EXPERIENCE WITH GEOSYNTHETIC DESIGN AND CONSTRUCTION OF LANDFILL STEEPWALL LINING SYSTEMS

E. M. G. Gallagher
EDGE Consultants UK Ltd, Atlas House, Manchester, England

A. D. Needham
EDGE Consultants UK Ltd, Bretby Business Park, Burton-on-Trent, England

D. M. Smith
EDGE Consultants UK Ltd, Reading, England

ABSTRACT: Creation of waste depositories in deep quarries with steep side walls (so called “canyon landfills” in the USA) is possible and can lead to economic development of sites and maximisation of void space utilisation. Various technical challenges must be addressed to create suitable conditions for lining with geomembranes at angles greater than 45° from the horizontal. Site specific factors include location, geometry, topography and anticipated waste streams. Next, the site geology and hydrogeology should be assessed in the context of groundwater protection. Engineering considerations relating to liner design include adequately supporting, securing and protecting the geomembrane, determining the optimum interface shear regime appropriate to multiple layers of geosynthetics, provision of appropriate drainage, interfacing with cap and basal liners as well as safety and buildability issues. A range of patented and proprietary systems, which use a variety of geosynthetics, has attempted to meet these requirements. Implications of the European Landfill Directive on steepwall lining systems are considered. The paper discusses the authors’ experience over a number of years in designing and supervising construction of steepwall lining systems for deep quarry landfills. Geosynthetics can be utilised to prevent unacceptable leakages of leachate and gases from the landfill. The paper reviews how this goal can be achieved in the context of ensuring a stable system and maintaining the integrity of the primary barrier.

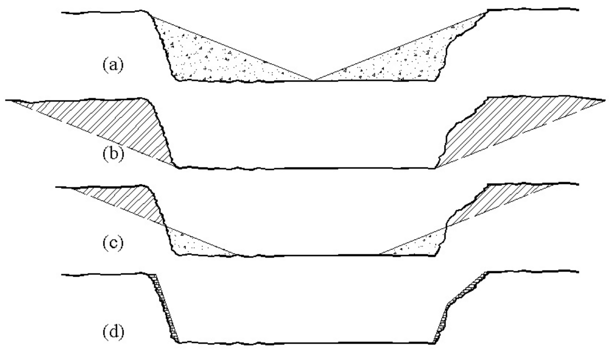
1 INTRODUCTION

Steep side walls to quarries and pits have been lined successfully to form containment landfills. Examples of such lining systems from the UK, USA, continental Europe, Australasia and Hong Kong are in service and demonstrate the versatility and potential of multi-layer geosynthetic barriers. Nevertheless, there remain significant technical challenges to be overcome in providing robust, stable designs for deep quarry landfills.

Steepwalls are defined here as landfill lining systems at greater than 45° from the horizontal. Non-mineral steepwall systems utilise various geosynthetics as barrier, drainage and protection layers placed against a smoothed supporting surface. Most steepwall systems depend upon lateral support from the waste for their stability, i.e. they could rarely be built to full height without support from the waste body.

If sufficient quarry reject or other materials are available, then the steep side slopes of a quarry may be reduced typically by filling to a 1 (vertical):2.5 (horizontal) gradient to allow the construction of a conventional composite geomembrane and mineral liner (see Fig.1). If land is available, the steep slopes may be re-profiled to this gradient by a cut and fill operation. Filling to flatten the slope can be uneconomic as it reduces valuable landfill void, especially in deep quarries, and requires considerable quantities of surplus materials to be available. It is useful to consider that the filling volume and gross void loss for flattening a 60° quarry face, 30m high to a 1:2.5 slope is 8,650m^3 for every 10m length of the face. In this context, use of a robust and effective steepwall lining system may mean the difference between a landfill meeting or failing financial criteria for the development of the site. During the operational life of a landfill, steepwall systems are usually built by staged construction in lifts as the waste level rises, enabling revenue income to be used rather than up-front capital expenditure. In addition, the liner is therefore not left exposed for long periods and vulnerable to damage as would be the case if constructed to full height from the start.

The range of steepwall systems in use is broad and has been summarised previously in the literature (see Blum, 1999; Brown *et al*., 1999; Cowland, 2000; Di Stefano & Needham, 1994; Edelmann *et al*., 1999; Gallagher *et al*., 2000 and 2003; and Ruppert, 1992).



