

Numerical analysis of a landfill stabilized with a Reinforced fill structure having geogrid and steel wire mesh as a reinforcing Element

Ahsan Rehman Khan

University Ghent Geotechnical Institute, Belgium, ahsanrehman.khan@ugent.be

Gemmina Di Emidio

University Ghent Geotechnical Institute, Belgium, Gemmina.DiEmidio@ugent.be

ABSTRACT: Slope stability is one of the main challenges in industrial landfill designs, where the stakeholders are much concerned about maximizing storage capacity. The heterogeneous composition of waste materials, combined with the potential presence of weak foundation, makes slope stability difficult and therefore slope geometries are formed by choosing either low slope angles or less height, for safe designs. In this study a vertical expansion of an industrial landfill is stabilized using a reinforced fill structure (RFS) designed with finite element method and limit equilibrium method. This RFS comprised a combination of wire mesh and geogrids, serving as primary and secondary reinforcement materials, respectively. Results indicate that RFS allows the increase in the storage capacity by increasing the height of the waste landfill without compromising stability which would otherwise be a concern without RFS. Having more initial cost associated with RFS, the findings highlight not only the economic benefits by accommodating higher storage capacity but also the sustainable waste management practice.

KEYWORDS: Reinforced fill structure, landfill, sustainability, geogrids, wire mesh, finite element method, limit equilibrium method.

1 INTRODUCTION

Geosynthetics are commonly used for reinforcement purposes in a variety of geotechnical applications. Their primary function is to enhance stability, distribute loads, and minimize tensile stresses, especially in systems with potential instability such as landfills, embankments, and steep slopes (Bathurst & Naftchali, 2021). The figure illustrates key applications (EUROPEAN STANDARD, 2022) as follows:

- A. Reinforced Walls and Abutments
- B. Reinforced Slopes
- C. Basal Reinforcement for Embankments
- D. Veneer Reinforcement on Landfill Slopes

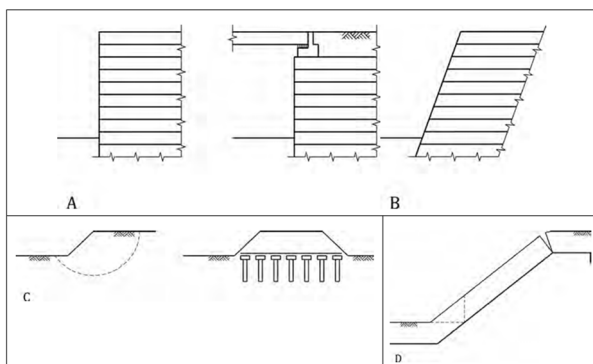


Figure 1. Reinforced fill structures as per BS EN 1997-3:2025 Eurocode 7

Its use in geotechnical engineering has become vital in modern infrastructure, offering innovative, sustainable solutions. Aligned with the UN 2030 Sustainable Development Goals, geosynthetics support clean water, resilient infrastructure, climate action (Cardile & Pisano, 2020). Miyata (2024) found that geosynthetic MSE walls have the lowest life-cycle CO₂ emissions compared to other retaining structures. Over a 50-year lifespan, their emissions can even become negative, highlighting their role in achieving carbon neutrality.

Their use in RFS, for instance, facilitates faster and more economical construction compared to traditional methods. This is due to simplified installation, reduced demand for skilled labor and heavy equipment, and the ability to reuse site-excavated materials, thereby minimizing environmental impact

and transportation cost (Koerner, 2012). Khan & Di Emidio (2025) assess three fill materials for reinforced fill structures: untreated onsite fill (Fill 1), lime-stabilized fill (Fill 2), and recycled construction waste (Fill 3). Fill 1 demonstrates poor strength and excessive deformation, rendering it unsuitable. In contrast, fill 2 and 3 meet Eurocode safety standards and effectively limit lateral displacement. Additionally, Khan & Di Emidio (2023, 2025) evaluated the prediction of long-term geogrid creep strain using Plaxis2D with a visco-elastic (time-dependent) model.

