Reinforced Earth Used in Uncontrolled Landfill Final Closures – The Case of Syros Landfill

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ABSTRACT: *The method of increasing the capacity and avoiding excavation of waste materials as part of the final closure of uncontrolled landfills with the use of a reinforced earth embankment of adequate height is described. The case of the Syros uncontrolled landfill (Cyclades islands, Greece) is presented, where the method was applied. The design principles are detailed along with the method of analysis, the analysis results, the construction specifications and finally the construction method that was used.*

KEYWORDS: landfill closure, reinforced earth, slope stability, gabions, geogrid

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

INTRODUCTION

In the present paper the use of a reinforced earth embankment as part of the final closure of uncontrolled landfills is presented. More specifically, it is described how the incorporation of a reinforced earth embankment in the downstream face of a landfill can contribute in increasing the capacity of the landfill and avoiding excessive waste excavation for the grading of the final closure slopes. It should be noted that uncontrolled landfills generally lack containment system as well as many of the engineered systems typically included in a modern landfill. It is noted that the authors have designed several (at least 10) landfill final closures using this method over the past 10 years in Greece with at least 4 of them having been constructed succesfully.

PROBLEM DESCRIPTION

In uncontrolled landfills the solid waste is simply off-loaded and pushed by bulldozers over the cliff, without following the maximum slope inclinations (1:3 – V:H) specified by Greek legislation. As a result of that the solid waste pile slopes are very steep (of the order of 40%-60% - 1:2.5 to 1:1.5 V:H). Additionally, taking into account that most landfills in Greece are active for a long period of time before they are closed, the accumulated quantity of solid waste is considerable, fully covering the available space and in many cases even exeeding the property limits.

The specified by Greek legislation slope inclinations for landfills (up to 33% for the side slopes and at least 3-5% for the top of the landfill according to "Guidelines and Specifications for Solid Waste Management" - Common Ministerial Decision 14218/97 and Technical Specifications for Uncontrolled Landfill Closures, bulletin 109974/3106) are fairly mild. By designing the closure of a landfill following the aforementioned restrictions the following issues arise:

- Excessive solid waste excavation is required in order to grade the slopes for the landfill's final closure (see figure 1).
- Shortage of available space in the perimeter of the landfill in order to expand it horizontally and form flatter slopes by simple filling (see figure 2).

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- Difficulty of disposing of the excavated excess solid waste in order to form the slopes for the landfill's final closure.
- Safety and health issues during excavation and transportation of large quantities of solid waste.

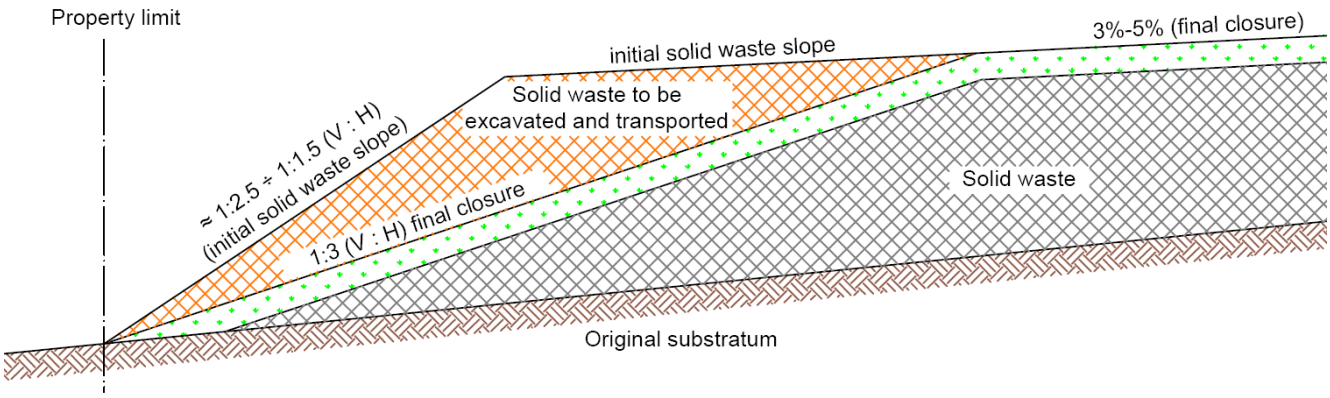


Figure 1. Typical section of an uncontrolled landfill to be regraded and closed by excavation and transportation of waste.

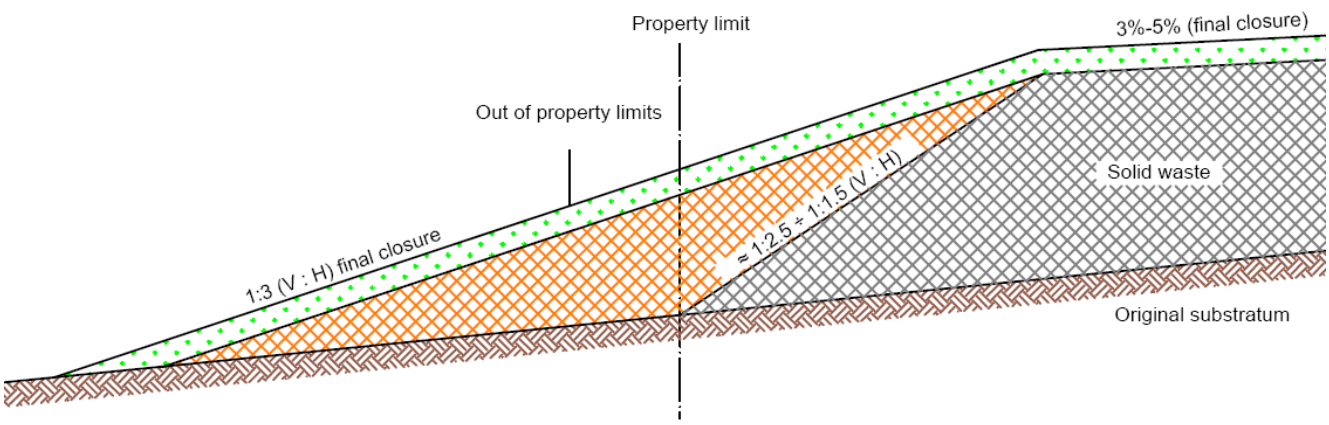


Figure 2. Typical section of an uncontrolled landfill to be regraded and closed by simple filling exceeding thus the property limits.

