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Landfill capacity enhancement from a slope inclination perspective and its implementation on the safety factor

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ABSTRACT

This study aims to investigate the impact of slope inclination on landfill capacity and safety factor to enable the construction of larger landfills and extend their lifespan. The geometrically determined capacity change with inclination is examined using a new probabilistic calculation method that considers the heterogeneity of waste layers. Safety factor analysis is carried out for different slope angles, with over 100 calculations for each inclination, to examine the effect of slope variation on the total safety of landfills. The results indicate that capacity increases significantly with the increase of inclination, with waste volume that can be placed increasing by 40% and 25% of the initial volume when passing from 1V:3H to 2V:3H and from 1V:3H to 1V:2H slope angles, respectively. The safety factor results show that, with the use of the conventional method (homogeneous waste) in the calculation, slopes of 1V:3H and 1V:2H are safe. However, the new method allows for consideration of a steeper slope of 2V:3H inclination as safe, especially since the calculation does not consider the safety-enhancing effect of daily cover layers. Based on the analysis presented in this paper, the multi-layered nonhomogeneous calculation method better characterizes the safety factor, as it is closer to representing the real state of landfills. This method provides more permissibility in design parameters, allowing for the construction of safe and cost-effective landfills. This study serves as a significant step forward in landfill construction, and the results have important implications for landfill design and management. Future research could investigate the effects of slope inclination on the consistency of covering layers and rehabilitation to further improve the overall stability of landfill systems.

Keywords: Landfill, Municipal solid waste, Slope inclination, Capacity, Safety factor.

1 INTRODUCTION

Waste management strategies around the world are faced with a number of challenges, primarily due to the increased generation of municipal solid waste (MSW) as a result of modern consumption-based lifestyles. At the same time, demographic growth and urban expansion have led to a reduction in suitable land for landfilling, resulting in a higher economic value for existing landfills. To address these limitations, it is necessary to explore methods for extending the capacity of landfills and rehabilitating older sites for future development without compromising safety.

A landfill is a constructed and intricate structure built to securely dispose of waste and prevent potential hazards such as contamination of soil, groundwater, and surface water. The waste is placed and compacted in cells on top of a lining system that isolates the base and sides of the landfill from the surrounding environment. The waste is covered with locally available soil, referred to as daily cover, after each operational period. The landfill is built by stacking lifts, forming a pyramid-like structure, where a bench is created between a particular number of lifts to increase the side slopes' stability. When the landfill reaches its maximum height, a final cover system consisting of several layers covers the entire external surface of the landfill. This signifies the end of the landfill's active phase.

According to research, even minor adjustments in operational parameters can greatly affect a landfill's storage capacity. Analytical models have revealed that slight variations in factors such as waste-to-soil cover ratio, height, active base area, and inclination can have a significant impact on the potential volume of waste preserved in a landfill (Aivaliotis et al.,2004) In addition, initial waste compaction plays an important role in enhancing the landfill's storage ability(Li et al., 2013).

This research aims to examine the design of landfills with the goal of maximizing storage volume from a slope inclination perspective. It provides a functional relationship between adjustments in slope inclination and waste volume for several landfill models. The current study analyzes the effect of modifications in the general side slope angle on the safety factor of a structure by comparing three different geometric models applying numerical modeling techniques in a novel method. The study provides an understanding of the relationship between slope inclination and waste volume in landfills. It highlights the importance of considering the non-homogeneous aspect of landfill, as it is closer to reality, in safety factor calculation as a novel approach to landfill designing. This method presents to be a reliable tool for design decision-making that increases the tolerance in slope angle selection enabling the exploration of higher inclinations and heights to determine optimal values for the maximum capacity. The results of this study can aid in the development of more efficient and secure landfills, and ultimately, contribute to the sustainable management of waste.

2 RELEVANT PARAMETERS AND METHODOLOGY USED IN THIS STUDY

2.1 Geotechnical parameters of MSW

The stability of landfills is significantly affected by various factors, with the unit weight and shear strength of the municipal solid waste (MSW) body being the primary contributors. The unit weight of MSW is heavily influenced by the composition of waste and the operational parameters of landfills, such as the application of cover soil, compaction, and leachate circulation (Zekkos et al., 2006). In this study, a unit weight value of 12 kN/m3 was utilized for calculations, following common practice in Hungary.

