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Optimizing Landfill Capacity: A Numerical Study of the Slope Inclination Variation Impact on Landfill Storage Capacity and Its influence on the Safety Factors under Different Models

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Abstract

As an attempt to enhance landfill capacity and extend its lifespan, this research explores the effect of slope inclination on landfill storage capacity and its implementation on the safety factors using numerical simulations. A geometric approach was used to determine the capacity change with inclination, and a new probabilistic calculation method, which accounts for the heterogeneity of waste layers, was employed to analyze the safety factor for different slope angles. Over 100 conducted calculations for each inclination were used to investigate the effect of slope variation on landfill safety. The results show that increasing inclination leads to a significant increase in landfill capacity. The safety factor results indicate that the conventional method, assuming homogenous waste, classifies 1:3 and 1:2 slopes as safe, while the new suggested method showed that a 2:3 inclination could be considered safe, especially since the calculation is not considering the safety-enhancing effect of daily cover layers. This study highlights the importance of considering the heterogeneity of waste layers in safety factor analysis, and the use of multi-layered nonhomogeneous calculation method, which provides more flexibility in design parameters. This research presents a significant step forward in constructing safe and cost-effective landfills. The use of a new probabilistic calculation method in designing landfills leads to more accurate and reliable results while maintaining safety standards. This research has important implications for the design and management of landfills and can be used as a guide for future studies in this field.

Keywords

landfill, municipal solid waste, slope inclination, capacity, safety factor

1 Introduction

As the world's population continues to grow, waste generation has increased dramatically in recent decades, and there are no indications of it slowing down. This has made solid waste management a global challenge. The expansion of city limits is straining the availability of suitable land for waste disposal construction, and the use of land for dumping municipal solid waste is a serious concern [1, 2]. Limiting areas for waste deposition and the recovery of landfills for future development are two significant concerns involved in waste management strategies. Due to the lack of space and the significant environmental and public health risks, the economic value of waste disposal areas has increased rapidly in the past few decades [3]. A change in landfill design has become necessary as a practical solution to help overcome this issue. However, the parameters that influence the full potential exploitation of landfills without endangering their safety need to be specified more precisely.

A landfill is a complex engineered structure designed to safely dispose of waste and prevent any potential risks of soil, groundwater, and surface water contamination. The waste is placed and compacted horizontally in cells on top of a multi-layered lining system that isolates the landfill base and sides from the surrounding environment. After each operational period, the waste is covered with locally available soil, known as a daily cover [4]. A complete layer of waste cells forms a lift, which is then stacked on top of each other in a pyramid-like structure. To increase the stability of the landfill's side slopes, a bench is created between a certain number of lifts. Once the landfill has reached its maximum designed height, a final cover system consisting of various layers covers the entire external surface of the landfill. This marks the end of the active phase of the landfill's life.

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The capacity of an engineered landfill is determined by various morphological parameters, including the active area base, side slope, height of the landrise, depth of the landfill, and operational parameters, such as daily incoming waste, its density after compaction, daily cell cover thickness, and final cover, among others [5]. During the planning and operation of a landfill, design engineers face numerous decision-making processes that significantly impact landfill capacity. Maximizing storage capacity is one of the most efficiency-oriented goals in planning and operating a landfill. Geometrical and operational parameters, such as total landfill height, thickness of covering layers, side slopes, and waste compaction, can all be optimized to maximize the volume of waste that can be placed on a given site with a set of operational rules. The selection of influencing parameters is subject to various constraints, including external morphology, construction security, impact on the surrounding environment, overall cost of the landfill during the operational and aftercare periods, as well as social repercussions and environmental sustainability, which are major factors to consider in the project development phase [4].

Studies have shown that the storage capacity of a landfill is highly sensitive to small variations in operational parameters. Analytical models investigating the tradeoffs between geometrical and operational factors and the potential volume of waste preserved in a landfill have demonstrated that even slight changes in the waste-to-soil cover ratio can have a significant impact on capacity, as well as height, active base area, and inclination [5]. Initial waste compaction also has a considerable influence on landfill storage capacity, as it enhances the landfill's storage ability [6].