SOLUTION APPROACH

In order to address the aforementioned difficulties, the construction of a downstream retaining embankment with a steep outer slope (in the order of 200-250%), placed at the lower elevation area of the perimeter of the landfill, is proposed. The purpose of this embankment is to:

- Avoid excessive excavation of solid waste in order to reform and close the landfill. This is not desirable from a health and safety perspective, whereas environmental issues may also arise.
- Regrade the slopes of the landfill with acceptable inclination by simple filling and/or limited excavation.
- Contain the final closure of the landfill within the available property limits.

The construction of a steep outer slope of the downstream embankment is absolutely necessary in order to minimize (a) the quantity of the required earth fill and (b) the extent of the footprint of the embankment (due to the unavalability of space). To achieve this slope inclination, the embankment is reinforced with geosynthetics (geotextiles or geogrids), while its face is formed by flexible elements (in order to withstand deformations without loss of structural integrity) with high drainage capacity (ensuring the drainage of the backfill and of the surface runoff from the crest of the closed landfill – see Figure 3).

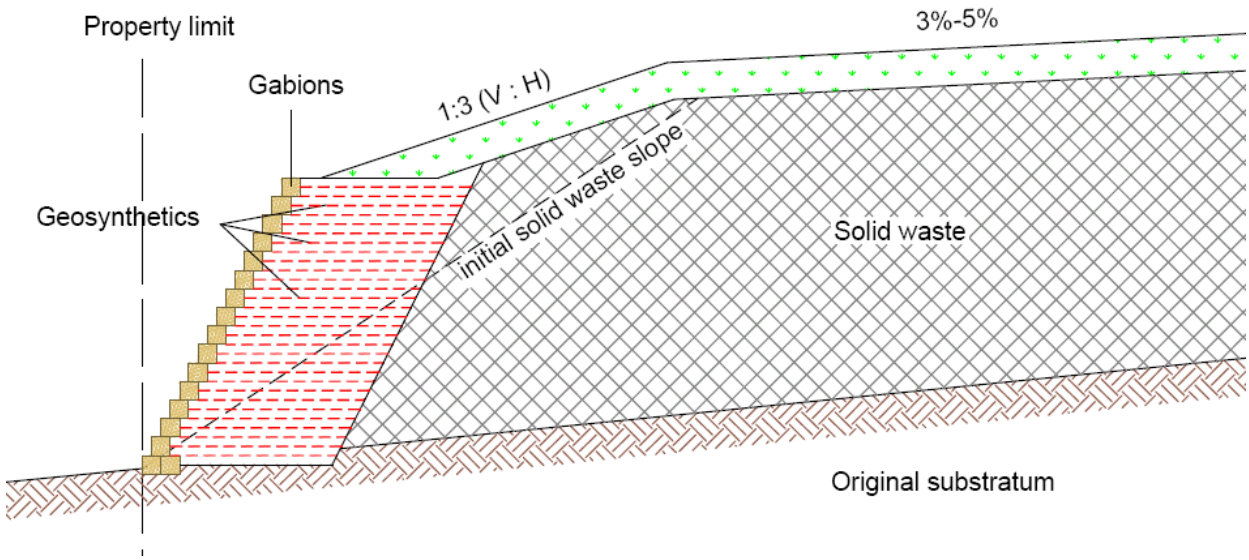


Figure 3. Final closure of an uncontrolled landfill with a downstream reinforced earth embankment.

APPLICATION OF THE METHOD – THE CASE OF SYROS LANDFILL

A case history, where all the aforementioned have been applied, is the Syros uncontrolled landfill, which is presented in the following paragraphs. Syros' uncontrolled landfill is located at the northeastern part of the island, adjacent to the sanitary landfill facilities (see figures 4a and 4b). A plan view of the sanitary landfill facilities along with the uncontrolled landfill is shown in figure 5, where the reinforced embankment's location is also marked.

Figure 4a. Syros island – Project location.

Figure 4b. Close up view of project location.

