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Appendix A4.3 Capping and Waste Slope Stability Assessment

Technical Note

Merrion House
Merrion Road
D4 Dublin
Ireland
T +353 1 269 5666

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1. Introduction

1.1 Purpose of this Technical Note

This Technical Note covers the initial, generic design analyses to support planning and waste licence applications, completed for optional configurations of multilayer capping systems for the steep perimeter slopes of the Kerdiffstown Landfill. This initial work provides factor of safety output for various optional design configurations and material combinations. In addition, initial slope stability assessments have been completed for the steep waste slopes on the northern perimeter of the site, following proposed trimming, for waste placement in lined Zone 3 and for temporary waste slopes which may be formed during the earthworks phase of the proposed remediation works. The results have informed the development of the pre-settlement surface profile of the site and have informed the subsequent selection of the preferred option for the multilayer capping system, which is further discussed separately in this report.

Overall waste mass stability is rarely an issue in waste slopes of modest gradient in a correctly designed and permitted landfill. However, for steep, high perimeter slopes of a land-raise landfill that are expected to have been placed in an uncontrolled manner, overall waste mass stability should be analysed, as it is likely that the slopes were never the subject of analytical design. Therefore, in anticipation of remedial construction works, overall waste mass stability analyses for the proposed, trimmed steep perimeter slopes has been undertaken. In addition, as indicated above, waste slope stability analyses have been completed for waste placement in lined Zone 3 and for temporary waste slopes which may be formed during the earthworks phase of the proposed remediation works.

1.2 The Potential Need for Capping the Surfaces of the Landfilled Waste

The Kerdiffstown Landfill site is the subject of a numerical, probabilistic hydrogeological risk assessment which has investigated the degree of risk of groundwater receptors to groundwater contamination resulting from infiltrating rainwater and surface water percolating through the placed waste and creating leachate in this largely unlined landfill site. This assessment has examined the present state of the landfill and has been run to assess the effects of proposed mitigation and capping measures. The provision of an efficient, robust capping system always has a beneficial impact on the mitigation of potential groundwater contamination in cases such as this.

1.3 The Presently Preferred Option for the Multilayer Capping System

A range of configurations and materials were considered at the commencement of this stage of multilayer capping system design analysis. Subsequently, the requirements for restoration soils were refined and a double textured, high density polyethylene (HDPE) flexible membrane “liner” (FML) has been selected as the preferred option for the low permeability element of the capping system. This option is one of those analysed in the initial stages of the development of capping system.

1.4 The Need for a Multilayer Capping System for the Steep Perimeter Slopes

Significant lengths of perimeter slopes of the Kerdiffstown Landfill are steep and high. Although some re-grading to achieve a reduction in slope gradient is proposed, gradients will be comparatively steep in the context of multilayer capping systems.

Conventional low permeability mineral capping systems are potentially the least stable and most difficult to construct on steep perimeter waste slopes. Furthermore, suitable low permeability material may not be readily available for the capping works. Multilayer capping systems which use geosynthetic clay lining elements (GCL) or linear low density polyethylene (LLDPE), medium density polyethylene (MDPE) or high density polyethylene (HDPE) flexible membrane “liners” (FMLs) as the low permeability capping element, are more practical than a mineral element in terms of ease of placement and construction and level of performance for a steep slope. Nevertheless, informed, careful numerical design analysis and a high standard of construction by experienced operatives are essential for successful completion of a suitable, effective and durable multilayer capping system.

1.5 Restrictions

This work has been undertaken in advance of completion of the additional ground investigation (GI) being undertaken for the site remediation works, thus review and checking of the analyses will be necessary following receipt and interpretation of the final GI data.

Following confirmation of the proposed capping material sources it will be necessary to undertake laboratory testing to determine the material properties of the mineral regulating layer and proposed restoration soils, together with large shear box testing to confirm the interface friction and adhesion properties for each interface between the chosen components of the multilayer capping system. At this detail design stage, capping stability checks will require re-running to demonstrate acceptability.

2. Multilayer Capping System Design and Construction Issues

2.1 Design Issues

In very general terms, for waste slopes with a gradient of 1 in 3 or shallower, multilayer capping stability problems are unlikely in a correctly designed capping system. For gradients steeper than 1 in 3, multilayer capping instability is more likely to be an issue. Therefore, for all sloping capping systems it is advisable to carry out multilayer lining stability analyses.

Multilayer capping system stability analyses must determine the factor of safety applying for each component at each stage of construction. For any design case where adequate factors of safety cannot be achieved for all capping system components, at all stages of construction, the addition of uniaxial geogrid reinforcement may be the means of achieving a satisfactory design. Although lower strength uniaxial geogrid reinforcement can raise the factor of safety when the shortfall is small, the required tensile capacity rapidly increases, as the initially analysed shortfall in factor of safety increases with increasing slope gradient and / or slope height.

The rated ultimate tensile strength of any given uniaxial geogrid is not that which can be taken for use in multilayer lining systems. The appropriate strain limited value should be taken. In most if not all cases, this will have to be the value applying at 2% strain to limit the movement which could be transmitted to, for instance, an HDPE FML and induce adverse tensile forces. The 2% strain value may be as little as 22% of the ultimate tensile value of a geogrid. These issues have cost implications for the provision of geogrid reinforcement.

For slopes of the order of 1 in 3 gradient, often a single-textured HDPE FML is used, which is placed with the textured side downwards on a suitable protective sub-grade, such as fine to medium sand. The textured surface helps to keep the HDPE FML in place during construction and the future operation of the capping system. The subsequent placement of sub-soil and topsoil (over, for instance, a geotextile protection layer) is likely to be stable in this case on 1 in 3 slopes. However, the smooth upper surface of the mono-textured HDPE FML allows small initial movements in the overlying layers to take place without inducing tension in the HDPE FML. This is because the textured underside restrains the HDPE FML and the small transmitted forces from above are taken in shear by the HDPE FML, rather than in tension. HDPE FML is very strong in shear, but not in tension. This is because "environmental stress cracking" arising from surface abrasion and scratches caused during construction activities, can result in tensile failure at loads far below those applied in factory conformance testing of the virgin HDPE FML. The foregoing matters are carefully considered at the analytical design stage.

If steeper gradient slopes require capping, double-textured FML may be required to allow stable deployment at the construction stage of the overlying geotextile protection layer and the overlying soils. For such steeper slopes, it is likely that geogrid reinforcement will be required in the restoration soils, to minimise the tensile forces in the geosynthetic components and to keep shear loads applied to the double-textured HDPE FML within reasonable bounds. Although HDPE has high strength in shear and double-textured HDPE FML in this configuration still acts in shear rather than in tension, any form of textured HDPE FML has lower tensile strength than smooth HDPE FML with the same sheet thickness. For this reason, textured HDPE FML is slightly more susceptible to environmental stress cracking than smooth sheet. Thus, the geogrid reinforcement must be designed to prevent tensile forces developing in the HDPE FML during construction and during its ongoing operation. Again, the foregoing matters are carefully considered at the analytical design stage.