However, the capacity of a landfill from a slope angle perspective has not been extensively investigated. There is limited research available on landfill simulation to examine alternative design values and their impact on stability and safety factors. This paper aims to maximize storage volume through landfill design. It seeks to assess the sensitivity of landfill storage capacity to changes in slope inclination and evaluate the impact on the safety factor. By comparing three geometrical models using a new numerical modeling method, this study investigates the influence of changes inside slope angles on the structure's safety factor. The research is a significant step forward in waste management, aiming to provide more flexibility in design values to construct safe and cost-effective landfills. This work offers an opportunity to advance understanding of design methods that offer safer and more reliable landfills with optimal economic solutions. It presents the landfill as a system that could benefit from design and economic performance optimization.

2 Material

Landfill instability appears because of various complex influences, where the shear strength of municipal solid waste (MSW) is an essential factor. The shear strength parameters used in this paper are a large data base of over two hundred cohesion and angle friction couples, collected earlier by Varga [7, 8] and from different research papers (Fig. 1). Numerous researchers have assessed these parameters with various geotechnical tests, such as direct shear test [9–13] triaxial test [14–17] in situ tests [18–20] and back analysis of failure slip surfaces of landfills [9], [21, 22].

The shear strength parameters computed in different studies vary widely, but they are usually connected to the landfill area, components, degradation age, test equipment, and test techniques [12, 23, 24]. As a result, these characteristics must be determined based on the individual conditions of each landfill. Fig. 1 shows the distribution of the shear parameters used in the study.

3 Method

3.1 The geometry

Landfills are designed in a sandwich structure where the waste is piled up on top of each other in horizontal layers. Based on the design, the operational factors and the safety measures, the geometrical parameters are determined. These parameters represent the base area, the total height of the landfill, the length of each lift, and the slope angles.

Three geometrical models were used to determine the effect of the slope angle on the storage capacity of a landfill. All the design parameters in the three models are kept

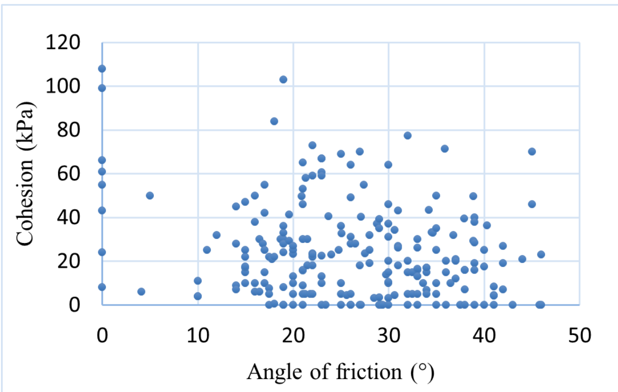

Fig. 1 Shear strength distribution used in the calculation (data source is given in the text)

constant; only the side slope inclination differs. As shown in Fig. 2, the total height of the landfill represented by *H* is 30 m; it is divided into three groups of layers based on the degree of degradation. The first, second, and third groups represent the old, medium, and fresh waste. Each group is formed from ten waste layers of 1 m thickness.

The slope angle has a major impact on the safety factor calculation of landfills; at the same time, it influences the capacity of waste disposed. Each regulation proposes a fixed value of slope angles to assure the maximum functional safety possible. Based on the Austrian standers,

wildly used by the Hungarian operators in landfills constructions, the slope angle used in the first model is 1:3. Two other steeper models were introduced to compare the profitability of the landfill's standers used in Hungary. A model of 2:3 slope inclination, used in some French landfills (data provided by ENKA Solution company) and an intermediate model of 1:2 slope angle.

For the geometric characteristics, the following assumptions were adopted:

- The active base area corresponds to the ground level area. As this study is focused on the relative storage capacity changes caused by the side slope variation in the land rise part, the land fill part was not included in the calculation.
- The soil layers of daily cover system of the landfill were not considered in the safety factor calculation, as it does not affect the reliability of the research (the daily covering systems tend to increase the safety of the structure, it can be neglect it for safety estimation).
- All slopes, both for the daily cell and the external sides, are assumed the same.

