ \varphi_i}{\sum_i^n W_i\ sin\ \alpha_i \left[cos\ \alpha_i + \frac{sin\ \alpha_i tan\ \varphi_i}{FS} \right]}, \tag{4}$$

where W_i is the weight of the slice, ϕ_i and c_i are the friction angle and cohesion on the sliding surface of the i-th slice, respectively, and α_i is the inclination of the lower edge of the i-th slice relative to the horizontal.

Reliability analyses were performed using the First Order Reliability Method (FORM), utilizing the Python programming language and its open-source libraries Pystra [32] and PySlope [33]. In this research, the reliability integral is composed of a bivariate normal–lognormal probability density function (Equation (5)) [25] and a limit state function derived from Equation (4).

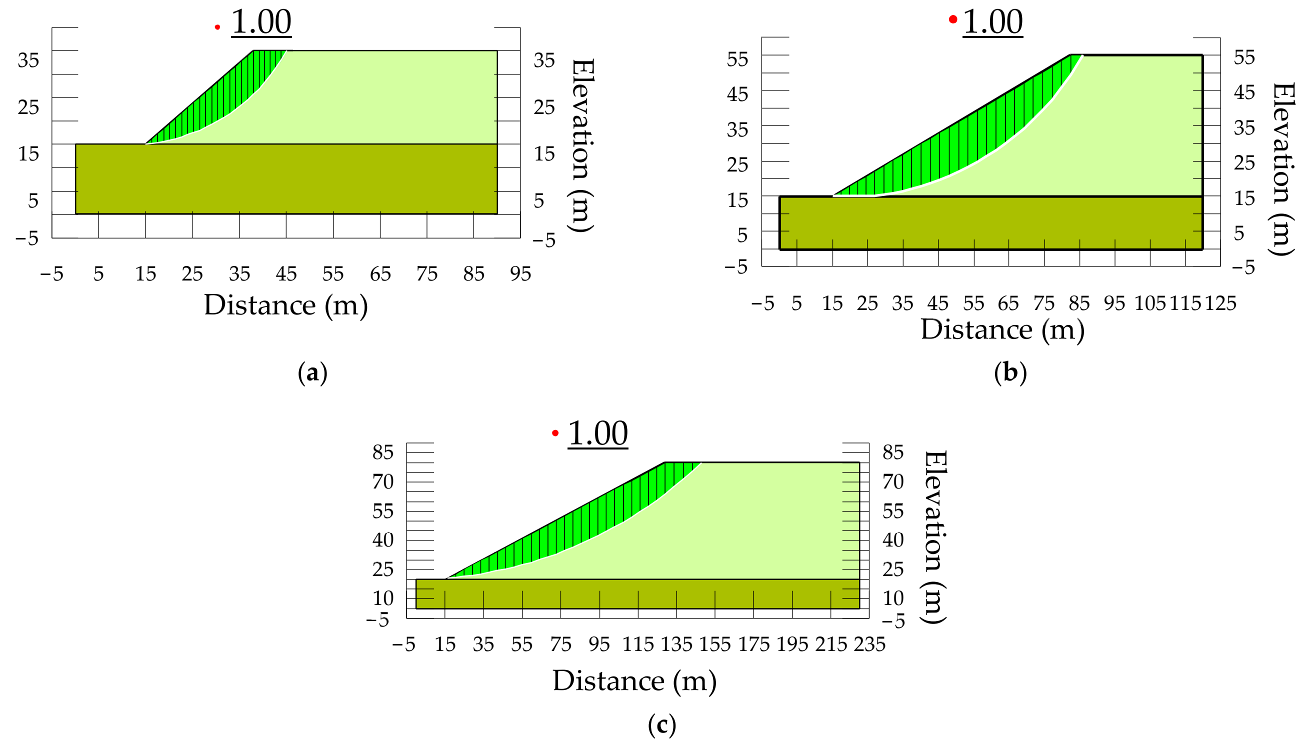
$$f(c,\varphi) = \frac{1}{2\pi\sigma_{ln(c)}\sigma_\varphi c\sqrt{1-\rho^2}} \cdot \exp - \frac{1}{2(1-\rho^2)} \cdot \left[\left(\frac{\varphi - \mu_\varphi}{\sigma_\varphi} \right)^2 - 2\rho \frac{\varphi - \mu_\varphi}{\sigma_\varphi} \cdot \frac{ln(c) - \mu_{ln(c)}}{\sigma_{ln(c)}} + \left(\frac{ln(c) - \mu_{ln(c)}}{\sigma_{ln(c)}} \right)^2 \right] \tag{5}$$

3. Results and Discussion

For different design approaches and heights of MSW landfills, a total of 32 stability analyses were conducted. Examples of the results of the stability analysis conducted to determine the maximum allowable slope angles ($\alpha_{\max}$) for various design approaches are presented in Figure 3. The $\alpha_{\max}$ values were determined according to the following criteria: case 1–3: ODF = 1, case 4: FS = 1.3, and case 5: FS = 1.5. In this way, the most optimal landfill slope geometries were obtained in terms of meeting the prescribed safety margins.