Single-textured GCL is available and would normally be used in a sloping multilayer capping system with the textured side downwards on a suitable protective sub-grade, such as fine to medium sand. If single-textured GCL is used as the low permeability capping element, depending on its proprietary design there may be potential for hydrated bentonite to pass out of the surface of the host material during the ongoing operation of the lining system. This could have a considerable effect on the original interface friction and adhesion properties. For these preliminary, generic analyses, what are intended to be conservative parameters have been assumed. However, later, laboratory testing of the specific, preferred proprietary single-textured GCL in conjunction with those elements with which it will be in contact, must be carried out to determine material-specific interface friction and adhesion properties for final design purposes.

2.2 Construction Issues

The steeper and higher the waste slope; the greater are the multilayer capping system construction difficulties and construction safety issues.

For landfill capping slopes of 1 in 3 gradient or shallower, benches can often be omitted from the slope design, especially since ongoing waste settlement due to waste degradation processes reduces further the gradient over time. However, if capping slopes have to be steeper, benches become increasingly likely to be needed to achieve multilayer lining stability. This is due to slopes of lesser height benefitting more in terms of stability from the "toe support" achieved in the thicker capping system layers such as the restoration soils. Also, a benched slope of moderate inter-bench height makes it easier to achieve successful deployment and placement of the capping system components.

Very high capacity uniaxial geogrids may be unsuitable for deployment in a sloping multilayer capping system due to their potential to have difficulty in conforming to the change of gradient between the waste slope and intermediate benches. This may be an even greater problem in the case of geogrid deployment into "anchor" trenches; however, currently it is proposed that the geogrid in the 1 in 2.5 gradient capping system will be anchored by continuing back through the capping system of the shallower slopes for a few metres behind the crest of the steep slopes. This will be the subject of design analyses at the detail design stage.

One potential option to accommodate the need for high capacity geogrid would be to provide two layers of geogrid to achieve the same tensile resistance. However, with proposed subsoil thickness being only 350mm, this may make successful placement of the subsoils and geogrid a complex process on 1 in 2.5 gradient slopes.

3. Multilayer Capping System Design Method

The method of analysis employed for analysing multilayer lining stability is that of Giroud, J.P., Williams, N.D., Pelte, T., Beech, J.F. (1995) "Stability of geosynthetic-soil layered systems on slopes", *Geosynthetics International*, Vol 2, No 6, pp1115-1148. This is a recognised method which is comprehensive in terms of the cases which can be analysed and which is rigorous in its approach. It has been one of the preferred multilayer capping system analytical methods of the past two decades.

At this preliminary stage, the approach adopted has been to examine the global factor of safety achieved for each element of the multilayer lining system, at each stage of construction. This is an appropriate, robust, rapid means by which a large number of analyses can be completed in a reasonable time. As these capping systems are to form a part of permanent perimeter slopes, a global factor of safety of 1.3 has been considered appropriate.

At the detail design stage, analyses compliant with Eurocode 7 can be undertaken.

4. Configurations of the Multilayer Capping System for Assessment and Analytical Approach

4.1 Defined Slope Geometry

Presently proposed remediation contours and slope gradients (pre-settlement) are shown in the following drawings:

- Drawing 32EW5604-00-022 – Remediation Contours
- Drawing 32EW5604/051 – Remediation Slope Gradients

The critical slope to be capped occurs along the north-eastern boundary of Zone 1 with the following characteristics:

- Toe of slope ~ 85mAOD
- Break in slope (lower steep to upper shallow) ~ 105mAOD
- Maximum height of landfill ~ 115mAOD

The resulting approximate maximum waste slope heights are as follows:

- Lower steeper slope: ~20m
- Upper shallow slope: ~10m
- Overall height: ~30m

The following slope gradients have been examined for the capping of the perimeter waste slopes:

- 1 vertical : 3 horizontal
- 1 vertical : 2.5 horizontal
- 1 vertical : 2 horizontal

The upper, shallow gradient, nominal 10 m high waste slopes require no separate multilayer capping system stability analysis at this stage, since the 1 in 3 slope analyses for the perimeter slopes can be considered indicative of the design case for the shallower 10m high slopes.

4.2 Capping System Configurations Examined Initially

In summary, the capping system configuration and components considered for each of the slope gradients are as follows:

<u>HDPE Options</u>

- Top soil 0.15m / Subsoil 0.35m / Geotextile Protection / HDPE / Regulating Layer / Waste
- Top soil 0.15m / Subsoil 0.85m / Geotextile Protection / HDPE / Regulating Layer / Waste
- Top soil 0.15m / Subsoil 0.35m / Geodrain / HDPE / Regulating Layer / Waste
- Top soil 0.15m / Subsoil 0.85m / Geodrain / HDPE / Regulating Layer / Waste

GCL Options

- Top soil 0.15m / Subsoil 0.35m / Geotextile Protection / GCL / Regulating Layer / Waste
- Top soil 0.15m / Subsoil 0.85m / Geotextile Protection / GCL / Regulating Layer / Waste
- Top soil 0.15m / Subsoil 0.35m / Geodrain / GCL / Regulating Layer / Waste
- Top soil 0.15m / Subsoil 0.85m / Geodrain / GCL / Regulating Layer / Waste

The above definitions of system configuration cover total restoration soil thicknesses of 0.5m and 1.0m. For the restoration soil parameters, typical mean values have been applied for the topsoil and subsoil together, but for restoration soil interface friction and adhesion, values appropriate for angular, gravelly subsoil have been applied.

4.3 Inclusion of Benches

As is demonstrated later by the results of the multilayer capping system stability analyses for a number of cases, for 1m restoration soils and 1v in 2h gradient slopes, continuous 20m high slopes are generally inappropriate, as excessive and impractical geogrid reinforcement would be required to render the multilayer capping system stable. Therefore, additional cases have been examined with intermediate benches forming one third height slopes of 6.7m. Other options can be considered at any later stage, if necessary.

4.4 Additional Description of Components Considered for the Multilayer Capping System

For all cases, as part of the multilayer lining system construction, an angular fine to medium sand regulating layer is placed above the landfilled waste of the perimeter slopes. Potentially, this form of regulating layer achieves the best interface parameter values and provides the overlying low permeability element adequate protection from the underlying waste.

For the basic double-textured HDPE and single-textured GCL cases, a protective non-woven geotextile layer has been included above each. These cases also cover the situations where a geosynthetic drainage layer is provided beneath the restoration subsoil, where the drainage layer design has outer layers of non-woven geotextile over a space-making geosynthetic component to carry the majority of the drainage flow.

The alternative cases for inclusion of a geosynthetic drainage layer beneath the restoration soils has been examined for a design which has outer layers of woven geotextile over a space-making geosynthetic component to carry the majority of drainage flow.

Where appropriate, the need for and capacity of geogrid reinforcement has been examined for the cases defined above.

4.5 The Range of Analyses

To examine sensitivity to variations in material parameters, two sets of parameters have been applied in the analyses. These are termed “best case parameter values” and “typical parameter values”. In the case of interface friction and adhesion properties, the best case parameters are based on the mean results obtained by laboratory testing for typical materials, reported in:

- UK Environment Agency R&D Technical Report P1-385/TR2, January 2003; and
- Lopes *et al.* (2001).