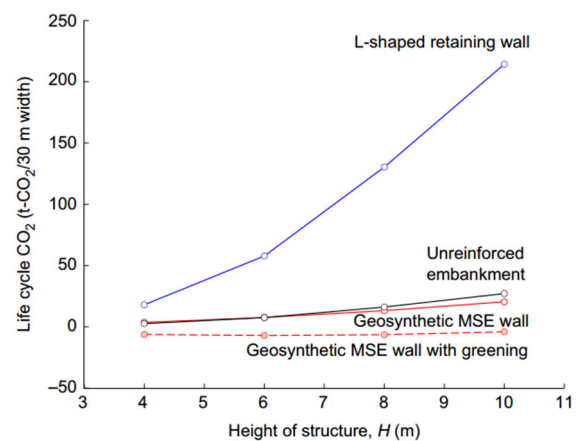


Figure 2. Comparative life cycle CO₂ emissions for geosynthetic MSE walls, L-shaped concrete retaining walls, and non-reinforced embankments (adapted from (Miyata, 2024))

Despite the recognized economic and environmental advantages of RFS, their broader implementation is constrained by several practical challenges. Beyond ensuring structural stability, the process must incorporate precise evaluation of critical performance indicators which includes horizontal displacement, differential settlement, reinforcement strain, facing compressibility, and facing alignment as specified in EN 14475:2006. Failures often result from inadequate reinforcement strength, stiffness, bond, or connection robustness. To mitigate these risks, it is essential to ensure internal stability and prevent both localized and compound failure mechanisms. This study aims to highlight these issues to ensure the safe and reliable performance of RFS.

2 MATERIALS AND METHODS

This study analyzed a landfill expansion stabilized with a 15.5 m high RFS on both sides of the landfill, using limit equilibrium and finite element methods as shown in figure 3. The initial proposal aimed to stabilize the landfill at a height of 41.5 meters using a sand dike. However, the need to increase the landfill's capacity without expanding its footprint led to the consideration of alternative solutions. As a result, an RFS was proposed, which enabled a significant increase of 12 m in the landfill's height. RFS involved in this study consists of two types of reinforcement with a combination of wire mesh and geogrids, which are commonly used as primary and secondary reinforcement materials (Khan & Emidio, 2023).

Usually, the design of RFS must satisfy both ultimate limit states (ULS) and serviceability limit states (SLS) as per Eurocode 7. ULS covers external stability (sliding, overturning, bearing failure) and internal stability (reinforcement rupture, pullout, connection failure), addressing risks of global collapse. SLS concerns, such as settlement and displacement, affect structural performance without causing failure. In this study limit-equilibrium method was used to assess external stability using a program called RSWall (ROSCIENCE). While finite element method-based software Plaxis was used to investigate different performance indicators which include horizontal displacement, differential settlement, strain in the HDPE geomembrane and geogrids, gabions alignment and gabions compressibility as per (EN 14475:2006). Table 1 presents the soil properties, which include foundation strata and the fill material.

Table 1. Properties of soil for Plaxis-2D

	γ_{dry} kN/m ³	γ_{wet} kN/m ³	Model	c'_{ref} kN/m ²	ϕ' [°]
Fill (lime stabilized)	18	19	HS	20	40
Waste (industrial)	17.4	20	HS	20	30
Clay 1	17	19	HS	08	22
Sand 1	18	20	HS	3	27
Sand 2	20	20	HS	02	35
Clay 2	19	19	HS	15	20
Sand 3	16	18	HS	02	30
Sand 4	18	18	HS	2	27
Clay 3	17	19	HS	8	20

Table 2, 3, & 4 presents the properties of geogrid, gabions and wire-mesh respectively. The strata exhibited complete heterogeneity and a mixed geological origin.

Table 2. Geogrid properties for Plaxis-2D

Property	Units	Geogrid
Axial Stiffness	kN/m ²	3160
Axial force	kN/m ²	158
Material type	---	Elastoplastic

The Hardening Soil Model was employed to simulate the realistic behavior of soil, as it effectively captures stress-dependent stiffness and provides a more accurate assessment of deformation. Unlike linear models, this advanced constitutive model reflects the inherent non-linearity of soil stiffness and accommodates the non-linear stress-strain response, including both soil softening and hardening behaviors. A geogrid was used as the primary reinforcement due to its tensile strength and slender geometry, which makes it ideal for resisting tension. Gabions constructed with wire mesh served as secondary reinforcement, primarily for erosion control and earth retention. The use of a double-twisted wire mesh configuration further

ensured structural integrity by minimizing potential strength reduction. For modeling purposes, gabions were represented as soil clusters, welded wire mesh panels were modeled using plate elements, and geogrids were simulated using elastoplastic model.

