Waste/Lining System Interaction: Implications for Landfill Design and Performance

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ABSTRACT: Despite the relative maturity of landfill design practice, world-wide there are still significant numbers of large scale failures of waste bodies, often incorporating the lining system. In addition, there is growing evidence that post waste placement deformations in the lining system are leading to loss of function (i.e. discontinuous drainage layers, loss on protection and leaking liners). Best practice has established that both stability and integrity of the lining system must be assessed during the design process, and specifically that interaction between the waste body and lining system should be considered both in the short-term (i.e. during construction) and long-term (i.e. following waste degradation). The paper introduces available analysis approaches, reviews knowledge of waste behaviour required for such analyses and provides guidance on the mechanisms to consider. The need for field monitoring to validate numerical models is established as is the need for extensive measurements of waste mechanics properties linked to a standard classification system to aid comparison and use. The benefits of using probability of failure analysis to incorporate material and test variability in design are highlighted.

1. INTRODUCTION

Engineering design of containment systems for municipal solid waste (MSW) is now a mature discipline. The large majority of landfill facilities world-wide use a combination of natural and geosynthetic materials to form lining systems that minimise leakage of contaminants into the environment. Lining systems have two primary functions, to act as a barrier to liquid and gas and to facilitate their collection and removal. A typical lining system is shown in Figure 1. It has been demonstrated that combining natural and geosynthetic materials results in improved performance of the composite system (e.g. Rowe 2005). However, construction of these planar systems introduces the potential for uncontrolled deformation through slippage at material interfaces, especially on cell lining side slopes and capping slopes. These stability failures can be defined as large uncontrolled deformations of the system and are ultimate limit states.

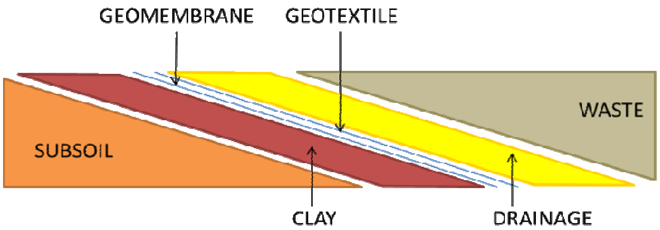


Figure 1 Typical lining system components and configuration

Well established analysis methods are available for use by designers to assess stability (e.g. Koerner & Song 1998) and it would appear that designing lining systems to ensure stability throughout the life of the facility is an established and routine process. Unfortunately this statement is proven to be false by the relatively large number of stability failures that have taken place since design procedures were established (e.g. Seed *et al.* 1988, Brink *et al.* 1999, Koerner & Song 2000, Eid *et al.* 2000, Jones& Dixon 2003). Failures have involved a wide range of lining system configurations and they have occurred world-wide including in countries with well-established design procedures. While some of the failures can be attributed to the use of inadequate materials and/or inappropriate construction, in a significant number of cases the cause of failure can be attributed to the design not considering the critical failure mechanism. A key limitation of standard design methods used for assessing lining stability is that they do not consider the influence of the waste body. The placement of waste against side slope lining systems and the subsequent waste deformations as it degrades can stress the lining elements and lead to failure. Many interfaces between geosynthetics/geosynthetics and soil/geosynthetics are strain softening (i.e. the shear strength of the interface reduces with displacement after a peak value is achieved). A key concern is that post peak shear strengths (i.e. reduced strengths) will be mobilised at interfaces between lining elements in response to waste settlement and this can result in uncontrolled deformation of the lining system leading to pollution of the environment.

A number of analytical and numerical modelling techniques have been proposed by practitioners and researchers to assess this influence of waste deformations on lining system stability (Section 3) and several studies have attempted to answer the questions as to whether peak, residual, or somewhere in between interface shear strengths should be used in side slope stability assessment. Analyses considering the waste body are challenging to carry out because they require information on the engineering properties of the waste and the sequence of waste placement. The high variability of waste mechanical properties both between landfills and within each facility makes the selection of appropriate material parameters for use in design a very difficult task. However, if interaction between the waste and lining is not considered in design then often adequate performance of the containment facility cannot be assured.

In addition to concerns regarding stability of the landfill construction, it is also essential that the integrity and hence long-term performance of the lining system is assured. Integrity failure can be defined as small scale deformations of elements of the lining system that lead to loss of function (i.e. increased permeability of a barrier element or discontinuity of a protection layer) and are serviceability limit states. Integrity failure mechanisms are linked to waste deformations and hence they are difficult to detect and repair as defects are buried beneath the waste. However there is substantial evidence that these types of failure occur in many landfills, for example gas leaks and cases of rapid increases in leachate levels in sub water table facilities. A design framework for lining systems that considers both stability and integrity has been developed by Dixon & Jones (2003) and extended by Fowmes *et al.* (2007). This framework was developed for the Environment Agency (England and Wales) and is incorporated in their permitting process for landfill facilities. Designers are required to demonstrate that they have considered all potential failure mechanisms for stability and integrity failure both prior to and following waste placement. Figure 2 summarises the lining system design considerations for stability and integrity of the six landfill elements: subgrade, basal lining system, shallow side slope lining system, steep side slope lining system, waste slopes and capping lining system.

