

Design of capping systems

LANDFILL GUIDANCE GROUP Industry Code of Practice no. LGG 111

Date: February 2018

Document version: Version 1

Version history

Version no.	Date	Remarks
1	15/02/18	Final version for approval by LGG

Prepared by the Engineering Subgroup of the Landfill Regulation Group. ICoPs are approved by the Landfill Guidance Group – an industry group of landfill professionals – with advice and input from regulatory bodies.

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DESIGN OF CAPPING SYSTEMS

SECTION A : INTRODUCTION

- A1 This document represents an Industry Code of Practice on the design of landfill capping systems and should be read in conjunction with other applicable landfill engineering guidance and/or Industry Codes of Practice.
- A2 The capping and restoration system forms either a temporary or final component in the construction of the landfill and comprises the **engineered cap** and the **restoration layer**. This document gives guidance on the factors to be considered in the design of the **engineered cap**. Detailed guidance as to the design of the **restoration layer** is not provided here, although given the interaction of the two components there are a number of references to the **restoration layer** in this document.
- A3 The objectives of the **engineered cap** are to:
- Contain the waste;
 - Manage leachate production by controlling the ingress of rain and surface water into the underlying waste;
 - Prevent uncontrolled escape of landfill gas or the entry of air into the waste;
 - Accommodate the environmental control measures; and
 - Provide a physical separation between the waste and overlying **restoration layer** and ultimately the wider environment.
- A4 Design of the capping system should be site specific and consider the topography and infrastructure present at that site. A Stability Risk Assessment (SRA) should be integral to the design process.
- A5 Temporary capping of a site will be required where the site has ceased accepting waste or it has reached pre settlement levels. This will be necessary for sites that are either mothballed or where waste acceptance has ceased for six months.. Temporary capping will aim to minimise the area of waste exposed and so reduce precipitation ingress and fugitive emissions from the site. Temporary capping in this context is considered to be part of operational best practice at the site. It is important that the design of any temporary capping should enable the installation and maintenance of gas extraction infrastructure.
- A6 Prolonged periods of temporary capping (ie; where a landfill is temporarily closed or “mothballed”) may be required due to transient waste inputs. Site operators shall ensure compliance with the Landfill Permit for the site during this period. The design of any temporary cap shall be in

accordance with the Landfill Permit unless otherwise agreed with the Regulator. Construction Quality Assurance will be required as part of the design and construction of a temporary cap.

Definitions

- A7 The Landfill Directive sets out requirements of the capping and restoration system which is dependent on whether the landfill site is permitted for the acceptance of hazardous, non-hazardous or inert waste. The components that may form the capping and restoration system from top to bottom and are defined in the Landfill Directive as follows:

RESTORATION LAYER

Restoration Soils: Comprises soils and or soil-forming materials to enable the planned after use to be achieved.

ENGINEERED CAP

The cap can contain several elements as follows:

Drainage Layer: The drainage layer lies beneath the restoration soils and above the artificial sealing and/or mineral layer. The objective of the layer is to facilitate the drainage of rainwater and surface water that percolate through the restoration layer.

Artificial Sealing Liner: A geosynthetic layer, which controls both the generation of leachate by minimising the infiltration of water and uncontrolled release of landfill gases.

Mineral Layer: A mineral layer which controls both the generation of leachate by minimising the infiltration of water and uncontrolled release of landfill gases.

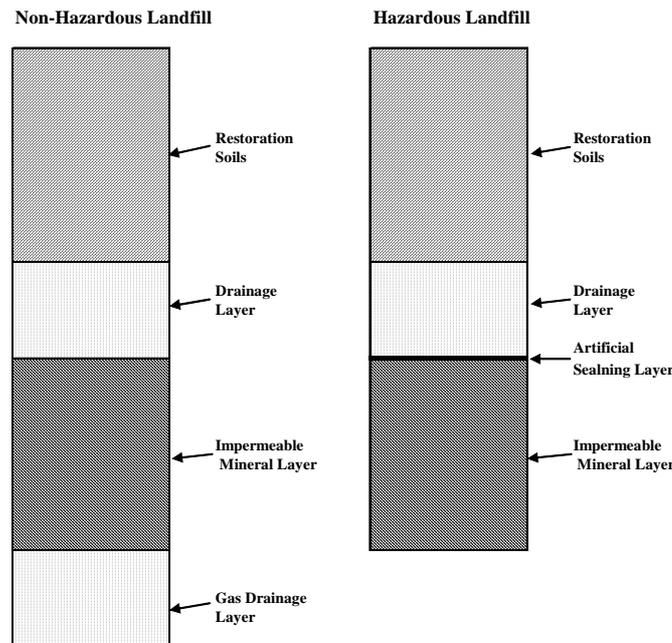
Gas Drainage Layer: A permeable layer that allows landfill gases to be collected directly beneath the artificial sealing or mineral layer.

- A8 In addition to the layers specified in the Landfill Directive, the inclusion of a **waste regulating layer** is also considered necessary from a “constructability” perspective. This layer should be placed above the final lift of waste in order to provide protection from underlying waste and an even surface on which to install the **engineered cap**.

- A9 The layers described above are shown in Figure B1. It should be noted that the Landfill Directive appear to suggest that the impermeable mineral layer should be placed above the artificial sealing liner. However, where

both layers are included in an **engineered cap**, the impermeable mineral liner should generally be installed below the artificial sealing liner to optimise the cap's hydraulic performance.

Figure B1: Landfill Directive Recommended Capping and Restoration Construction



A10 The recommendations made in the Landfill Directive for the layers which make up the **engineered cap** and **restoration layer** for each landfill classification, are set out below:

TABLE B1: LANDFILL DIRECTIVE CAPPING GUIDELINES

Layer	Category of Landfill	
	Non -hazardous	Hazardous
Top soil cover > 1m	Required	Required
Drainage layer > 0.5m	Required	Required
Artificial sealing liner	Not Required	Required
Impermeable mineral layer	Required	Required
Gas drainage layer	Required*	Not Required

*Typically not required in UK Practice

A11 It is important to note that the Landfill Directive makes no recommendations in respect of the construction of the capping and restoration system for an inert landfill.

Design Philosophy and Document Structure

A12 The recommendations for the components of the **engineered cap** as described in the Landfill Directive and as detailed in Table B1 above are not considered to be prescriptive. A key theme of this Code of Practice is the need for the design of capping and restoration schemes to be risk based. Hence, the recommendations of the Directive that are set out in Table B1 should be considered to be a starting point for the design of a particular capping and restoration system, with variations to this considered in, and justified by, the risk based design. In this respect, this document describes the factors that need to be considered in the design process and these include the technical considerations and the land-use and aftercare requirements of the restoration scheme. This document is structured as follows:

Engineered Cap Material Options: Describes the most common materials that may be considered within each element of the capping and restoration system.

Design Considerations: Discusses the design considerations which have been divided in to the following elements:

- Hydraulic considerations;
- Landfill gas considerations;
- End use considerations; and
- Other considerations.

Stability Assessment: Details the requirements of the Stability Assessment, including; potential failure mechanisms, general methods of analysis, selection of appropriate factor of safety, input parameters and analysis methodology.

Summary of Design Methodology: briefly reviews the step by step design of a capping and restoration system and presents a flow chart which graphically sets out the design process.

SECTION B : ENGINEERED CAP MATERIAL OPTIONS

B1 This section details the potential material options for each layer within the **engineered cap**. The design considerations are discussed in Section C.