Formation of slope for mineral liner (1V : 2½H shown) by (a) fill, (b) cut, (c) cut and fill. Latter two depend on land availability.
(d) Steepwall lining, following the existing quarry wall profile.

Figure 1: Options for lining quarry voids

The two main types of steepwall system in use in the UK are reinforced soil with polystyrene facings (see Fig. 2) and variations on the theme of revetment type frameworks (see Fig. 3). At the time of writing about 14 UK landfills have steepwall systems and several other sites are actively considering use of steepwall liners. An alternative approach developed by Ruppert (1992) in Germany is shown in Fig. 4. Shotcrete has been used for levelling-out and support in Hong Kong (Cowland, 2000) and New Zealand (see Fig. 5) prior to placement of the lining geosynthetics but is generally not favoured in the UK on grounds of cost.

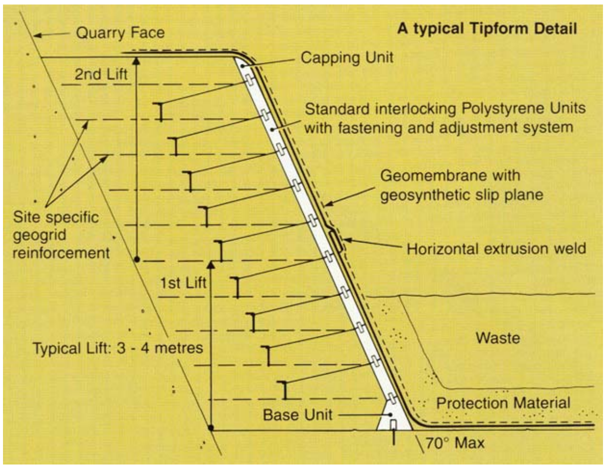


Figure 2: Typical construction detail for reinforced soil with polystyrene facings steepwall system.

Figure 3: Revetment framework type steepwall system during construction within an operational landfill cell. The contractor requires a 6m to 8m clear bench and works in 3m vertical lifts from the base up. The landfill operator benefits from paying for the steepwall construction from his revenue income as the site is filled with waste rather than as part of the initial capital expenditure.

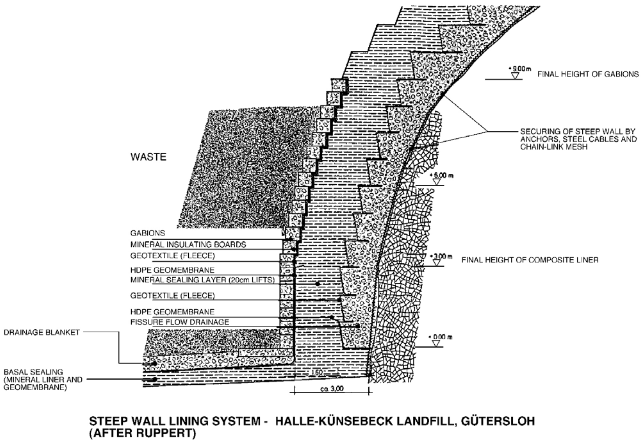


Figure 4: Steepwall lining system, (after Ruppert, 1992).

Figure 5: Installation of steepwall geosynthetics against a trim-blasted then shotcreted quarry face. In this instance, a GCL has been placed against the shotcrete, then a double layer of low density polyethylene is used to create a low shear interface. The face will subsequently be protected by a layer of waste plastic in bulk sacks before placement of the landfill waste.

The authors are also aware of various steepwall systems outside of Europe which comprise multi-layers of geosynthetics placed directly on the quarry wall (see Fig. 6). Treatment of the quarry face can potentially include pre-split blasting, smooth or trim blasting, stitch drilling, pyrotechnics, expansive grouts or pneumatic breakers. In all these cases, it is anticipated that significant protection of the geomembrane would be required.

Figure 6: Steepwall multi-layer geosynthetics draped in one continuous layer directly against a quarry wall prior to placement of waste; in this case the geosynthetics are secured by an earth bund at the slope crest.

2 COMPONENT GEOSYNTHETICS IN STEEPWALLS

Steepwalls are perhaps unique in offering the opportunity and challenge of utilising geosynthetics in multiple, adjacent layers for such a broad range of functions including: barrier, protector, shear interface, reinforcement and drainage. Filtration and separation are generally secondary or ancillary geosynthetic functions within steepwalls. It is the exception for all functions to be required within one system.