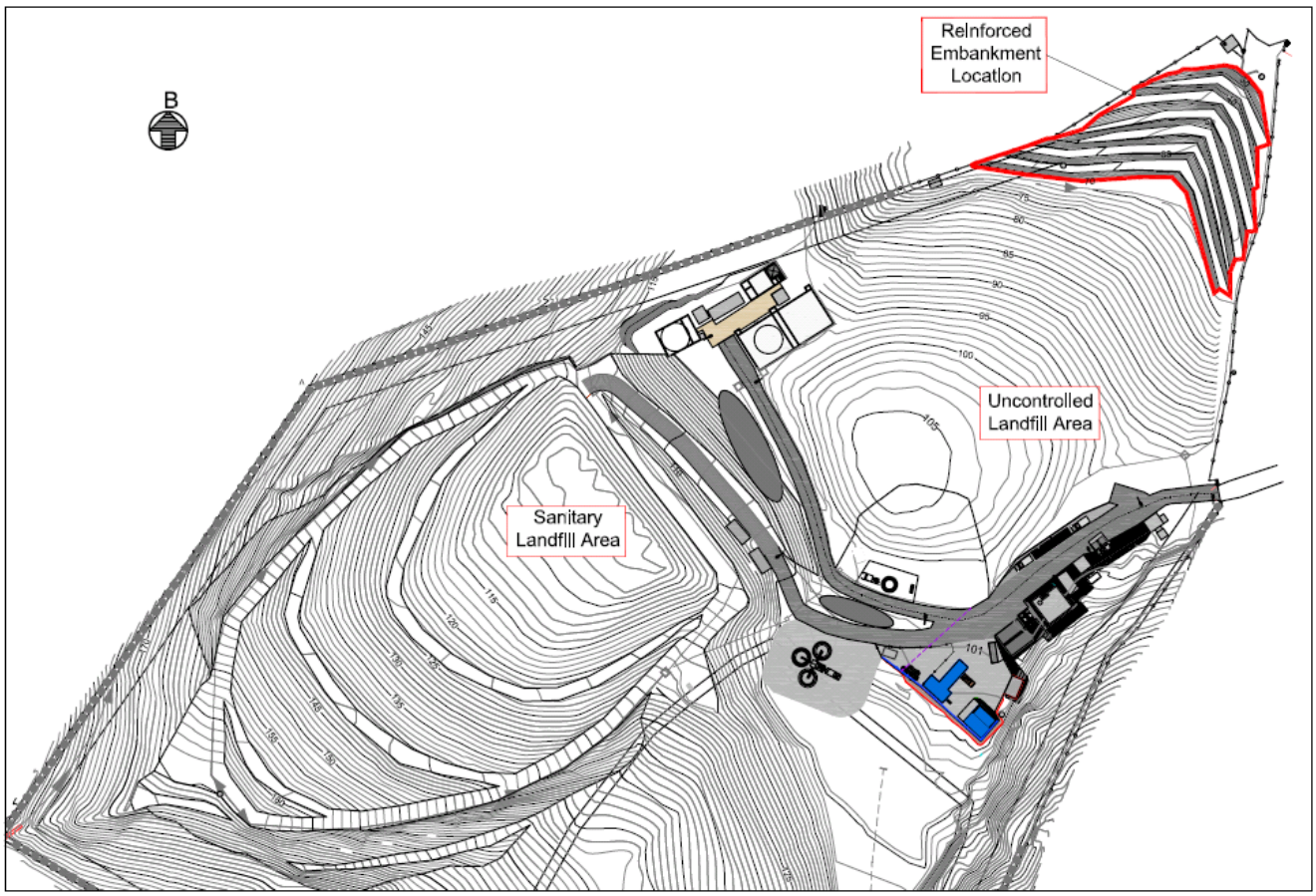


Figure 5. Plan view of sanitary landfill facilities, uncontrolled landfill and reinforced embankment.

Geometry

Within the framework of the detailed design of the project "Closure of Syros Landfill", the writers have carried out a geotechnical design (December 2007) regarding the regrading/reinforcement works of the downstream embankment of the landfill with the use of reinforced earth (see typical sections in Figures 6a and 6b).

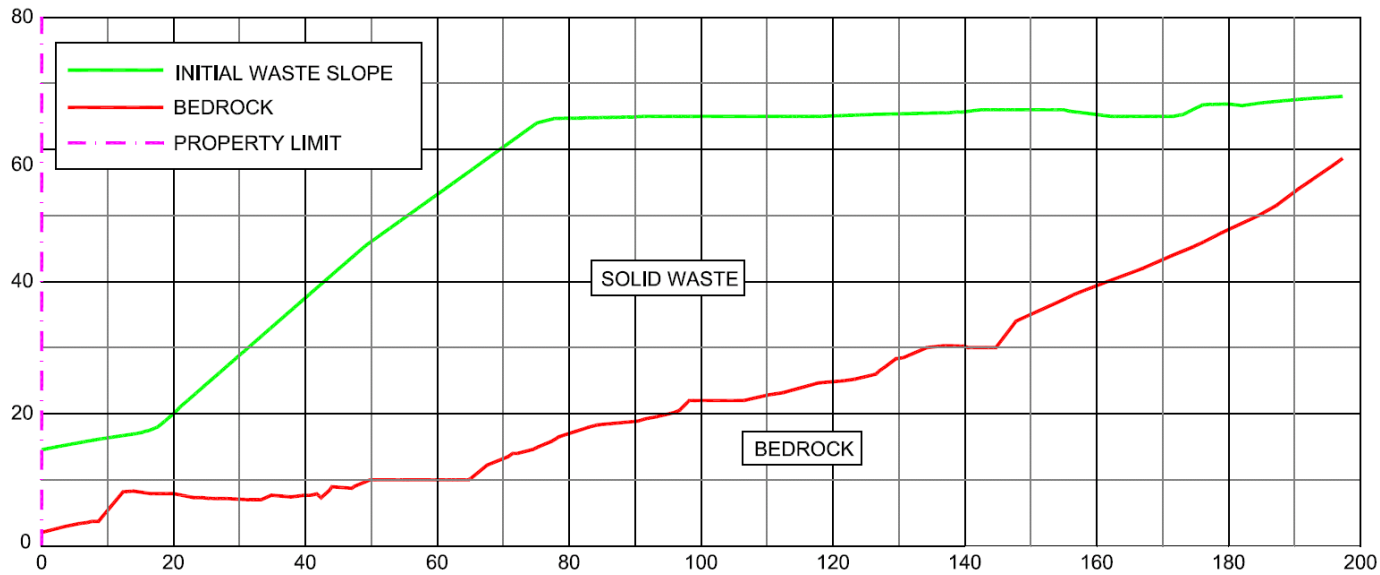


Figure 6a. Typical section of Syros uncontrolled landfill before closure.