Drainage Layer

B2 Historically, in the UK, drainage layers installed below the **restoration layers** have not been used to a great extent, although their use has

- increased in recent years. The drainage layer should be placed between the **restoration layer** and the artificial sealing or mineral layer, to minimise the head of water on these layers and to provide drainage to the restoration soils. The inclusion of such a layer not only reduces the infiltration of water through the cap into the waste, therefore reducing leachate generation, but will also improve the fertility of the restoration profile.
- B3 The Landfill Directive recommends that the drainage layer should be a minimum of 500mm thick, but do not give an indication as to the type of material that could be used or the hydraulic conductivity of such a layer. In line with the risk based approach, and having assessed all design considerations, the designer may deviate from the recommendations made in the Landfill Directive for this layer. This means the drainage layer may be reduced in thickness, or even excluded, subject to the detailed risk based design.
- B4 The materials typically used in the drainage layer are naturally occurring granular soils or secondary aggregate or geosynthetic materials for which a wide range of products are available.
- B5 Granular soils used in drainage layers are either a sand or gravel, or secondary drainage media such as crushed brick or glass, with a hydraulic conductivity sufficient to drain the restoration soils. The designer should demonstrate via calculation that the combined drainage and underlying artificial sealing and/or mineral layers can achieve the desired infiltration rate into the waste deposits (**hydraulic considerations**). The design should also consider the need for a filter geotextile above the drainage layer, to prevent the migration of fine grained material downwards from the overlying restoration soils into the drainage layer. Where gravel, or coarse secondary aggregate, is to be used as the drainage layer overlying either the mineral layer or an artificial sealing liner, a separation geotextile or geotextile protector below the drainage layer should be included as part of the design. Where gravel is underlain by a geomembrane, for example, it should be demonstrated that adequate protection is provided by the proposed geotextile.
- B6 In the absence of a readily available source of natural or recycled granular drainage media, an alternative approach to consider should be the use of geosynthetic materials. The term “geosynthetic” is the generic term for man made products used in geotechnical engineering and geosynthetic materials can be divided in to a number of specific products. Where one or more products are combined, this is defined as a “geocomposite”. Geocomposites are commonly used in drainage applications. As with naturally occurring granular materials, the designer should demonstrate via calculation that the combined drainage and underlying sealing system

can minimise infiltration into the underlying waste deposit (**hydraulic considerations**). There are a number of geocomposite products available, all of which provide a pathway along which water may flow using a three dimensional geosynthetic product, such as a grid or cusplate, overlain by a geotextile separator to prevent fine soil particles from clogging the void. It is essential that where a geocomposite product is used that it is installed to the manufacturer's recommendations. A summary of material options for the drainage layer are detailed in Table B2.

Artificial Sealing Liner

- B7 An artificial sealing liner is an impermeable geosynthetic layer, which may be installed in conjunction with a mineral layer or on its own in order to form a composite seal over the underlying waste, controlling both the generation of leachate by minimising the infiltration of water and uncontrolled release of landfill gases. Although the artificial sealing liner can be installed directly above the low permeability mineral layer and below the drainage layer, in most circumstances, it is used without an impermeable mineral layer. Where this is the case, the designer should demonstrate that the capping system meets the desired infiltration rate.
- B8 There are a number of geosynthetic products on the market that are suitable for use as an artificial sealing liner and these can be divided into two groups, namely polymeric geomembranes and geosynthetic clay liners.
- B9 There are a number of polymeric geomembrane commercially available, the most common types used for capping are:
- High density polyethylene (HDPE);
 - Linear Low density polyethylene (LLDPE);
 - Polypropylene (PP); and
 - Polyvinyl chloride (PVC).
- B10 Of these products, HDPE and LLDPE are most commonly used in the UK market. In practice these materials should be installed with adjacent panels welded together. Welding of the geomembrane provides a water and gas tight seal to the underlying waste. The overlapping of seams should be avoided as this method will be limited in preventing rain and surface water infiltration and landfill gas emissions. It is therefore recommended that a welded geomembrane system should be used.
- B11 Theoretically, polymeric geomembranes have very low infiltration rates, since the mechanism by which water and gas may pass through the layer

- is one of vapour diffusion. However, the presence of defects, such as tears, punctures, and defective seams in a geomembrane greatly increases the infiltration rate. It is recommended, therefore, that when considering the use of a geomembrane the likelihood of defects and their influence on the infiltration should be considered carefully (**Hydraulic considerations**).
- B12 Interface stability of the capping system can also be critical when using multiple layers of geosynthetic materials and therefore the use of textured materials should be considered by the designer (stability assessment). All the geosynthetic lining products described above can be supplied with texturing on one or both sides in order to improve the frictional characteristics when capping steeper slopes. Geosynthetic interface testing will need to be undertaken in line with the Industry Codes of Practice 'LGG115: Geosynthetic interface shear resistance testing' and 'LFE4 / LGG104: Earthworks in landfill engineering' and will require site specific testing.
- B13 The magnitude of differential settlement of the capping system should be considered in the designer's choice of geomembrane. The three dimensional axisymmetric stress-versus-strain parameters differ between the geomembrane products, with LLDPE and PVC geomembranes performing better in such scenarios. The designer should consider the magnitude of the anticipated differential settlement and based upon this select the appropriate product (**stability assessment**).
- B14 Further detailed guidance on the design of geomembranes can be found in Industry Code of Practice 'LFE 5 / LGG 105: Using geomembranes in landfill engineering'.
- B15 Geosynthetic clay liners (GCLs) comprise a layer of bentonite placed either between two geotextiles or bonded adhesively to a geomembrane. The hydraulic performance of a GCL is dependent upon the bentonite layer, due to its low permeability ($1 \times 10^{-10} \text{ms}^{-1}$ to $5 \times 10^{-10} \text{ms}^{-1}$). Further details on capping may be found within the Industry Code of Practice 'LFE3 / LGG 103: Using Geosynthetic Clay Liners in Landfill Engineering'.
- B16 Whilst the presence of defects in a geomembrane can significantly affect the performance of a geomembrane cap, the bentonite has the ability to self-heal. This is due to the swelling of the bentonite as it hydrates, plugging perforations and sealing around penetrations in the material. Care needs to be taken constructing GCL overlaps in order to minimise surface water infiltration, oxygen ingress and landfill gas emissions.
- B17 Interface and internal shear strength of a particular GCL product should also be considered under site specific conditions and follow the Industry

Code of Practice(s) 'LFE 115: Geosynthetic interface shear testing' and 'Earthworks in landfill engineering'. Differential settlement should also be considered, since the strains at which the permeability of GCLs start to deteriorate may be dependent upon the type of product (stability assessment).

Mineral Layer

B18 The mineral layer should be placed over the gas drainage layer and/or the waste regulating layer to minimise the production of leachate and the uncontrolled release of landfill gas. The mineral layer is recommended in the Landfill Directive for both non-hazardous and hazardous waste landfills, although in some cases there may need to be some form of sealing layer for an inert landfill. The Landfill Directive gives no indication as to the thickness or permeability of this layer. In line with the risk based approach, the designer should determine the required thickness, based upon the permeability of the materials available in order to meet the desired infiltration rate (**Hydraulic considerations**).

B19 In general, low permeability mineral layers placed as caps in the UK have been formed using a naturally occurring fine grained material, with a permeability of less than $1 \times 10^{-9} \text{ ms}^{-1}$, and placed to a minimum of thickness of 1m. Ideally, the material for a mineral layer should be sourced from an on-site source. However, many sites in the UK do not have a readily available source of low permeability material suitable for capping applications. In such cases, where a mineral layer is required, alternative options should be considered as follows:

- Import suitable low permeability mineral layer material; or
- Manufacture a bentonite enriched soil (BES) material using an on-site or imported host material.

It should be noted that the differential settlement of the underlying waste may induce unacceptably high strains to a mineral cap and any design will need to assess the impact of such strains on its long term performance. In particular, the impact the anticipated strains will have on the hydraulic conductivity of the capping layer and what effect this will have on the ability of the cap to minimise infiltration and surface emissions will need to be assessed.