Shear strength of MSW is assessed through multiple geotechnical tests, treating waste as a soil-like material. The cohesion and friction angle data used in this paper were gathered from an extensive database by Varga (2010, 2011)and from numerous research papers (Keramati et al., 2020; Mokhtari et al., 2019; Pelkey et al., 2001; Pulat & Yukselen-Aksoy, 2017; Raviteja & Munwar Basha, 2017; Zekkos et al., 2006, 2008, 2010; Zhang et al., 2021). The wide variation in shear results found in the literature can be attributed to multiple factors that impact test outcomes, such as waste composition, degradation, age, and testing techniques (Keramati et al., 2020). Figure 1 illustrates the distribution of the collected shear strength parameters from the literature used in this study.

The large range of shear parameters in MSW can be further analyzed by considering the heterogeneous nature of municipal solid waste. Waste composition varies greatly from one landfill to another and can include a mix of organic materials, plastics, metals, and other materials. This variability results in differing unit weights and shear strengths, making it difficult to determine a consistent value for these parameters. Additionally, the degradation process that occurs in landfills over time, along with various test methods and techniques, further contributes to the wide range of shear parameters observed in the literature.

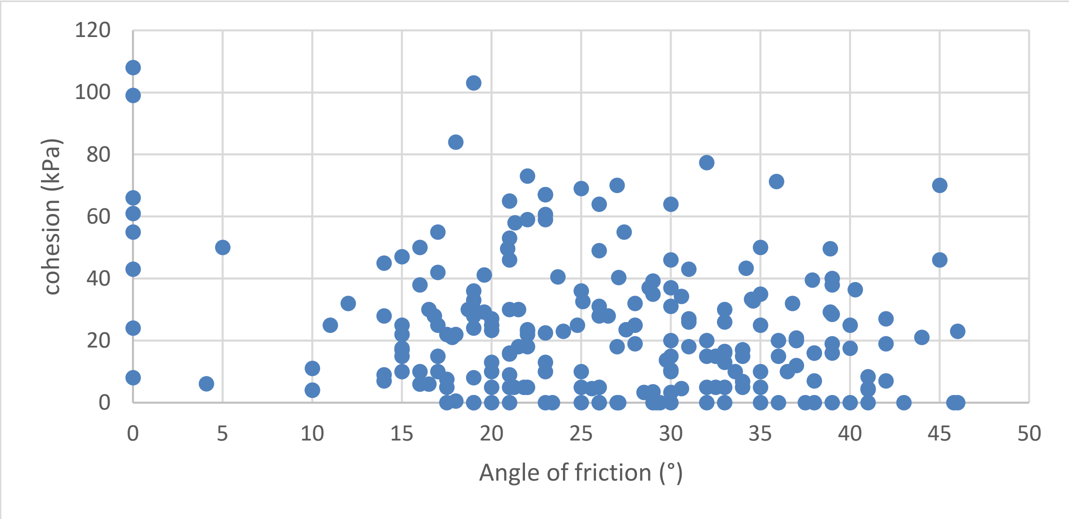

Figure 1. Shear strength collected in the database.

2.2 Capacity calculation

The stability of landfills is a critical aspect of their design and operation and is influenced by a variety of factors, such as the shear strength and unit weight of the municipal solid waste (MSW) body, and the slope angle. In this study, the impact of slope angle on the storage capacity of a landfill was examined using three distinct geometrical models, each representing a different slope configuration.

As illustrated in Figure 2, the modeling process considered a cross-section of an active base of 150 meters and a total height of 30 meters, divided into three lifts of 10 meters height each, with 10-meter benches separating the lifts. The design parameters for the three models were kept constant in all calculations, except for the slope angle ø, which varied as follows: Model 1 had a slope of 1:3 Model 2 had a slope of 1:2, and Model 3 had a slope of 2:3.

To determine the storage capacity of each model, the cross-sectional area was calculated geometrically by applying the appropriate mathematical equations. These calculations provided the volume for each model by multiplying the cross-sectional area by the landfill length. The results were then compared to establish a ratio between the different models, defining the percentage of capacity change with varying slope angles.