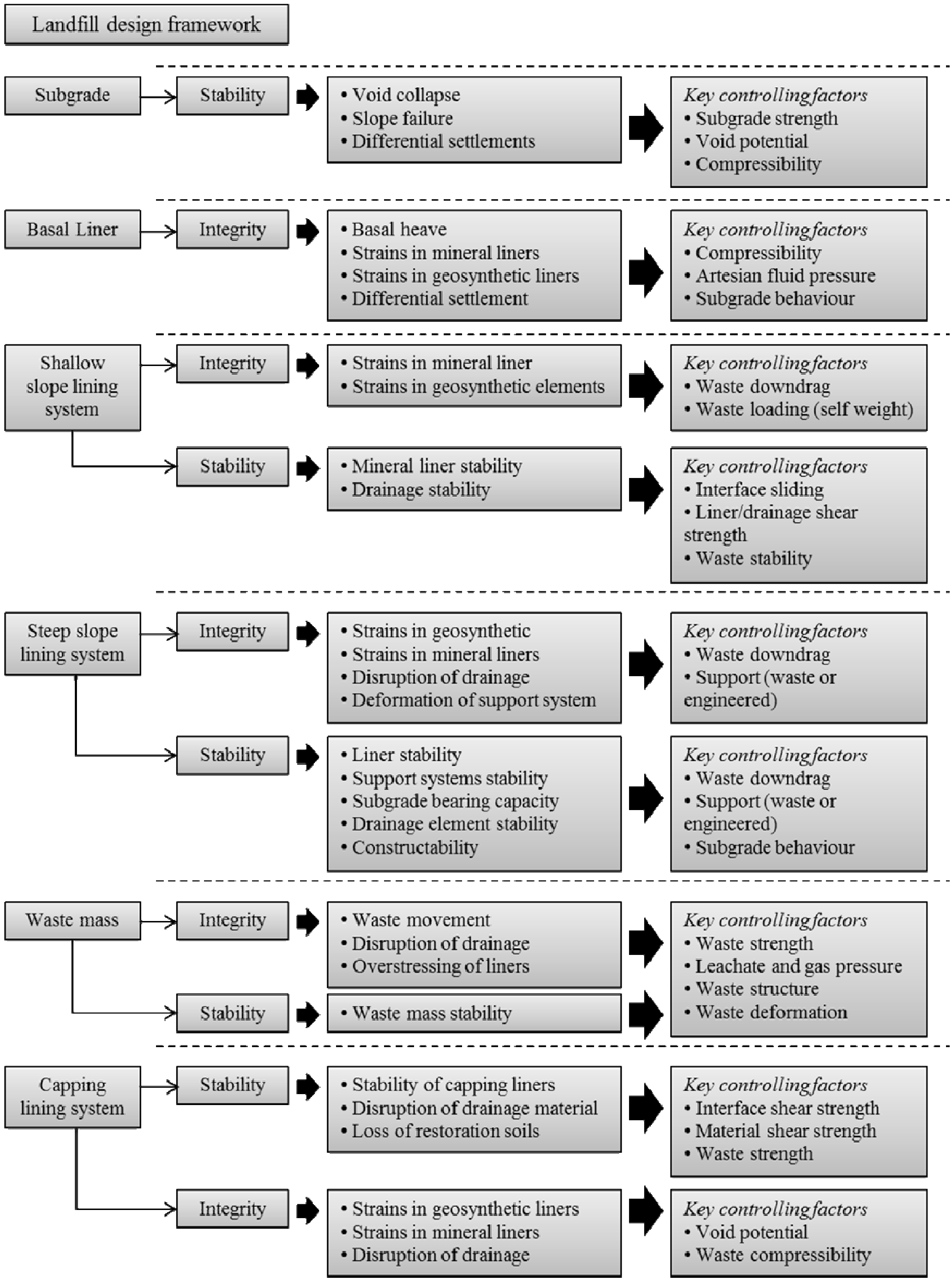


Figure 2 Landfill stability and integrity design framework (after Fowmes *et al.* 2007)

As an example, Figure 3 illustrates stability and integrity failure mechanisms for a shallow side slope lining system before and after waste placement.

There is often poor use of terminology surrounding steep sided lining systems, andthere is often an assumption that steep sided landfill lining systems are near vertical.Jones & Dixon (2003) suggest slope angles in excess of 30° are "steep". An alternative approach is to consider the stability of internal components of the lining system and the following definition can be used: A steep slope lining system is a side slope lining system placed at an angle, at, or greater than the limiting value at which the geological barrier, drainage layer, or artificial sealing liners are naturally stable without application of additional loads from the waste mass, anchorage or engineered support structures.

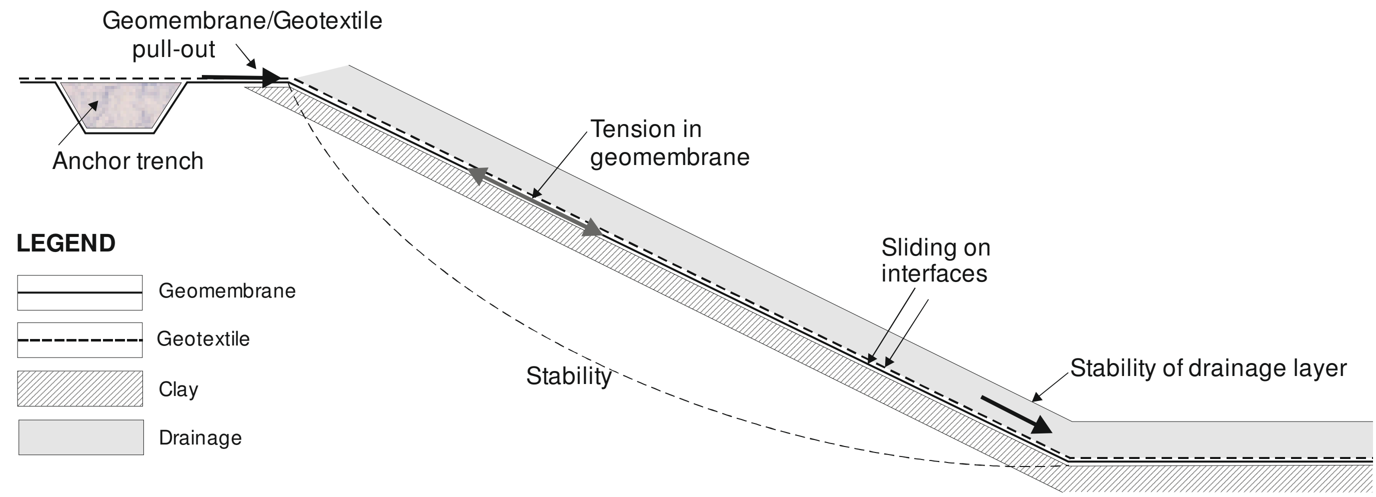
This paper summarises the current state of understanding of waste/lining system interaction, it considers waste types and behaviour, describes the use of numerical modelling methods to assess interaction between the waste and lining elements and highlights the implications of uncertainty and variability for design.