The corresponding “typical parameters” are a slightly more conservative set to include, at this stage, a nominal degree of conservatism. It should be noted that the analytical design method considers the theoretical toe buttressing effect in all components, but this is only truly significant in the thicker components such as the restoration soils. Other than unit weight, and other than in the case of toe buttressing in the regulating layer and in the restoration soils, the remaining material properties of each component have little bearing on the calculations of multi-layer lining stability, but they help inform the selection of interface friction and adhesion values.

Therefore, to cover the combination of cases described above in Sections 4.1 to 4.3, approximately 130 generic, multilayer capping design analyses have been completed. The results informed the development of the pre-settlement surface profile of the site and the later selection of the “preferred” form of the multilayer capping system. The presently “preferred” configuration for the multilayer capping system is covered in Section 7.

5. Material Parameters

The approach to the selection of material parameters has been described above in Section 4.5.

Although it is intended that representative values for the design parameter values have been selected from published data, the material parameters and interface parameters are very dependent on the specific mineral materials and proprietary geosynthetic materials which will be finally chosen. Therefore, for completion of the final detail design, it will be necessary to undertake laboratory testing to determine the material properties of the mineral regulating layer and proposed restoration soils, together with large shear box testing to confirm the interface friction and adhesion properties for each interface between the chosen components of the multilayer lining system.

In Tables 1 to 8, the first item shown is the first component placed in construction and so on down the first part of the table to the last item placed. In the second part of each table, Interface 1 is that between the subgrade and the first component placed, Interface 2 is between the first and second components placed, Interface 3 is between the second and third components placed and Interface 4 is between the third and fourth components placed.

For the restoration soil parameters, mean values have been applied for the topsoil and sub soil together, but for restoration soil interface friction and adhesion, values appropriate for an angular, gravelly subsoil have been applied. The parameters for the principal cases examined are tabulated below.

	Unit Weight kN/m²	Internal Friction degrees	Cohesion, c' kN/m²	Thickness m
Angular sand regulating layer	19	26	0	0.3
Double-textured HDPE	9.22	30	5	0.008
Prot. non-woven geotextile/drain	1.22	24	0	0.01
Topsoil and subsoil (mean values)	17.5	23	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	24	0
Interface 2	24	3
Interface 3	24	3
Interface 4	24	0

Table 1: "Typical Parameters" for HDPE Case with Protective Geotextile and for HDPE Case with Non-woven Outer Geotextile Components for the Geosynthetic Drainage Layer

	Unit Weight kN/m²	Internal Friction degrees	Cohesion, c' kN/m²	Thickness m
Angular sand regulating layer	19	28	0	0.3
Double-textured HDPE	9.22	30	5	0.008
Prot. non-woven geotextile/drain	1.22	26	0	0.01
Topsoil and subsoil (mean values)	17.5	25	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	26	0
Interface 2	25	4
Interface 3	25	4
Interface 4	26	0

Table 2: "Best Case Parameters" for HDPE Case with Protective Geotextile and for HDPE Case with Non-woven Outer Geotextile Components for the Geosynthetic Drainage Layer

	Unit Weight kN/m²	Internal Friction degrees	Cohesion, c' kN/m²	Thickness m
Angular sand regulating layer	19	26	0	0.3
Single-textured GCL	9.22	26	2	0.01
Prot. non-woven geotextile/drain	1.22	24	0	0.01
Topsoil and subsoil (mean values)	17.5	23	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	24	0
Interface 2	23	0
Interface 3	13	1
Interface 4	24	0

Table 3: "Typical Parameters" for Single-textured GCL Case with Protective Geotextile and for Single-textured GCL Case with Non-woven Outer Geotextile Components for the Geosynthetic Drainage Layer

	Unit Weight kN/m²	Internal Friction degrees	Cohesion, c' kN/m²	Thickness m
Angular sand regulating layer	19	28	0	0.3
Single-textured GCL	9.22	26	2	0.01
Prot. non-woven geotextile/drain	1.22	26	0	0.01
Topsoil and subsoil (mean values)	17.5	25	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	26	0
Interface 2	25	0
Interface 3	13	2
Interface 4	26	0

Table 4: "Best Case Parameters" for Single-textured GCL Case with Protective Geotextile and for Single-textured GCL Case with Non-woven Outer Geotextile Components for the Geosynthetic Drainage Layer

	Unit Weight kN/m^2	Internal Friction degrees	Cohesion, c' kN/m^2	Thickness m
Angular sand regulating layer	19	26	0	0.3
Double-textured HDPE	9.22	30	5	0.008
Protective woven geotextile drain	1.22	24	0	0.01
Topsoil and subsoil (mean values)	17.5	23	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	24	0
Interface 2	24	3
Interface 3	10	2
Interface 4	26	0

Table 5: "Typical Parameters" for HDPE Case with Woven Outer Geotextile Components for the Geosynthetic Drainage Layer

	Unit Weight kN/m^2	Internal Friction degrees	Cohesion, c' kN/m^2	Thickness m
Angular sand regulating layer	19	28	0	0.3
Double-textured HDPE	9.22	30	10	0.008
Protective woven geotextile drain	1.22	26	0	0.01
Topsoil and subsoil (mean values)	17.5	25	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	26	0
Interface 2	25	4
Interface 3	11	3
Interface 4	28	0

Table 6: "Best Case Parameters" for HDPE Case with Woven Outer Geotextile Components for the Geosynthetic Drainage Layer

	Unit Weight kN/m^2	Internal Friction degrees	Cohesion, c' kN/m^2	Thickness m
Angular sand regulating layer	19	26	0	0.3
Single-textured GCL	9.22	26	2	0.01
Protective woven geotextile drain	1.22	24	0	0.01
Topsoil and subsoil (mean values)	17.5	23	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	24	0
Interface 2	23	0
Interface 3	13	1
Interface 4	26	0

Table 7: "Typical Parameters" for Single-textured GCL Case with Woven Outer Geotextile Components for the Geosynthetic Drainage Layer

	Unit Weight kN/m^2	Internal Friction degrees	Cohesion, c' kN/m^2	Thickness m
Angular sand regulating layer	19	28	0	0.3
Single-textured GCL	9.22	26	2	0.01
Protective woven geotextile drain	1.22	26	0	0.01
Topsoil and subsoil (mean values)	17.5	25	0	Either 0.5 or 1.0 as applicable to case analysed

	Interface Friction	Interface Adhesion
Interface 1	26	0
Interface 2	25	0
Interface 3	13	2
Interface 4	28	0

Table 8: "Best Case Parameters" for Single-textured GCL Case with Woven Outer Geotextile Components for the Geosynthetic Drainage Layer

6. Factor of Safety Considerations and Summary of Results of the Initial, Generic Multilayer Capping System Design Analyses

6.1 Reporting of Results

6.1.1 Presentation of results

The detailed model output for each separate analysis comprises the factors of safety for each capping system component at each stage of construction. Since 155 generic analyses have been completed to cover the alternative configurations and components of the cases defined above in Sections 4.1 to 4.4, the results obtained are summarised below in a simplified form in Tables 9, 10, 11 and 12, rather than 155 separate comprehensive result tables being presented for each case analysed.