By understanding the relationship between slope angle and storage capacity, landfill designers and operators can optimize their designs and make informed decisions to enhance the capacity and stability of the landfill. This can lead to more efficient land use, reduced environmental impact, and extended operational life of the landfill.

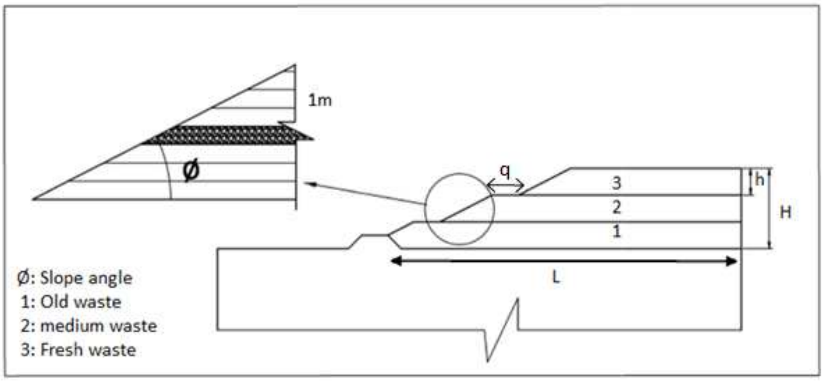

Figure 2. *Landfill geometrical parameters (H: Total height 30m; h: lift 10m; L: length 150m; q: bench10m)*

2.3 Slope stability calculation

The inclination of side slopes is a crucial factor in the safety and stability of landfills. In this study, the influence of slope angles on landfill stability was calculated using the Coulomb method and the finite element approach (FEM) solved in Plaxis software. The geometrical model of the landfill was first created in the program, and then the material properties were defined for each layer of waste. A probabilistic computation was used based on the method proposed by Szabó, (2012) that assesses landfill slope stability by incorporating uncertainties in the geotechnical parameters of municipal solid waste (in this case, shear strength) in a deterministic analysis of randomly generated samples.

To obtain more accurate and representative results, three scenarios were considered in the analysis, with each of the three geometrical models tested for every scenario:

First Scenario (SC1) - Homogeneous Waste Body: This scenario considered the waste in a landfill as a single homogeneous body, treating the entire waste mass as having uniform properties. This assumption simplifies the computational process and allows for an initial evaluation of the landfill's stability. However, it should be noted that real-world landfills often have varying waste properties due to differences in waste composition, age, and degradation levels.

In this scenario, three sets of calculations were conducted based on different sets of shear parameters, which play a significant role in determining the stability of the landfill slopes. Shear parameters include cohesion and friction angle, both of which influence the landfill's resistance to shear forces.

- First Simulation - Austrian Standards: The first simulation utilized the shear parameters specified in Austrian standards, with a cohesion value of 5 kPa and a friction angle of 25°. These values represent the typical parameters used in the Austrian practice, providing a reference point for the stability analysis.

- Second Simulation - Sanchez et al. (1993) Recommendation 1: The second simulation was based on the recommendations provided by Sanchez et al. (1993), which suggested using a cohesion value of 10 kPa and a friction angle of 20°. These values reflect the researchers' findings on the shear strength properties of MSW, which may differ from the values used in the Austrian standards.

- Third Simulation - Sanchez et al. (1993) Recommendation 2: The third simulation also followed the recommendations of Sanchez et al. (1993), but used a higher cohesion value of 20 kPa while maintaining the friction angle at 20°. This set of parameters considers the possibility of stronger waste cohesion, which could affect the overall stability of the landfill slopes.

Second Scenario (SC2) - Waste Age Division: This scenario considered the influence of waste age on the landfill's stability by accounting for the aging factor of waste. As waste ages, its geotechnical properties change due to factors such as decomposition, settlement, and moisture content variations. These changes can have a significant impact on the landfill's stability, particularly the shear strength of the waste.

In this scenario, the landfill was divided into three 10-meter layers to represent different stages of waste aging:

- First Layer - Fresh Waste: The first layer represented newly disposed waste with minimal degradation. Fresh waste typically has higher moisture content and lower shear strength due to the lack of compaction and decomposition. In this stage, the waste is more susceptible to movement and instability.