2.1 *Geomembranes*

Geomembranes offer flexibility, are generally compatible with basal and cap liner construction and are well understood. They are readily handled on site, amenable to construction quality assurance (CQA) and are cost effective. Welding of steepwall geomembranes can prove more complex than basal geomembranes. Depending upon the system, more extrusion welding can be required compared to basal liners, the welders have to work in a non-horizontal plane and weld lengths are generally much shorter. Steepwall geomembranes can differ in formulation from the standard basal high-density polyethylene (HDPE). Various geomembranes have been used for steepwall lining including HDPE, LLDPE, VLDPE (linear low density polyethylene and very low density polyethylene, respectively) and polypropylene. The difference in materials to be welded at joints (base to steepwall, also steepwall to cap) affects the selection of the weld temperature and welding rod etc. These challenges demand that adequate allowance is made in drafting particular specifications, CQA inspection regimes and tender documents.

The semi-crystalline nature of HDPE makes it particularly prone to stress cracking compared to LLDPE. The avoidance of constant stress on a HDPE geomembrane in a steepwall lining system has to be considered carefully with the provision of adequate protection and by ensuring isolation from waste down-drag stresses. It can be argued that the more forgiving characteristics of LLDPE compared to HDPE outweigh the lower long-term durability of LLDPE in steepwalls, given the less onerous exposure conditions (compared to basal liners) and the barrier function of a drainage geocomposite.

2.2 *Geotextiles*

Geotextiles are used primarily in steepwalls as protection layers, in which case needle-punched non-woven fabric is the preferred option. Woven geotextiles have also been specified by the authors in double layers to form low-shear interfaces.

The adequacy of a proposed geotextile protector can be demonstrated by means of a cylinder test (Environment Agency, 1998), a performance test devised specifically for HDPE. The cylinder test investigates the proposed site-specific profile of materials (drainage aggregate, protector and HDPE) all contained within a 300mm diameter confining cylinder when subjected to pressures comparable to those at the base of a landfill. Loads are factored by up to 2.5 to account for temperature and time effects. Deformations in the geomembrane from the overlying drainage aggregate, which are transmitted through the geoprotector to the HDPE, would not be readily discernible on disassembly after the tests because of the elastic rebound of the geomembrane. These deformations are recorded on a thin sheet of lead plate positioned under the HDPE. Deformations in the lead sheet are compared to a maximum permissible “local strain”, currently defined as 0.25%.

Although the practicalities of the test are straightforward and it is accepted as a useful means to demonstrate geoprotector efficiency, the linkage between the failure criterion and the rheological properties of HDPE is less transparent (refer to Gallagher *et al*., 1999 also Seeger, 2003 for fuller discussions). The various limitations in the cylinder test have important implications for steepwall design. Strictly, the cylinder test is only valid for investigating protector efficiency in conjunction with the semi-crystalline membrane, HDPE, and, according to Seeger (2003), only at a thickness of 2.5mm. There are no alternative, broadly accepted failure criteria for other less crystalline geomembranes such as polypropylene or LLDPE. Additionally, the failure criterion (0.25%) for HDPE can be questioned as over conservative and of dubious justification, having been based on results extrapolated from long-term hydrostatic tests on HDPE pipes. The factor of 2.5 on loading can also be questioned as over conservative. The overburden pressure used in the test is a multiple of the landfill depth and unit weight of waste, prior to being factored. This pressure must be factored by a lateral pressure coefficient in the case of steepwalls. Lateral pressure within waste bodies is the subject of ongoing research. Finally, the profile of materials envisaged in the original cylinder test is much simpler than many steepwall system profiles. Steepwall profiles can include a geomembrane sandwiched on each side by complex sequences of support material and drainage and protection geosynthetics.

Despite numerous reservations in relation to the currently available means for determining protector efficiency, the cylinder test is still considered by the authors to be a useful if limited tool in steepwall design when used with caution.

2.3 *Geocomposites*

A drainage layer is required to the waste side of the primary liner to act as conduit for downward flow of leachate to basal leachate drainage system. This drainage layer also acts as the conduit for upward flow of landfill gases, interfacing with the cap gas management system. The steepwall drainage layer effectively provides a preferential drainage path for leachate compared to gravitational flow through the waste body and minimises perched leachate heads at the periphery of the waste body.