3.2 Capacity calculation

The methodology used in this study to evaluate the capacity variation for different slopes is based on geometrical calculations. For each computation, a cross-section of the specific model was taken into consideration, and the area of that cross-section was determined. The percentage of the capacity change was then revealed based on the area ratio between two different models. To facilitate the calculation process, a program written in Fortran language, compatible with both Linux and Windows systems, was developed and made available on github.com.

To estimate the economic impact, the landfill volume was calculated by assuming a square-shaped base, as shown in Fig. 2. the average cost of one ton of waste, which was

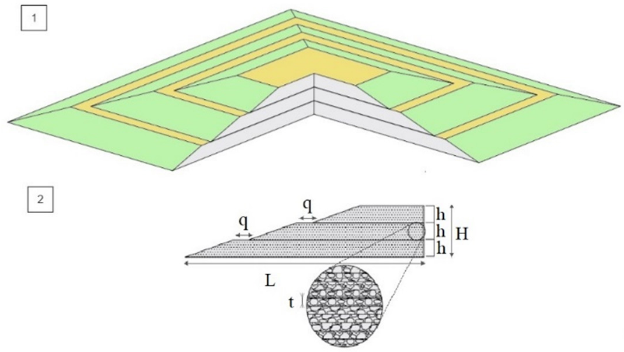

Fig. 2 Landfill geometry (1: landfill morphology; 2: cross section used in the calculation; *H*: total height of the landfill 30 m; *h*: lift height 10 m; *t*: MSW layer thickness 1 m; *q*: benches 10 m; *L*: total length of the landfill section 150)

$53.72 USD, based on statistics from 2020 in the United States [25]. This approach enables a better understanding of the overall expense of the landfill and the impact of capacity variation on economic considerations.

3.3 Stability calculation

In this research, the safety factor will be calculated using the Coulomb method with the finite element method (FEM). After creating the geometrical shape of the structure in the program, the material properties, including the bulk unit weight, the odometrical modulus, and shear strength indices, will be defined for each waste layer in the same way for the three models. Landfill stability will be evaluated under different scenarios with FEM solved by Plaxis, the geotechnical analyzer software from Bently, for an accurate analysis. The calculation will use the probabilistic analysis methodology proposed by Szabó and Szabó [26].

In the first calculation scenario SC1, all three landfill models will be considered as one homogeneous waste body divided into three layers of 10m height. The simulation will be carried out with the shear parameter values recommended in international practice. Three sets of calculation will be generated. The first safety factors will be determined under the Austrian standers that precise the value of cohesion end friction angle to be respectively 5 kpa and 25°. In the second calculation, the cohesion and friction angle will respectively be equal to 10 kpa and 20° as recommended by Sanchez-Alcitturi et al. [27] and Szabó and Szabó [26]. he third calculation will be performed with a cohesion of 20 kPa and a friction angle of 20° [27]. These studies will be conducted to examine the reliability and the economic impact of each recommendation under the same calculation method.

The second scenario SC2 will be based on considering the relative changes in waste layers parameters according to the degree of degradation. The first layer will represent the old waste placed in the bottom of the landfill, the second layer will refer to medium waste, and the third one will define the fresh waste recently placed. The waste friction parameters used will be determined from the database according to literature founding.

The third calculation scenario SC3 represent a more detailed analyses, where each waste category previously introduced in the SC2 (old, medium, and fresh) was divided into ten layers of 1m height. Fig. 3 shows the different scenarios used.

To increase the reliability of measures and have an accurate statistical analysis, each calculation operation will be repeated for all three models one hundred times. For each calculation, the safety factor was determined under different waste parameters. A custom program written in Python script run the analyses. The material parameters attributed to each layer will be automatically changed for each calculation and randomly chosen from the shear strength database. The same calculation scenarios will be replicated for each slope angle model. The calculation procedure will be summarized in Fig. 4.