6.1.2 Factors of safety for construction stage and permanent works

For any configuration to be considered a stable design, a factor of safety of 1.3 must apply for each component at the end of construction. At intermediate stages of construction a minimum factor of safety of 1.2 can apply, provided that the inclusion of geogrid in the restoration soil layer will be sufficient to bring all components in the capping system to a factor of safety of 1.3. The abovementioned factor of safety of 1.2 is normally the minimum which can apply for temporary slopes. In some specific cases, a factor of safety of a little below 1 in 2 may be acceptable, depending on the analysed effect of the placement of the overlying component or components on the factors of safety of the previously placed component or components. At the detail design stage, analyses of downslope braking forces and upslope acceleration forces also must be carried out if mechanical plant will be used at any stage of sloping multilayer capping system construction.

6.1.3 Construction stage factors of safety for GCL interfaces

In many of the initial, generic multilayer capping system analyses presented in this report where GCL is used in the capping system, the consideration of factors of safety in the construction stage is a “special case”. This is because, as explained in Section 2.1, depending on the proprietary GCL component design, there may be potential for hydrated bentonite to pass out of the surface of the host material during the ongoing operation of the capping system. This could have a considerable effect on the original interface friction and adhesion properties. For these preliminary, generic analyses, what are intended to be conservative parameters have been assumed. However, in an un-hydrated state in the construction stage, GCL will be stable in many of the analysed cases, but geogrid reinforcement will be needed to achieve the factor of safety for the ongoing operation of the capping system should the GCL have the potential to pass out of the host material following hydration.

Thus, later, laboratory testing of the specific, preferred GCL proprietary item, in conjunction with those elements with which it will be in contact, must be carried out to determine whether or not following hydration, bentonite may pass out of the host material and to determine the material-specific interface friction and adhesion properties for final design purposes. Under the best circumstances, it is possible that in a number of GCL cases, the magnitude of the tensile strength of necessary geogrid reinforcement could be reduced from the values obtained in the preliminary analyses presented in this report.

6.2 HDPE Low Permeability Component Cases without a Geodrain below the Subsoil and HDPE Cases with a Geodrain with Non-woven Outer Components below the Subsoil

The overall results for HDPE low permeability component cases without a geodrain below the subsoil and for HDPE Cases with a geodrain with non-woven outer components below the subsoil are the same. This is because in the first category, the protection layer above the HDPE is a non-woven geotextile which has the same interface properties as those of a geodrain with non-woven outer components.

The overall results of the analyses for the suitability of each option covered in this section are shown below in Table 9. However, firstly some general comments are made.

1 in 3 slopes

For all 1 in 3 waste slope capping system cases, with or without the provision of geodrain with non-woven geotextile face elements below the subsoil layer, a stable design can be achieved without the provision of geogrid reinforcement.

1 in 2.5 slopes

In all cases for the results reported in this section for the 1 in 2.5 slopes of 6.7m inter-bench height, the case with 1.0m restoration soil cover is more stable than the case with 0.5m restoration soil cover. This is because in these particular cases the increased mass of the restoration soils has a beneficial effect in the mobilisation of interface friction for the sand regulating layer and waste and for the restoration soils and the non-woven geotextile. A similar situation applies for the 1 in 2.5 slopes of 20m height, with the "best parameters" applying.

1 in 2 slopes

No practical, conventional solution can be developed for 1 in 2 multilayer capping system slopes based on the presently examined cases and presently applied soil material parameters, interface friction and adhesion parameters, together with the provision of geogrid reinforcement. If 1 in 2 slopes prove necessary for the perimeter waste slopes, special, non-standard multilayer capping approaches (which would not be acceptable for the design of a new landfill) may be capable of achieving a configuration which would be stable, but that is beyond the scope of this present study.

Material Parameters	Total restoration soil thickness m	Inter bench Slope Height m	Gradient	Without Geogrid	Geogrid Capacity if required and feasible kN/m (ultimate)
"Best"	0.5	6.7	1 in 3	✓	—
			1 in 2.5	✓	—
			1 in 2	x	x
		20	1 in 3	✓	—
			1 in 2.5	x	105
			1 in 2	x	x
	1.0	6.7	1 in 3	✓	—
			1 in 2.5	✓	—
			1 in 2	x	x
		20	1 in 3	✓	—
			1 in 2.5	x	x
			1 in 2	x	x
"Typical"	0.5	6.7	1 in 3	✓	—
			1 in 2.5	x	65
			1 in 2	x	x
		20	1 in 3	✓	—
			1 in 2.5	x	x
			1 in 2	x	x
	1.0	6.7	1 in 3	✓	—
			1 in 2.5	x	25
			1 in 2	x	x
		20	1 in 3	✓	—
			1 in 2.5	x	x
			1 in 2	x	x

Symbols:- ✓ case feasible without geogrid. — geogrid not required. x no practical, conventional solution can be developed

Table 9: Results of Analyses for HDPE Cases without a Geodrain and for HDPE Cases with a Geodrain with Non-Woven Outer Components

6.3 HDPE Low Permeability Component Cases with a Geodrain with Woven Outer Components below the Subsoil

The overall results of the analyses for the suitability of each option in the classes covered in this section are shown below in Table 10. However, firstly some general comments are made regarding 1 in 2 slopes.

1 in 2 slopes

No practical, conventional solution can be developed for 1 in 2 multilayer capping system slopes based on the presently examined cases and presently applied soil material parameters and interface friction and adhesion parameters together with the provision of geogrid reinforcement. If 1 in 2 slopes prove necessary for the perimeter waste slopes, special, non-standard multilayer capping approaches (which would not be acceptable for the design of a new landfill) may be capable of achieving a configuration which would be stable, but that is beyond the scope of this present study.

Material Parameters	Total restoration soil thickness m	Inter bench Slope Height m	Gradient	Without Geogrid	Geogrid Capacity if required and feasible kN/m (ultimate)
"Best"	0.5	6.7	1 in 3	✓	—
			1 in 2.5	✓	—
			1 in 2	x	x
		20	1 in 3	✓	—
			1 in 2.5	x	44
			1 in 2	x	x
	1.0	6.7	1 in 3	x	5
			1 in 2.5	x	100
			1 in 2	x	x
		20	1 in 3	x	205
			1 in 2.5	x	x
			1 in 2	x	x
"Typical"	0.5	6.7	1 in 3	✓	—
			1 in 2.5	x	85
			1 in 2	x	x
		20	1 in 3	x	60
			1 in 2.5	x	460
			1 in 2	x	x
	1.0	6.7	1 in 3	✓	—
			1 in 2.5	x	205
			1 in 2	x	x
		20	1 in 3	x	605
			1 in 2.5	x	x
			1 in 2	x	x

Symbols:- ✓ case feasible without geogrid. — geogrid not required. x no practical, conventional solution can be developed

Table 10: Results of Analyses for HDPE Cases with a Geodrain with Woven Outer Components

6.4 Single-textured GCL Low Permeability Component Cases without a Geodrain below the Subsoil and Single-textured GCL Cases with a Geodrain with Non-woven Outer Components below the Subsoil

The overall results are the same for single-textured GCL low permeability component cases without a geodrain below the subsoil and for single-textured GCL Cases with a geodrain with non-woven outer components below the subsoil. This is because in the first category, the protection layer above the GCL is a non-woven geotextile which has the same interface properties as those of a geodrain with non-woven outer components.