2. WASTE TYPES AND ENGINEERING BEHAVIOUR

2.1 Classification and engineering properties

Waste is the largest structural element of any landfill. It loads the basal and side slope lining systems and supports the capping system and gas/leachate collection infrastructure. Mechanical behaviour of the waste body controls many aspects of the lining system design and performance including stability and integrity of the geosynthetics and mineral lining components. Waste is a highly heterogeneous material and its mechanical properties change with time due to physical changes in components that result from degradation processes. The significant challenges posed by this spatial and temporal variability mean that it is not possible to fully characterise the engineering properties of a waste body. However, it is important that the basic behaviour of broad categories of waste is understood and that likely ranges of the controlling engineering properties are known for a specific site. Table 1 lists properties required to perform analyses of the stability and integrity failure modes summarised in Figure 2.

a)



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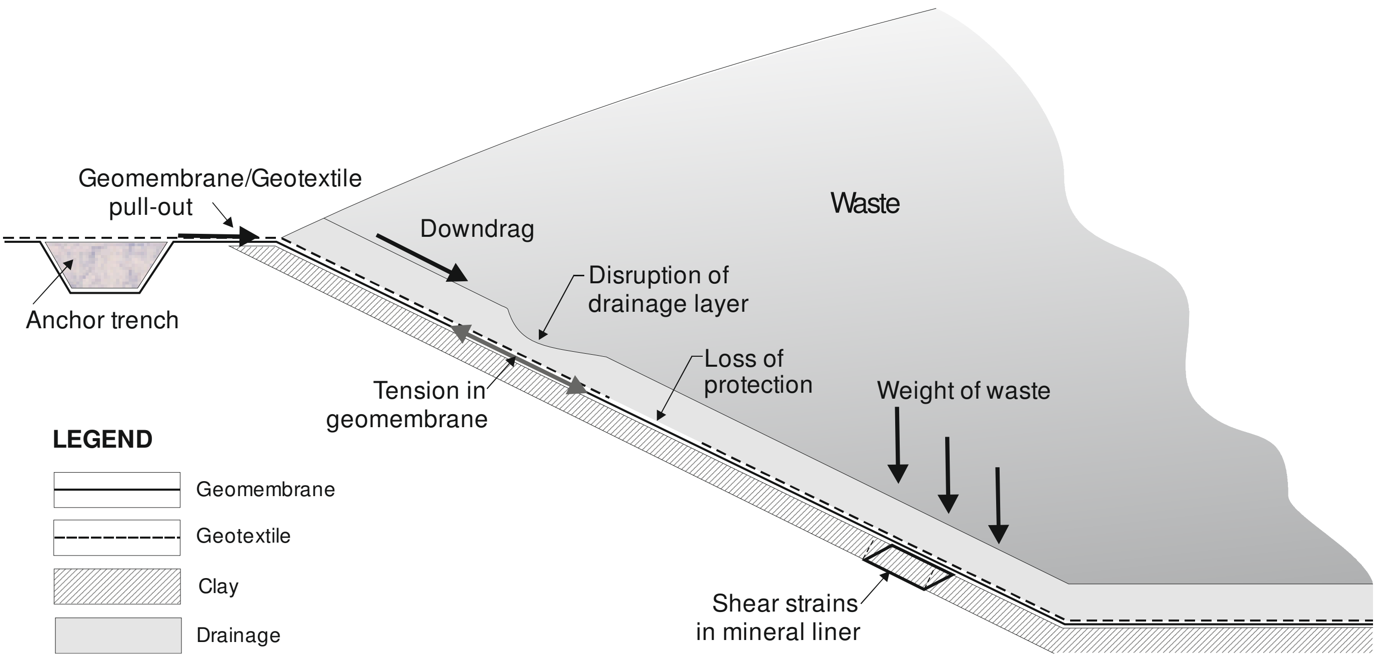

Figure 3 Potential failure mechanisms for a shallow side slope lining system a) unconfined, b) confined by waste (after Fowmes *et al.* 2007)

Table 1 Municipal solid waste engineering properties required for stability and integrity lining design (after Dixon & Jones 2005)

Design case	**Unit weight**	**Vertical compressibility**	**Shear strength**	**Lateral stiffness**	**Horizontal in-situ stress**	**Hydraulic conductivity**
Subgrade stability	X		X		X	
Subgrade integrity	X		X	X	X	
Waste slope stability	X	X	X			X
Shallow slope liner stability	X		X		X	X
Shallow slope liner integrity	X	X	X	X	X	
Steep slope liner stability	X		X		X	X
Steep slope liner integrity	X	X	X	X	X	
Cover system integrity	X	X	X			
Drainage system integrity	X				X	
Leachate/gas well integrity	X	X	X	X	X	X

MSW is a mixture of wastes that are primarily of residential and commercial origin. Typically, MSW consists of food and garden wastes, paper products, plastics, rubber, textiles, wood, ashes, and soils (both waste products and material used as cover material). A wide range of particle sizes is encountered ranging from soil particles to large objects such as demolition waste (reinforced concrete and masonry). The proportion of these materials will vary from one site to another and also within a site. Life style changes, legislation, seasonal factors, pre-treatment and recycling activities result in a changing waste stream over time. Examples are increasing plastic and decreasing ash content over the past few decades in developed countries. In addition, over the past decade member states of the European Union have effected a reduction in biodegradable waste in landfills through the introduction of Biodegradable Municipal Waste diversification targets defined in the Council of European Community (1999). It should be noted that the composition of MSW varies from region to region and country to country. For example, developing countries often have waste streams that contain more biodegradable material and fewer plastics, and countries such as Germany with a well-developed re-cycling and pre-treatment policy (e.g. the use of mechanical and biological pre-treated waste), have wastes with less biodegradable content and a more uniform and consistent grading. These variations produce fundamental and significant differences in waste engineering behaviour and they must be taken into consideration when using results from tests on waste reported in the literature.