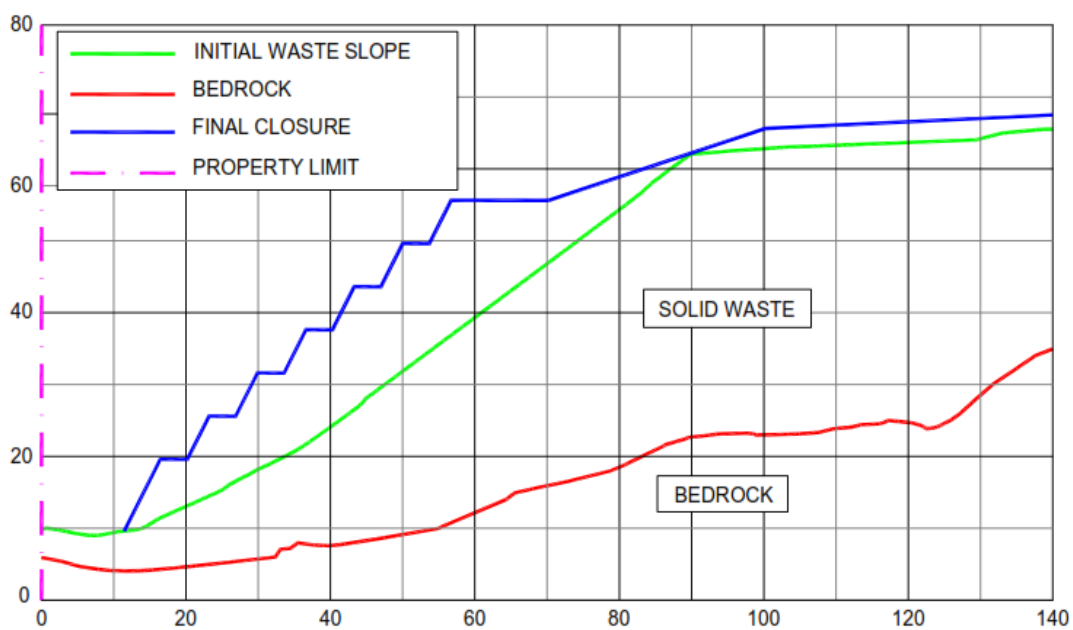


Figure 6b. Typical section of Syros landfill final closure.

The embankment had a maximum total height of 46 m and was graded with a 10.0 m high by 3.75 m wide lower bench and then up to its final height with six 6.0 m high by 3.70 m wide benches. Gabions 1.00x1.00x3.00 m were used as facing elements, placed in such a way as to obtain an average inclination of 2:1 (V:H). Geogrids were used as reinforcement, spaced at 0.25-0.50 m vertically, with an inwards inclination of 1:10 (V:H - see figure 7).

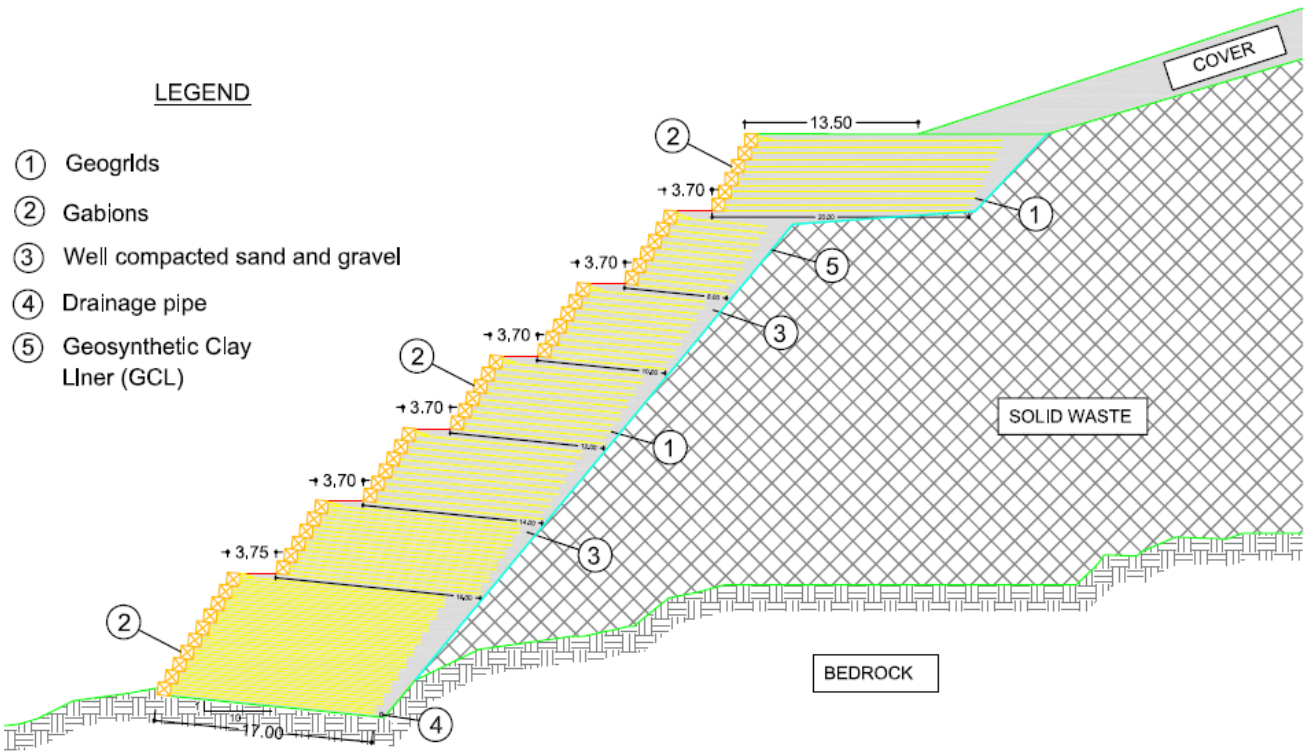


Figure 7. Typical section of Syros landfill final closure with the use of reinforced earth.