For all single-textured GCL capping system cases which require geogrid reinforcement, the “special case” which applies to the construction stage 1.2 factors of safety and to the potential for hydrated bentonite to pass out of the host material, as described above in Section 6.1, is relevant.

The overall results of the analyses for the suitability of each option in the classes covered in this section are shown below in Table 11. However, firstly some general comments are made regarding 1 in 2 slopes.

1 in 2 slopes

No practical, conventional solution can be developed for 1 in 2 multilayer capping system slopes based on the presently examined cases and presently applied soil material parameters and interface friction and adhesion parameters together with the provision of geogrid reinforcement. If 1 in 2 slopes prove necessary for the perimeter waste slopes, special, non-standard multilayer capping approaches (which would not be acceptable for the design of a new landfill) may be capable of achieving a configuration which would be stable, but that is beyond the scope of this present study.

Material Parameters	Total restoration soil thickness m	Inter bench Slope Height m	Gradient	Without Geogrid	Geogrid Capacity if required and feasible kN/m (ultimate)
"Best"	0.5	6.7	1 in 3	✓	—
			1 in 2.5	x	35
			1 in 2	x	x
		20	1 in 3	✓	—
			1 in 2.5	x	275
			1 in 2	x	x
	1.0	6.7	1 in 3	x	40
			1 in 2.5	x	130
			1 in 2	x	x
		20	1 in 3	x	325
			1 in 2.5	x	x
			1 in 2	x	x
"Typical"	0.5	6.7	1 in 3	x	50
			1 in 2.5	x	180
			1 in 2	x	x
		20	1 in 3	x	200
			1 in 2.5	x	x
			1 in 2	x	x
	1.0	6.7	1 in 3	x	140
			1 in 2.5	x	290
			1 in 2	x	x
		20	1 in 3	x	635
			1 in 2.5	x	x
			1 in 2	x	x

Symbols:- ✓ case feasible without geogrid. — geogrid not required. x no practical, conventional solution can be developed

Table 11: Results of Analyses for Single-Textured GCL Cases without a Geodrain and for Single-Textured GCL cases with a Geodrain with Non-Woven Outer Components

6.5 Single-textured GCL Low Permeability Component Cases with a Geodrain with Woven Outer Components below the Subsoil

For all single-textured GCL capping system cases which require geogrid reinforcement, the "special case" which applies to the construction stage 1.2 factors of safety and to the potential for hydrated bentonite to pass out of the host material, as described above in Section 6.1, is relevant.

The overall results of the analyses for the suitability of each option in the classes covered in this section are shown below in Table 12. However, firstly some general comments are made regarding 1 in 2 slopes.

1 in 2 slopes

No practical, conventional solution can be developed for 1 in 2 multilayer capping system slopes based on the presently examined cases and presently applied soil material parameters and interface friction and adhesion parameters together with the provision of geogrid reinforcement. If 1 in 2 slopes prove necessary for the perimeter waste slopes, special, non-standard multilayer capping approaches (which would not be acceptable for the design of a new landfill) may be capable of achieving a configuration which would be stable, but that is beyond the scope of this present study.

Material Parameters	Total restoration soil thickness m	Inter bench Slope Height m	Gradient	Without Geogrid	Geogrid Capacity if required and feasible kN/m (ultimate)
"Best"	0.5	6.7	1 in 3	✓	—
			1 in 2.5	X	35
			1 in 2	X	x
		20	1 in 3	✓	—
			1 in 2.5	X	225
			1 in 2	X	x
	1.0	6.7	1 in 3	X	40
			1 in 2.5	X	130
			1 in 2	X	x
		20	1 in 3	X	325
			1 in 2.5	X	x
			1 in 2	X	x
"Typical"	0.5	6.7	1 in 3	X	50
			1 in 2.5	X	150
			1 in 2	X	x
		20	1 in 3	X	200
			1 in 2.5	X	x
			1 in 2	X	x
	1.0	6.7	1 in 3	X	140
			1 in 2.5	X	265
			1 in 2	X	x
		20	1 in 3	X	635
			1 in 2.5	X	x
			1 in 2	X	x

Symbols:- ✓ case feasible without geogrid. — geogrid not required. x no practical, conventional solution can be developed

Table 12: Results of Analyses for Single-Textured GCL Cases with Geodrain with Woven Outer Components

7. Presently Selected Preferred Design for the Multilayer Capping System

7.1 Background

It should be noted that the "presently selected preferred design for the multilayer capping system" is that for the capping system on the 1 in 2.5 gradient Zone 1 northern perimeter waste slopes. A modified design in terms of some of the capping system elements can be applied to sloping capping systems of 1 in 3 gradient or shallower, subject to final detail design following the receipt and interpretation of the additional GI data. This matter is addressed briefly at the end of Section 7.2.

A range of configurations and materials were considered for the initial generic analytical design of the multilayer capping system for the northern perimeter waste slopes. These covered the alternative use of GCL and HDPE for the low permeability element in the capping system. Total restoration soil thicknesses of 0.5m and 1.0m were analysed for all cases. Cases analysed included 1 in 2.5 gradient slopes of 20m height without any intermediate benches.

7.2 The Preferred Configuration

Subsequent to the generic analytical design process covering the numerous, potentially viable multilayer lining system generic configurations and based on subsequent technical discussions, a "preferred" configuration for the multilayer capping system was confirmed. This comprised 1 in 2.5 gradient slopes of 20m height without any intermediate benches, with a double textured, HDPE FML as the low permeability element of the capping system. A geo-composite drainage layer be provided and will also act as the HDPE FML protection layer. The total restoration soil thickness was the 0.5mm. This is made up of 350mm of subsoil and 150mm of topsoil. This is one of the generic designs examined in the earlier part of this study.

To achieve an adequate factor of safety four requirements must be addressed:-

1. Careful selection must be carried out of the materials for use in the multilayer capping system to obtain materials with better than average internal friction, interface adhesion and interface friction values. It is possible that materials and interfaces with "average" values could be used but the heavy geogrid reinforcement would be needed, which may be impractical to install on the 1 in 2.5 slopes. One potential option to accommodate the need for high capacity geogrid would be to provide two layers of geogrid to achieve the same tensile resistance. However, with subsoil thickness being only 350mm, this may make successful placement of the subsoils and geogrid a complex process on 1 in 2.5 gradient slopes.

2. To achieve an adequate factor of safety of 1.3 for this multilayer lining system design, it would be necessary to incorporate geogrid reinforcement within the subsoil layer. This would need to have an ultimate tensile capacity of 105kN/m to ensure the 2% strain limited value would be sufficient.

3. As normal good practice and to ensure that item1 above is correctly addressed, later it will be necessary to undertake laboratory testing to determine:

   a. the material properties of the mineral regulating layer and proposed restoration soils, together with; and

   b. large shear box testing to confirm the interface friction and adhesion properties for each interface between the chosen components of the multilayer capping system.