Geocomposites are particularly suitable and economical means to provide the required drainage capacity. Standard flow net analysis can be used to determine leachate loading for subsequent assessment of required permittivity, transmissivity and filtration as appropriate to the system and materials under consideration. These calculations tend towards the conservative for a number of reasons:

- leachate loading at steepwalls is occasional rather than continuous;
- the flow regime within a waste body is generally dominated by vertically downwards rather than lateral flow (noting that waste types, placement methods and cover materials may affect flows);
- some steepwalls systems provide additional voids (e.g. large spaces between bulk sacks) which are generally ignored; and
- the waste body is assumed fully saturated although a partially saturated state will generally prevail especially at its perimeter.

Design should allow adequate additional capacity to accommodate biological clogging, although it is arguable whether this impacts significantly on steepwall geocomposites. In general, geocomposite design can readily demonstrate significantly greater flow capacity than that required and certainly more than adequate to accommodate potential reductions due to biological clogging (Gallagher, 1998 and Koerner & Koerner, 1992).

2.4 *Geosynthetic clay liners (GCLs)*

Although geosynthetic clay liners (GCLs) can in principle be used to form the primary barrier in a steepwall system either as a single liner or as part of a composite system, this has not been usual UK practice to date (examples of some non-European steepwall systems incorporating GCLs are shown in Figs 4 and 5).

A GCL depends upon intimate and continuous contact with the two layers on each side together with prompt application of confining pressure as its bentonite powder sealing component hydrates. Steepwalls are not ideal applications to achieve these conditions. The two layers each side of the GCL should ideally be of low permeability to avoid leaching of bentonite from the GCL. It is doubtful whether this criterion is adequately satisfied on the underside. It is then questioned whether hydration can be adequately achieved, of particular importance for preventing gas migration.

GCLs are relatively heavy compared to other geosynthetics, particularly in their hydrated state and require adequate support and fixity to the steepwall support system or quarry face. In turn, the designer must consider how these stresses at the fixing points will be accommodated within the GCL. Typical GCL comprises a woven carrier geotextile sometimes bonded but more generally stitched or needled to a needle-punched non-woven geotextile. The design must review how this combination will behave under load in the short and long term. What for example is the propensity for downward creep of the bentonite when GCLs are used in near vertical orientations? GCLs will be held in place by the waste, particularly as the slope angle decreases. Formation of effective joints in GCLs at near vertical inclinations is challenging. Interface shear must also be considered as with all multi-layer geosynthetic systems. In summary, there are many serious challenges to be overcome if it is proposed to use GCLs in steepwall lining systems.

3 EUROPEAN LANDFILL DIRECTIVE

3.1 *Engineering requirements*

The Landfill Directive (Council of the European Communities, 1999) introduced a common regulatory framework across the European Community for the permitting of current and future landfill for various categories of waste. Implementation by member states of detail within the Landfill Directive is likely to show some national variation in interpretation. Implementation in the UK commenced on 15th June 2002 with the Landfill Regulations (Stationery Office, 2002), to be followed by similar legislation in Scotland and Northern Ireland. The UK Environment Agency has produced a series of guidance documents on the legislation (Environment Agency, 2002a and 2002b). Key points, particularly relating to steepwalls, from these various documents are paraphrased below, with a commentary given separately.

The two overriding principles applicable in all cases for short, medium and long-term assessment of engineering proposals of lining systems are that there must be no risk of unacceptable emissions and that physical stability of the lining system and wastes must be assured.

Engineering requirements vary depending upon site location and the type of waste accepted. Most municipal solid waste (MSW) sites will be classified as non-hazardous landfills in which case the base and the sides should consist of a geological barrier comprising a mineral layer satisfying a permeability $k \leq 1.0 \times 10^{-9}$ m/s and a thickness ≥ 1.0m. For hazardous sites, the thickness requirement is ≥ 5.0m for a permeability $k \leq 1.0 \times 10^{-9}$ m/s. Where the natural geology does not meet these conditions, it may be augmented, giving equivalent protection but, in this case it should be at least 0.5m thick. Exceptions to the above are where the geological barrier provides protection in or on major aquifers, within source protection zones of minor aquifers and in certain sub-water table situations. In these instances the geological barrier must be of in situ low permeability material meeting the permeability and thickness criteria without being artificially enhanced.

Additional to the geological barrier, an "artificial sealing liner" and a leachate drainage layer >0.5m thickness (hydraulic conductivity not specified) are required for the base of all sites where there is a need to collect leachate. Subject to site-specific risk assessment, it may be shown that the artificial sealing liner is not required for some non-hazardous landfills. Further, it may be shown subject to site specific risk assessment that an artificial sealing liner does not need to extend up side slopes or, by inference, up steepwalls. The need for an artificial sealing liner on side slopes/steepwalls must be assessed in terms of landfill gas considerations as well as preventing potential leachate emissions.