4 Results and discussion

4.1 Capacity variation

As observed, the slope angle has a strong influence on the landfill's capacity. The cross-sectional area analysis of the three slope models reveals that a change in slope inclination from 1:3 to 1:2 and 2:3 leads to an increase in area of 14% and 32%, respectively as mentioned in Table 1. The impact of cross-sectional expansion varies depending on the landfill's morphology, and this has a significant effect on the total landfill volume.

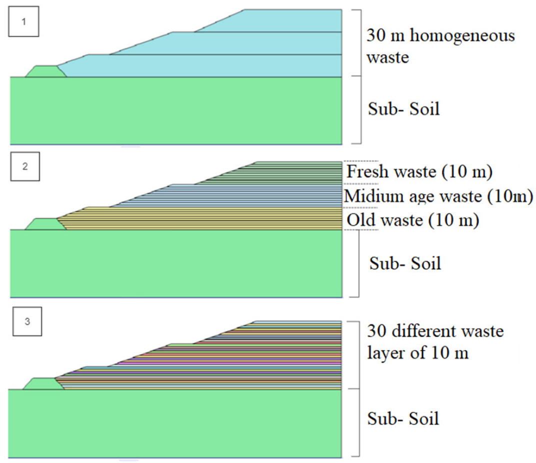

Fig. 3 Modeling scenarios (1: SC1; 2: SC2; 3: SC3)