- Second Layer - Medium Waste: The second layer represented waste that has undergone some degree of decomposition and settlement. This medium-aged waste exhibits an intermediate stage of geotechnical properties, with moderate shear strength and reduced moisture content compared to fresh waste. The decomposition process and consolidation of the waste in this layer lead to increased stability compared to fresh waste.
- Third Layer - Old Waste: The third layer represented waste that has undergone significant degradation and settlement over an extended period. Old waste exhibits the highest shear

strength and the lowest moisture content among the three layers. The advanced decomposition and compaction processes in this layer result in improved stability compared to the other layers.

For each layer, the shear parameters, such as cohesion and friction angle, were obtained from the literature outcomes. These parameters were used in the stability analysis to account for the changes in geotechnical properties as the waste ages.

Third Scenario (SC3) - Sandwich-like System: This scenario aimed to create a more realistic model of landfills by considering the complex layering structure typically found in landfill operations. Instead of treating the waste as a single homogeneous mass or just a few distinct layers, the landfill was divided into 30 layers of 1-meter height each. This finer layering approach more accurately represents the sandwich-like structure of landfills.

The 30 layers of 1-meter height each were defined to account for the varying geotechnical properties of the waste and the influence of cover soils within the landfill. This approach captured the complexities arising from different waste types, ages, and degrees of decomposition, as well as the mechanical interaction between waste layers and cover soils. The cohesion and friction angle were automatically attributed to each layer using a Python script that drew from a large database of shear strength parameters collected from various studies and literature. This allowed for a more accurate representation of the spatial variability of geotechnical properties throughout the landfill. Over 100 calculations were conducted for each slope angle model, considering the different combinations of shear strength parameters for each of the 30 layers. This
extensive analysis provided a comprehensive assessment of the landfill's stability under various conditions
and accounted for the uncertainties related to the shear strength parameters.