B20 Importing mineral layer material may prove extremely costly in some parts of the UK and it may be considered that this approach is not the best environmental option, given the number of vehicle movements required. Accordingly, the use of a BES layer may prove more cost effective and may have less environmental impact, since the lower permeability of such

materials in comparison to naturally occurring soils may allow a thinner cap to be constructed and the use of on-site granular materials as a host that would not otherwise be suitable for capping purposes.

- B21 Detailed guidance on the design of mineral layers can be found in the Industry Code of Practice 'LFE4 / LGG104: Earthworks in Landfill Engineering.' Guidance on the use of BES materials can be found in the Industry Code of Practice 'LFE10 / LGG110: Using bentonite enriched soils in landfill engineering'.

Gas Collection Layer

- B22 The gas collection layer is envisaged as a continuous permeable layer that extends across the final waste levels to allow the free flow of gas at the top of the waste mass to enable its collection and to prevent its migration through the sealing layer(s) of the cap. The Landfill Directive does not require a minimum thickness for this layer or a minimum flow capacity requirement. The Directive only recommends its use on non-hazardous waste landfill sites.
- B23 The gas collection layer may be formed from either a granular layer or a geocomposite drainage material. Therefore, material options for this layer are similar to those discussed in relation to the surface water drainage layer.
- B24 Whilst it is envisaged that gas collection beneath the cap is to be achieved by the use of a drainage layer, it is generally possible to demonstrate that the gas immediately beneath the cap would be collected successfully using a system of gas extraction wells. In such cases the gas collection layer may not be required. The presence of a gas drainage layer may also cause problems with conventional gas extraction systems by exacerbating cross well suction effects and allowing air ingress through defects to affect a larger area. Accordingly, the use of gas collection layers may be more appropriate when designing capping systems for landfills that may only generate low volumes of landfill gas such that conventional gas extraction systems are inappropriate.

Waste Regulating Layer

- B25 A regulating layer should be incorporated in the design of a capping scheme especially where the cap is to consist of a geosynthetic layer. It should be installed over the final lift of waste and should consist of fine grained soils, although a variety of materials may be appropriate including suitable material from the incoming waste stream. The material to be used for this purpose will need to be justified as part of the design. The thickness and the nature of the material to be used for this purpose will

also need to be the subject of an engineering specification and a Construction Quality Assurance Plan and evidence provided, via a validation report, that the regulating layer was constructed to the agreed specification and Construction Quality Assurance Plan. The inclusion of a waste regulating layer has a number of benefits which include:

- Protection of the over lying **engineered cap** from puncture by protruding objects within the waste mass;
- Reduction of the magnitude of strains on the **engineered cap**; and Provision of a firm, even surface against which to place the **engineered cap** therefore making control and monitoring of material placement easier.

B26 The design of such a layer is dependent upon the materials available on site and the waste to be covered. Generally a waste regulating layer should be specified to be nominally no greater than 300mm thick, since control of layer thickness thinner than this is difficult on an undulating surface which also may deflect when loaded. It is unlikely that such a regulating layer would be required beneath a mineral cap.

B27 The designer should define the source of the regulating layer material and/or suitability criteria for the material to meet its desired performance. These criteria should include; maximum particle size to prevent damage to immediately overlying geosynthetic materials and minimum undrained shear strength to prevent rutting during placement.

B28 Should the design of the capping system include a granular gas drainage layer, the waste regulating layer is unlikely to be required as a continuous layer. However, due to the undulating surface of the waste, the volume of material actually used in creating the gas drainage layer, of a consistent minimum thickness, may increase, in which case the inclusion of a waste regulating layer to localised hollows may be beneficial if a gas drainage layer is required. Should a granular gas drainage layer be require and this be placed between a regulating layer or a mineral cap then a geotextile separator is likely to be required between both interfaces.

TABLE B2: MATERIAL OPTIONS SUMMARY

Engineered Cap Layer	Material Options	Comments
Drainage Layer	Naturally occurring sand and gravel	<p>May require screening and washing May require geotextile separator below restoration soils May require geotextile separator or protector above underlying sealing liners Will require large number of vehicle movements to bring the material onto site</p>
	Geocomposite drainage layer	<p>Variety of products available but generally incorporate a drainage core with overlying geotextile May require laboratory testing to establish shear strength parameters May require laboratory testing to establish discharge capacity</p>
Artificial Sealing liner	Geomembrane	<p>Number of options available of the market: High Density Polyethylene (HDPE), Linear Low Density Polyethylene (LLDPE) (1), Polypropylene (PP) Polyvinyl Chloride (PVC) Most commonly used in the UK are HDPE and LLDPE May require laboratory testing to establish shear strength parameters Will need to consider performance under anticipated settlement conditions Will require protection from overlying and underlying granular layers</p>
	Geosynthetic Clay Liner (GCL)	<p>Variety of alternative products on the market May require laboratory testing to establish shear strength parameters Will need to consider performance under anticipated settlement conditions In the event of damage once installed the bentonite swells to effectively self healing properties Permeability can degrade when subjected to wetting and drying cycles</p>

TABLE B2 (CONTINUED): MATERIAL OPTIONS SUMMARY

Engineered Cap Layer	Material Options	Comments
Mineral Layer	Naturally occurring mineral (clay)	<p>Source of material will need to be established, either site won or imported</p> <p>Layer thickness generally 1m but may be reduced demonstrated acceptable by risk assessment</p> <p>Materials will need laboratory testing to establish permeability</p>
	Bentonite Enriched Soil (BES)	<p>Poor gas permeability</p> <p>Measurement of thickness of as constructed cap will need to take account of the settlement of the underlying waste during the construction process. Direct thickness measurements via hand auguring and/or trial pitting are likely to be required. Soil host and mix design will need investigation to demonstrate compliance with required permeability criteria</p> <p>Layer thickness generally 0.3m but may be reduced demonstrated acceptable by risk assessment. Polymer modified products available on the market that can be used at thickness less than 0.1m</p> <p>Materials will need laboratory testing to establish permeability</p> <p>May require laboratory testing to establish shear strength parameters</p> <p>Material performance affected by freeze/thaw, wetting and drying cycles and settlement</p> <p>Measurement of thickness of as constructed cap will need to take account of the settlement of the underlying waste during the construction process. Direct thickness measurements via hand auguring and/or trial pitting are likely to be required.</p>

TABLE B2 (CONTINUED): MATERIAL OPTIONS SUMMARY

Engineered Cap Layer	Material Options	Comments
Gas Drainage Layer	Naturally occurring sand and gravel	<p>May require screening and washing</p> <p>Will require large number of vehicle movements to bring the material onto site A geotextile separator or protector may be required both above and below the granular gas drainage layer.</p>
	Geocomposite drainage layer	<p>Variety of products available but generally incorporate a drainage core with overlying geotextile</p> <p>May require laboratory testing to establish shear strength parameters</p> <p>May require laboratory testing to establish discharge capacity</p>
Waste regulating Layer		<p>On site soils or selected waste stream</p> <p>Will require adequate compaction and shear strength.</p> <p>Will require an adequate particle size and a justified layer thickness.</p>

SECTION C: DESIGN CONSIDERATIONS

- C1 This section discusses the considerations which should be taken into account in the design of each element of the capping and restoration system. Reference should be made to the flow chart in Figure B7 which graphically represents the step by step design process. These considerations will determine the layers to be included within the engineered cap and the fundamental performance requirements of each layer. All this information should then be used to provide the input parameters for the Stability Assessment, which ultimately will determine whether or not the design is suitable or whether design modifications are required. Alternatively, the Stability Assessment can be used to provide some design parameters if others are assumed.