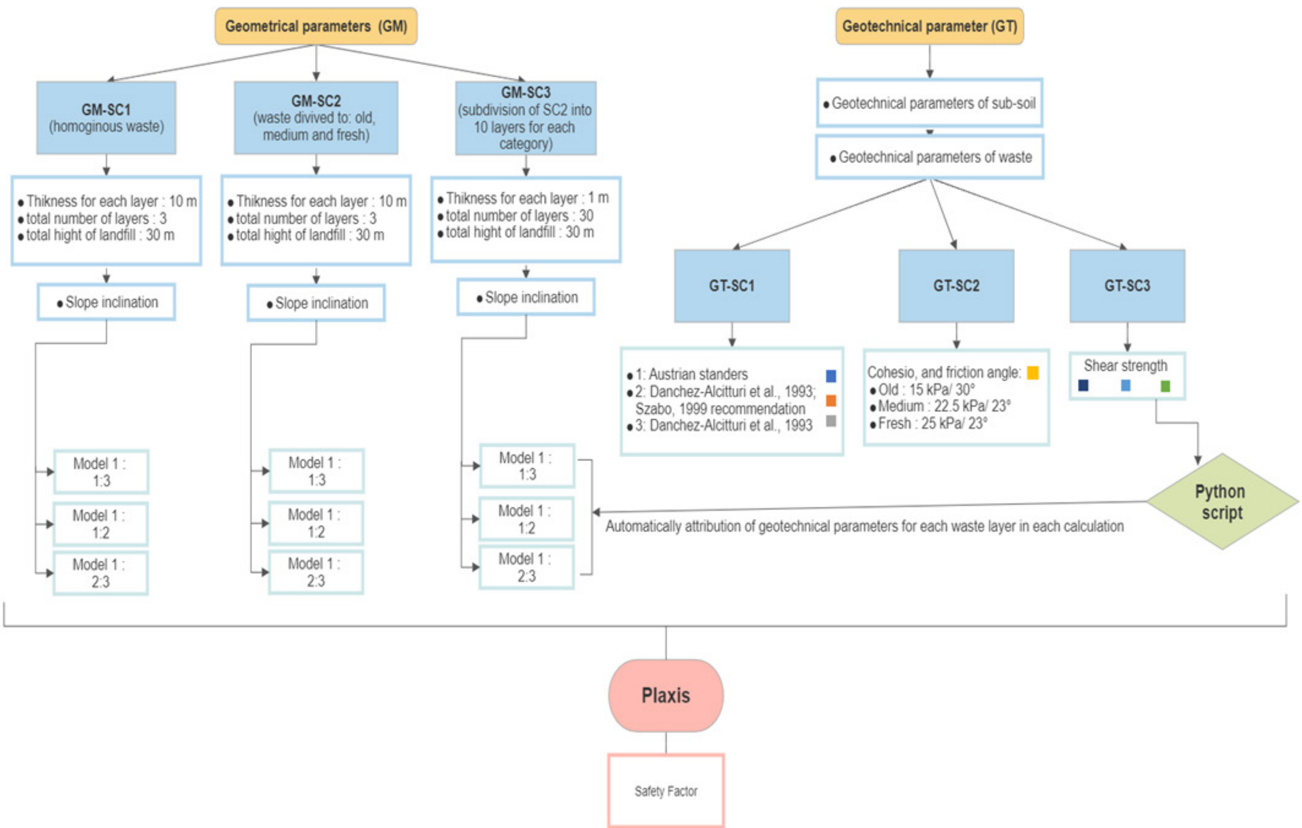

Fig. 4 Landfill slope stability calculation procedure

Table 1 Capacity calculation results

	Model one 1:3	Model two 1:2	Model three 2:3
Area of the cross section	2850	3300	3750
Percentage of area change (2:3)	32%	14%	
Percentage of area change (1:2)	16%		
Volume of the landfill (rectangle base)	1220000.00	1527999.99	1709000.00
Percentage of volume change (2:3)	40.08%	11.85%	
Percentage of volume change (1:2)	25.25%		

The volume variation shows a notable sensitivity to side slope angle, with an increase of 40% and 25% from 1:3 to 2:3 and 1:3 to 1:2, respectively.

This increase in capacity has a significant economic impact on the landfill project. In a cubic dump with the same geometrical specifications as the example, opting for a side inclination of 1:2 can result in a profit increase of $ 16,545,759.5, whereas a steeper slope of 2:3 can lead to an additional profit of $ 157,345,880.

4.2 Safety factor

The safety factor was determined using finite element methods rather than the traditional limit equilibrium approach in this study. Examples of the traditional limit equilibrium approaches include the Bishop-technique [28], Ordinary method [29], Spencer method [30] M-P method [31] and Janbu method [32]. The limit equilibrium approach involves dividing the landfill sliding slope into small blocks and calculating the safety factor by developing a force balance equation for the forces acting on these blocks. This methodology is widely used for determining slope stability because of its quick computation of landfill settlement [33, 34]. However, the main drawback of limit-equilibrium approaches is their disregard for slope deformation. In comparison to traditional design methodologies, FEM has gained a strong position in geotechnical analysis and design due to its ability to handle complex problems [35, 36]. In continuum mechanics, this method is essentially a systematic numerical procedure for solving boundary value and some starting value issues due to its capacity to simulate the stress-strain behavior of the soil. Several researchers have employed FEM to study embankments and slopes, as well as to solve problems related to earth pressure [8, 33, 37–40].

The safety factor results of this study reveal several important findings. Table 2 indicates a significant correlation between the safety factor and the number of layers used in the same landfill model. Inhomogeneous, multi-layered models calculated with randomly chosen shear parameters exhibit higher safety factor values compared to homogeneous, constant shear strength parameter models.

This relation can be attributed to the fact that multi-layered models, which reflect the actual sandwich-like design of landfills where waste is piled in heterogeneous layers, enhance the support effect in the total waste body due to the variation of waste shear parameters. Fig. 5 summarizes the results of safety factor calculations for each scenario, with histograms and normal distribution functions representing the values of the 100 calculated safety factors to facilitate evaluation. Fig. 6 plots a summary of safety factor variation for the three geometrical models under different calculation circumstances, highlighting the decrease in safety factor with an increase in slope angle.

The safety factors in this study demonstrate an inverse relationship with the slope angles, as depicted in Fig. 6. Increasing the slope angle leads to a decrease in the safety factor, in line with established regulations that mandate

Table 2 Safety factor results

	Cohesion	Friction angle	Safety factor slope 1:3	Safety factor slope 1:2	Safety factor slope 2:3
GT-SC1-1 homogeneous waste (Austrian standard)	5	25	1.77	1.54	1.27
GT-SC1-2 homogeneous (Sanchez-Alcitturi et al., [27], Szabó and Szabó [26])	10	20	1.80	1.58	1.39
GT-SC1-3 homogeneous waste (Sanchez-Alcitturi et al., [27])	20	20	1.94	1.76	1.62
GT-SC2 3 waste layers	15	30	1.98	1.72	1.68
	22.5	23			
	25	15			
GT-SC3 30 waste layers	Randomly generated for the data base (Fig. 1)		Average value		
		2.78	2.34	2.07	
			Min value		
		1.63	1.59	1.52	
			Max value		
		3.66	2.76	2.63	
		F90			
		2.52	2.11	1.81	