3.2 *Commentary*

As reported above, it is now a requirement that there is a geological barrier in the side slopes in accordance with the Landfill Directive. Often the natural geology will provide this barrier, but where fractured rock or other highly permeable material is present between the quarry face and the groundwater, or other relevant compliance point, then the geological barrier may have to be provided within the steepwall system. Clay or other low permeable material may then have to be incorporated as a continuous zone within the artificial support system. Systems specifically designed to meet the new requirement have yet to be constructed. These changes pose the need and opportunity to develop alternative approaches to achieve adequate compliance with the Directive.

The introduction of the requirement for the geological barrier to extend up the sides of landfills marks a significant point of transition in the design of steepwall systems as used to date in the UK. It is arguable whether there is technical justification for the prescriptive geological barrier requirements for steep quarry side slopes (as introduced in the Landfill Directive).

Wider engineering implications of the Landfill Directive on steep sidewalls relate to possible changes in the composition and geomechanical behaviour of the waste body from the less biodegradable waste stream. These could include changes to the density, settlement behaviour, absorptive capacity, shear strength and permeability of wastes. These will affect the stresses imposed on steep sidewall liner systems, potentially reduce differential settlements between the waste and the steepwall system, and have implications on their stability.

4 STEEPWALL DESIGN CONSIDERATIONS

4.1 *Quarry wall stability*

The stability of any steep quarry slope should be properly assessed as part of the review of suitable steepwall liner options. The verticality and integrity of any quarry wall depend on the geology and rock fabric (fractures including bedding planes, joints and faulting. A comprehensive assessment of any quarry should be made at an early stage by a Geotechnical Specialist (Stationery Office, 1999) to assess the need, extent and methods of remedial works to minimise the risk of rockfalls during the steepwall construction and subsequent landfilling.

Having assessed the suitability of the site as a potential landfill and the potential means of lining the side walls, the key design criteria for any steepwall systems are:

- provision of an adequately smooth supporting surface, as required;

- ensuring the stability of the whole system; and
- selection of a system that will ensure the required support, integrity and compatibility of the barrier, the protector and the drainage layers in the context of a settling waste body.

Steepwall facing and lining systems need to provide a smoothed surface for any subsequent lining system to overcome irregularities in the quarry wall profile including corners and significant benches. This may be achieved by preparation of the quarry face by techniques including scaling, blasting and gunite (i.e. shotcrete or sprayed concrete), or by constructing an artificial surface. Next, the lining system, supported by the prepared quarry face or artificial surface, must provide adequate barriers and drainage consistent with the site requirements.

4.2 *Steepwall system stability*

The stability of the whole steepwall system should be assessed in terms of the support available from the underlying quarry wall, the internal stability of the proposed system and the degree of lateral support available from the waste body. Stability must be assessed and satisfied in the construction condition, in the long term (full depth of landfill) and for interim loading scenarios. Dixon & Jones (2003) have proposed a framework for assessing steepwall stability and integrity.

The authors of this paper have developed a numerical analysis approach to assess likely stresses and deformations from backfill stone upon revetment type steepwall systems. The 2-D finite difference program FLAC, an industry standard geotechnical continuum modelling and analysis tool, was used. See Fig 6 showing typical FLAC outputs demonstrating beneficial silo/arching mechanisms developing within the backfill stone. The lateral pressures internal to the framework system derived from these analyses are generally around 65% of those obtained by standard K_a assessment, backing up site observation of various systems and leading to more economical revetment design.

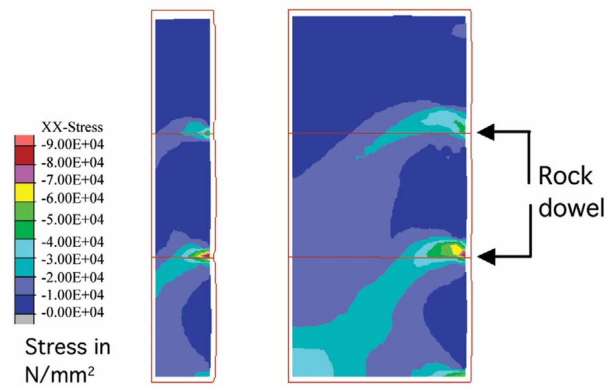


Figure 6: Typical lateral stress distribution contours within the backfill stone derived from finite difference models of revetment-type steepwall systems of two different widths (offsets from quarry wall) showing beneficial arching effects concentrated at rock dowel positions. Quarry wall shown to the left of each model, framework system to the right shows deflections. The two models shown are 4.2m high and of 0.7m and 2.0m widths.

