# THE LINING OF STEEP LANDFILL SLOPES IN SOUTH AFRICA AND THE APPLICABILITY OF THE "MINIMUM REQUIREMENTS FOR WASTE DISPOSAL BY LANDFILL" BY THE DEPARTMENT OF WATER AFFAIRS AND FORESTRY

**Avinash Shripersadh Dookhi**

**In partial fulfilment of the**

**MASTERS OF SCIENCE IN ENGINEERING**

**College of Agriculture, Engineering and Science**
**University of KwaZulu- Natal**
**Durban**
**South Africa**

**November 2013**

**Supervisor: Mr SM Jewaskiewitz**

# ABSTRACT

In August 2013, the landfill liner designs prescribed by the Minimum Requirements for Waste Disposal by Landfill was superseded by the containment barriers of landfills, now prescribed by the National Norms and Standards for Disposal of Waste to Landfill. These newly prescribed lining systems were assessed in terms of mineral layers, geosynthetic materials and alternatives of equivalent performance. A Class B landfill lining system was then selected to determine its performance on various slope angles.

Various geosynthetic materials were tested for their interface shear strength parameters using a ring shear apparatus. These shear strength parameters were then used as inputs to calculate the selected factors of safety. The factors of safety for stability on slopes of 1:4, 1:3, 1:2 and 1:1 using 2-D limit equilibrium analyses were then calculated. The factors of safety for the integrity of the selected geosynthetic materials were also calculated.

Where factors of safety were found to be less than the accepted value of 1.5, the lining system components were replaced with geosynthetics of equivalent performance and the factors of safety for stability on slopes of 1:4, 1:3, 1:2 and 1:1 were recalculated. Where factors of safety were still below 1.5, another geosynthetic in the form of veneer reinforcement was used to increase the factor of safety to an acceptable value. Alternative single sided textured and double sided textured HDPE geomembrane liners were also used to help increase the interface shear parameters.

The findings from this dissertation will provide a greater understanding to landfill designers about the selection of materials of equivalent performance, the interface shear strengths of the materials tested and the performance of various landfill lining systems on steep and varying slopes. This research will also assist landfill designers to determine the relationship between various lining systems, the slope angles and factors of safety. Although this research will provide assistance with the above concepts, site specific testing is still required.

Finally, the recommendations for further research on the lining of steep slopes are also highlighted.

*In Memory of*

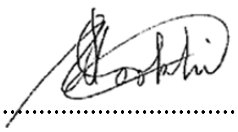
*Reya Dookhi*

(22 March 2011 – 28 March 2011)

# DECLARATION

I, Avinash Shripersadh Dookhi, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a) Their words have been re-written but the general information attributed to them has been referenced
    b) Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.
5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.



............................................................ 22.7.2014

**Signed:** Avinash Shripersadh Dookhi **Date**

As the candidate's Supervisor I agree / do not agree to the submission of this thesis

............................................................ 22.7.2014

**Signed:** Mr SM Jewaskiewitz **Date**

# ACKNOWLEDGEMENTS

Firstly, I would like to thank my Supervisor, Mr SM Jewaskiewitz, for his wisdom and assistance and the extra hours that he has put in in helping me achieve my objectives and meet my deadlines. Thank you, your assistance is much appreciated.

I would like to thank my Employer, Envitech Solutions, for giving me the time off for completing this research. I have been trying to balance work and this research for the year; however without the time given to me towards the end of this research I would not have been able to complete this research.

Kaytech Engineered Fabrics and Aquatan Lining Systems for providing me with all the geosynthetic samples that I needed and the technical data sheets. Apologies for hassling you guys.

Mr Preneshen Govender and Mr Mark Holder, your assistance with the shear box testing is much appreciated. Sitting in the laboratory taking continuous readings for four hours straight for weeks is no easy task. Your assistance has helped me to continue with work pressures when I needed it the most. Thank you.

To my family, who always believes that I can do more, I express my deepest gratitude. To my mum and dad, if it wasn't for the occasional nagging of "when are you going to finish", I could have let this research / degree that I started so long ago slide. Thank you for wanting more for me and for giving me all that you can.