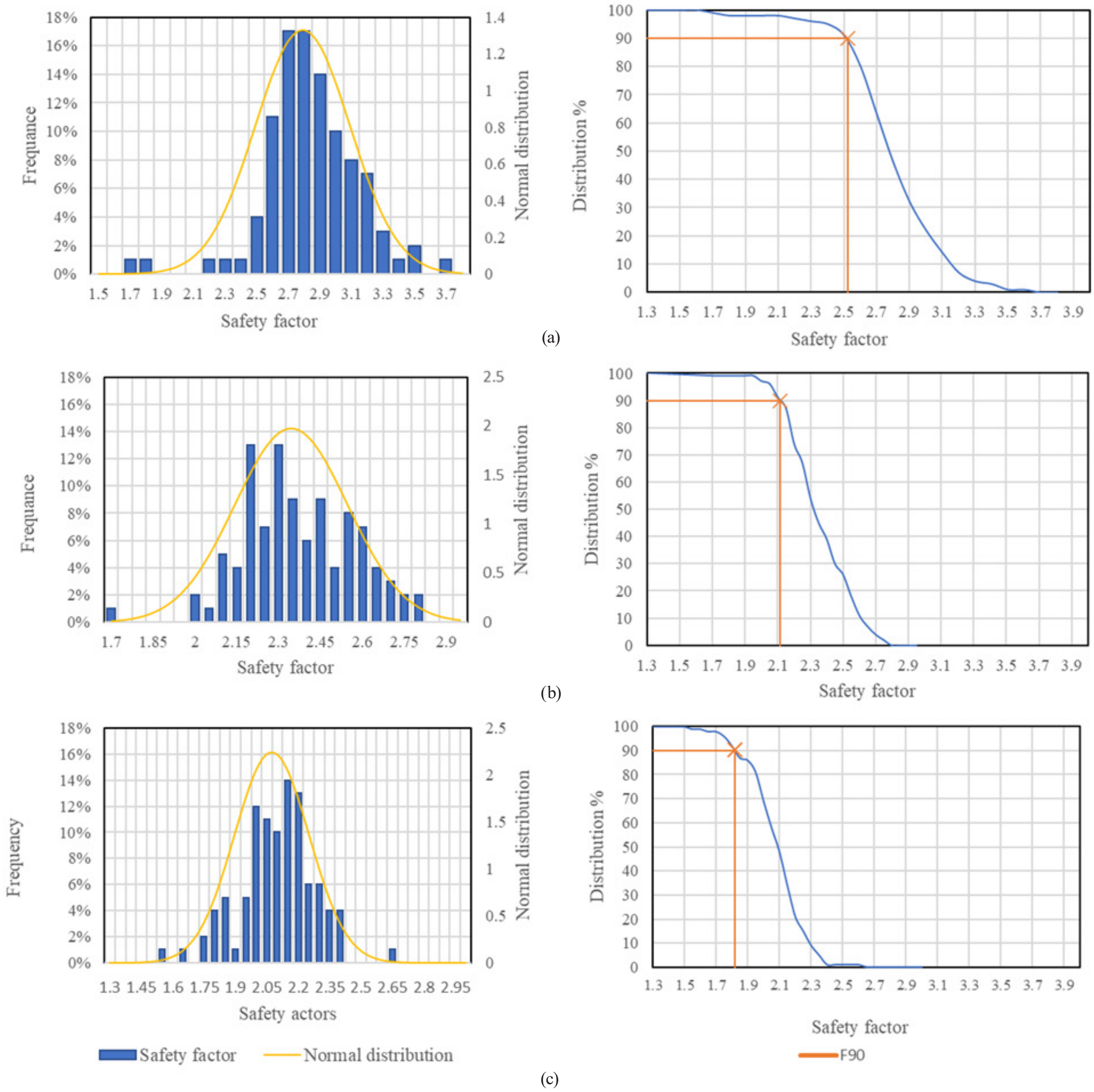

Fig. 5 Probability density function of safety factor and the relative normal distribution curve; (a) Slope 1:3; (b) Slope 1:2; (c) Slope 2:3