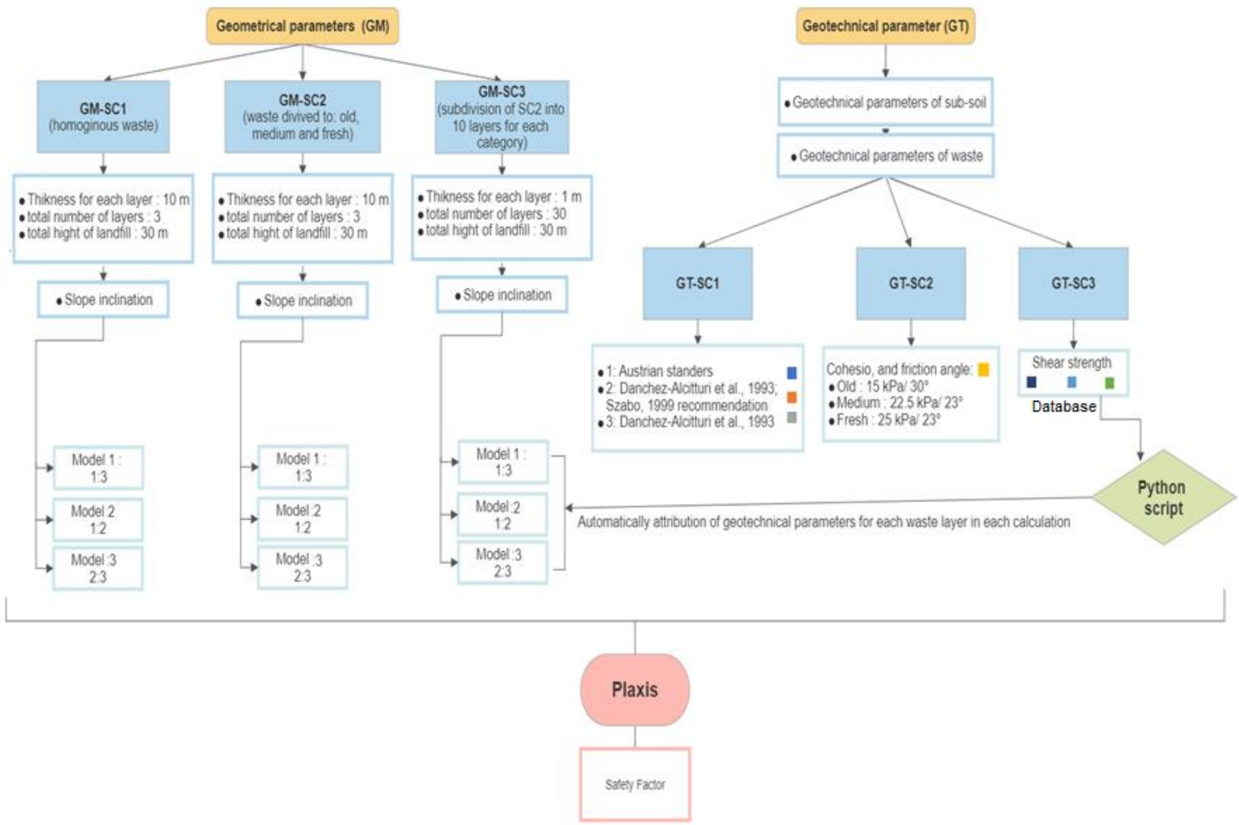

Figure 3. *Landfill slope stability calculation procedure*

A statistical analysis of the results was performed to quantify the probability of failure and to identify the critical factors influencing the landfill's stability. This analysis provided valuable insights into the role of layering and variability of geotechnical properties in determining the landfill's performance under different slope angles.

The stability analysis was performed for each slope angle model using the same calculation scenarios. Throughout these calculations, several assumptions were consistently applied to maintain a consistent framework for the analysis:

- The calculations focused on the land rise portion of the landfill, treating the ground level as the base level. This assumption allowed the analysis to concentrate on the potential instability area.
- The daily and final cover layers were not included in the calculations. While these layers typically contribute to the overall stability of the landfill, their exclusion from the analysis does not compromise the reliability of the research. By focusing on the waste material itself, the study aims to provide insights into the fundamental stability characteristics of the landfill, which can then be further refined by incorporating the effects of cover layers in future analyses.

By adhering to these assumptions across all calculation scenarios and slope angle models, the study maintains a consistent approach in evaluating the stability of landfills, ensuring the comparability and reliability of the results.

3 RESULTS

The results of this study demonstrate the significant influence of slope angle on landfill capacity and stability, offering valuable insights into the optimization of landfill design and operation. The key findings and their implications for landfill engineering design can be divided into two sections:

3.1 Impact of Slope Angle on Capacity

The results highlight the high sensitivity of landfill capacity to changes in slope angle. As shown in Table 1, transitioning from a slope of 1:3 to 1:2 and 2:3 increases the capacity by 25% and 40%, respectively. Moreover, changing from a slope of 1:2 to 2:3 enhances the capacity by 11.85%. This substantial growth in capacity has significant economic implications for landfill projects, emphasizing the importance of considering slope angle in landfill design to maximize storage potential.

Table 1. *Capacity calculation results*

Slope angle	1:3	1:2	2:3
The volume of the landfill (m^3)	1220000	1527999	1709000
Percentage of volume growth compared to 2:3 angle	40.08%	11.85%	-
Percentage of volume growth compared to (1:2)	25.25%	-	-

3.2 Safety Factor Analysis

The study reveals several notable findings concerning the safety factor of landfill slopes. Figure 3 illustrates a strong correlation between the safety factor and the number of layers employed within the same landfill model. Inhomogeneous, multi-layered models calculated using randomly chosen shear parameters exhibit higher safety factor values compared to homogenous models using constant shear strength parameters. This can be attributed to the fact that multi-layered models, which more accurately reflect the sandwich-like structure of landfills with heterogeneous waste layers, provide greater overall support due to the variation in waste shear parameters.