Design Parameters - Materials

The design parameters that were adopted in the geotechnical calculations are presented in Table 1 and were selected taking into account the following:

- Based on a geotechnical investigation carried out in the wider area of the landfill, the bedrock consists mainly of marbles and schists (the design parameters that have been used for the bedrock were in Demiris (2003).

- The reinforced soil consisted mainly of silty to clayey sand and gravel, a material that originated from the excavation of the bedrock at the site (mainly schists). Based on laboratory test results, the fines content ranged between 30-50% while the coarse material content ranged between 50-70%. The average values of the liquid limit and the plasticity index were LL ≈ 30% and PI ≈ 10%. No shear strength tests were carried out on this material and the design parameters used were based on literature and shear strength tests carried out in-house on other similar materials.

- The main bulk of the waste was domestic waste, including a low percentage of construction/demolition materials. The design parameters for the waste were based on the literature (Landva and Clark, 1992).

The length of the reinforcement (geogrids) varied between 7.00÷19.00 m and they were placed at a spacing of 0.25÷0.50 m. The ultimate tensile strength of the geogrids (T_{ult}) varied between 50-150 kN/m (in the main reinforcement direction). This variation in terms of length, strength and arrangement of the geogrids was dictated, in this particular case, by the global slope stability analyses as shown in the example figures of the analyses results subsequently (Figures 9 & 10).

The gabions were fabricated from steel wire, galvanised with a zinc/aluminium alloy and were filled with stones. They also had diaphragms every 1.00 m of gabion length and their cross section was 1.00x1.00 m. On the back of the gabions a nonwoven filter geotextile weighing at least 100 gr/m^2 was attached. The geotextile also covered half-width of the top of the gabion, in order to prevent the sand of the reinforced fill from infiltrating into the gabion (as shown in Figure 8). The flow rate of the non woven geotextile was specified to at least 65 l/m^2/s with an opening size of O_{90} = 75 – 100 μm.

Table 1. Material design parameters.

Material	Bulk unit weight γ (kN/m^3)	Friction angle φ (°)	Cohesion c (kPa)
Bedrock	25	24	200
Reinforced soil	20	35	2
Waste	8	25	10

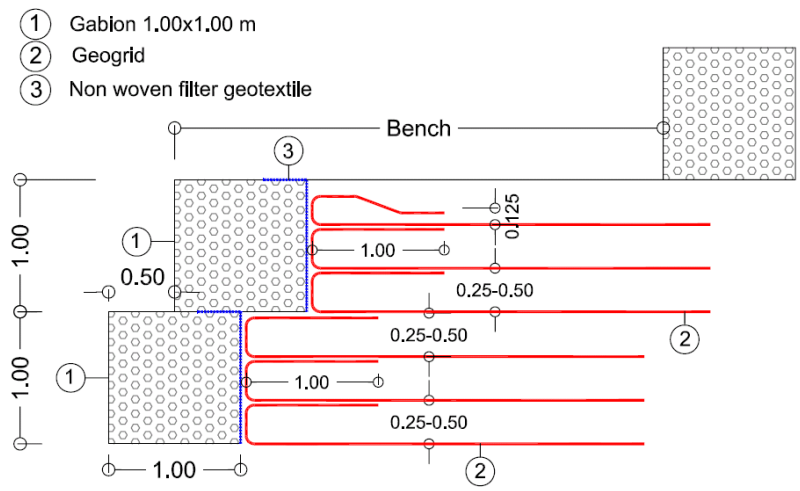


Figure 8. Reinforced earth gabion and geogrid details.

At the lower point of the base of the reinforced embankment, a drainage pipe was placed. The pipe was wrapped around with a nonwoven filter geotextile and was perforated at the upper 2/3 of its perimeter. The strength of the pipe was designed to carry the overburden pressure of at least 30 m of earthfill. In addition, GCL was placed at the interface between waste and reinforced embankment in order to prevent leakage of leachate through the granular reinforced earth, supplemented by a leachate collection pipe at the toe of the solid waste slope.

Method of analysis – Results

The reinforced embankment design involved general slope stability analyses of the final geometry of the landfill, under static and seismic conditions (as shown in Figures 9 and 10), along with analyses of the reinforced embankment regarding ground bearing capacity, eccentricity, overturning, reinforcement pull-out resistance, direct sliding and long term geogrid strength.

The slope stability analyses under seismic loading were carried out according to E.A.K.-2000 (Greek Seismic Code) for α = 0.16g (seismic coefficient of the project area - zone I) assuming:

- horizontal design seismic coefficient equal to $\alpha_h = \alpha/2 = 0.16/2 = 0.08$ and
- vertical design seismic coefficient equal to $\alpha_v = \pm\alpha_h/2 = \pm 0.08/2 = \pm 0.04$.

The calculated factor of safety (FS) in each analysis was compared with the minimum allowable value (except for the eccentricity e/d that was compared with the maximum allowable value) imposed by national and international regulations, such as DIN 4017 (bearing capacity in static conditions ≥ 2.0), DIN 1054 (direct sliding ≥ 1.5, overturning ≥ 1.5, eccentricity ≤ 0.167), Guidelines for Conducting Reinforced Embankment Road Works Designs (O.S.M.O.E.E.O.) (pull-out resistance ≥ 1.5), EC-7 (slope stability analysis ≥ 1.38) and Greek Seismic Code (E.A.K.-2000) (FS ≥ 1.0 for all cases and e/d ≤ 0.333).