To Nerissa, your support during this research has been amazing and your understanding when I was neglecting you even more so. Without you, this would not have been possible. I am forever grateful and indebted to you. Thank you! And finally, to my little man Sahil, who I have not spent enough time with during this research either, although he always wanted to do "work" with me. Maybe one day you will understand that this was all for you, trying to protect this earth for you and your future generations…

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| CCL | Compacted Clay Liner |
| DWAF | Department of Water Affairs and Forestry |
| FS | Factor of Safety |
| GCL | Geosynthetic Clay Liner |
| UKZN | University of Kwa-Zulu Natal |
| vs | Versus |

# CHAPTER 1

# INTRODUCTION

This Chapter introduces the research topic and the reasons and motivation for this research. The introduction also highlights the importance of the topic in the waste management industry in South Africa and the important possible impacts thereof. The main objectives are also defined. Chapter 1, Introduction, is concluded by an outline of the chapters to follow for this dissertation.

## 1.1 Introduction

The focus of this dissertation is to assess the lining system of landfill slopes as recommended by the Minimum Requirements for Waste Disposal (MRWD) Second Edition 1998 by the South African Department of Water Affairs and Forestry and to determine whether the minimum requirements specified are applicable to steep landfill slopes. The introduction will briefly explain the history of waste management and the progression thereof globally and within South Africa with regards to general practice and legislation. The introduction will also clarify the definition of steep landfill slopes.

Since the beginning of mankind, waste has been generated. It was only around 10 000BC when man abandoned his nomadic behaviour and started living in communities that waste became a problem. The waste within the communities then started jeopardising the city defences. It was around 500BC in Athens, Greece that the first recorded municipal waste dump was established. However, the practice of dumping waste within cities was still common in the United States and Europe until the late 1800s. Towards the end of the 19th Century and the beginning of the 20th Century, communities realised that the waste was causing ill health and diseases and began collecting the waste and disposing of it in open dumps, in the sea or burning the waste. Global waste management then progressed rapidly from the precursor to the modern landfill that was started in California in 1935, to the first guidelines for a “sanitary landfill” published by The American Society of Civil Engineers in 1959, to the American Solid Waste Disposal Act of 1965, to the American Resource Conservation and Recovery Act of 1976 to eventually the new American Federal Standards for Municipal Solid Waste (MSW) Landfills established by the Environmental Protection Agency (EPA) in 1991.

Following closely behind the global progression of waste management, the Waste Management Series produced by the South African Department of Water Affairs and Forestry was published in 1994. The Waste Management Series comprises of the following documents:

Document 1: Minimum Requirements for the handling, Classification and Disposal of Hazardous Waste

Document 2: Minimum Requirements for Waste Disposal by Landfill

Document 3: Minimum Requirements for Monitoring at Waste Management Facilities

After various workshops and consultation, the Second Edition of the Waste Management Series was published in South Africa in 1998.

As new technologies become available and experience is gained, waste regulations, legislations, policies and standards are continuously adapted to ensure maximum protection to the human health and the environment. Currently, Waste in South Africa is governed by means of a number of pieces of legislation, including:

- The South African Constitution (Act 108 of 1996)
- Hazardous Substances Act (Act 5 of 1973)
- Health Act (Act 63 of 1977)
- Environment Conservation Act (Act 73 of 1989)
- Occupational Health and Safety Act (Act 85 of 1993)
- National Water Act (Act 36 of 1998)
- The National Environmental Management Act (Act 107 of 1998)
- Municipal Structures Act (Act 117 of 1998)
- Municipal Systems Act (Act 32 of 2000)
- Mineral and Petroleum Resources Development Act (Act 28 of 2002)
- Air Quality Act (Act 39 of 2004)
- National Environmental Management: Waste Act, 2008 (Act 59 of 2008)

During the compilation of this dissertation on 23 August 2013, The Minister of Environmental Affairs published the following Regulations, Norms and Standards for immediate implementation:

- R634 Waste Classification and Management Regulations
- R635 National Norms and Standards for the Assessment of Waste for Landfill Disposal
- R636 National Norms and Standards for Disposal of Waste to Landfill

The implementation of the above National Norms and Standards has had a direct impact on my dissertation and research, as the landfill classification and liner system / containment barrier specified in the Minimum Requirements for Waste Disposal by Landfill has been superseded. This dissertation and research will be based on the containment barrier specified in the new National Norms and Standards for Disposal of Waste to Landfill dated 23 August 2013.