Table 3. Gabion properties for Plaxis-2D

Property	Units	Gabion
Unit weight	kN/m ³	18
Angle of internal friction	Degree	40
Cohesion	kN/m ²	27
Poisson's ratio	-	0.3
Elastic modulus	MPa	40
Material model	-	Mohr-Coulomb

Table 4. Wire-mesh properties for Plaxis-2D

Properties	Symbol	Units	value
Axial stiffness	EA	kN/m	62832
Flexural Rigidity	EI	kNm ² /m	0.251
Weight	W	kN/m/m	0.023
Poisson's ratio	ν	-	0.3
Maximum bending moment	Mp	kN/m/m	0.23
Maximum axial force	Np	kN/m	135
Cohesion	C	kN/m ²	27

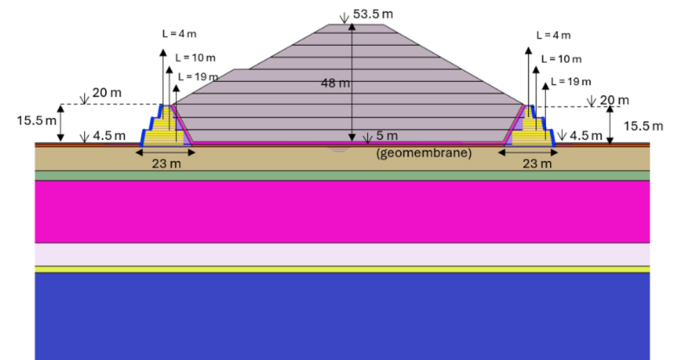


Figure 3. Analyzed landfill structure stabilized with Reinforced fill structure

3 RESULTS

The performance evaluation of the RFS was conducted in accordance with Eurocode 7, supplemented by the guidelines outlined in EN 14475:2006 and BS 8006. The assessment addressed both ultimate and serviceability limit states. Stability against sliding, overturning, and bearing capacity was analyzed using a limit equilibrium-based computational program. These are assessed by comparing driving and resisting forces or moments. Eurocode 7 requires applying partial factors to loads and material properties to address uncertainties and ensure design reliability. The resulting Factor of Safety should meet or exceed 1.0 when all recommended partial factors are applied. The results are shown in table 5.

Figure 4. presents the results of a finite element method (FEM) analysis conducted using Plaxis, performed in parallel to investigate key serviceability performance indicators. These include horizontal displacement, differential settlement, reinforcement strain, geomembrane strain, gabion compressibility, and gabion alignment tolerances.