As mentioned earlier, the length, strength and arrangement of the geogrids was dictated, in this particular case, by global stability rather than by the reinforced earth design. More specifically, a parametric analysis was carried out, in which the length (L), strength (T_{ult}) and density (s) of the geogrids was varied in order to determine the optimum ones in terms of cost and constructability. The results of this parametric study are summarized in Table 2. It is observed that, in order to achieve an acceptable factor of safety against global stability, one would either have to extend all the geogrids far back, so that as many as possible are intersected by the critical failure surface, or increase their number and strength, in order to increase their overall contribution to the resisting forces. The first option (i.e. increasing their overall length) would require extensive excavation of the waste at the lower part of the waste pile, which was unfavorable in terms of constructability and health and safety. The second option (i.e., increasing their number and strength instead of their length) would lead to an excessive geogrid cost (approximately 4 times higher than the base case). Instead, by using:

(a) longer geogrids at the upper part of the reinforced earth (where only filling takes place and no waste excavation is required),

(b) stronger and in denser arrangement geogrids at the lower part of the reinforced earth and

(c) shorter and weaker geogrids in between,

resulted in:

(a) "pushing" the critical failure surface further back; and

(b) forcing the critical failure surface to daylight higher than the toe of the reinforced earth;

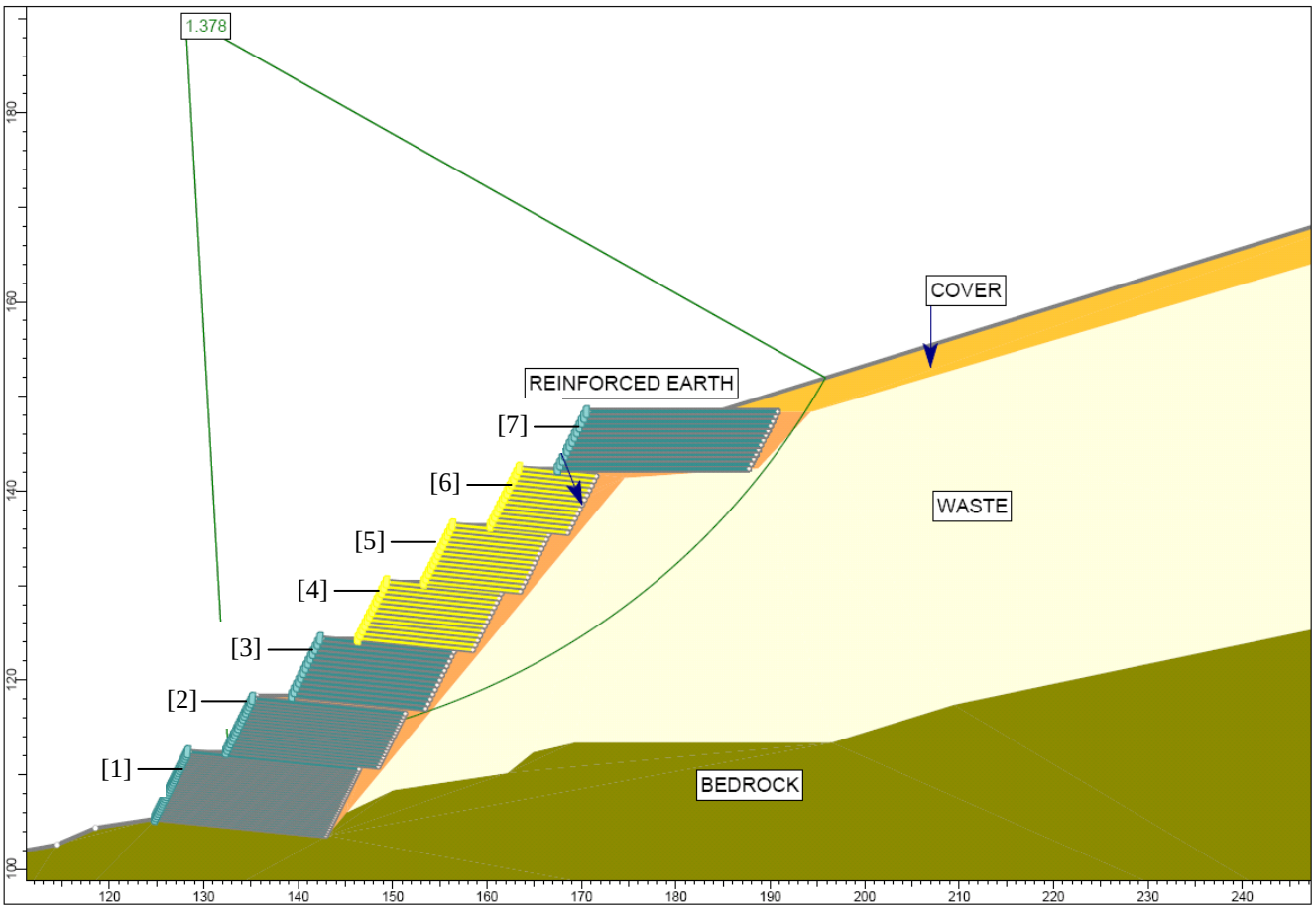
thus increasing the calculated overall factor of safety. This way, a balanced utilization of length, strength and density of geogrids led to lower cost and minimum excavation of waste.

Table 2. Summary of results of parametric global stability analyses.