The support provided by the waste is integral to the design philosophy of several steepwall systems. Additionally, the strains in the steepwall system resulting from the differential movements between the steepwall system and the landfilled waste have to be taken into account, as do the differential strains between the system and the quarry face. This is not a new problem as it is akin to the considerations in earth dam design where differential movements occur within the dam between the different materials (e.g. clay core and rockfill shoulders) and between the dam and the adjacent natural ground abutments (Sherard *et al.*, 1963). The lower the lateral support and the greater the differential movements, the larger the strains within the steepwall construction will be. In recognition of this, the polystyrene faced reinforced soil system was originally designed in 1992 with a substantial zone of high density, low settlement "inert" wastes placed in front of the completed system to act as a stiff buttress. A further benefit of the low compressible waste zone was the reduction in the differential settlement in the cap across the waste/quarry edge transition. The reduction in the availability of these wastes has made the provision of such buttressing more difficult but as waste types change following implementation of the Landfill Directive requirements, less compressible wastes should again become more plentiful.

Edelmann *et al*. (1999) undertook full-scale laboratory tests that compared the effects of weak and stiffer wastes on a steepwall clay liner. The laboratory tests were undertaken with two different waste materials simulating a weak waste such as MSW and a stiffer waste such as MSW incinerator residues. The test arrangement modelled a construction height of 37m by the application of surcharge loads. Waste settlements were 28% and 6% of the waste height for the weaker and stiffer wastes respectively, and much smaller vertical, horizontal and volumetric deformations were recorded in the 80^o clay liner for the stiffer waste. The larger horizontal deformations of the clay liner in the weak waste case were required to mobilise sufficient support in the waste body to prevent failure. These findings emphasise the benefits of using selected stiffer wastes in the zone in front of all steepwall systems that rely on the waste for support. The slope angle of steepwalls can vary typically between 50^o and 80^o. The potential failure mode of a steepwall system will change as the slope angle reduces, other conditions being equal. Depending on the landfill geometry and phasing, the stability of the waste mass may also reduce as the steepwall system inclination lessens and a larger de-stabilising wedge of waste is formed.

4.3 *Stress transfer from differential settlement*

A key design issue to be addressed is the provision and location of a low shear interface so that settlement of the waste body is not transferred as tension on to the lining system. Movement at the low shear interface must not compromise the other functional elements of the lining system. This can be achieved by the provision of a dedicated low shear interface and positioning this to the landfill side of the geomembrane and its overlying drainage layer.

Preliminary designs of the interface should be investigated and proven by an appropriately devised set of large-scale shear box tests, representative of site conditions. In a multi-layer barrier system, it is prudent to incorporate a sequence of increasing shear interfaces from landfill side to quarry wall side. This should be proven by shear box testing, using performance testing of the whole multi-layer system with selected control tests on individual interfaces. The authors' experience is that using test data solely from individual interfaces is likely to give an erroneous picture of interface mechanisms in the full-scale structure. The test regime should include consideration of repeatability of the test results (variability between tests, both index and performance, as well as between laboratories can be anticipated) and appropriate test parameters (rate of shearing, normal forces, etc) consistent with anticipated service conditions.

The authors have undertaken performance shear box tests on multi-layer lining systems and revetment support structures to examine interface shear resistances and the location of the lowest friction slip surface. Fig. 7 illustrates the difference between “index” and performance testing for one particular interface. The test arrangement and sequence of materials to simulate field conditions (i.e. performance testing of the whole multi-layer system) to measure the shear resistance at the geomembrane-drainage geocomposite interface are shown on Fig. 7a. The materials to the waste side of the geocomposite were considered to give a reasonably even support and were not included in the test arrangement. Friction values of 23.2° (peak) and 17.8° (residual) for the geocomposite-geomembrane interface were obtained. Minor values of apparent cohesion of around 1.5kPa (peak) and 1.7kPa (residual) were recorded.