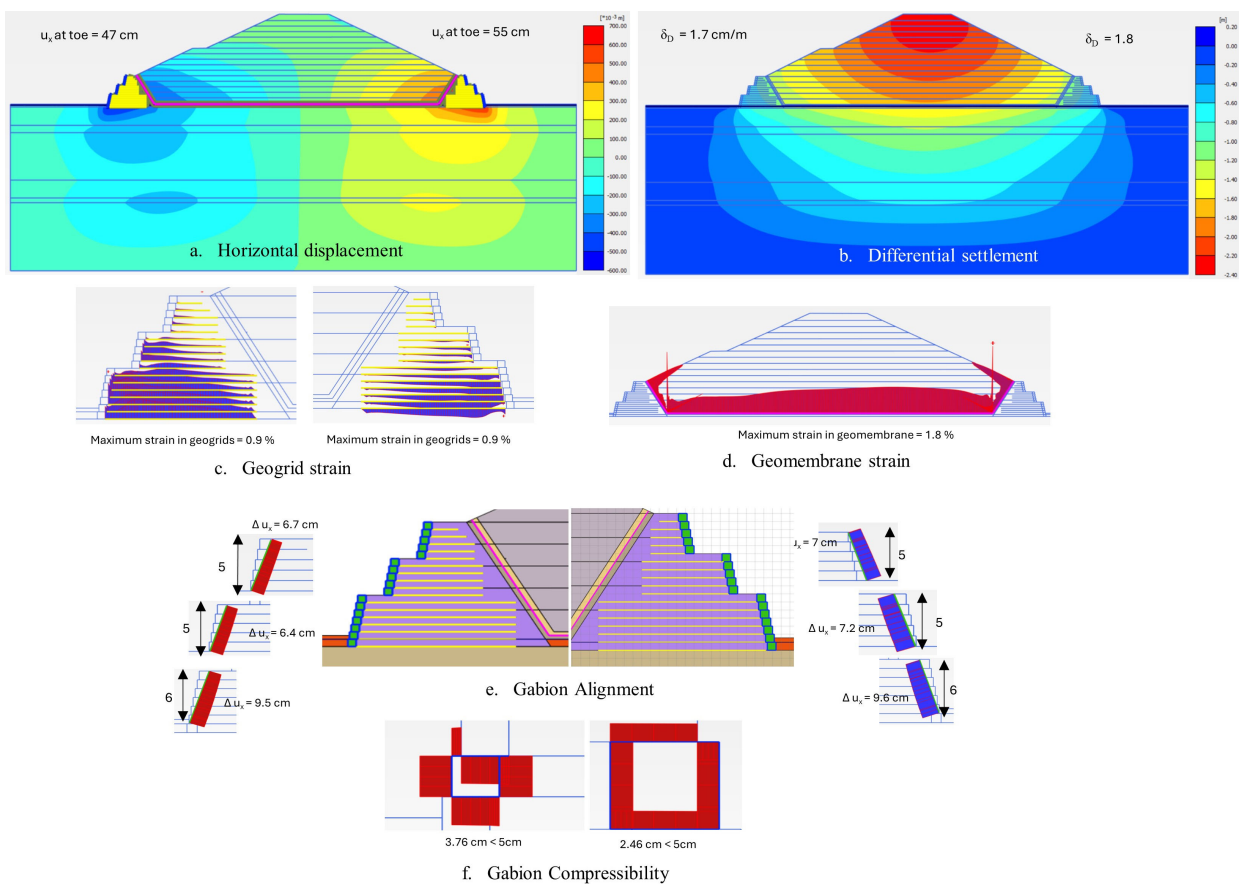


Figure 4. Various performance indicators analyzed using Plaxis, a finite element software

Table 5. Safety factor using LEM

Factor of safety against Sliding	1.09 > 1
Factor of safety against Overturning	5.14 > 1
Factor of safety against Bearing	1.96 > 1

3.1 Horizontal Displacement

Horizontal displacements measured at the facing elements were 47 cm on the left and 55 cm on the right as shown in figure 4a. The excessive displacements are attributed to mobilized shear stresses at the structure base surpassing the available soil shear strength due to the substantial load exerted by the landfill. These values exceed the stakeholder-defined serviceability limit of 25 cm, indicating non-compliance with the horizontal displacement criteria.

To address this issue, parametric analyses were conducted, considering factors such as consolidation time, compaction quality of individual layers, implementation of dual berms on both sides, and variation in the shear strength parameters (cohesion c and friction angle ϕ) of industrial waste. Also, the performance of two different fill materials was also evaluated. The results will be available in our upcoming publication.

3.2 Differential Settlement:

Measured differential settlements were 1.7 cm/m and 1.8 cm/m on left and right side of the landfill respectively, remaining within the prescribed tolerance of 2% as per EN 14475:2006. This indicates acceptable performance in terms of vertical deformation as shown in figure 4b.

3.3 Strain in geogrid:

Strains observed in the geogrid reinforcement remained below 1%, significantly lower than the 5% permissible limit specified in BS 8006. This confirms that the reinforcement operated well within the allowable deformation range and did not reach a limit state as shown in figure 4c.

3.4 Strain in geomembrane:

The HDPE geomembrane strain was maintained within the maximum allowable limit of 3%, in accordance with recommendations by Rowe & Yu, 2019. This suggests no excessive tensile demand from combined deformation sources as shown in figure 4d.

3.5 Gabions Performance:

Gabion compressibility was measured below the 5% limit and alignment tolerances were within ± 100 mm, complying with EN 14475:2006 requirements as shown in figure 4e and 4f respectively. No significant deformation or misalignment was observed during service loading.

4 CONCLUSION:

This study assessed the performance of a RFS supporting a landfill, in accordance with Eurocode 7 and supplementary guidelines including EN 14475:2006 and BS 8006. Ultimate limit state checks using limit equilibrium analysis confirmed the structure's stability against sliding, overturning, and bearing failure. Serviceability performance was evaluated using finite element modeling, focusing on deformation and strain criteria. The analysis revealed that while differential settlement, reinforcement strain, geomembrane strain, gabion compressibility, and alignment tolerances all remained within acceptable limits, horizontal displacements exceeded the threshold value. This indicates potential serviceability concerns

under the current loading conditions, likely driven by mobilized shear stresses exceeding the available soil strength at the base of the structure.

A comprehensive discussion of a series of parametric analyses which includes effects of various factors, including consolidation time, the compaction quality of individual layers, the effect of banquette and variations in the shear strength parameters, specifically cohesion (c) and friction angle (ϕ), of the industrial waste will be presented in detail in our upcoming publication.

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