There is a growing body of literature on the measurement of engineering properties of MSW and numerous summaries of the state-of-the-art have been produced over the past 20+ years (e.g. Landva& Clark 1990, Fasset*et al.* 1994, Manassero*et al.* 1996, Eid *et al.* 2000, Kavazanjian 2001, Qian*et al.* 2002, Dixon & Jones 2005, Reddy *et al.* 2010 and Stoltz*et al.* 2010). These are a valuable resource but have limitations as they do not use an agreed waste classification system or test standards to present and group information on mechanical properties. This makes it difficult to compare and interpret results from the different studies and to apply findings to other sites. Dixon & Langer (2006) attempt to address this issue by proposing a MSW classification system for the evaluation of mechanical properties, however, such a system can only be effective if it is used by multiple researchers and practitioners so as to build a data base of measured waste behaviour linked to the classification. A milestone event in the development of a unified framework for waste mechanics is the International Symposium on Waste Mechanics held in New Orleans, March 2008. The objectives of this symposium were to: develop consensus on procedures and guidelines for waste characterisation, field testing and laboratory testing of MSW; summarize the state of knowledge on waste properties for use in research and engineering practice; and identify research needs in waste mechanics. The proceedings of the symposium have been published as an ASCE Geotechnical Special Publication (Zekkos 2011). This includes a chapter on waste characterisation (Dixon *et al.* 2011) which presents an agreed system, based on Dixon & Langer (2006), with a recommendation that it be used for future studies of waste mechanics thus fulfilling the requirement for a universal classification framework. Zekkos (2011) includes specific sections covering the key MSW engineering properties listed in Table 1 and their measurement. It also considers dynamic properties of MSW that are of relevance to landfill design in seismically active regions of the world. It is important to note that studies of MSW mechanics have demonstrated that although waste is heterogeneous it has properties that vary in a consistent and predictable way (e.g. with respect to stress state and method of placement).

2.2 Waste body deformations

Stability and integrity of side slope lining systems are primarily controlled by the magnitude and distribution of adjacent waste deformations during the life of the structure. Waste deformation can be separated into two components: primary compression which is a short-term response to load from the overlying waste, and secondary longer-term response to degradation and creep. Historically, studies of waste deformation have been restricted to measurement of surface settlements that are used to improve efficiency of site management and to predict final landfill capping profiles. These measurements are of limited use for assessing waste deformations adjacent to side slope lining systems as they rarely provide information on primary compression that occurs during the filling process. This is because filing of waste often takes place to a predetermined reduced level and therefore compression of the underlying waste during placement is masked by overfilling to meet the fill level requirement. This means that use of surface settlement measurements grossly underestimates the actual waste deformation depth profile. However, surface settlement measurements provide useful information on secondary deformation from degradation and creep, although again they do not provide information on depth distributions.

For these reasons, in order to obtain information required to assess waste/lining system interaction it is necessary to install instruments within the waste body to measure settlement at depth intervals during waste filling and degradation. The few studies reported in the literature that have presented such measurements confirm that large waste deformations occur. For example, Dixon *et al.* (2004) report measured immediate settlements of 300 to 700 mm of a 3 metre thick layer of MSW when a further 3 metre layer of waste was placed above. These, when related to measurements of the stress changes that caused the deformations, can be used to derive stiffness values for use in numerical models (Dixon *et al.* 2004). On-going, long-term projects to measure landfill post-closure surface settlements are providing valuable information on degradation induced waste deformations, but longer time-series of measurements are required before conclusions can be drawn on the magnitude and distribution of final waste deformations related to waste classification and site specific construction and operation approaches.

A further complication is that waste adjacent to side slopes may not behave the same as the maximum thickness of waste above the base where to date the majority of monitoring has focussed. This is a results of the slope geometry, which could include changes of slope, and differences in waste materials selected and method of placement used (i.e. in attempts to protect the lining system from damage during waste placement). Gourc*et al.* (1998) report a study to measure the sub-surface waste deformations adjacent to a side slope and this has produced useful information on the magnitude and distribution of waste deformations for the specific waste, filling sequence and slope geometry studied. A comparable study is currently underway at Bletchley Landfill Site near Milton Keynes, UK, where a series of landfill settlement monitoring instruments has been installed. The instrumentation is installed at 6m vertical increments in two locations, one at the toe of the side slope and the other near to the middle of the landfill cell. The waste depth is approximately 40m. At each location a vibrating wire pressure cell, thermistor and hydrostatic settlement cell are installed and connected via HDPE pipes to a monitoring cabin at the crest of the side slope. The instrumentation has allowed analysis of the settlement profile within the waste mass during the filling process which was completed in late 2011. Monitoring will continue during the site aftercare period. The measurements and interpretation will be reported following completion of the detailed analysis, including influence of waste type and filling sequence.

2.3 Modelling waste body deformations

It is well established that landfill deformation is the product of a combination of phenomena, including load and biodegradation-related processes, and there are numerous useful reviews of models that can be used to calculate surface waste settlement (e.g. McDougall 2011). However, to date, these models are not able to routinely consider waste deformations in two dimensions, and this function is required to investigate waste deformations adjacent to side slopes (i.e. to analyse a cross section through the waste and lining system). A promising approach is the HBM model that combines three models each describing the hydraulic, biodegradation and mechanical behaviour of landfilled waste. A summary of the HBM model is provided by McDougall (2011) and further details of the constitutive formulation are given by McDougall (2007). This type of model gives the promise of being able to investigate time dependant waste deformations in two dimensions from initial filling to completion of degradation, and hence to directly link waste behaviour with lining system performance. However, to date there is still a need for further model development and validation, and specifically to measure the many MSW material parameters that are needed to run the model. Currently, waste models used to investigate lining system performance have concentrated on short-term construction and waste placement activities by using standard soil mechanics constitutive models to represent the waste (Section 3), but it is only a matter of time before a fully coupled waste (i.e. such as HBM) and lining system model is available.

3. NUMERICAL ANALYSIS OF WASTE / LINING SYSTEM INTERACTION

3.1 Limit equilibrium approach

Waste/lining system interaction cannot be fully considered using limit equilibrium analysis as it is unable to provide information on whether strain softening will occur on a specific interface. Limit equilibrium can be used to analyse overall stability of a system but the designer must select interface shear strength parameters (i.e. whether peak, residual or a factored strength should be used). Selection of the shear strength parameters requires assessment of whether waste settlement (or any other mechanism, see Section 5.1) will generate post peak strengths. There is evidence that generation of post peak strengths by a progressive failure mechanism can lead to catastrophic large scale movements of a waste mass against the lining system (e.g. the Kettleman Hills failure – Seed *et al.* 1988). However, in the majority of instances it is the liner integrity that could be compromised if displacements occur along an interface following waste placement. It is difficult to monitor lining systems once waste has been placed, and this is seldom done, but there is evidence of integrity type failures caused by waste settlement next to the lining system (e.g. Fowmes *et al.* 2006). For landfill side slopes the shear strength mobilised at a liner interface through waste deformation will vary along the interface and this cannot be modelled by a simple limiting equilibrium approach (Long *et al.* 1995).