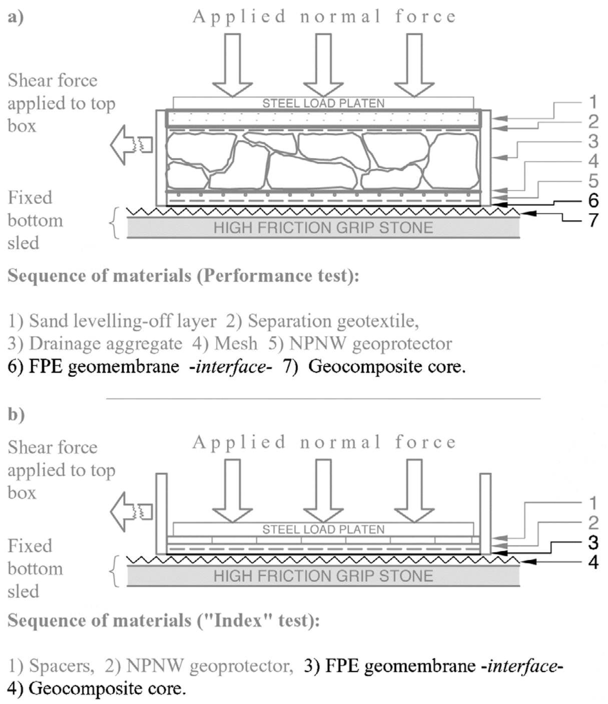


Figure 7: Typical 300mm shear box set-up for (a) performance test and (b) “index” test on profiles of site specific materials used in steepwall designs. **Tested interfaces are shown highlighted.** NPNW is 1,200g/m^2 needle-punched non-woven geotextile; FPE is 2mm smooth flexible polyethylene, LLDPE.

In comparison, the shear resistance on the geocomposite-geomembrane interface under standard “index” conditions was measured (Test 2 - see Fig. 7b). The geocomposite-geomembrane interface friction angle was measured in Test 2 at 14.3° peak and 13.3° residual. The post-peak reduction in friction angle (1°) was much reduced in this “index” version of the test set-up. Apparent cohesion values of around 2.6kPa (peak) and 1.7kPa (residual) were obtained.

A 9^o difference in peak friction was obtained. Comparison of the results of Test 1 and Test 2 showed that a large portion of the frictional resistance obtained in Test 1 on the geocomposite-geomembrane interface resulted from the uneven support provided to the geomembrane by the simulated site conditions. If the geomembrane-geocomposite interface were relied upon to provide the low friction slip surface, then this reliance would be misplaced. These results illustrate that designers can potentially be seriously misled if they use the results of index shear box tests in isolation rather than conducting performance tests that attempt to replicate actual site conditions.

Following on from the laboratory testing for that site, the authors have recently devised an instrumentation regime for a revetment-type steepwall system. The idea of monitoring strains within a geomembrane is not new; the practicalities of achieving this in a landfill environment are however considerable. Challenges to be overcome include:

- Developing adequate physical protection to the instruments (noting the instrument location will be buried as the waste body is placed);
- Including instrumentation within an already complex sandwich of geosynthetics and other materials without disturbance to ensure readings obtained are representative of actual conditions;
- Monitoring results remotely – 80m distance – over a period of at least three years, with no opportunity to return to the instruments for repairs etc;
- Avoiding induced strains in the geomembrane local to the points of attachment which would give anomalous readings; and
- Ensuring the functionality of the geomembrane barrier is not compromised.

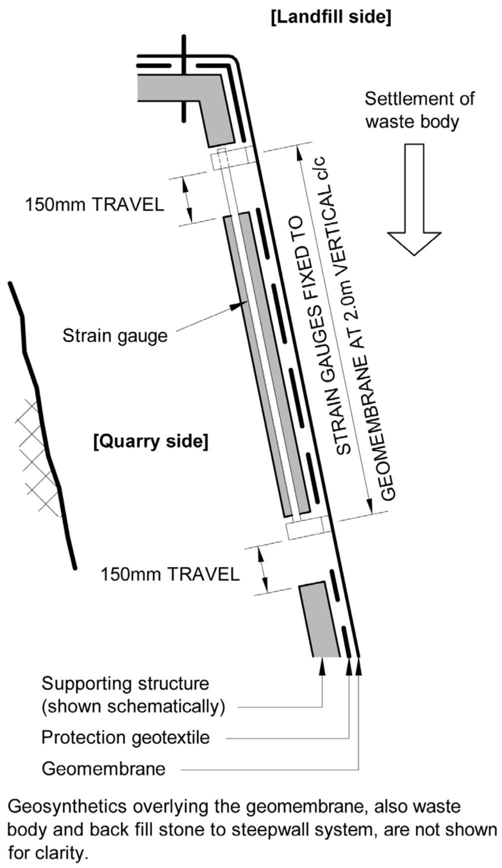


Figure 8: Schematic of instrumentation for steepwall geosynthetics with large strain gauges fixed directly to the geomembrane within an operational site. The steepwall design incorporates a geocomposite drainage layer and, to minimise frictional down-drag on the liner, a low shear interface (neither shown) between the geomembrane and the settling waste body