The Minimum Requirements for Waste Disposal by Landfill states that the impoundment slope must not be steeper than 1 vertical to 3 horizontal and, depending on geotechnical factors, may have to be flatter than this whereas the National Norms and Standards for Disposal of Waste to Landfill states that alternative design layouts for slopes exceeding 1:4 (vertical:horizontal) may be considered provided equivalent performance is demonstrated.

Although currently, in South Africa and globally the concept of Integrated Waste Management, which also includes waste minimisation, recycling and treatment is being promoted, there is, and will be, the need for landfill sites in the foreseeable future. As land for these landfill sites become scarcer, and although there are greater technical design challenges, the use of land with slopes greater than 1 in 4 and 1 in 3 become more commercially viable.

The definition of a steep slope is often subjective and is often assumed to be near vertical. Jones and Dixon (2003) suggest that slope angles in excess of 30° are “steep”. Fowmes (2007) suggests that the classification of steep sided landfill be based on the stability of the internal components, and the following definition of a steep slope is suggested and will be used for this dissertation:

**"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." Fowmes (2007)**

The general objective of a landfill design is to provide a cost effective, environmentally accepted waste disposal facility and the main objective of the lining system is to prevent pollution by leachate of the adjacent ground water and surface water. Therefore, the stability and integrity of the lining system on steep slopes, in both the short and the long term, are vital in its performance as a barrier.

## 1.2 Motivation for the Investigation

During the design of various lining systems for different sites, the stability and integrity, of the lining system is always in question. Although the National Norms and Standards for Disposal of Waste to Landfill provides the minimum requirements for the lining system and states that alternative design layouts for slopes exceeding 1:4 may be considered, the design engineer is always left with the decision of what the optimum lining system would comprise of and what the most desirable landfill side slopes should be taking into consideration the cost implications and whether the design is environmentally acceptable for the duration of its intended life.

Although every lining system design is site specific, the design of lining systems on steep slopes has and always will be a global challenge. Elton et al., 2002 paper which details geomembrane research needs states that further research is required on geomembranes on steep walls, thus the motivation for this investigation.

## 1.3 Aim of the Investigation

The aim of this investigation was to assess the stability of legislated landfill lining systems on varying slopes by calculating the factors of safety whilst using the critical interface parameters.

## 1.4 Objectives of the Investigation

The objectives of this investigation were:

1. To select a representative landfill lining system from the various classes of landfills prescribed by the National Norms and Standards for Disposal of Waste to Landfill.
2. To determine the various landfill system interfaces and performing direct shear tests between these interfaces.
3. To determine the stability of the prescribed landfill lining systems on various slopes by calculating the Factors of Safety on the critical interfaces by using the limit equilibrium analyses for a finite slope length.
4. To determine whether the use of alternative geosynthetics instead of the prescribed mineral layers in the lining system will help increase the Factors of Safety on steep slopes.
5. To determine whether the landfill lining systems prescribed by the National Norms and Standards for Disposal of Waste to Landfill is stable and suitable for steep slopes.

Although not one of the primary objectives, this investigation was to act as a first generation preliminary guide to designers of lining systems to determine the relationship between the various lining layers, slopes and factors of safety that may be encountered, although site specific testing must be carried out.

The Mariannhill Landfill site was selected as a case study due to the varying and steep valley side slopes, the variability of the lining system elements for the various landfill cells, as technology improved and legislation changed, and the overall complexity of the site. The site specific conditions of the various lining system elements were assessed to determine the stability of the lining system on the steep side slopes. The aim was to determine the overall factor of safety and to confirm that the design was conservative.