a minimum or maximum slope angle. Nonetheless, as per the Eurocode, which requires a stable slope (SF = 1.35), all three models in this study are deemed stable. Only when using shear parameters prescribed by the Austrian regulations for the steepest model (Model 3) does an unstable slope emerge, suggesting that Austrian regulations are more stringent and restrictive in design options. All the safety factor values obtained, including for the steepest slopes, conform to Colomer-Mendoza et al. [41] SF variation diagram based on slope inclination and height. While traditional methods permit an inclination angle of up to 26° (1:2) for a landfill height of 30 m, the multi-layered calculation method permits steeper slopes. Our results demonstrate that slopes can be stable against sliding even at an inclination of around 34° (2:3), particularly since the calculations do not consider the safety-enhancing effect of the daily cover system for each lift. As a further investigation, we recommend assessing the impact of increasing both the slope inclination and the height of the landfill to extend its capacity. However, this should be tested for the stability of the cover layers to evaluate the overall stability of the landfill system, which is currently under study and will be the subject of the forthcoming paper. Overall, the results support the use of the multi-layered models in finite element method over traditional homogeneous approaches in geotechnical design of landfills due to its ability simulate the real stat condition of waste disposal.

5 Conclusions

The inclination of landfill slopes has a significant impact on their capacity, and therefore, on the economic aspect of landfill operation. This study has demonstrated that using non-homogeneous landfills with randomly attributed shear parameters for analyzing safety factors is a reliable tool for making design and construction decisions, providing more flexibility for designers in choosing slope angles. The study also explored the potential for increasing both the inclination and height of landfills to find optimal values for maximum capacity. However, it is important to note that any increase in storage capacity must be evaluated based on the site's specifications.

While this study focused on the safety of waste bodies with steep slopes, further research is needed to determine the optimal values for each design factor, taking into account the significance of their impacts on the environment and economy. Such research would enable the development of an intelligent system to assist in making design decisions that meet predetermined goals for environmental and economic efficiency.

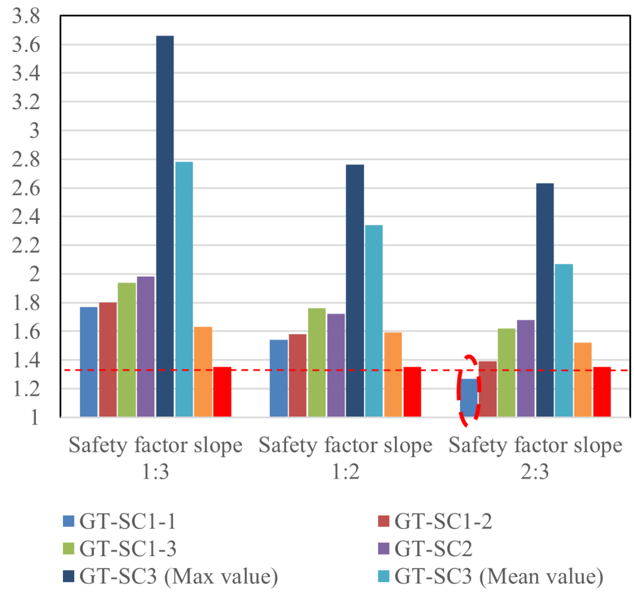

Fig. 6 Summary of safety factor variation (See Fig. 4)

Overall, this study provides valuable insights into the relationship between landfill slope inclination and capacity, and the use of non-homogeneous landfills with randomly attributed shear parameters for safety factor analysis. These findings have important implications for the design and operation of landfills, and can help guide decision-making to ensure that landfill facilities are safe, efficient, and sustainable.

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