The system is shown schematically in Figure 8 and was installed and commissioned in September 2003. The instrumentation includes a series of 2m-long extensometers attached directly to the rear face of a steepwall geomembrane. The extensometers are enclosed in a robust, galvanised steel supportive housing compatible in design with the revetment framework type steepwall used at this site. Relatively large instruments were chosen to minimise effects of the strain gauges local to their point of attachment to the geomembrane. Three gauges were used at 1m horizontal intervals to give a degree of redundancy within the constraint of cost. Displacements in the 2m extensometer rods are monitored by linear voltage displacement transducers (LVDTs) connected to a remote data logger, which is periodically interrogated and downloaded for displacement and temperature data. It is proposed to monitor deformations experienced at the geomembrane in relation to waste placement in front of the steepwall for the next three years. This system allows direct measurements of strains in the plane of a steepwall geomembrane at an operational landfill, work that is believed to be unique. The authors acknowledge the financial support of Onyx Environmental Trust Ltd and Onyx Landfill Ltd, who have co-funded this research under the UK's Landfill Tax Credit Scheme.

4.4 *Durability*

The durability of all elements of steepwall systems needs to be considered in relation to their long-term function and exposure conditions. Considerable research effort is being expended into the durability of HDPE geomembranes. See for example the review by Rowe & Sangam, 2002; Müller, 2002; Müller & Jakob, 2003; and current Environment Agency R&D project P1-500/1 (Likely medium to long-term generation of defects in flexible membrane liners), due for completion in the autumn of 2003 (Needham *et al.* 2004). Attention must also be given to the durability of other components of lining systems and the materials used in the steepwall support system. The less onerous exposure conditions and barrier requirements of steepwall liners compared to basal liners has enabled LLDPE and VLDPE geomembranes to be used at some sites (Blum, 1999 and Gallagher *et al*., 2000).

The service life of geoprotectors and drainage geocomposites in relation to the projected period that the landfill will remain an environmental hazard also requires consideration although, again, the conditions at the steepwall will usually be less severe than at the base.

Expanded polystyrene (EPS) in the facing elements of the reinforced soil system is a civil engineering construction material that has been used in numerous applications (Horvath, 1995 and Saunders, 1996) including lightweight fill in motorway embankments. It will not be in direct contact with leachate unless a leakage occurs through the drainage geocomposite and geomembrane barriers, and then only in localised areas. EPS is resistant to the substances found in the concentrations prevailing in "normal" landfill leachates. In common with the other polymeric materials used in landfill lining systems, EPS is susceptible to damage by organic solvents, fuels and other hydrocarbons but these are not present in landfill leachates except in very dilute form. In the operating temperatures at the liner (20^o to 40^oC), as opposed to the body of the waste, the functionality of EPS is unaffected (Horvarth, 1995).

The protection from corrosion of metal elements such as mesh, framework and bolts in any of the facing support systems requires consideration together with the significance of their corrosion to the lining system should it occur. After completion of landfilling, and if adequate support is provided by the waste, the structural function of the system becomes largely redundant. The main concern will then be to ensure that damage will not be caused to the geosynthetic lining system by corroded metal elements.

5 CONCLUSIONS

Steepwall linings to landfills are relatively complex, multi-layer geosynthetic systems, whose design requires holistic consideration of numerous interactions. Properly specified, they offer the opportunity for economic development of quarry sites. The essential aspects include:

- Inclusion of a buffer zone of inert, low-compressibility material to the waste body side of the steepwall liner
- Inclusion of an appropriately positioned, low-shear interface, ideally without the geomembrane being a component of this interface
- Designing the sequence of interfaces in the system with increasing friction angles as one moves from waste body towards quarry wall.

The ramifications of Landfill Directive on steepwall design, particularly the need to provide a geological barrier, pose new challenges to designers and are likely to increase the use of combined mineral with geosynthetic lining systems.

6 REFERENCES

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