As expected, an inverse relationship between the safety factor and slope angles was observed. Figure 3 shows that an increase in slope angle leads to a decrease in the safety factor. While certain standards impose minimum or maximum slope angles (Canadian regulations mandate a minimum slope of 1:4 (14º), which ensures a stable slope even at heights exceeding 60m, under saturation conditions, and with seismic coefficients greater than 0.15), not all regulations are as stringent; many countries either require only stable slopes, as seen in the Philippines, European Union, Japan, and India, or impose a maximum inclination of 1:3 (18.4º), as is the case in Chile, Australia, and South Africa (Colomer-Mendoza, 2013). Based on the Eurocode, which only requires a stable slope (SF=1.35 for Hungary), all three models are deemed safe. Only the use of shear parameters recommended by the Austrian standards in model 3 (the steepest) results in an unstable slope, illustrating the stringent nature of these standards and the limitations they impose on design options. The safety factors obtained in this study, including those for the steepest slopes, are in agreement with the diagram of safety factor variation with respect to slope inclination and height proposed by Colomer-Mendoza, (2013). Traditional methods permit a slope inclination of up to 26° (1:2) for a 30m landfill height, while the multi-layered calculation method allows for steeper slopes. The results indicate that slopes can be safe against sliding even at an inclination of 34° (2:3), particularly when the effect of the daily cover system on safety is not taken into account in the calculations. However, this result 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 a forthcoming publication.

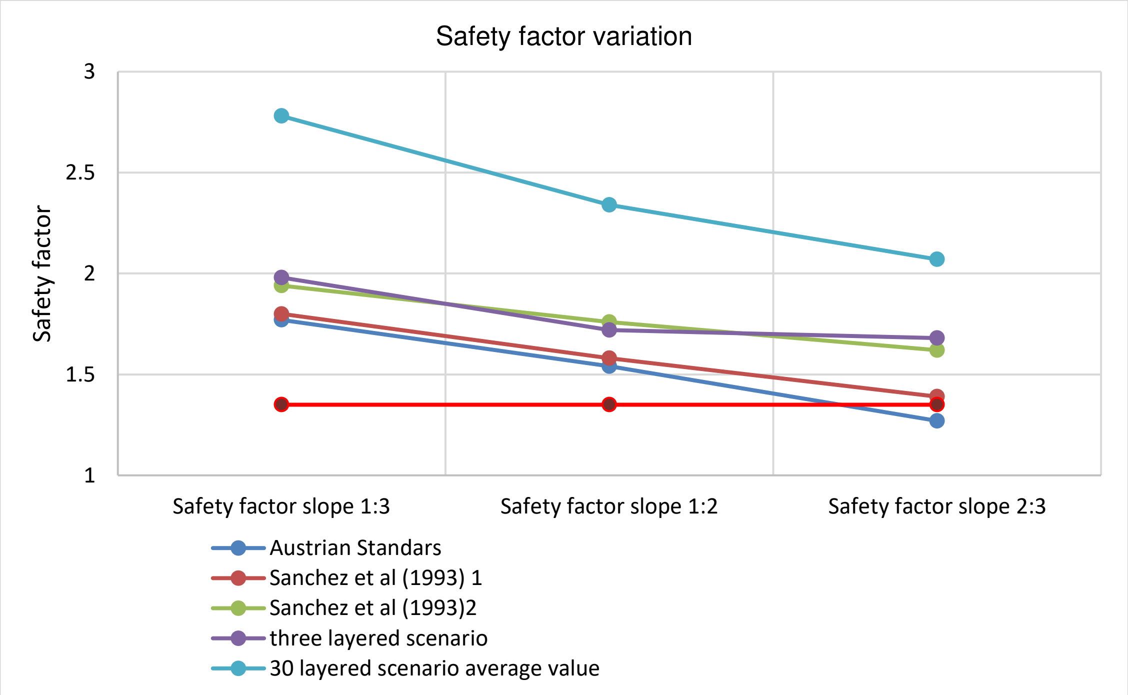

Figure 4. *Safety factor calculation*

4 CONCLUSIONS

This study highlights the significant influence of slope inclination on landfill capacity and stability. A high sensitivity of landfill capacity to changes in slope angle has been observed, with increased slope angles leading to substantial improvements in available storage capacity and economic feasibility. The use of non-homogeneous landfill methods, incorporating random shear parameters, has proven to be a reliable approach for analyzing safety factors in landfill design and construction. This approach allows for greater flexibility in slope angle selection, enabling the exploration of steeper inclinations and heights to determine the optimal values for maximum capacity while maintaining stability.

However, it is crucial to consider the specific characteristics of each landfill site and balance the potential gains in capacity with the need to ensure the long-term stability of the landfill structure, particularly regarding the stability of covering layers and rehabilitation efforts. While this study provides valuable insights into the relationship between slope angle, capacity, and stability, further research is recommended to refine the understanding of optimal design values and their implications for landfill engineering and environmental sustainability. By continuing to investigate these factors, future research can contribute to the development of more efficient and environmentally responsible landfill designs and management practices.