## 1.5 Outline of the Dissertation

Chapter Two of this dissertation details the changes in legislation and prescribed lining systems and introduces the various liner components. The available tools used for determining the stability of lining systems is discussed and explained. The decision on whether to use the peak or residual shear strengths is also discussed.

Chapter Three presents the methodology used for determining the stability of lining systems from the tools available in chapter two. The use of alternative lining components is investigated where the prescribed lining components are not suitable. The test methods used are also discussed and the direct shear testing methods used for this dissertation is detailed.

Chapter Four presents the results obtained from the direct shear testing, by means of ring shear tests, and the stability analyses, for the prescribed lining system components, as well as the alternative geosynthetics used to help improve the stability. The self-weights of the various lining system components are also assessed. The use of geogrids as veneer reinforcement is analysed. Finally, the factors that were not considered during this investigation are discussed.

The case study used for this dissertation is presented in Chapter Five. The case study aims to assess the lining system on a steep sided valley landfill site. The complexity of this site is discussed and the reasons for selecting this site are explained. The selected lining system is analysed and the factor of safety is checked for stability.

Chapter Six presents a summary of the research and conclusions for the dissertation. The results obtained from the research are explained and the objectives of this research are revisited. Recommendations for further research on this topic are also highlighted.

# CHAPTER 2

# LITERATURE REVIEW

Chapter Two assesses the change in legislation with regards to the prescribed lining systems and introduces the various liner components. The definitions and a review of various geosynthetics are undertaken. The concept of landfill stability is discussed. The limit equilibrium concept is explained and the limit equilibrium forces are shown. The applicable factors of safety are assessed. The various applicable test methods are reviewed. Finally, the decision on whether to use peak or residual shear strengths is discussed.

## 2.1 Review of Past and Present Prescribed Lining Systems

The Waste Management Series that was published in 1998 by the Department of Waters Affairs and Forestry is the prescribed reference framework of standards for waste management in South Africa. Document 2 of the Waste Management Series, Minimum Requirements for Waste Disposal by Landfill detailed the landfill liner designs when the research for this dissertation commenced and will therefore be highlighted. The landfill liner designs were based on the following criteria:

- Waste Class, and the waste class may be:
    - General Waste **(G)** or
    - Hazardous Waste **(H)**

- Landfill Size Class, and the landfill size class may be:
    - Communal **(C)**, with a maximum rate of deposition of less than 25 tonnes per day,
    - Small **(S)**, with a maximum rate of deposition of more than 25 tonnes per day and less than 150 tonnes per day,
    - Medium **(M)**, with a maximum rate of deposition of more than 150 tonnes per day and less than 500 tonnes per day or
    - Large (L), with a maximum rate of deposition of more than 500 tonnes per day

- The Potential for Significant Leachate Generation, and may be:
  - Does not generate significant leachate **($B^-$)** or
  - Generates significant leachate **($B^+$)**

The landfill liner designs based on the Minimum Requirements for Waste Disposal by Landfill, that was applicable to all slopes i.e. gentle and/or steep, are illustrated in Figure 2.1 to Figure 2.7.