3.1. Influence of Landfill Front Slope Angle and Height on Reliability Index

Figure 4 shows the relationship between the reliability index and α_{max} for different landfill heights. The red horizontal lines represent the target values of the reliability index specified in Eurocode. These values are associated with different consequence of failure classes (CC1, CC2, CC3), as shown in Table 1. CC1 represents the low consequence class, CC2 represents the medium consequence class, and CC3 represents the high consequence class. In this context, consequences are associated with structural failure that may result in loss of human life or personal injury, as well as adverse effects on the economy, society, or environment.



(**a**) (**b**) (**c**)

Figure 3. Example of stability analysis results for MSW landfills of different heights: (**a**) H = 20 m, (**b**) H = 40 m, (**c**) H = 60 m.

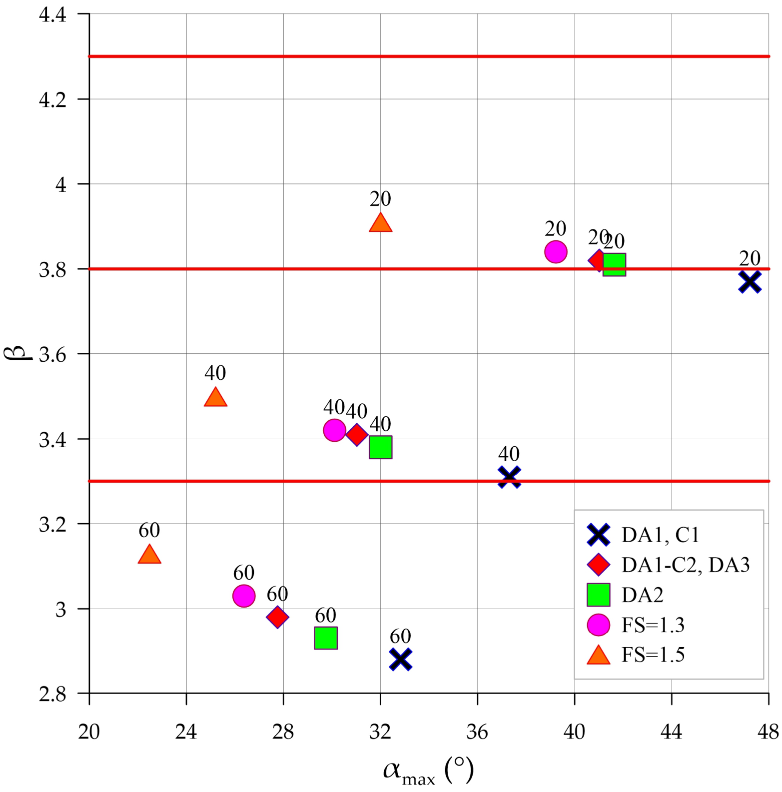


Figure 4. The relationship between the reliability index and α_{max} for various landfill heights.

A landfill with a height of 60 m does not meet the target reliability index values in any of the considered design approaches. In the case of a 40 m height landfill, the criteria for

CC1 are satisfied, while for a 20 m height landfill, four out of five cases meet the criteria for CC2. None of the analysed cases meet the criteria for CC3.

For all considered heights, the highest reliability index is provided by the design approach FS = 1.5, followed by FS = 1.3, DA1-C2, DA3, and DA2, while the lowest reliability index is attained by the design approach DA1-C1. The design approach DA1-C1 equates to the scenario where ODF = FS, as both the partial factors for shear strength parameters and the resistance to sliding are equal to 1. Therefore, it was expected that this case results in the lowest reliability index value.

Generally speaking, an MSW landfill designed with a steeper front slope angle is more cost-effective. This is attributed to its capacity for larger storage within the same surface area compared to a landfill with a gentler slope.

While the DA1-C1 design approach might initially seem economically favorable due to its higher α_{max} value, it presents greater reliability risks than other approaches. In contrast, design approaches FS = 1.3, DA1-C2, DA3, and DA2 offer similar outcomes in terms of both economy and reliability, whereas the FS = 1.5 approach is the least economical. This approach yields a notably smaller α_{max} angle compared to other design approaches, yet its increase in reliability is not significant when compared to them. This aligns with the findings of a study by Gao et al. [14], in which it is also concluded that landfill slopes with steeper angles are more cost-effective regarding their storage capacity, although this comes at the expense of decreased reliability.

From Figure 4, it can be seen that there is a negative correlation between the α_{max} angle and the reliability index, i.e., a lower angle corresponds to a higher reliability index value.