4. Following completion of the testing described above in item 3, the detail analytical design will require re-running to demonstrate acceptability.

As mentioned previously, for geogrid anchorage, it is proposed that the geogrid in the 1 in 2.5 gradient capping system will be anchored by continuing back through the capping system of the shallower slopes for a few metres behind the crest of the steep slopes. This will be one of the subjects of design analyses at the detail design stage.

Based on the results of present design analyses, for all 1 in 3 gradient waste slope capping system cases, with or without the provision of geodrain with non-woven geotextile face elements below the subsoil layer, a stable design can be achieved without the provision of geogrid reinforcement. However, this will be a subject of further design analyses at the detail design stage.

For the multilayer capping systems provided for slopes of less than 1 in 3 gradient, it is likely that the specification of the sand regulating layer and of the subsoil layer can be reduced in terms of the angle of internal friction required. Similarly some relaxation in the specified values for the interface adhesion and friction values for some interfaces could be accommodated. That would enable the use of lapped, linear low density polyethylene (LLDPE) FML in place of HDPE FML at some gradients shallower than 1 in 3. This could bring cost and construction time savings to the project. These matters will be the subject of further design analyses at the detail design stage.

8. Waste Slope Stability

8.1 Introduction to assessment of waste slope stability

Overall waste mass stability is rarely an issue in waste slopes of modest gradient in a correctly designed and permitted landfill. However, for steep, high perimeter slopes of a land-raise landfill that are expected to have been placed in an uncontrolled manner, overall waste mass stability should be analysed, as it is likely that the slopes were never the subject of analytical design. Therefore, in anticipation of construction works, overall waste mass stability analyses for the proposed, trimmed steep perimeter slopes has been undertaken. In addition, as indicated above, waste slope stability analyses have been completed for waste placement in lined Zone 3 and for temporary waste slopes which may be formed during the earthworks phase of the proposed remediation works.

This waste slope stability work has been undertaken in advance of completion of the additional GI for the site, thus review and checking of the analyses will be necessary following receipt and interpretation of the GI data. In this regard it should be noted that all evidence presently points to there being no greater than very shallow leachate levels in the waste and no obvious perched leachate levels. Typically, the toes of the relevant waste slopes are a few metres above the base of the waste, at the floor level of previous mineral extraction operations. Due to this, the present studies have not considered the presence of leachate but this situation will be revisited following receipt and interpretation of the GI data.

8.2 Northern Perimeter Waste Slope Stability

It should be noted that the present steep waste slopes on the northern boundary approach a gradient of 1 in 2 and have remained generally stable to date. In the remediation works these will be trimmed to a shallower gradient of 1 in 2.5. These slopes will be capped with a multilayer capping system, presently anticipated to be in the form of the presently preferred design described in Section 7.

Slope stability analyses compliant with Eurocode 7, Design Approach 1 and Combination 2 for the application of partial factors of safety, have been completed for the wastes slopes in their 1 in 2.5 face slope configuration. For all analyses, the bulk unit weight assumed at this stage for the landfilled waste, which has a high inert content, was 18kN/m^3. The shear strength parameters applied in the analyses were based on the recommended design value from UK Environment Agency R&D Technical Report P1-385/TR2 "Stability of Landfill Lining Systems: Report No 2 Guidance", ISBN 1 85705 945, January 2003, but included a number of sensitivity analyses to model suitably, the nature of the waste landfilled at Kerdiffstown, based on currently available borehole logs.

The range shear strength parameters applied in the sensitivity analyses were in steps from effective cohesion c' = 5kPa and effective friction = 25° to effective cohesion c' = 0kPa and effective friction = 32°. The results demonstrated that stability was in compliance with the requirements of Eurocode 7. However, following receipt and interpretation of the additional GI data for the site, these analyses will be re-run.

8.3 Stability of Waste Placement in Lined Zone 3

If waste is placed adjacent to a sloping multilayer lining system in a landfill cell on a strip parallel to the lined face and to full face height there is considerable potential for instability to be caused in the lining system if the strip along which waste is placed is comparatively narrow.

Planar failure surfaces within the multilayer lining system have been examined for waste placed in a strip to the sloping lining system, in widths of 4m, 6m and 8m. For all analyses, the bulk unit weight assumed at this stage for the landfilled waste, which has a high inert content, was 18kN/m^3.

The interface friction and adhesion values applied to the multilayer lining system interfaces for these analyses were as shown in Table 13.

Interface	Interface Friction Phi' degrees	Interface Adhesion kPa
Subgrade to geosynthetic clay lining (GCL)	26	0
GCL to smooth HDPE	18	0
GCL to textured surface of mono-textured HDPE	30	10
Smooth HDPE to geosynthetic drainage layer	19	0
Geosynthetic drainage layer to landfilled waste	24	0.5

Table 13:- Zone 3 Sloping Multilayer Lining System Interface Friction and Adhesion Values

From the analyses, it was found that failure of the sloping multilayer capping system could occur if waste were placed adjacent to the sloping lining system to full height, on a strip 4m wide. If waste were placed adjacent to the sloping lining system to full height, on a strip 6m wide marginal stability would be achieved. If waste were placed adjacent to the sloping lining system to full height, on a strip 8m wide adequate factors of safety would apply if the waste were left in this configuration in the long term.

However, for waste placement in a single cell of limited area as applies in Zone 3, the most reliable approach in terms of waste slope stability would be to place waste in turn in compacted layers of 1m thickness across the complete, available base of Zone 3.

8.4 Preliminary, Indicative Stability of Temporary, Cut Waste Slopes

As a preliminary indication of the stability of temporary slopes cut in waste as part of the earthworks stage of the reprofiling of the site, a selection of slope stability analyses were undertaken for a range of temporary wastes slope heights and gradients. These comprised 5m, 10m, 15m and 20m slope heights and cut slope gradients of 1 in 2 and 1 in 2.5.

For all analyses, the bulk unit weight assumed at this stage for the landfilled waste, which has a high inert content, was 18kN/m^3. The shear strength parameters applied in the analyses were based on the recommended design value from Environment Agency R&D Technical Report P1-385/TR2 "Stability of Landfill Lining Systems: Report No 2 Guidance", ISBN 1 85705 945 X, January 2003, but considerably adjusted in light of the nature of the waste landfilled at Kerdiffstown, based on currently available borehole logs. A conservative set of shear strength parameters were applied, namely effective cohesion, c' = 0.5kPa and effective friction = 25°.

On the basis that due to unforeseen circumstances, at any stage temporary cut slopes may be left in place for a number of weeks or months, a selection of slope stability analyses were undertaken compliant with Eurocode 7, Design Approach 1 and Combination 2 for the application of partial factors of safety, have been completed for the temporary wastes slopes. Hence, in these analyses, the temporary slopes were examined against factors of safety which should apply to permanent slopes.

The results demonstrated that for any slope height up to 20m for 1 in 2.5 gradient slopes, the temporary slopes would achieve an acceptable factor of safety to accommodate being left in place and unchanged in the longer term. Conversely, for any slope height for 1 in 2 gradient slopes, the temporary slopes would not achieve an acceptable factor of safety to accommodate being left in place and unchanged in the longer term.