3.2 Numerical modelling approach

Numerical modelling techniques such as finite element and finite difference formulations can be used to assess the shear stresses mobilised at strain softening geosynthetic interfaces for a range of waste properties and landfill geometries. A summary of literature on modelling waste/barrier interaction was provided by Jones & Dixon (2005) and this is extended below to demonstrate the advances in analysis methods that have been made in recent years and the guidance developed from the studies. Filz*et al.* (2001) demonstrated that numerical modelling could be used to assess progressive failure of a geomembrane/clay interface in response to staged placement of MSW against a landfill side slope. They showed that average mobilised shear strengths along the interface were close to residual for the configurations assessed, and that limit equilibrium analyses carried out using peak strength values significantly overestimated the degree of stability. They concluded that strain softening interfaces must be considered in the design of landfill lining systems. In addition they provided guidance on the selection of appropriate shear strength parameters for use in limit equilibrium analysis of stability. The work by Filz*et al.* (2001) is important because it demonstrates the appropriateness of the numerical approach. However, the guidance they produced is restricted to a geomembrane/clay interface and for relatively short-term construction related behaviour. A further limitation of this work is that deformations on the interface are not reported and therefore issues of lining system integrity are not addressed.

Long-term degradation controlled waste settlements play an important role in lining system behaviour. Meissner and Abel (2000) present results for numerical modelling of tensile stresses in a geomembrane basal and side slope liner resulting from waste degradation. A numerical model was presented that allows time dependent waste settlements to be considered. Displacements at a geotextile/geomembrane interface are predicted. This type of information could allow issues of lining integrity to be considered. Unfortunately, the model employed to represent the interface was not strain softening and this invalidates many of the results obtained, although the approach of using numerical modelling techniques to assess long-term waste degradation effects on the lining system is valid.

Jones and Dixon (2005) used both limit equilibrium and numerical analysis techniques for assessing stability and integrity of a lining system containing a strain softening interface. The condition considered is for waste/liner interaction resulting from long-term, degradation controlled, waste settlement adjacent to a landfill side slope. A strain softening geotextile/geomembrane interface is introduced as the controlling interface in the lining system. The influence of waste properties, slope angle and waste height are assessed. Comparison of the results from the limit equilibrium and numerical analyses has shown that simple limit equilibrium analysis does not satisfactorily assess the local stability of geosynthetics on a landfill side slope. Even with the use of mobilised shear strengths for the geosynthetic interfaces obtained from the numerical analyses, the limit equilibrium analysis does not give a reliable indication of the stability of the slope. Limit equilibrium methods can only be used to predict instability along a continuous failure plane, and therefore cannot be used to assess integrity failure of a geosynthetic lining systems caused by localized displacement along interfaces. Interface shear displacements in the order of metres were obtained in numerical analyses while the limit equilibrium assessment showed the lining system to be stable. Figure 4 shows displacement distributions along the base and side slope for a range of angles in response to placement of 30 metres of waste. For the steeper slopes it can be seen that displacements of metres take place on the side slope even though the waste mass is still globally stable.

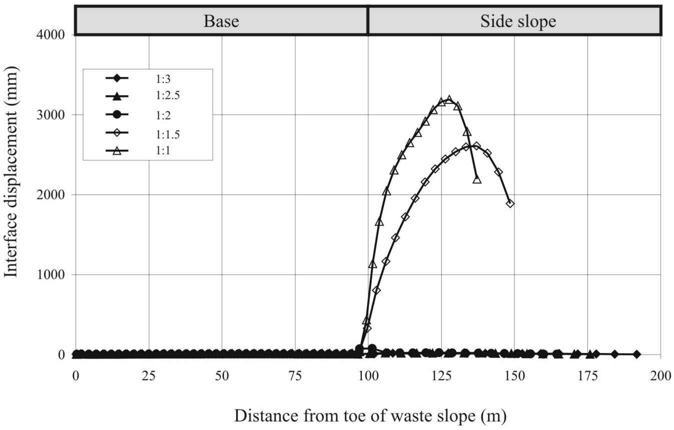

Figure 4 Results from numerical modelling of a range of side slope angles each 30 metre high, which show large relative displacements at a geotextile vs. geomembrane interface caused by long-term waste settlement (after Jones & Dixon 2005).

Villard *et al.* (1999) presented results from finite element modelling of a side slope lining system comprising geosynthetic and mineral components in response to placement of a gravel drainage layer. Their model included strain softening interface behaviour and material stiffness. This enabled consideration of tensile stresses in geosynthetic components and hence assessment of the integrity of lining components. They concluded that the comparison between the numerical model results and full-scale experimental observations was generally satisfactory. However, difficulties were encountered in reproducing measured mobilised tensile forces in geosynthetics. This was believed to be due to the formation of wrinkles at the base of the slope. Unfortunately this work was not extended to investigate the influence of waste placement and subsequent waste settlement. It is not clear whether the approach developed by Villard *et al.* (1999) could be used to assess the integrity of all lining components (i.e. relative displacement and tensile stresses) in response to waste settlement. Fowmes *et al.* (2006) extended the work of Villard *et al.* (1999) and Jones & Dixon (2005) by modelling the waste body and individual lining components with strain softening interfaces between them. This allows transfer of stresses through the lining components, calculation of tensile stresses in lining components and hence an assessment of system integrity (e.g. likely continuity of the geotextile protection layer) as reported by Fowmes *et al.* (2006).

Long *et al.* (1995) presented an approach to assess the integrity of all components in a lining system. This uses a finite difference formulation that includes non-linear mechanisms to model the shear stress/displacement behaviour of each interface and the axial load/displacement behaviour within each component. The waste body is not modelled directly but effects of waste load and settlement are considered by imposing the combination of displacement and load boundary conditions on the top layer of the lining system. While this approach provides information on the integrity of elements it is based on an assumed waste settlement profile along the side slope. The Long *et al.* (1995) approach could be coupled with those that model waste settlement behaviour in order to obtain more rigorous assessments of lining component integrity (i.e. in respect to over stressing).