Hydraulic Considerations

- C2 Whilst the Landfill Directive includes recommendations for capping, these can be changed on the basis of a risk assessment, with an important element of this assessment being the hydraulic considerations. With regards to these considerations, it is necessary to consider the potential implications of cap design on two key elements; leachate generation and the generation of surface water runoff. Both of these elements are considered in more detail below.

Leachate Generation

- C3 The Landfill Directive requires control of “rainwater” entering the landfill body and that “leachate accumulation at the base of the landfill should be kept to a minimum”. Once the landfill has been restored, assuming that there is no groundwater influx, then the majority of the leachate generated will be by the infiltration of rainfall through the cap.
- C4 In order to meet these requirements of the Landfill Directive, it is critical to manage the volume of infiltration through the cap. In addition, controlling the volume of leachate generated by a landfill has significant implications for:
- ***The volume of leachate that would need to be extracted in order to keep leachate levels below specified compliance levels.*** This could have significant cost implications owing to the requirement to dispose of, and possibly pre-treat, the leachate. In turn, this could have significant implications for the level of financial provision required for the site.

- **The ease at which the leachate levels are maintained below specified compliance levels.** Again, there are cost implications associated relating to management time, extraction system specification;
- **The compliance of the landfill with the requirements of the Groundwater Directive.** If a landfill's containment engineering does not provide sufficient attenuation of the migrating leachate, either through physical or chemical means, then by placement of a very low permeability capping system it might be possible to sufficiently limit leachate generation so as to prevent the discernible discharge of Hazardous Substances and the pollution of the groundwater by Non Hazardous pollutants.
- **The length of time required before a landfill's waste mass has stabilised.** If it is assumed that the time to stabilisation is linked to the volume of water "flushing" the waste mass, then it follows that shorter stabilisation periods are associated with higher volumes of infiltration into the site.

The efficient extraction and overall management of landfill gas.

- C5 It has been generally considered that the mean infiltration through a restored cap is approximately 50 mm/year¹. However, it is important to recognise that actual infiltration rates could vary between close to zero to whatever the appropriate effective rainfall value is². This variation, and the potential implications set out above, are the reasons why a risk-based approach to cap and restoration scheme design should be taken.
- C6 Infiltration through a landfill cap is controlled by four of the elements that are required by the Landfill Directive; namely the impermeable mineral layer, the artificial sealing liner, the surface water drainage system and the restoration soils including the final vegetation cover. It is therefore important to consider all these elements when assessing the hydraulic performance of a capping system. Each of these elements is considered below:

The Artificial Sealing Liner and Impermeable Mineral Layer

¹ Derived from LandSim in which 50 mm/year was proposed as the default infiltration rate through a capping system.

² ETSU, 1995, Review of the Behaviour of Fluids in Landfill Sites, ETSU B/LF/00465/REP, stated that infiltration through a landfill cap could vary between close to zero and 100 mm/year. However, this was before it was recognised that these systems could potentially degrade with time.

- C7 The artificial sealing liner and impermeable mineral layer are the elements of the capping system that are designed to have low permeability so as to inhibit the infiltration of water into the waste mass. For a mineral sealing layer, the ability to inhibit infiltration depends upon its thickness and permeability, while for an artificial sealing liner, important factors include the type of geosynthetic material used, jointing technique utilised, and the number and size of defects as well as the permeability of the materials that directly underlie it. If the underlying materials are of low permeability, then it may be possible to regard the capping system as a geomembrane/mineral composite.
- C8 As with the surface water drainage layer, it is important to recognise that the hydraulic functioning of the sealing layer might not necessarily remain constant with time. For example,
- Differential settlement of the waste mass might affect the integrity of both the impermeable mineral and artificial sealing layers.
 - The geosynthetic materials might degrade with time; and
 - The integrity of a mineral sealing layer might be affected by the growth of roots.
 - Potential for loss of integrity of the capping system around protuberances such as landfill gas and leachate monitoring/extraction wells.
- C9 As with the surface water drainage layer, the hydraulic functioning of the sealing layer can be assessed by a variety of techniques ranging from use of simple Darcian equations to the use of relatively complex software, such as LandSim. Again, whilst LandSim was not designed for this purpose, it is possible to parameterise this software so that it considers the potential leakage through a sealing layer. In order to do this, the software should be parameterised as if it were dealing with a landfill capping system rather than a basal containment system (including parameters such as mineral permeability, number and size of defects etc).

Surface Runoff Generation

- C10 Whilst the most important function of the capping and restoration system is to minimise the ingress of rainwater into the restored landfill site, it should also be recognised that it can also have a potential impact upon a site's ability to generate surface runoff. More specifically, the hydraulic functioning of the restoration soils and surface water drainage system could potentially impact both the timing and volume of surface runoff. This, in turn, could affect the magnitude of potential flood-risk presented by the restored site.

- C11 The assessment of the potential impacts upon surface runoff is complex. However, the following examples demonstrate the potential effects of the capping system.

Example 1: If a landfill has been restored within impermeable cover soils and an insufficient surface water drainage system, then the discharge of runoff from the restored surface will be both high and rapid.

Example 2: If, on the other hand, a landfill has been restored using sandy soils and a granular surface water drainage system, then the generation of runoff would be inhibited by the preference for the rainwater to infiltrate the soil profile owing to the permeable nature of the soils and the probable lack of antecedent moisture within the restoration profile.

- C12 However, once the restoration profiles of both of the above examples are fully saturated, then the nature of the capping system will not affect the generation of surface water runoff from subsequent rainfall events. However, it is far more probable for the first landfill's capping and restoration system to be fully saturated than that of the second example and so, for any period of time, the chances of rapid run-off would be greater for the first landfill than in the case of the second. This also will mean that a greater potential flooding risk is associated with the first capping system.

Landfill Gas Considerations

- C13 One of the main benefits from capping a landfill with a low permeability material is to improve the performance of the landfill gas management system. The Environment Agency has issued guidance on landfill gas management that the designer of a landfill capping system should be aware of and should make reference to it.
- C14 The guidance sets out the requirements of the directive, the framework under which landfill gas is to be managed and provides technical details and information of current best practice on landfill gas management. Further detailed guidance on gas management can be found in Industry Code of Practice 'The Management of landfill gas' (March 2012) and the relevant regulatory sector guidance.
- C15 The designer of the landfill cap should be particularly familiar with the 'Guidance for monitoring landfill gas surface emissions' as it is the integrity of the landfill cap that fundamentally controls these emissions directly to atmosphere.

- C16 The gas collection system is a key element in controlling and minimising risks from landfill gas and the **engineered cap** forms an integral part of this system.
- C17 The installation of gas wells and associated collection pipework are key features of a landfill gas management system and can have a significant potential effect on the capping system. Gas wells and leachate extraction wells and monitoring points are installed with head works above the surface. This facilitates management of the impact of settlement on the vertical pipework and to locate the wells/monitoring points. Connecting pipe work is either surface laid (when it needs to be laid onto a gradient to help manage condensate in gas pipework) for the first few years until the most significant settlement has occurred or is laid in the restoration soils again to a gradient to manage condensate. The protrusion of gas and leachate infrastructure through the capping system can also be a source of point source emissions of landfill gas. The design of the cap should ensure that the emission of landfill gas (or conversely the potential for air ingress under suction) around such protrusions is minimized.
- C18 The Landfill Directive recommends that a gas drainage layer is incorporated into the capping of landfills that are classified as non-hazardous. Gas drainage layers can form an integral part of the gas control system, with layers of coarse aggregate, sands, geonets or geo-composites being incorporated to collect gas when gas collection wells are not being installed in the waste mass. However, the designer should consider how such layers will interface with other elements of the system and whether they are compatible; for example how gas will be removed, whether it could provide a means for air ingress, what effects settlement might have, what protection measures would be needed, whether access can be provided for monitoring, and how deterioration in the long term might affect performance. In assessing the most appropriate design of environmental control measures for landfills, a risk assessment approach should be followed that will aid the decision making process.
- C19 The provision of a low permeability capping layer has a number of effects in relation to landfill gas:
- It minimises the uncontrolled emissions of landfill gas into the atmosphere thus minimising fugitive odour emissions and reducing any impact on local or global air quality. In this latter context, methane has a global warming potential 21 times that of carbon dioxide, and its uncontrolled release should be avoided.
 - The organic rich restoration soils placed above the low permeability capping material will serve to oxidise low emissions of methane that

permeate through the capping layers, thus further reducing the environmental impact of the landfill gas. The Environment Agency is conducting research into methane oxidation which is considered to be an important mechanism for passive gas control for end of life landfill management when gas combustion is no longer feasible.