In Table 5, the influence of landfill height on the reliability index is presented. Its value generally decreases with increases in landfill height. With an increase in height from 20 to 40 m, the average reliability index value decreased by 0.14 (≈11%). Increasing the height to 60 m resulted in a reduction in the reliability index value by 0.19 (≈12%) compared to a landfill height of 40 m. Table 5 also illustrates that the range between the minimum and maximum values of the reliability index increases with height. This is a consequence of the increased standard deviation of the limit state function used within reliability analyses (Equation (4)), as observed in Table 6.

Table 5. The influence of landfill height on the reliability index.

H (m)	β_{min}	β_{max}	$\beta_{max} - \beta_{min}$	$\beta_{average}$
20	3.77	3.91	0.14	3.83
40	3.31	3.50	0.19	3.41
60	2.88	3.13	0.25	2.99

Table 6. The influence of landfill height on α_{max}.

H (m)	β	σ_{FS}
20	3.82	0.48
40	3.41	0.61
60	2.98	0.71

From Table 7, it can be observed that a reduction in landfill height leads to an increase in α_{max}, which is a consequence of the relatively high cohesion of the MSW. The contribution of cohesion to slope stability is more pronounced at lower landfill heights because the slope's resistance to sliding due to cohesion does not depend on the normal stress on the sliding surface, as is the case with the friction angle. With an increase in landfill height, the range between α_{max} and α_{min} decreases. Similar to the previously mentioned increase in the range of $\beta_{max} - \beta_{min}$, this is attributed to the elevation in the standard deviation of the limit state function used in reliability analyses (Equation (4)).

Table 7. The standard deviation of the limit state function for cases DA1, CA2, and DA3.

H (m)	α_{min}	α_{max}	$\alpha_{max} - \alpha_{min}$	$\alpha_{average}$
20	32.01	47.23	15.23	40.35
40	25.20	37.30	12.10	31.05

3.2. *Coefficient of Variation in Limit State Function*

As part of the analyses conducted within the Slope/W application, statistical analyses of the limit state function (FS) were carried out using the Monte Carlo method (Table 6). For the purpose of performing these analyses, cases DA1, CA2, and DA3 were selected.

The standard deviation of the limit state function (σ_{FS}) has a significant role in influencing the outcomes of structural reliability analyses. A larger standard deviation is indicative of a higher likelihood of failure, or, in other words, reduced reliability [20].

The results shown in Table 6 demonstrate that the σ_{FS} increases with landfill height. This can be attributed to the increased length of the critical sliding surface, the larger volume of sliding material, and the reduced contribution of cohesion to the shear strength of the slope in taller MSW landfills. This outcome is consistent with the observation that the reliability index decreases as landfill height increases. The same conclusion was reached by Rajesh et al. [12] in their study on reliability-based assessments for MSW landfill slopes, where an increase in the coefficient of variation in the limit state function significantly reduced the reliability index value.

3.3. *Influence of Landfill Front Slope Angle and Height on Factor of Safety*

Figure 5 illustrates the relationship between α_{max} and the factor of safety. Design approaches DA1-C2 and DA3 yield the highest factor of safety values. As expected, approach DA1-C1 results in the lowest factor of safety values because the partial factors for strength parameters and soil resistance to sliding are both equal to one. Since the calculations were performed for the case with the slope inclination α_{max} (the case when ODF = 1), the factor of safety should also be equal to one, as can be observed in Figure 5. This figure also reveals that for the given ODF = 1 value, the FS remains constant for the selected design approach, irrespective of landfill height.

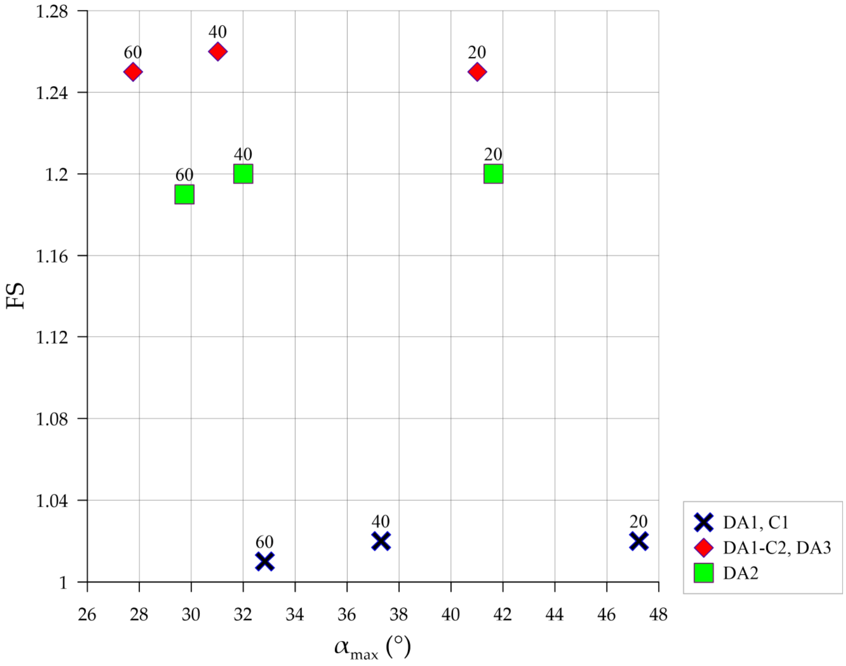


Figure 5. The relationship between the reliability index and α_{max} for various landfill heights.