4. VALIDATION OF NUMERICAL MODELS

4.1 Requirement for validation

The above numerical methods are capable of providing useful information and insights that can be used to assess the stability and/or integrity of side slope lining system components during construction and subsequent degradation, and hence settlement, of the waste body. Their use has become commonplace in the UK as part of the Stability Risk Assessment required for the permitting process, although analyses incorporating multiple strain softening interfaces are not routine as they require specialist software and a high level of expertise to run the models. However, despite their regular use there is still only limited information available that can be used to validate the numerical models. In traditional geotechnical engineering it would be inconceivable to design and construct a geotechnical system where there are serious implications if it fails and not to monitor the structure and surround to ensure adequate performance. However, in landfill engineering this is the norm. Landfill containment systems are significant and important geotechnical structures the failure of which can have major consequences for the environment. Current designs are complex soil, geosynthetic, structural systems and novel designs are regularly used particularly for lining steep slopes. However, despite the importance and complexity of these lining systems they are seldom directly monitored during operation to prove adequate structural performance, and hence to confirm the validity of the design assumptions and methodology.

4.2 Validation of numerical models

Fowmes *et al.* (2008) describe a series of large-scale laboratory tests containing geosynthetic elements of a multi-layered lining system exposed to down-drag forces from a compressible synthetic waste material, which was designed to produce data to validate numerical analysis of the same problem. It is recorded that this approach was taken because of difficulties in gaining access to instrument and monitor an in-service lining system. The numerical results presented by Fowmes *et al.* (2008) are from initial best estimate analyses, with interface and synthetic waste properties derived from a laboratory testing programme and geosynthetic material properties supplied by manufacturers. It is reported that the observed trends of tensile stresses in the geosynthetics and relative displacements at interfaces in the laboratory model test are reproduced by the numerical models to an acceptable degree of accuracy that would be appropriate, using site specific input data, for use in commercial design. However, it is noted that although the use of numerical modelling techniques allows prediction of displacements, stresses and strains in multilayer geosynthetic lining systems with non-linear interface behaviour, the outputs are always limited by the accuracy of the input parameters, the constitutive equations and the application of the numerical calculation technique and this must be considered by the design engineer. It is also stated that whilst it is believed that the laboratory study represented a significant step in the validation of the numerical model behaviour, full scale field instrumentation of a landfill site is still required to allow for assessment of the numerical model accuracy under in-service conditions.

Using this validated numerical model detailed in Fowmes *et al.* (2008), Fowmes *et al.* (2006) report analysis of the interaction between waste and a geomembrane based lining system for a benched steep slope lining system in a hard rock quarry. The analysis was able to replicate the observed tensile failure of the geomembrane, which occurred at the corner of the benches as a result of down-drag forces from the settling waste being transferred into the geomembrane liner element.

In response to the identified need for validation using site performance measurements, Zamara *et al.* (2010) detail on-going research to instrument a side slope lining system with the aim of monitoring structural performance of the components during and post waste placement, and using the measurements to validate a numerical model of the waste/lining system interaction. The lining system comprises a compacted clay layer overlain by a geomembrane, which is in turn overlain by a geotextile protection layer. A sand drainage layer is present above the geotextile. Figure 5 shows the lining system components and instrument layout. Instruments installed during construction of the lining system include pressure cells to measure the stress on the lining components from placement of waste, extensometers to measure strains in the geomembrane and geotextile and the relative displacement at the interfaces between clay and geomembrane, and geomembrane and geotextile. Fibre optic bragg strain gauges and demic gauges have also been used to measure strains in the geomembrane. Monitoring has been carried out during staged construction of the sand veneer drainage layer and waste placement on the 31 metre long and 11.6 metre high slope (i.e. 21.8° slope angle). Monitoring commenced in July 2009 and is continuing. Waste filling will be completed in summer 2012. Results from the monitoring programme are presented by Zamara *et al.* (2012) for the sand veneer construction. Monitoring will be continued after cell closure during waste degradation. The monitoring to date has shown relative displacements between the geomembrane and geotextile that would mobilise post peak interface shear strengths, which is consistent with the results from numerical models of similar systems. Multiple direct shear laboratory tests have been conducted on the clay/geomembrane, geomembrane/geotextile and geotextile/sand interfaces to provide data for use in a multi-layered strain softening interface numerical model of the construction sequence. It is planned to use the detailed field measurements to fulfil the requirement to assess performance of the numerical modelling approach.

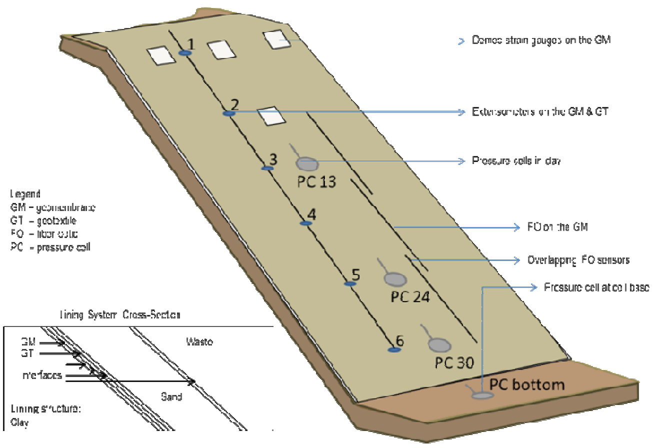

Figure 5 Details of the lining system, instrument types and locations for the field trial at Milegate Landfill, UK, which is being used to validate numerical models of waste/barrier interaction (after Zamara *et al.* 2012).

5. DESIGN GUIDANCE

5.1 Mechanisms producing interface post peak shear strengths

Field observations and the output of numerical models of waste/lining system interaction are consistent in showing that post peak interface shear strengths can be mobilised. Therefore, this produces a requirement for the designer to select shear strength parameters and factors of safety to ensure adequate performance of the landfill facility. Since the magnitude and distribution of shear strength mobilised between lining components is dependent upon magnitude of displacements at the interfaces, the design approach used must include assessment of likely relative displacements and the implications of these for both stability and integrity of the system. This paper has focused on the role of waste/lining system interaction, however there are a number of additional mechanisms associated with the construction and operation of landfill facilities that can result in relative displacements occurring at geosynthetic/geosynthetic and geosynthetic/soil interfaces and hence in mobilization of post-peak shear strengths. Those related to construction activities are:

- Dragging geosynthetic materials over one another to position correctly.
- Construction plant loads (including acceleration and braking forces) from trafficking interfaces with inadequate cover. Particular attention should be given to placement of veneer soil layers on slopes (Koerner and Daniel 1997, Jones *et al.* 2000).
- Compaction of fine grained soils above geosynthetic layers. This should be particularly discouraged on slopes.
- Improper storage and handling of geosynthetics leading to loss of internal strength (e.g. breaking of glued connections in geocomposites).