- It increases the efficiency of gas management and control that can be achieved from the wastes beneath the cap as oxygen levels are kept at a minimum. The design of the cap should also encourage gas to move through the control system. This increases the quality of the gas which in turn aids the combustion process and increases the potential to utilise the gas.
- Reducing the ingress of air into the waste also minimises the risk of triggering landfill fires which can damage gas management systems irreparably, and which, once burning, are difficult to extinguish fully as the fire moves around using up available oxygen in the wastes. The issue of fires within landfills is the subject of the Industry Code of Practice on the Management and Prevention of Subsurface Fires dated June 2008 and to which the designer of the cap should refer.
- A cap will however increase the risk of lateral gas migration in sites that have deficiencies in their side wall lining as the potential for upwards gas movement and dispersal to atmosphere is removed. This is most likely to be an issue at existing older sites where the high standard of landfill lining currently required at newer sites has not been installed.
- The designer should also consider the gas permeability of the sealing layers, for example a geomembrane theoretically has much lower gas permeability than an impermeable mineral layer.
- By reducing the ingress of water into the wastes, the lower moisture content will in turn slow the rate of waste degradation and hence landfill gas production, thereby increasing the time period for on-going gas management and the length of the period until site completion is achieved.

C20 It is therefore vital for the landfill designer to fully assess the implications of the design and construction of the landfill cap to that of the site's landfill gas management and control systems.

C21 Whilst the capping system is the final component in the construction of the landfill, it is most likely to be installed progressively and needs to be

considered in the context of the environmental control measures, the site's closure, afteruse and long-term aftercare and post-closure management. Whilst the technical issues relating to landfill gas management are presented in separate specific regulatory guidance, related issues that the designer should consider are as follows:

- The potential for settlement to occur, especially during active extraction of landfill gas. With settlement there is potential for damaging the gas management system, the capping layer or both. Whilst uniform settlement of the waste can normally be accommodated by the capping materials, differential settlement around gas extraction wells, at phase boundaries, across the site or at the site perimeter can give rise to serious problems such as cracking of the cap or damage to the wells and pipework, thus opening up gas migration routes.
- The phasing of the installation of the capping and the gas management system. The gas management system may be installed concurrent with filling, or retrospectively when filling is complete, or by a combination of these techniques. Whatever the programme, the two need to be considered jointly.
- Both capping and gas control systems need to be subject to full Construction Quality Assurance, the detailed requirements for which are presented in separate technical guidance. However neither system should compromise the integrity of the other.
- Seals to leachate and gas extraction wells are a common source of problems, requiring careful design and frequent checking and maintenance
- Both systems are long term controls that may require repairs and maintenance if their performances deteriorate with time. It is therefore important to consider provision of vehicle access and if large vehicles for heavy repairs and maintenance might be needed, the capping, or parts of it, may need to be designed accordingly. If only light vehicles for routine monitoring and repairs are needed, access tracks should be provided that interface with the site's planned after-use, but which are kept to a minimum and do not damage the cap, its profile nor the restoration layers.
- If retrospective drilling of gas wells is proposed, the final slopes need to be graded to facilitate safe access and suitable platforms for drill rigs to operate safely and effectively.

- C22 At all times the designer of the cap should work closely with the designer of the gas management system and others to remain aware of any changes to the site's gas control scheme. This should be achieved through the risk assessment process which should be on-going and re-assessed periodically during the site's development, operation and closure. If at any time changes are required to the site's gas management plan, which is the specific document that sets out the framework for gas control and monitoring throughout the period that the site is permitted, the implications to the capping needs to be reviewed and addressed as appropriate.

After Use Considerations

- C23 The cap designer should be aware of after use intentions such as the desire to return the landfill site to high quality agricultural land, public amenity land or woodland. Dependent upon the operator's intended after-use, the designer should consider the impact of the intended after-use on the capping system that is being designed and it may be considered that certain after-use is incompatible with the environmental performance of the cap that is being designed. The operator remains responsible for maintaining, monitoring and controlling activities in the aftercare phase for as long as required by their permit. This means until the permit is surrendered. Where developments are proposed on closed landfills, those developments must not compromise the operator's ability to manage and monitor their site in accordance with their permit.

Other Factors

- C24 This section details a variety of other considerations that the designer should take into account when formulating the design of a capping and restoration system. The following is not intended to be exhaustive, since many issues are site specific. However it is intended to highlight the most common issues.

Nature of Waste Deposits

- C25 Whilst the Landfill Directive categorise waste as either; inert, non-hazardous or hazardous, the nature of wastes within these categories will be site specific. In particular, with the introduction of the concept of mono-disposal for hazardous waste, shear strength parameters and settlement characteristics will need to be reconsidered as the current accepted waste parameters will no longer be applicable for such sites.

Final Waste Lift

- C26 The final waste lift can have a significant impact on the hydraulic performance of the **engineered cap**, as the degree of differential settlement is governed by the materials forming this layer and the compactive effort applied when placing the layer.
- C27 Strains induced by differential settlement on the sealing layers may be minimised by selective placement of the incoming waste streams. The waste within the final lift should be of a consistent nature, devoid of large elements that may not degrade at the same rate as the majority of material. Objects such as containers and furniture that may collapse, leaving a void directly beneath the cap, should be removed from this layer or they should be crushed before disposal.
- C28 A higher degree of compaction of the final waste will not only reduce the magnitude of the total settlement beneath the cap but will also minimise the presence of voids within the waste that have been overlooked during placement of the layer.

Penetrations through the Engineered Cap

- C29 There are a number of management systems that need to penetrate the cap in a modern landfill facility, namely; leachate extraction wells, leachate recirculation pipes and landfill gas extraction and monitoring wells. Each of the penetrations through the cap needs to be sealed if the cap is to achieve its intended hydraulic performance. The method of sealing should be dependent upon;
- the materials used to form the sealing layers;
 - when the penetrating pipework is to be installed (i.e. pre/post-installation of the cap), and
 - the inclination of the penetration.
- C30 Where pipework penetrates through a mineral sealing layer, the materials can be compacted carefully around the penetration to form a seal. However, this seal may not be water tight or gas tight since it is not possible to ensure that compaction at the interface between the pipe and the mineral layer has been perfectly achieved. It will also prove more difficult to compact the mineral layer, if the pipework is installed after the installation of the capping system.
- C31 It is therefore considered that a bentonite seal should be used to achieve a water tight and gas tight seal. Upon placement of the mineral layer an annulus is excavated around the penetration, normally 300mm wide, which should be backfilled with hydrated bentonite. The swelling of the

bentonite upon the addition of water removes any pathways around the pipe for surface water to pass into the underlying waste. It is also considered that the bentonite seal will perform better than the mineral layer as the waste settles due to its ability to swell and its very low friction angle which will minimise forces on the pipework. Regular inspection and maintenance of the bentonite is required in order to minimise the potential for dehydration and desiccation to occur.