For the set of shear strength parameters considered, 1 in 2 gradient slopes would be unsatisfactory as temporary slopes. At this stage, it has not been considered appropriate to consider further analyses in the form of sensitivity analyses, due to the number which would be require to give indicative results for various slope heights and gradients which could be considered for temporary slopes. However, if necessary, following the receipt and interpretation of the additional GI data for the site, these analyses can be re-run for a range of sets of shear strength parameters, slope heights and slope gradients.

9. Discussion

9.1 Approach to the Discussion of the Results

Although a presently preferred design option has been selected for the multilayer lining system, full discussion is presented first for the numerous potentially viable multilayer lining system configurations examined in the first stage of this study. This is because full understanding of the capping options is useful in case the results of the additional GI or the later testing to determine material specific for the components of the multilayer capping system or any other factors require the selection of a different design option. Discussion related to the presently preferred capping system is presented in subsequent text.

Discussion of waste slope stability follows that of the multilayer lining system options.

9.2 Multilayer Capping System Generic Design Option Study

Although it is intended that representative values for the design parameter values have been selected from published data, the material parameters and interface parameters are very dependent on the specific mineral materials and proprietary geosynthetic materials which will be finally chosen. Therefore, for completion of the final detail design, it will be necessary to undertake laboratory testing to determine the material properties of the mineral regulating layer and proposed restoration soils, together with large shear box testing to confirm the interface friction and adhesion properties for each interface between the chosen components of the multilayer lining system. This is likely to be most critical for cases which include a single-textured GCL and components with woven geotextile surfaces.

Based on the presently applied values for the design parameters, the generic analyses generally define what configurations of slope and capping system can be achieved for different soil materials, geosynthetic components, restoration soil thicknesses, slope angles and slope heights.

Safe design for the satisfactory performance of the multi-layer lining system must be based on the assumption that no geosynthetic component other than geogrid can accommodate tensile forces. Thus, where needed, geogrid reinforcement must be sized to take all the tensile forces identified in each multi-layer capping system design calculations. To ensure that any induced tensile forces are kept to an absolutely minimum, the geogrid reinforcement must limit strain movements induced in the capping system during construction activities and over the design life of the multi-layer capping system. This normally requires that the tensile strength of the necessary geogrid reinforcement is that of the 2% strain case. The tensile strength of geogrid reinforcement at 2% strain is approximately one fifth of the ultimate strength; the value of which usually forms part of the name of a particular geogrid.

No practical, conventional solution can be developed for 1 in 2 multilayer capping system slopes based on the presently examined cases and applied soil material parameters and interface friction and adhesion parameters together with the provision of geogrid reinforcement. If 1 in 2 slopes prove necessary for the perimeter waste slopes, special, non-standard multilayer capping approaches (which would not be acceptable for the design of a new landfill) may be capable of achieving a configuration which would be stable, but that is beyond the scope of this present study.

An alternative, should 1 in 2 perimeter slopes be required, would be to reduce inter-bench slope height by adding one or more benches, but this has the disadvantage of requiring greater volumes of excavation of the waste materials from the existing steep perimeter slopes. Thus, on this basis, adopting a lower slope gradient in the design is considered a more practical option.

If it were acceptable to restrict total restoration soil thicknesses to 0.5m and sloping cap construction materials and components could be selected and demonstrated by laboratory testing to achieve the "best parameters", a 1 in 2.5 slope without benches could be capped if the low permeability element were textured HDPE, appropriate geogrid reinforcement were provided and any geodrain installed beneath the restoration soils were of the type faced with non-woven geotextile. The same would be the case if a geodrain were not installed but the HDPE protection layer were non-woven geotextile.

The same situation applies for a case where double-textured HDPE is replaced with single-textured GCL, but geogrid with more than twice the tensile capacity of that needed for the double-textured HDPE case would be required.

For the case of a single-textured GCL combined with a geodrain faced with woven geotextile, with total restoration soil thickness of 0.5m and sloping cap construction materials and components achieving the "best parameters" values, a 1 in 2.5 slope without benches would be feasible with the provision of appropriate geogrid reinforcement which would not have to be very high tensile capacity. For this particular combination of materials and geosynthetic components, the necessary geogrid tensile strength is slightly less than the single-textured GCL case combined with a non-woven protection layer or a geodrain of the type faced with non-woven geotextile.

For the flatter waste slopes present above the steep perimeter slopes, any of the multi-layer capping systems examined in this study could be used. This is demonstrated by the results obtained from the analyses of 1 in 3 waste slopes.

With the provision of benches, a wider range of options are feasible for 1 in 3 and 1 in 2.5 slopes, however, the provision of benches compared with using planar slopes requires greater volumes of excavation of the waste materials from the existing steep perimeter slopes.

9.3 Discussion of the Preferred Multilayer Capping System Option

The presently "preferred" configuration for the multilayer capping system comprised 1 in 2.5 gradient slopes of 20m height without any intermediate benches, with a double textured, HDPE FML as the low permeability element of the capping system. A geo-composite drainage layer be provided and will also act as the HDPE FML protection layer. The total restoration soil thickness was the 0.5m. This is made up of 350mm of subsoil and 150mm of topsoil. This is one of the generic designs examined in the earlier part of this study.

In section 7.2, four issues have been identified which must be addressed at the final detail design stage to ensure an adequate factor of safety will be achieved. One important issue is the execution of material specific laboratory testing and another is the provision of geogrid reinforcement in the subsoil layer. A further important issue is careful selection the materials for use in the multilayer capping system to obtain materials with better than average internal friction, interface adhesion and interface friction values. However, it is possible that materials and interfaces with "average" values could be used but the heavy geogrid reinforcement would be needed, which may be impractical to install on the 1 in 2.5 slopes, nevertheless there is potential to increase geogrid reinforcement so some practical degree to overcome one or two material suitability problems, should they arise.

One potential option to accommodate the need for high capacity geogrid would be to provide two layers of geogrid to achieve the same tensile resistance as for a single layer. However, with subsoil thickness being only 350mm, this may make successful placement of the subsoils and geogrid a complex process on 1 in 2.5 gradient slopes.

9.4 Multilayer Capping Systems for Slope Gradients Shallower than 1 in 3

It should be noted that the "presently selected preferred design for the multilayer capping system" is that for the capping system on the 1 in 2.5 gradient northern perimeter waste slopes. A modified design in terms of some of the capping system elements can be applied to sloping capping systems of 1 in 3 gradient or shallower, subject to final detail design following the receipt and interpretation of the additional GI data.

For the multilayer capping systems provided for slope of less than 1 in 3 gradient, it is likely that the specification of the sand regulating layer and of the subsoil layer can be reduced in terms of the angle of internal friction required. Similarly some relaxation in the specified values for the interface adhesion and friction values for some interfaces could be accommodated. That would enable the use of lapped, linear low density polyethylene (LLDPE) FML in place of HDPE FML at some gradients shallower than 1 in 3. This could bring cost and construction time savings to the project. This will be one of the subjects of design analyses at the detail design stage.