Activities associated with landfill operations are:

- Compaction of waste against side slopes (i.e. similar issues as placement of veneer soil layers)
- Differential settlement of the sub-grade beneath a basal liner or of waste beneath a cap.

The designer must consider all possible mechanism that could potentially result in the mobilisation of post-peak, and even residual, strength conditions for the interfaces under consideration. This assessment should be used to justify the selection of strength parameters and factors of safety used in the design.

5.2 Design assessment and parameter selection

If a mechanism exists to generate post-peak shear strengths then it is recommended that residual shear strengths are used in the limit equilibrium stability analysis. A factor of safety that would be deemed acceptable in this instance would be less than the factor of safety against failure using peak shear strengths. If the design allows for the development of post-peak shear stresses, then it follows that displacements will occur at the interfaces and the lining system must be designed to ensure that these do not cause integrity failure. If such displacements are not desired or integrity cannot be assured through design, then it is suggested that peak shear strengths are used in the analysis with a suitable factor of safety that reflects the consequence of failure. The mobilisation of post-peak shear strengths could result in a loss of integrity as large displacements along a side slope interface could lead to the loss of liner protection (e.g. Figure 4). A common approach in landfill design is to ensure that the weakest interface is above the primary liner so that any deformations do not result in movement within the liner itself with loss of integrity leading to leakage of gas and leachate (e.g. Gallagher *et al.* 2003). However, adequate protection must be ensured when large displacements are anticipated above the primary liner and this is particularly an issue when considering steep wall lining systems since the relative displacement at the interfaces can be in the order of several metres.

The consequence of failure must be reflected in the selection of both the interface strength parameters and factors of safety. For example, failure of a basal lining system would be costly and difficult to repair, whereas veneer stability failure, although highly undesirable, could be repaired with lower disruption and cost. For high risk design cases such as failure of a basal liner, both Gilbert (2001) and Thiel (2001) proposed an approach based on ensuring that the factor of safety using the residual strength controlling lining system stability is > 1.0 (if only just so), with a higher factor of safety obtained using the peak strength (e.g. 1.5). Essentially in this approach the consequence of failure is being taken into consideration, although only in a simplistic way.

An important consideration when selecting whether to use peak or residual shear strengths in design is to understand that the residual strength controlling stability of the whole lining system is not the interface with the lowest residual strength, but the residual strength for the interface with the lowest peak strength (Gilbert 2001). This approach confirms the importance of carrying out site specific interface tests for all combinations of materials to be used in the lining system, and the need to obtain the full shear strength/displacement relationship for each interface. It is only when armed with this information that the designer can identify the interface(s) controlling stability and then apply appropriate factors of safety. It should be noted that at locations along a lining system it is possible for the controlling interface to be different. This can occur due to the normal stress dependency of interface shear strength.

As discussed in Section 5.1, many of the mechanism that can lead to the mobilization of post-peak shear strengths are construction related. The construction quality assurance process (CQA) should control:

- Method of material placement to minimise any dragging
- Specify minimum soil cover over geosynthetic before being trafficked, and limit the type of plant and its operation
- Specify methods of soil placement on slopes (i.e. spread up slope not down) and minimise vehicle operations (e.g. braking);
- Discourage construction of haul roads on side slopes
- Control handling and storage of geocomposite materials so that internal strength is not compromised.

The following design issues should also be considered:

- If interfaces with low strength are used to isolate the geomembrane from shear stresses then the constructability of the lining system must be checked (e.g. check veneer stability and any temporary waste slopes)
- Check the tensile stress in each layer in addition to assessing stability. This assessment also requires peak and residual strength information for each interface.
- Designs should limit the use of compacted soils over geosynthetics, especially on slopes.

6. UNCERTAINTY AND VARIABILITY

6.1 Limit equilibrium

Stability of landfills is controlled by slippage at interfaces between the lining components. Designers must ensure that all potential failure mechanisms are considered, with appropriate strength parameters selected (i.e. peak, residual or somewhere in-between) and the interface that controls stability identified. Information on the variability of interface shear strength is required both to carry out limit equilibrium stability analysis using characteristic shear strengths and to analyse the probability of failure. Current practice is still to carry out a limited number of site-specific tests, and this provides insufficient information on the variability of interface strength for design. Measured shear strength variability of commonly used interfaces has been reported by Criley& Saint John (1997), Koerner&Koerner (2001), Stoewahse*et al.* (2002), McCartney *et al.* (2004), Dixon *et al.* (2006) and Sia& Dixon (2007). Sia& Dixon (2007) demonstrate that interface shear strengths and derived strength parameters can be represented by normal distributions. They also demonstrate that variability of interface strengths computed using published global data sets are 3 to 5 times, and reach up to 8 times, higher for the derived parameters compared to repeatability datasets (i.e. data obtained for material from single sources, tested by one operative using one shear device). It is concluded that variability and uncertainty computed using global and inter-laboratory datasets yield unreliable designs and this leads to a strong recommendation that published data should not replace measurements from site specific testing.

With the availability of interface variability data it is possible to undertake risk assessment of landfill stability using probability of failure. Common stability mechanisms (i.e. veneer and waste slope stability) have been considered by Koerner & Koerner (2001), Sabatini *et al.* (2002), McCartney *et al.* (2004), Dixon *et al.* (2006) and Sia& Dixon (2007). All employ the first-order, second moment reliability-based methodology proposed by Duncan (2000). These studies show that designs based on published global datasets result in unacceptably high probabilities of failure for controlling stability mechanisms, and they highlight the need for landfill designers to give greater consideration to variability of interface shear strength and to the consequences of failure. Design based on combined criteria for factor of safety and probability of failure would allow uncertainty in measured interface strength to be considered fully. However, appropriate and attainable target factors of safety and probability of failure values need to be selected if this methodology is to be implemented in general practice. A key requirement is that regulators, operators and designers need to agree acceptable design requirements in relation to probability of failure. This will support justification of the cost of obtaining the required quality of input parameters in relation to the cost and consequences of failure. Although reliability based assessment using the approach proposed by Duncan (2000) is relatively straightforward, it is perceived by the Authors that there is reluctance for engineers to incorporate it into the design process. In an attempt to overcome this inertia, Sia& Dixon (2008) have developed a reliability based design chart for veneer cover soil stability. The chart can be used to enhance decision-making by taking into account uncertainties in the design parameters, such as the variability of interface shear strength parameters. Additionally, the chart can also be used to determine the optimum slope angle for a containment facility that will satisfy both the target factor of safety and acceptable failure probability. It is believed that currently reliability based approaches are seldom used by designers.