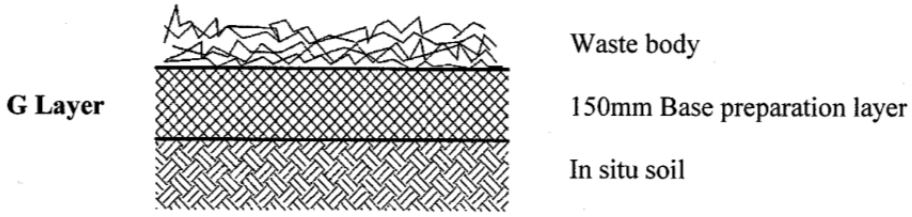



**Figure 2.1: G:S:$B^-$ Landfills (DWAF, 1998)**

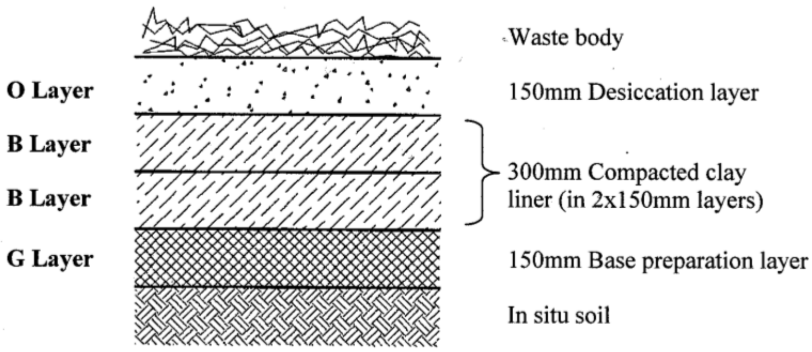



**Figure 2.2: G:M:$B^-$ Landfills (DWAF, 1998)**

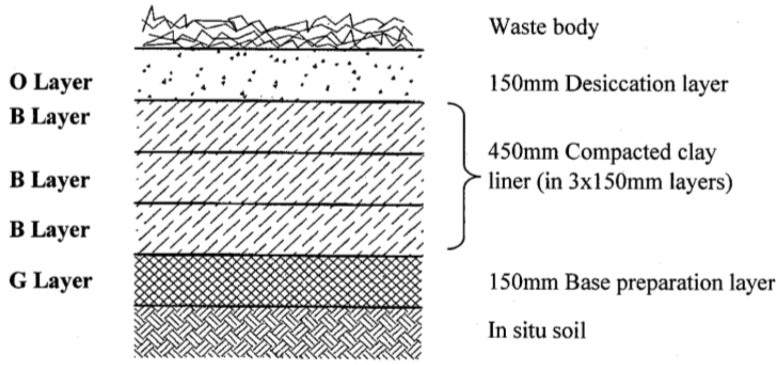



**Figure 2.3: G:L:B$^-$ Landfills (DWAF, 1998)**

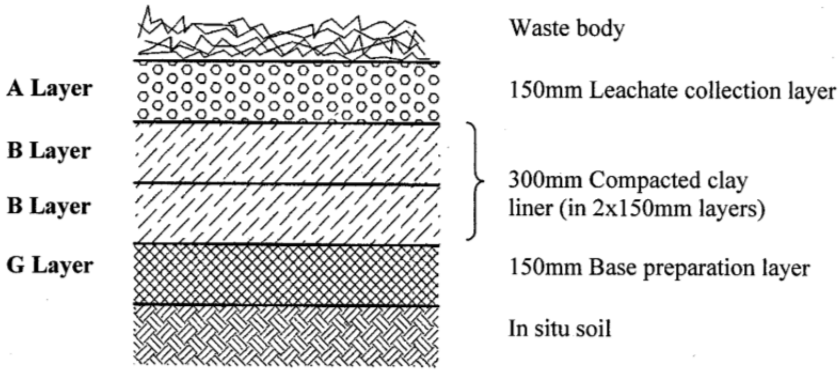



**Figure 2.4: G:S:B$^+$ Landfills (DWAF, 1998)**

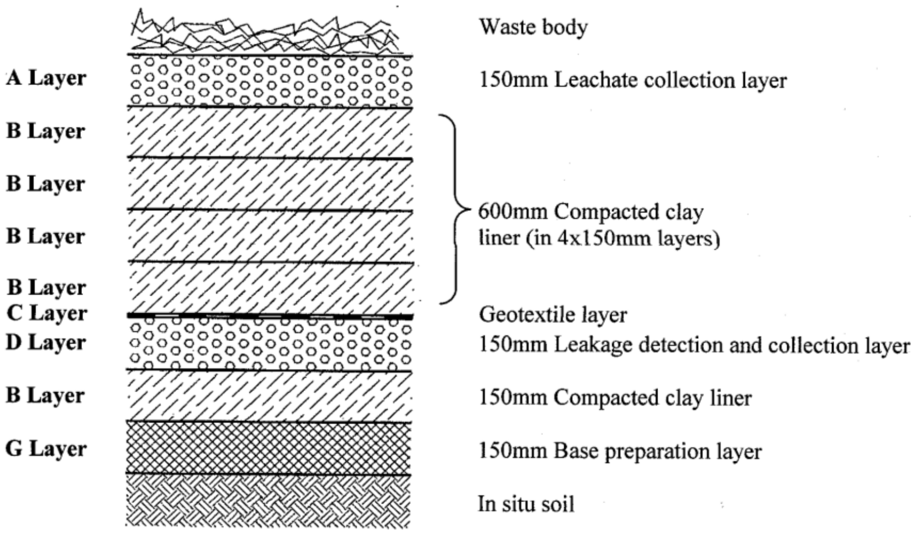



**Figure 2.5: G:M:B$^+$ and G:L:B$^+$ Landfills (DWAF, 1998)**

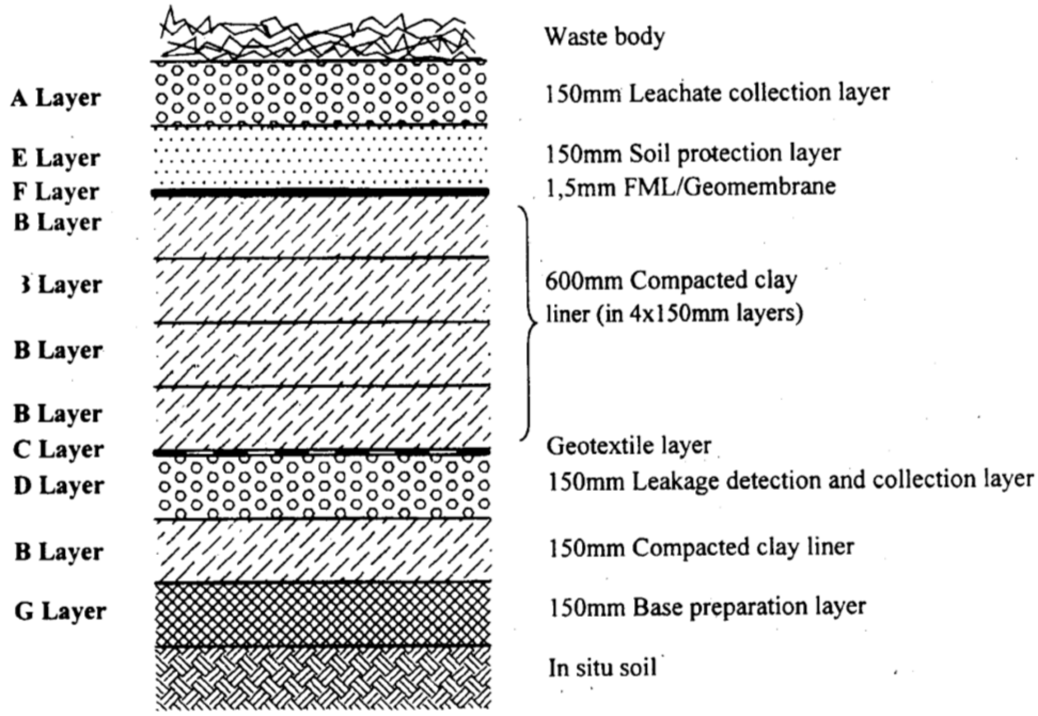



**Figure 2.6: H:h Landfills (DWAF, 1998)**

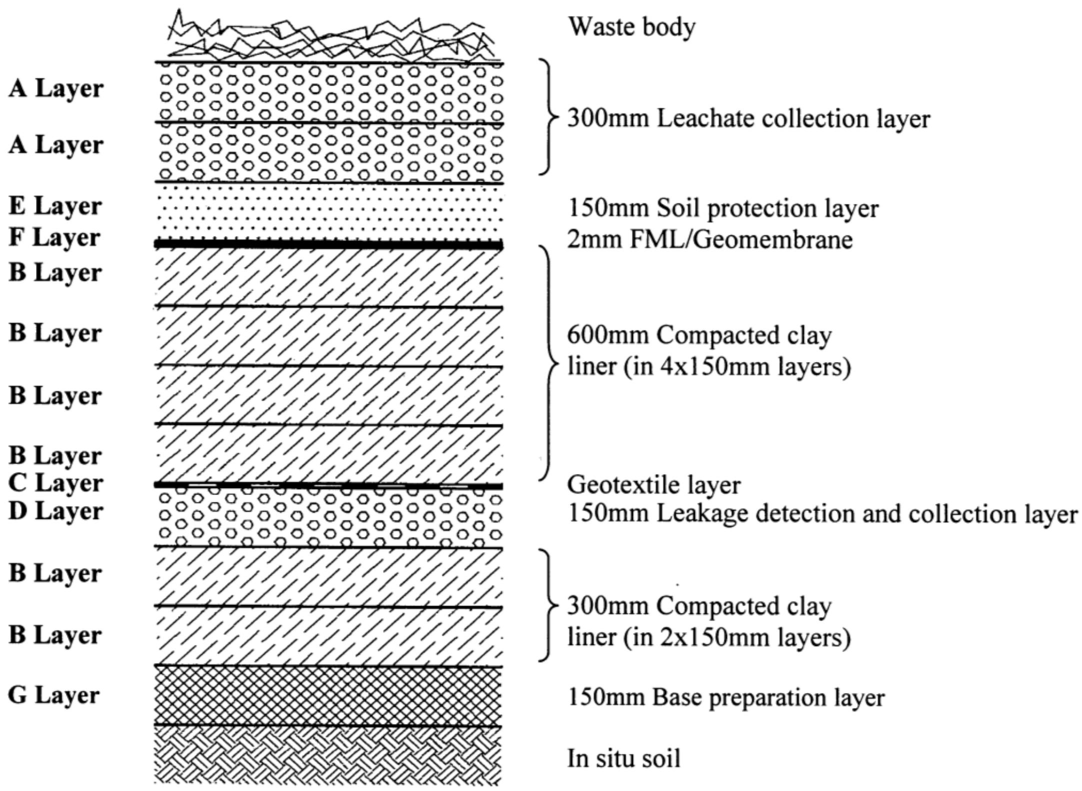