3.4. Limitations and Implications for Future Research

This study investigates the feasibility of applying EC7 in the design of MSW landfill slopes, with the aim of ensuring prescribed reliability levels. Analyses were conducted on simplified models, introducing certain assumptions. These assumptions limit the results to cases where the critical sliding surface passes exclusively through the waste body. In practice, this represents about 70% of the cases of realized failures of landfill slopes. The results presented in this study cannot be directly applied to cases where the critical slip surface may also pass through the subsoil.

Additionally, it is assumed that the landfill is free from defects that could compromise its stability and reliability. These defects might typically arise from improper construction or maintenance. Although the results of this study cannot be directly applied in such cases, it is logical to assume that in these instances, the landfill will have lower reliability and stability compared to a landfill without these defects. Therefore, it can be concluded that in those cases as well, the application of EC7 will not ensure an adequate level of reliability.

Additional research is needed to determine how to quantify the potential occurrence of such defects and to incorporate their effects on stability into the design procedure. An appropriate design for a municipal solid waste (MSW) landfill should account for the possibility of such events, ensuring that the landfill operates safely until these threats are identified and eliminated, thereby preventing catastrophic consequences.

It has been shown that only an MSW landfill with a height of 20 m meets the targeted reliability value for CC1 and CC2. A height of 40 m satisfies CC1, while 60 m does not meet the criteria for any consequence class. Accordingly, when selecting a location, special attention must be paid to the reliability and the potential consequences that the failure of an MSW landfill slope can have on humans, society, the economy, or the environment. Conversely, if the location is predetermined and cannot be changed, the design of the MSW landfill must be adapted to the given location in accordance with the chosen consequence class.

Based on the results of this study, it can be concluded that uncritical application of EC7 in the design of MSW landfill slopes can lead to solutions with excessively steep slopes of insufficient reliability. This applies to all considered design approaches. In real-world scenarios, this could result in a higher number of landfill slope failures compared to other geotechnical structures. To prevent this, additional research is needed to determine the optimal way of implementing MSW into EC7. An alternative approach involves developing dedicated guidelines for MSW landfill design, independent of EC7. In both approaches, it is necessary to ensure that environmentally and economically sustainable solutions are promoted. This may involve practices that minimize environmental impact, enhance waste management efficiency, and consider long-term sustainability in landfill design. This process should be interdisciplinary and involve expertise from various professions, such as waste management experts, geotechnical engineers, environmental engineers, and policymakers.

4. Conclusions

The main goal of this study is to give a broad assessment on whether MSW landfill slopes designed in accordance with EC7 and meeting its stability criteria also meet the target reliability levels prescribed in EC0.

The design approaches defined in EC7 were considered, along with two cases where the values of the safety factors were predefined. The approach FS = 1.5 results in the most reliable, but also the most expensive, solution, whereas the DA1-CA1 approach is the least reliable and the least expensive. Consequently, engineers in everyday practice are advised to avoid using the DA1-CA1 approach for designing slopes in MSW landfills. Other approaches that were considered, including DA1-C2, DA2, and DA3, result in similar solutions in terms of reliability and cost-effectiveness, as illustrated in Figure 5.

Reliability analyses conducted within this study indicate that designing MSW landfill slopes according to EC7, and treating MSW as soil, typically results in a reliability index lower than the target values prescribed in EC0 (Table 1). Therefore, it is concluded that the application of EC7 is not suitable for designing MSW landfill slopes. In situations where Eurocode 7 (EC7) is applied due to the absence of other appropriate regulations, it is recommended to not only meet the standard stability criteria but also to ensure that the MSW landfill slope complies with the required reliability levels as prescribed by EC0. In addition to ensuring structural stability and reliability, the design of MSW landfills should prioritize long-term sustainability and minimal environmental impact.

Additionally, it is crucial to emphasize that establishing the maximum height of a municipal solid waste (MSW) landfill during the planning phase is essential prior to construction. As evidenced by Tables 5–7, the landfill's height significantly impacts the reliability index and the required slope inclination. Constructing a landfill beyond its planned height could also pose risks to its stability.

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