- C32 Penetrations through geomembrane cap should be sealed using a “top-hat” or “boot” detail. The geomembrane should extend above the level of the surface water drainage level and a bentonite seal provided. Penetration through a GCL cap should be sealed by the provision of the bentonite seal alone.

Drainage Systems

- C33 Consideration should also be given to construction details for the drainage layer particularly at the toe of the restoration profile, where a collection system should be sized, in consultation with a hydrologist, to provide sufficient capacity during a storm event. Prior to discharge of this water from the site, the water from the collection system should be controlled, via a surface water management system.

- C34 Precautions should also be taken to prevent silting-up of surface water ditches with material eroded from the restoration soils, particularly when the vegetation has not had sufficient time to establish itself. In such cases there are a number of options the designer should consider:

- construction of a sacrificial ditch up gradient of the permanent ditch, which will initially receive the surface water until such time that the vegetation has established itself;
- provision of erosion matting; or
- Installation of a barrier up gradient of the ditch to dissipate the energy of the flowing water prior to entering the ditch, such as a close boarded fence or a line of hay bales.

Phased Construction

- C35 The capping and restoration of a landfill is generally undertaken on a phased basis, in line with waste inputs achieving the required pre-settlement levels. The designer should consider therefore how adjoining phases of the capping system will be joined and how the system will operate in the interim period before the entire cap is completed. The following is not intended to be a definitive list but lists some of the considerations:

- How will the edge of the landfill be finished off to ensure that the layers which will need to be joined in the next phase of capping can be easily located and connected to;
- How will the gas drainage layer be sealed to allow the extraction of gas without drawing in oxygen;
- How will surface water be managed; and
- How will connections between adjoining phases be constructed if materials used in the capping system change?
- Design consideration needs to be provided to ensure that the installation of temporary capping over areas of waste which are to remain for indefinite time periods prior to further waste deposition taking place is adequately catered for.

Vehicle Trafficking

- C36 Vehicular access to the restored area is often required if a site is to achieve its intended end use, as a park land or agricultural land. To protect the cap, from excessive rutting and erosion along access routes, hardcore roads should be included.
- C37 The designer should consider the size and weight of the vehicles that may be required to access the site and, in the case of cranes or other plant, what area they will require in order to work safely and also the effect of the road on site infrastructure.

Ease of Repair and Maintenance

- C38 Given the possibility of breaches to the sealing layers, the designer should consider how the cap and any services within the cap can be repaired and maintained. A breach in the integrity of the sealing layers can result from a number of sources, such as accidental damage or degradation of the materials.
- C39 To repair such defects, careful excavation of the overlying soils is required such that further damage is not caused. Consideration should be given to the location of service corridors in relation to tree planting and hedgerows, such that excavation to expose the services does not result in damaging such features.
- C40 Leachate risers and monitoring points that are founded on the base of the landfill and extend vertically through the cap will tend to push-up through the restoration profile if sufficiently rigid. The designer should therefore make provision for such occurrences by either including telescopic

sections within the design of the riser or by allowing the upper sections of the riser to be easily removed, i.e. by making the joints threaded and the shaft sections shorter.

- C41 Of particular concern when undertaking repair and maintenance to a cap is the presence of landfill gases which under the right conditions could be explosive. This can restrict the use of welding and other electrical equipment in confined spaces. Any repair and maintenance works will need to take account of the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) (HSE 2002)

Erosion Control

- C42 Erosion of the restoration soils can prove problematic, particularly in the short term prior to the establishment of vegetation. The erosion of the soils from the restoration profile can not only degrade the ability of the restoration scheme to meet its intended end use but also can also impact on the performance of the surface water drainage system by clogging ditches and lagoons where it settles out or by discharging elevated levels of suspended solids to off-site water courses.

- C43 Depending on the prevailing soil types, the designer should consider the following options in order to control short term erosion:

- construction of the capping system to provide adequate time within the growing season for plants to establish themselves;
- provision of geosynthetic erosion control materials;
- provision of sacrificial ditches cut at shallow gradients across the slope to slow the velocity of runoff; and
- provision of surface armour where severe erosion is anticipated, i.e. ditches on steeper gradients or sudden changes in ditch direction.

SECTION D: STABILITY ASSESSMENT

- D1 When considering the capping and restoration system, the designer should demonstrate that the proposed system is stable and that the likely forces acting on each element of the system will not adversely affect their intended performance in both the ultimate and serviceability limit states. In order to demonstrate this, adequate factors of safety must be shown to have been achieved for the proposed design. If the assessment demonstrates that the proposed design is not able to achieve adequate factors of safety in respect of either stability or integrity, then the design must be altered. The designer should then revisit the initial design to determine whether one or more element of the capping and restoration system needs to be altered or the maximum gradient of the restoration

profile reduced. You must consider interactions between all the elements of the capping system in your stability risk assessment.

- D2 This section details the current practice of designing capping systems to landfills, which is based upon the recommendations made in the Environment Agency's R&D Technical Report³. The potential failure mechanisms are reviewed, general methods of analysis presented and then for each failure mechanism an analysis methodology is suggested.

Capping Failure Mechanisms

- D3 Failure of a capping system can be either due to instability of the slope profile or a failure in the integrity of one or more elements in the **engineered cap**. The stability and integrity of a capping system may be compromised by one or more of the following potential mechanisms:

- failure of the waste mass;
- failure along an interface within the capping and restoration system placed on a slope due to mass of materials;
- failure in the integrity of capping system due to excessive differential settlement; and
- other extraneous forces.

- D4 It should be noted that in a particular landfill not all of the above failure mechanisms may be relevant to a particular site and in an assessment the designer may screen out those mechanisms that are not applicable.

Method of Analysis

- D5 There are several methods of analysis available to investigate both the stability and integrity of the capping and restoration system. The designer should select and justify the methods selected to best represent the mode of failure being assessed.

- D6 It is not the intention of this report to detail and compare the merits of these methods and their reported accuracy. Designers should, where appropriate, carry out designs in accordance with Eurocode 7⁴.

Material Parameters

³ Environment Agency R&D Technical Report P1-385/ TR1 and TR2, 'Stability of Landfill Lining Systems', February 2003.

⁴ BS EN 1997-1 (2004) Eurocode 7 Geotechnical design. Part 1: General rules . Final Draft, EN 1997-1:2004 November 2004 , Brussels : European Committee for Standardization

- D7 The selection of appropriate shear strength parameters for the stability assessment is critical to the design process. The designer should justify the various parameters used in the stability analyses, in order to demonstrate that the conclusions of the stability assessment are sound.
- D8 Shear strength parameters can be derived in a number of ways:
- site specific testing;
 - empirical data taken from published research; and
 - back analysis of existing slopes or previous failures.
- D9 Site specific testing of the materials to be used is required by current landfill engineering specific guidance. Specifically, geosynthetic interface testing will need to be undertaken in line with the Industry Codes of Practice 'LGG115: Geosynthetic interface shear resistance testing' and 'LFE4 / LGG104: Earthworks in landfill engineering' and will require site specific testing.
- D10 The geotechnical parameters for limit equilibrium analysis include the shear strength and unit weight of each material within the model together with pore water or gas pressure assumptions and where appropriate stiffness.

Waste

- D11 The laboratory testing of waste parameters is extremely difficult since commercial laboratories do not have the facilities to undertake such testing and in any case the materials tested will probably not represent what is actually on site. It is therefore recommended that published data on the shear strength, unit weight and elastic properties of the materials are used except where wastes can be characterised accurately in laboratory conditions (e.g. in the case of certain relatively homogenous industrial wastes).
- D12 The designer should consider conservative parameters initially, but if existing conditions on site can be shown to demonstrate that the initial assumptions are too conservative then the parameters can be adjusted accordingly with appropriate justification being provided. A review of published data is presented and recommendations made as to the shear strength and unit weight of waste in TR1⁵.
- D13 Leachate and landfill gases can also affect the stability of the waste mass, and these can be modelled using the pore water pressure ratio (R_u). Recommendations are made in TR1 as to the appropriate value of R_u ,

⁵ Environment Agency R&D Technical Report P1-385/ TR1 and TR2, 'Stability of Landfill Lining Systems', February 2003. TR1 – Section 8 "Waste Properties"

although should the initial calculations demonstrate that the assumptions are too conservative or if the site has an active gas extraction system, then the value may be reduced to reflect the specific site conditions.