9.5 Northern Perimeter Slopes Waste Stability

Slope stability analyses compliant with Eurocode 7, Design Approach 1 and Combination 2 for the application of partial factors of safety, have been completed for the wastes slopes in their 1 in 2.5 face slope configuration. A range shear strength parameters applied in the sensitivity analyses in steps from effective cohesion c' = 5kPa and effective friction = 25° to effective cohesion c' = 0kPa and effective friction = 32°. The results demonstrated that stability was in compliance with the requirements of Eurocode 7. However, following receipt and interpretation of the additional GI data for the site, these analyses will be re-run.

9.6 Stability of Waste Placement in Lined Zone 3

If waste is place adjacent to a sloping multilayer lining system in a landfill cell on strip parallel to the lined face and to full face height there is considerable potential for instability to be caused in the lining system if the strip along which waste is placed is comparatively narrow. Therefore, planar failure surfaces within the multilayer lining system have been examined for waste placed in a strip to the sloping lining system, in widths of 4m, 6m and 8m.

From the analyses, it was found that failure of the sloping multilayer lining system could occur if waste were placed adjacent to the sloping lining system to full height, on a strip 6m wide or less. However, for waste placement in a single cell of limited area as applies in Zone 3, the most reliable approach in terms of waste slope stability would be to place waste in turn in compacted layers of 1m thickness across the complete, available base of Zone 3.

9.7 Indicative Stability of Temporary, Cut Waste Slopes

On the basis that due to unforeseen circumstances, at any stage temporary cut slopes may be left in place for a number of weeks or months, a selection of slope stability analyses were undertaken compliant with Eurocode 7, Design Approach 1 and Combination 2 for the application of partial factors of safety, have been completed for the temporary wastes slopes. Hence, in these analyses, the temporary slopes were examined against factors of safety which should apply to permanent slopes.

The results demonstrated that for any slope height up to 20m for 1 in 2.5 gradient slopes, the temporary slopes would achieve an acceptable factor of safety to accommodate being left in place and unchanged in the longer term. Conversely, for any slope height for 1 in 2 gradient slopes, the temporary slopes would not achieve an acceptable factor of safety to accommodate being left in place and unchanged in the longer term.

For the set of shear strength parameters considered, 1 in 2 slopes would be unsatisfactory as temporary slopes. At this stage, it has not been considered appropriate to consider further analyses in the form of sensitivity analyses, due to the number which would be require to give indicative results for various slope heights and gradients which could be considered for temporary slopes. However, if necessary, following the receipt and interpretation of the additional GI data for the site, these analyses can be re-run for a range of sets of shear strength parameters, slope heights and slope gradients.

10. Conclusions

10.1 Multi-layer Capping System

1. The conclusions regarding sloping multi-layer capping design are based on the presently applied values for the design parameter, which are considered representative in advance the receipt and interpretation

of additional GI data and in advance of the laboratory testing which should be undertaken at the detail design stage. The present analyses should be re-run following receipt and interpretation of the additional GI data and on receipt of the laboratory testing which should be undertaken at the detail design stage.

2. Based on the generic analytical design process covering the numerous, potentially viable multilayer lining system generic configurations, and based on subsequent technical discussions, a “preferred” configuration for the multilayer capping system was confirmed. This comprised 1 in 2.5 gradient slopes of 20m height without any intermediate benches, with a double textured, HDPE FML as the low permeability element of the capping system. A geo-composite drainage layer be provided and will also act as the HDPE FML protection layer. The total restoration soil thickness was the 0.5mm. This is made up of 350mm of subsoil and 150mm of topsoil. This is one of the generic designs examined in the earlier part of this study.

3. To achieve an adequate factor of safety four requirements must be addressed:

   a. Careful selection must be carried out of the materials for use in the multilayer capping system to obtain materials with better than average internal friction, interface adhesion and interface friction values. It is possible that materials and interfaces with “average” values could be used but the heavy geogrid reinforcement would be needed, which may be impractical to install on the 1 in 2.5 slopes. One potential option to accommodate the need for high capacity geogrid would be to provide two layers of geogrid to achieve the same tensile resistance. However, with subsoil thickness being only 350mm, this may make successful placement of the subsoils and geogrid a complex process on 1 in 2.5 gradient slopes.

   b. To achieve an adequate factor of safety of 1.3 for this multilayer lining system design, it would be necessary to incorporate geogrid reinforcement within the subsoil layer. This would need to have an ultimate tensile capacity of 105kN/m to ensure the 2% strain limited value would be sufficient.

   c. As normal good practice and to ensure that item1 above is correctly addressed, later it will be necessary to undertake laboratory testing to determine:

      i. the material properties of the mineral regulating layer and proposed restoration soils, together with

      ii. large shear box testing to confirm the interface friction and adhesion properties for each interface between the chosen components of the multilayer capping system.

4. The geogrid in the 1 in 2.5 gradient capping system should be anchored by continuing back through the capping system of the shallower slopes for a few metres behind the crest of the steep slopes. This should be a subject of design analyses at the detail design stage.

5. For all 1 in 3 gradient waste slope capping system cases, with or without the provision of geodrain with non-woven geotextile face elements below the subsoil layer, a stable design can be achieved without the provision of geogrid reinforcement. However, this should be a subject of further design analyses at the detail design stage.

6. For the multilayer capping systems provided for slope of less than 1 in 3 gradient, it is likely that the specification of the sand regulating layer and of the subsoil layer can be reduced in terms of the angle of internal friction required. Similarly some relaxation in the specified values for the interface adhesion and friction values for some interfaces could be accommodated. That would enable the use of lapped, linear low density polyethylene (LLDPE) FML in place of HDPE FML at some gradients shallower than 1 in 3. This could bring cost and construction time savings to the project. This should be one of the subjects of design analyses at the detail design stage.

10.2 Waste Slope Stability

1. Present analyses of the stability of the northern perimeter waste slopes demonstrate that stability was in compliance with the requirements of Eurocode 7. However, following receipt and interpretation of the additional GI data for the site, these analyses should be re-run.

2. From the stability, it is found that failure of the sloping multilayer lining system of Zone 3 could occur if waste were placed adjacent to the sloping lining system to full height, on a strip 6m wide or less. However, for waste placement in a single cell of limited area as applies in Zone 3, the most reliable approach in terms of waste slope stability would be to place waste in turn in compacted layers of 1m thickness across the complete, available base of Zone 3. This approach should be adopted

11. Recommendations

1. The present analyses for multilayer capping system design and waste slope stability analysis should be re-run following receipt and interpretation of the additional GI data and on receipt of the laboratory testing which should be undertaken at the detail design stage.

2. For final, detail design of the sloping multilayer capping system, laboratory testing should be undertaken to determine the material properties of the mineral regulating layer and proposed restoration soils, together with large shear box testing to confirm the interface friction and adhesion properties for each interface between the chosen, proprietary components of the multilayer lining system.

3. A preliminary, indicative study of the stability of temporary, cut waste slopes has been undertaken in this stage of work and the results discussed. However, if necessary, following the receipt and interpretation of the additional GI data for the site, consideration should be given to rerunning these analyses for an appropriately extended range of sets of shear strength parameters, slope heights and slope gradients.

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