REFERENCES

Aivaliotis, V., Dokas, I., Hatzigiannakou, M., & Panagiotakopoulos, D. (2004). Functional relationships of landfill and landraise capacity with design and operation parameters. *Waste Management and Research*, *22*(4), 283–290. https://doi.org/10.1177/0734242X04045437

Colomer-Mendoza, F. J. (2013). Influence of the Design on Slope Stability in Solid Waste Landfills. *Earth Sciences*, *2*(2), 31. https://doi.org/10.11648/j.earth.20130202.12

Keramati, M., Shahedifar, M., Aminfar, M. H., & Alagipuor, H. (2020). Evaluation of the Shear Strength Behavior of aged MSW using Large Scale In Situ Direct Shear Test, a case of Tabriz Landfill. *International Journal of Civil Engineering*, *18*(7), 717–733. https://doi.org/10.1007/s40999-020-00499-3

Li, Y. C., Liu, H. L., Cleall, P. J., Ke, H., & Bian, X. C. (2013). Influences of operational practices on municipal solid waste landfill storage capacity. *Waste Management and Research*, *31*(3), 273–282. https://doi.org/10.1177/0734242X12472705

Mokhtari, M., Heshmati Rafsanjani, A. A., & Shariatmadari, N. (2019). The effect of aging on the compressibility behavior and the physical properties of municipal solid wastes: a case study of Kahrizak landfill, Tehran. In *Environmental Earth Sciences* (Vol. 78, Issue 16). https://doi.org/10.1007/s12665-019-8523-6

Pelkey, S., Valsangkar, A., & Landva, A. (2001). Shear displacement dependent strength of municipal solid waste and its major constituent. *Geotechnical Testing Journal*, *24*, 381–390.

Pulat, H. F., & Yukselen-Aksoy, Y. (2017). Factors affecting the shear strength behavior of municipal solid wastes. *Waste Management*, *69*, 215–224. https://doi.org/10.1016/j.wasman.2017.08.030

Raviteja, K. V. N. S., & Munwar Basha, B. (2017). *Probabilistic Back Analysis of Koshe Landfill Slope Failure*.

Szabó, I., & Szabó, A. (2012). *HULLADÉKLERAKÓK REKULTIVÁCIÓJA, UTÓGONDOZÁSA* (G. Zoltán & T. Szemmelveisz, Eds.; Kiadja Mis). Miskolci Egyetem. https://docplayer.hu/4170410-Szabo-imre-szabo-attila-hulladeklerakok-rekultivacioja-utogondozasa.html

Varga, G. (2010). *Hulladéklerakók állékonysági kérdései PhD értekezés* [PhD]. Budapest University of Technology and Economics.

Varga, G. (2011). Some geotechnical aspects of bioreactor landfills. *Periodica Polytechnica Civil Engineering*, *55*(1), 39–44. https://doi.org/10.3311/pp.ci.2011-1.05

Zekkos, D., Athanasopoulos, G. A., Bray, J. D., Grizi, A., & Theodoratos, A. (2010). Large-scale direct shear testing of municipal solid waste. *Waste Management*, *30*(8–9), 1544–1555. https://doi.org/10.1016/j.wasman.2010.01.024

Zekkos, D., Bray, J. D., Kavazanjian, E., Matasovic, N., Rathje, E. M., Riemer, M. F., & Stokoe, K. H. (2006). Unit Weight of Municipal Solid Waste. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(10), 1250–1261. https://doi.org/10.1061/(asce)1090-0241(2006)132:10(1250)

Zekkos, D., Bray, J. D., & Riemer, M. F. (2008). Shear modulus and material damping of municipal solid waste based on large-scale cyclic triaxial testing. *Canadian Geotechnical Journal*, *45*(1), 45–58. https://doi.org/10.1139/T07-069

Zhang, Z., Zhang, J., Wang, Q., Wang, M., & Nie, C. (2021). *Research on Direct Shear Strength Characteristics of Mechanically Biologically Treated Waste*. https://doi.org/10.21203/rs.3.rs-207864/v1