**Figure 2.7: H:H Landfills and Encapsulation Cells (DWAF, 1998)**

On 23 August 2013, the above landfill liner designs were superseded by the Landfill Classification and Containment Barrier Designs as contained in the new National Norms and Standards for Disposal of Waste to Landfill. The containment barrier designs are now based on the new waste classification and are prescribed by the waste types.

The waste types are extensively prescribed in Government Gazette, No. 36784, 2013.

The landfill disposal requirements for the waste types are also included in Government Gazette, No. 36784, 2013 and are summarised in Table 2.1 and compared to the Minimum Requirements for Waste Disposal by Landfill.

**Table 2.1: Landfill Disposal Requirements Based on Waste Type**

| Waste Type | Landfill Disposal Requirements and Comparison | |
|---|---|---|
| | National Norms and Standards for Disposal of Waste to Landfill classification | Minimum Requirements for Waste Disposal by Landfill classification |
| Type 0 Waste | Waste to landfill is not allowed. Waste must be treated and re-assessed | |
| Type 1 Waste | Class A landfill | H:h / H:H |
| Type 2 Waste | Class B landfill | $G:L:B^{+}$ |
| Type 3 Waste | Class C landfill | $G:L:B^{+}$ |
| Type 4 Waste | Class D landfill | $G:L:B^{-}$ |

The containment barriers that are now applicable to all slopes i.e. gentle and/or steep are illustrated in Figure 2.8 to Figure 2.11.