Bench	L (m) / s (m) / T_{ult120} (kN/m) (*)			
	Case 1	Case 2	Case 3	Case 4 (Base case)
1st	15.00 / 0.20 / 300	25.00 / 0.50 / 100	15.00 / 0.25 / 150	17.00 / 0.25 / 75
2nd	15.00 / 0.20 / 300	25.00 / 0.50 / 100	15.00 / 0.25 / 150	16.00 / 0.33 / 75
3rd	15.00 / 0.20 / 300	25.00 / 0.50 / 100	15.00 / 0.25 / 150	14.00 / 0.50 / 75
4th	15.00 / 0.20 / 300	25.00 / 0.50 / 100	15.00 / 0.25 / 150	12.00 / 0.50 / 25
5th	15.00 / 0.20 / 300	25.00 / 0.50 / 100	15.00 / 0.25 / 150	10.00 / 0.50 / 25
6th	15.00 / 0.20 / 300	25.00 / 0.50 / 100	15.00 / 0.25 / 150	8.00 / 0.50 / 25
7th	15.00 / 0.20 / 300	25.00 / 0.50 / 100	25.00 / 0.25 / 150	20.00 / 0.50 / 75
FS (**)	1.371	1.377	1.379	1.377
RC (***)	399%	162%	250%	100%
Remarks	-	Difficult construction	-	Applied case

(*) L = Geogrid length / s = Distance between geogrids / T_{ult120} = Geogrid design tensile strength @ 120 years.
(**) FS = Minimum factor of safety under static loading
(***) RC = Relative cost compared to the base case

In Tables 3 and 4, the factors of safety for static and seismic loading conditions with the adopted length, strength and arrangement of the geogrids (case 4) are summarized. It is observed that the critical aspect of the design is the global stability rather than the design of the reinforced earth itself (as evidenced by the very high factors of safety in Table 3).



LEGEND

[1] Geogrids 17.00 m long, spaced vertically every 0.25 m, with long term design strenght T_{ult120} = 75 kN/m
[2] Geogrids 16.00 m long, spaced vertically every 0.33 m, with long term design strenght T_{ult120} = 75 kN/m
[3] Geogrids 14.00 m long, spaced vertically every 0.50 m, with long term design strenght T_{ult120} = 75 kN/m
[4] Geogrids 12.00 m long, spaced vertically every 0.50 m, with long term design strenght T_{ult120} = 25 kN/m
[5] Geogrids 10.00 m long, spaced vertically every 0.50 m, with long term design strenght T_{ult120} = 25 kN/m
[6] Geogrids 8.00 m long, spaced vertically every 0.50 m, with long term design strenght T_{ult120} = 25 kN/m
[7] Geogrids 20.00 m long, spaced vertically every 0.50 m, with long term design strenght T_{ult120} = 75 kN/m

Figure 9. Global stability analysis results (static conditions).

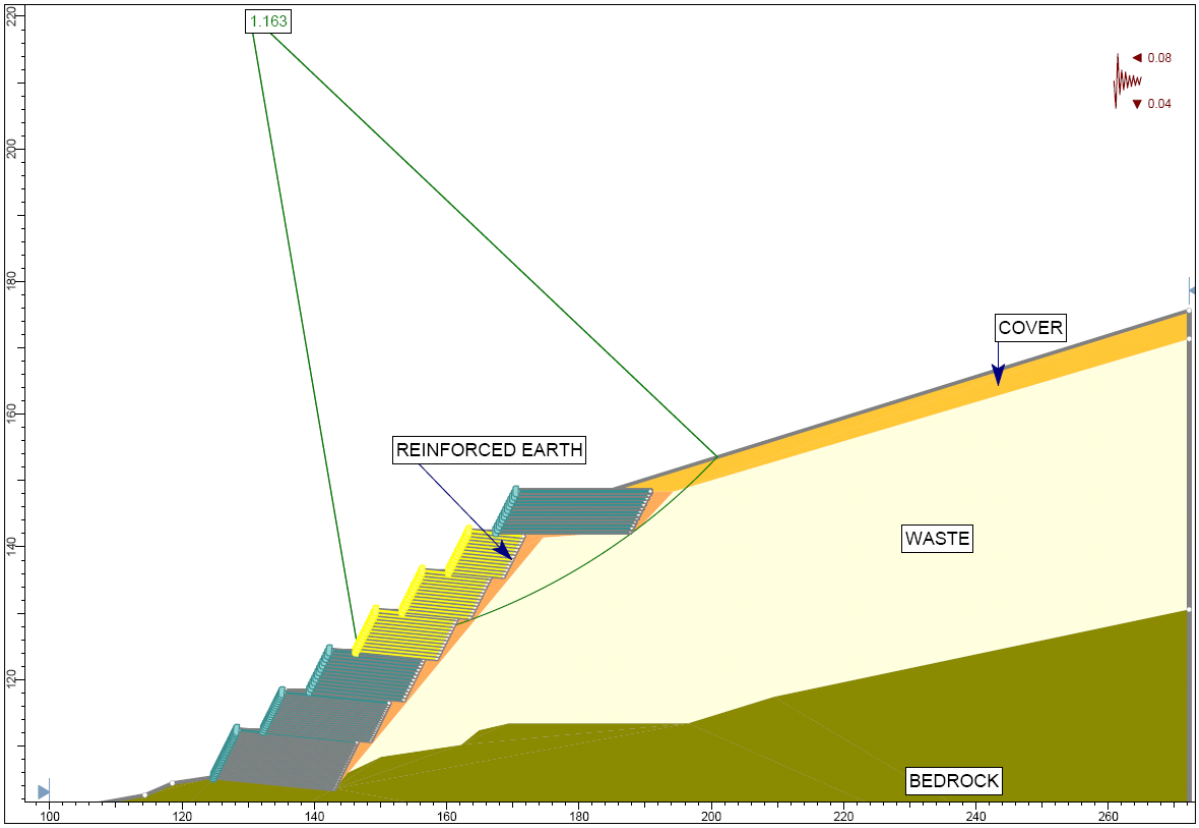


Figure 10. Global stability analysis results (seismic loading conditions).