6.2 Numerical analysis

The influence of variability and uncertainty on integrity of lining system components cannot be assessed using limit equilibrium and the reliability based techniques outlined in Section 6.1. Specifically, tensile stresses generated in geomembrane and geotextile layers by waste settlement requires analyses that can represent material variability, geometry variability and the construction process, including waste placement. Sia (2007) presents numerical analyses to examine the integrity of a constructed shallow sloped landfill lining system (i.e. including staged waste placement), in which the uncertainty of significant input parameters are treated probabilistically using Monte Carlo simulation. Long-term waste degradation effects are not considered. Statistical information required to derive distributions of input parameters were obtained from literature, a laboratory interface repeatability testing programme and an expert elicitation process. Strain softening interfaces were incorporated between the lining elements. Outputs from the analyses include the relative shear displacements within the lining system, informing the likelihood of generating post peak strengths and discontinuity of elements, and the tensile strains in the geosynthetic components, both generated by downdrag settlement during waste placement. It was concluded that discounting the variability of significant input parameters, such as interface strength, can lead to unsafe design as a result of not considering potential failure scenarios. The analyses presented by Sia (2007) are complex and time consuming to undertake and it is unlikely that this approach would be used for routine landfill design. However, such studies can guide the engineer regarding combinations of landfill geometry and lining materials that could produce unsafe designs and/or loss of integrity.

7. SUMMARY

This paper reviews current understanding and practice for design of landfill lining systems. Both stability (large scale movements leading to collapse) and integrity (small scale deformations leading to loss of function) failure mechanisms are identified. There is evidence in the literature that significant waste slips involving the lining system are still occurring, despite what appears to be established design guidance. In addition, there is growing evidence that integrity failures are occurring post waste placement. Many of the failure mechanisms are linked to the adjacent waste body behaviour and the requirement to consider interaction between the waste body and lining components in all designs is established. In design it is no longer acceptable to ignore interaction between waste and lining system and/or to wish the waste body in place thus ignoring the influence of waste placement process and sequence on lining system performance.

Despite the heterogeneous nature of MSW, the extreme range of materials around the world and the spatial and temporal variations within a given landfill, research has demonstrated that mechanical properties of MSW often vary in a logical and consistent relationship (e.g. depth/stress dependency of stiffness). While there is a growing literature on measured properties that can be used to support selection of parameters for design, lack of a standardised classification system and test procedures has meant that in many cases it is difficult to translate tests on waste from one site and application to another. This situation is improving with the publication and acceptance of a classification framework. Given the importance of waste mechanics information there is still significant further work required to produce relevant information to enable routine design of robust lining systems. In addition, further development and validation of waste constitutive models is required if combined short-term compression and long-term creep and degradation behaviour is to be incorporated in two dimensional models of waste deformation.

Traditional limit equilibrium analysis methods can be used to assess stability of the lining elements and waste body (i.e. ultimate limit states), however the designer must select appropriate shear strength parameters (i.e. peak, residual or somewhere in between) by taking into consideration all possible mechanism that could cause relative displacement at interfaces, including waste settlement. There is now a significant body of information in the literature based on experience, numerical modelling and a limited number of field measurements to guide the designer on which strength parameters to select. This information includes aspects of interface type, slope angle, waste stiffness and waste thickness.

Limit equilibrium techniques cannot be used to assess integrity of the lining components. Use of numerical analysis to investigate integrity of the lining system has become common in the UK as part of the design process used to obtain a permit. However, it should be noted that this level of analysis is not required if the design engineer can demonstrate that the site specific landfill geometry (i.e. shallow side slope), waste type (i.e. high stiffness, low organic content) and mode of operation (i.e. waste filling sequence) are unlikely to produce integrity failure mechanisms. If numerical modelling is considered relevant the designer must establish shear behaviour for the interfaces, including any post peak reduction in strength, typical waste properties such as unit weight, stiffness and compression due to degradation, and the lining system and waste construction sequence. Such analyses are capable of identifying conditions that could lead to relative deformations in the order of 100s to 1000s mm at side slope lining component interfaces even though global stability is acceptable. If deformations are indicated below the primary liner (e.g. geomembrane) then the design should be revised to provide a weaker interface above the geomembrane so that the integrity of the liner is not compromised. If significant deformations are indicated above the liner then the design must ensure that materials employed to protect the liner and form a drainage layer remain continuous. Although use of numerical models of waste/lining system interaction is becoming common it should be noted that there is still a dearth of data available to validate the models. A research project is currently in progress to provide field measurements of in-service liner performance for use in a validation exercise.

Despite recent advances in numerical modelling, measurement of waste mechanical properties and design practice, there is still significant uncertainty regarding many of the material parameters and processes required to analyse and hence design landfill lining systems interacting with waste. Probability of failure analysis can be used to better understand the significance of poor or limited input data for limit equilibrium analyses of stability. A growing number of published databases from repeatability testing programmes can be used to establish variability of interface shear strength data. In order for probability of failure analyses to be used more widely, designers, operators and regulators must agree threshold levels for acceptable performance. Numerical analysis using Monte Carlo simulation to investigate the influence of parameter variability on integrity mechanism has produced interesting results that could be used to guide engineers. However, the complexity and extended time required to conduct such analyses mean that they are unlikely to be used for standard design situations in the foreseeable future.

8. ACKNOWLEDGEMENT

The Engineering and Physical Sciences Research Council funded Centre for Innovative and Collaborative Engineeringat Loughborough University and Golder Associates UK Ltd are supporting Engineering Doctorate student Katarzyna Zamara.

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