Geosynthetics

- D14 The interface shear strength characteristics of geosynthetic products such as geotextiles and geomembranes are of paramount importance. In the case of geosynthetic clay liners and geocomposite drainage layers the internal shear strength of the material is also important.
- D15 The interface shear strength between the various elements of the capping and restoration system are site and product specific. Accordingly, laboratory testing, specific to the materials to be used, will be required.
- D16 Laboratory measurement of the interface shear strength between geosynthetics and soils is now undertaken at a number of commercial laboratories and research establishments. The derivation of the appropriate shear strength parameters from laboratory testing is discussed in TR1⁶.
- D17 The internal shear strength is a function of the product alone and is therefore not site specific. The designer may use data published by the manufacturer, if they are available. However, the designer should determine under what conditions the material was tested, as this can have a major impact on the performance of the material, (eg the degree of hydration of a GCL and the stress conditions under which it was hydrated). If the test conditions do not replicate those anticipated on site then further laboratory testing will be required in order to determine the internal shear strength of a product where this is applicable.
- D18 Since the interface and internal shear strength parameters are product specific and the majority of capping construction works are undertaken on a contract basis, the designer may not have the actual input parameters for the analysis at the design stage. It is therefore recommended that the designer should use conservative values derived from published data for type of products to be used in the design. The specification should then detail a minimum shear strength criterion for each interface and a minimum factor of safety to be achieved for a specified set of site conditions. Site specific interface testing should then be undertaken and the stability calculations re-run.

⁶ Environment Agency R&D Technical Report P1-385/ TR1 and TR2, 'Stability of Landfill Lining Systems', February 2003. TR1 – Section 7 "Interface Shear Strength"

- D19 As part of the contract it should be required that the contractor provides supporting data to demonstrate that the products proposed exceed the minimum shear strength requirement criteria, and can achieve the required factor of safety, prior to their inclusion in the works.

Soils

- D20 Laboratory testing of the soils on site will be required.
- D21 Where soils are to be imported into site the designer should demonstrate that the capping and restoration system is stable based upon conservative shear strength parameters. The specification should then require the contractor who will be providing the soils to site to demonstrate that the material can achieve the required specifications for the given site conditions, prior to the material being approved.

Analysis

- D22 The following sections provide guidance as to appropriate methods of analyses for each of the mode of failure discussed above, detailing the required input parameters and identifying where mitigating measures may be adopted in order to screen out a possible mode of failure.

Waste Slope Stability

- D23 This mode of failure can involve a deep seated failure of the waste that passes predominantly through the waste, but which will affect the integrity of the capping and restoration system if this has been installed.
- D24 The stability of waste slopes at the gradients usually adopted for restoration have historically not been problematic. However, with the introduction of mono-disposal under the Landfill Directive and the increase in the percentage of material that is recycled, the nature of waste will change in the future.
- D25 The stability of the final restoration profile is rarely considered to be the worst case scenario when considering the stability of the waste mass as part of a Stability Risk Assessment for a Permit Application. However, the designer should consider the changes in the leachate levels and gas pressures in the long-term as these could prove to be critical to stability. The Stability Risk Assessment should also be re-visited should the site be closed or mothballed prior to the final restoration profile being achieved and where any waste slopes are steeper than originally designed.

- D26 The stability of the waste slope may be modelled using a limit state equilibrium technique. There are many computer packages available on the market capable of undertaking such analytical work.
- D27 The following input parameters will be required for the analysis:
- overall restoration profile;
 - shear strength parameters of waste;
 - shear strength parameters of the lining system and underlying geology; and
 - pore fluid pressure regime (leachate and landfill gas conditions within the waste).
- D28 The assessment should concentrate upon the pre-settlement profile as this will be the worst case scenario. Depending upon the geometry of the waste and underlying lining system and the underlying geological conditions, the critical failure plane could pass through or along the lining system as well as the waste. Hence, both circular and non-circular failure modes should be investigated.
- D29 The pore fluid regime in this analysis is considered to be a principal area of investigation, since the factor of safety for the slope prior to capping would have been in excess of unity in order to have constructed the cap. Subsequently, the only parameters which are likely to vary are leachate heads and landfill gas pressures, which prior to capping would not have been contained.
- D30 It is generally considered unnecessary to include the shear strength parameters of the capping and restoration system in the stability model, as they will usually have little effect on the stability of the waste slope, since they account for a relatively small proportion of the profile through which the failure would occur.

Interface Failure

- D31 A failure along one of the material interfaces within the capping and restoration system is considered to be the most critical mode of failure in most cases.
- D32 A limit state equilibrium package may be used to analyse such a failure mode, although a closed form calculation method proposed by Jones & Dixon (1998)⁷ is considered most appropriate. The calculation provides

⁷ Jones, D.R.V. & Dixon, N. (1998). The Stability of Geosynthetic Landfill Lining Systems. Published in Geotechnical Engineering of Landfills, Thomas Telford, London, 1998.

- an assessment of the stability of restoration soil over several layers of geosynthetics together with an assessment of the tension within the geosynthetics.
- D33 This method of analysing the stability of the component parts of capping uses the following input parameters:
- worst case restoration gradient;
 - slope height;
 - properties of restoration soil;
 - interface shear strength data on each of the component parts within the capping design; and
 - parallel submerged ratio.
- D34 By analysing the proposed design based on the worst case pre and post settlement contours, i.e. gradient and height of slope the feasibility and/or the minimum shear strength of each element of the design can be assessed. Minimum shear strength parameters will need to be determined via site specific shear box testing.
- D35 The parallel submerged ratio (PSR) is the ratio of the height of the groundwater surface within the soil, above the impermeable geomembrane or clay barrier, to the total depth of the soil from the surface, to the impermeable geomembrane or clay barrier.
- D36 The calculation of stability and geosynthetic integrity is sensitive to the PSR value. The PSR can be influenced by a number of factors, such as the:
- presence of a drainage layer above the sealing layers;
 - establishment of vegetation;
 - permeability of the restoration soils; and
 - climatic conditions.
- The designer should demonstrate therefore that the assumed PSR is appropriate.
- D37 The designer should also consider how the capping and restoration profile will be affected over time as settlement occurs. For example, the clogging of a drainage layer could lead to an increase in the PSR over time.
-

- D38 Stability of the capping system can also be affected by landfill gas pressures beneath the sealing layers. A close form calculation to assess gas pressure on the integrity of the capping liner components was proposed by Thiel (1999)⁸. Within this calculation, one of the most sensitive parameters (u_g) is that of the gas pore pressure on the lower side of the geomembrane. It is considered that this parameter is difficult to quantify in the absence of meaningful instrumentation data. However, if active gas extraction is taking place then excessive gas pressures should not develop in the first instance, and consequently the effect on the integrity of the cap due to gas pressure should not be an issue.
- D39 During the construction of the capping and restoration system, the integrity of the geosynthetic elements is at risk due to the possibility of a block sliding type failure as the construction traffic places the material and this should be considered by the designer. Kerkes (1999)⁹ presents a solution algorithm for the calculation of factor of safety against block sliding and tensional failure within a geosynthetic, when forces from construction equipment are induced into the capping system.