Table 3. Reinforced earth analysis results.

Bench	Max eccentricity	Factor of safety (*)			
		Bearing capacity	Direct sliding	Overturning	Pullout resistance
1st	-0.026 / -0.022	73.2 / 74.5	36.45 / 14.84	261.1 / 88.5	196.8 / 42.3
2nd	-0.056 / -0.024	27.0 / 31.0	11.48 / 4.81	31.9 / 11.4	60.7 / 14.5
3rd	-0.054 / -0.037	31.5 / 34.1	10.95 / 5.66	31.3 / 15.9	112.4 / 41.7
4th	-0.051 / -0.039	37.4 / 39.3	11.70 / 6.55	44.5 / 23.4	144.0 / 59.1
5th	-0.044 / -0.037	43.9 / 45.4	11.85 / 7.17	43.4 / 26.4	177.3 / 80.4
6th	-0.049 / -0.043	47.7 / 48.9	14.72 / 8.78	62.0 / 37.9	316.7 / 150.0
7th	-0.050 / -0.035	33.4 / 35.7	11.28 / 5.97	33.2 / 17.5	304.2 / 97.7

(*) Factor of safety - The first value refers to static loading and the second to seismic loading conditions.

Table 4. Global Stability Analysis Results.

Type of surface	Analysis method	Conditions	Factor of safety*
Circular	Bishop simplified	Static	1.38
		Seismic	1.16 > 1.00

* Minimum allowable factor of safety: Static conditions: FS_{min} = 1.38 (EC-7 National Annex), Seismic conditions: FS_{min} = 1.00 (Greek Seismic Code - EAK 2000).

CONCLUSIONS – FINAL COMMENTS

The incorporation of a reinforced earth embankment in the downstream face of a landfill to increase the capacity of the landfill and avoid excessive waste excavation for final grading of the closure slopes is presented. As an example of the use of this method, the case of the Syros island uncontrolled landfill final closure has been presented. This particular project commenced in 2008 and was successfully completed in 2010. In Figures 11-14 some characteristic photos from the construction of the reinforced embankment as well as of the final closure are presented. It is observed that by properly applying the reinforced earth method it became possible to:

- design the final closure of the landfill into the available property limits,
- avoid extensive excavations and transportation of solid waste and
- construct an environmentally friendly structure by using local materials.

Other similar cases that the proposed method has been successfully applied by the Authors for the final closure of landfills in Greece are:

- Uncontrolled landfill of North Corfu island (reinforced embankment 10 m high – completed in 2008)
- Uncontrolled landfill of Paxoi island (reinforced embankment 15 m high – under construction)
- Uncontrolled landfill of South Rhodes island (reinforced embankment 8 m high – under construction)

Figure 11. Syros landfill before final closure.

Figure 12. Construction of reinforced earth during landfill final closure.

Figure 13. View of Syros uncontrolled landfill after final closure.

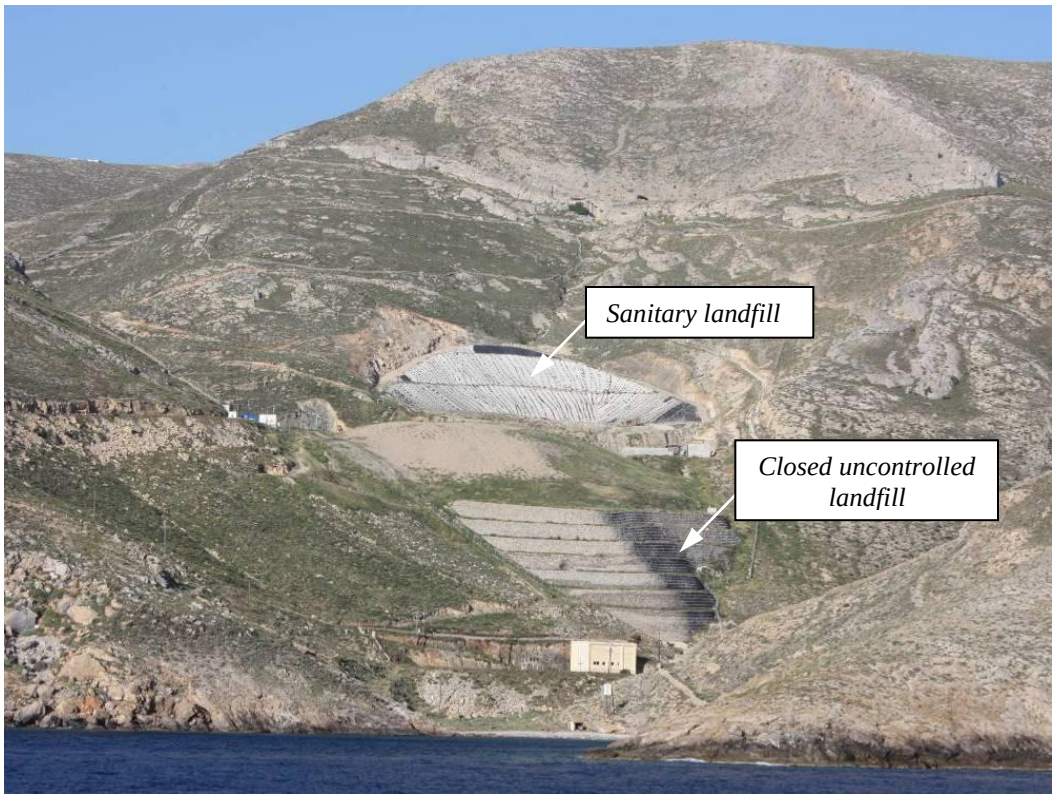


Figure 14. General view of Syros uncontrolled landfill and the surrounding area after final closure.

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