Differential Settlement

- D40 Whilst the overall strains induced by the settlement of underlying waste are generally not sufficient to affect the integrity of the sealing layers, differential settlement within the waste can result in excessive straining of the **engineered cap**.
- D41 Differential settlement can be the result of a number of factors:
- Founding of heavy structures on top of the cap;
 - Active gas extraction at widely spaced wells;
 - The location of leachate re-circulation infrastructure;
 - Leachate recirculation;
 - Presence of relatively large incompressible objects within the waste immediately below the **engineered cap**; and
 - Presence of voids within the waste immediately below the cap
- D42 The installation of heavy structures, such as leachate storage tanks on top of the capping system should be avoided wherever possible although it is recognised that this may be necessary at sites with limited land available

⁸ Thiel, R. (1999). "Design of a gas pressure relief layer below a geomembrane cover to improve slope stability".

⁹ Kerkes, D. J. (1999). Analysis of equipment loads on geocomposite liner systems. Published in Proc. Geosynthetics 1999.

for such ancillary structure. However, in such circumstances it is possible to design a slip mechanism around such a feature to accommodate the differential settlement.

- D43 Careful selection and compaction of the final waste lift and the waste regulating layer will reduce the risk of differential settlement, particularly in respect of large incompressible objects. Similarly, spacing of gas extraction wells should be sufficiently close to achieve homogeneous extraction, and thus avoid differential settlement taking place around well heads.
- D44 A close form calculation, proposed by Jones & Pine (2001)¹⁰, can be used to assess the presence of a void on the integrity of the capping liner component. Again it should be noted that, if the final lift of waste is carefully selected and a waste regulating layer used, voids in the top layer of waste will not form, and consequently the need to conduct this analysis becomes unwarranted. For most landfills this is probably the safest solution to maintain the integrity of the geosynthetic used.

Other Extraneous Forces

D45 The presence or likelihood of other extraneous forces damaging a capping system should be considered on every site. Such forces may be unique to a particular site, but nevertheless it is the responsibility of the design engineer that they should be considered. Some examples of such forces are given below, but this list is by no means comprehensive:

- side slope rockfall;
- side slope soil failure;
- erosion by surface waters;
- erosion by flood waters;
- erosion of restoration soil by other means;
- damage caused by uprooting of large trees growing on restoration soil;
- earthquake or vibration damage; and
- vandalism.

SECTION E: SUMMARY OF DESIGN METHODOLOGY

E1 The design methodology which should be followed is summarised in the flow chart presented in Figure B7.

¹⁰ Jones, D.R.V. & Pine, R.J. (2001). Design of inclined geosynthetic lining systems for vertical landfill expansion. Published in Proceedings Sardinia 2001, Eighth International Waste Management and Landfill Symposium. Edited by S. Margherita di Pula, Cagliari, Italy, 1-5 October 2001.

- E2 The design of a capping and restoration system is considered to perform a number of functions, the most significant of which is to protect the environment. This is achieved by controlling the emission of landfill gas, by minimising the generation of leachate and by separating waste from the environment.
- E3 It is therefore considered that the primary design considerations relate to landfill gas and hydraulic conditions, and that the most important aspect of the design is to determine an appropriate infiltration rate that will encourage a more rapid stabilization of the waste, thereby increasing gas generation, whilst minimizing the leakage of leachate through the basal liner. Figure B8 presents a flow chart for the determination of the required infiltration rate for the engineered cap.
- E4 Once this has been determined then suitable materials for the **engineered cap** can be selected and secondary considerations can be brought into the design.
- E5 The stability assessment should be integral to the design process and should consider the hydraulic, landfill gas, end use and other considerations that have been used to develop the design of the capping and restoration system. The assessment will determine appropriate slope angles and heights for the capping system which can then be used to inform the restoration design.

FIGURE B7: DESIGN OF CAPPING AND RESTORATION SYSTEM FLOW CHART

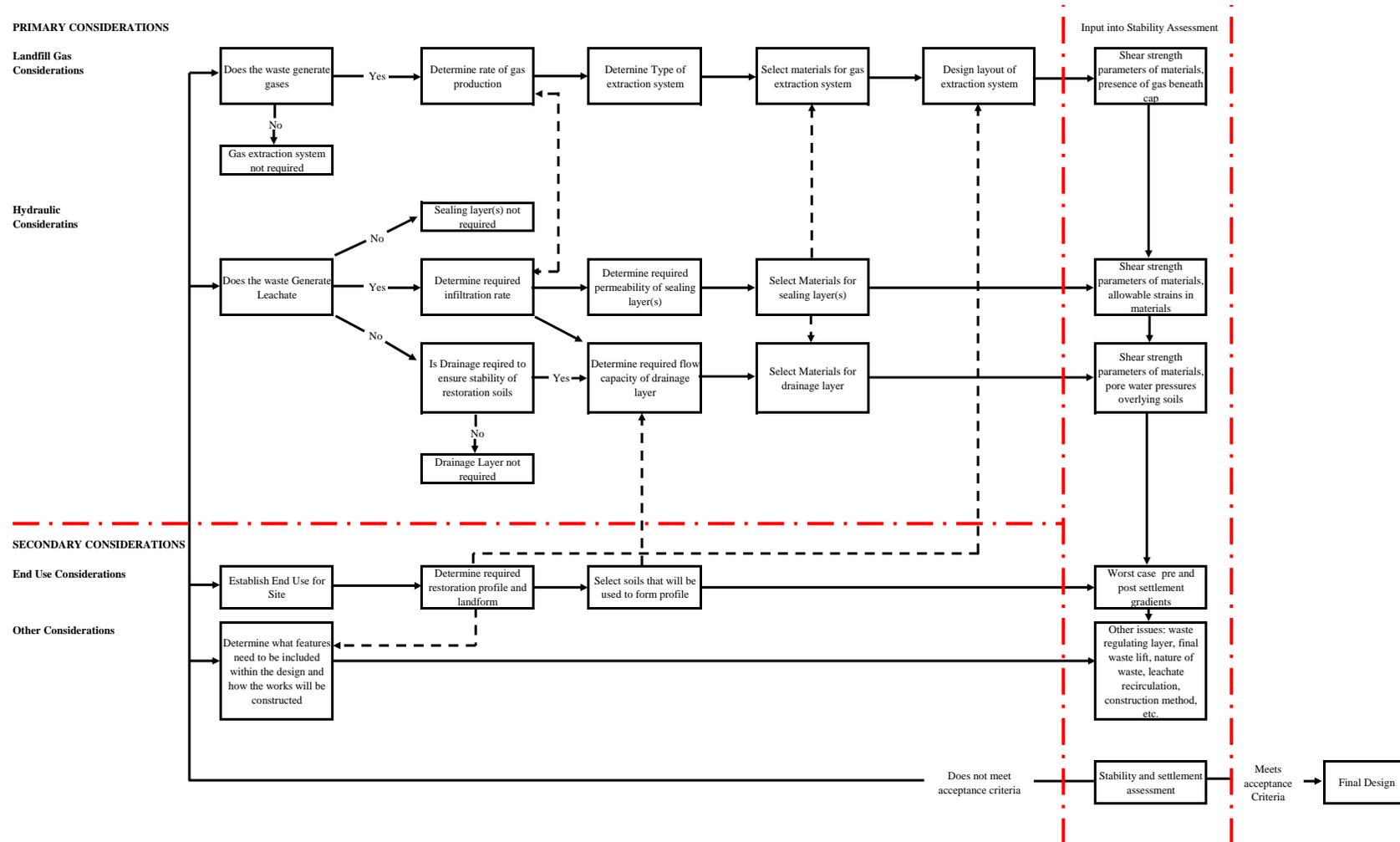


FIGURE B8: CALCULATION OF THE INFILTRATION THROUGH THE CAP DESIGN FLOW CHART