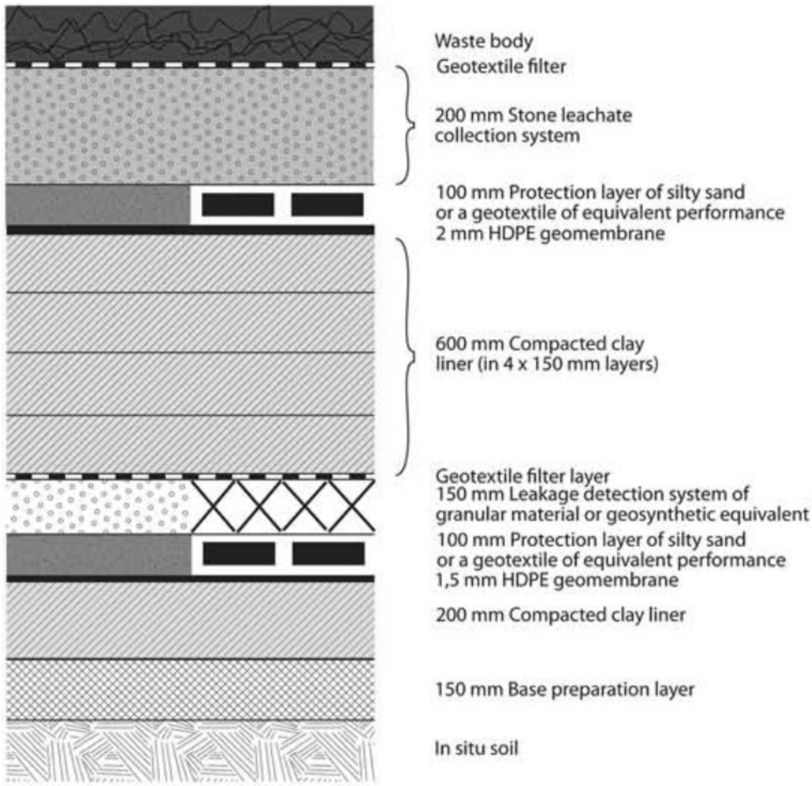



**Figure 2.8: Class A Landfill (Government Gazette, No. 36784, 2013)**

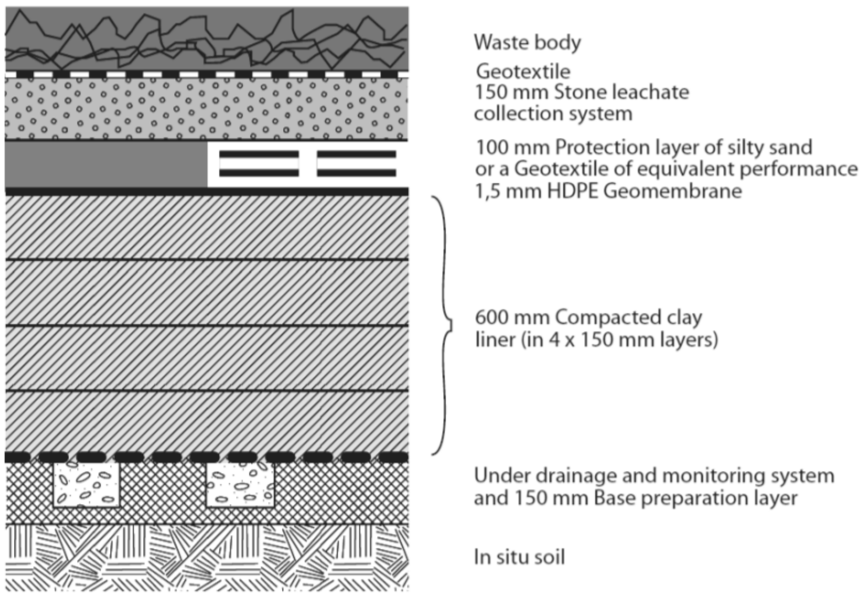



**Figure 2.9: Class B Landfill (Government Gazette, No. 36784, 2013)**

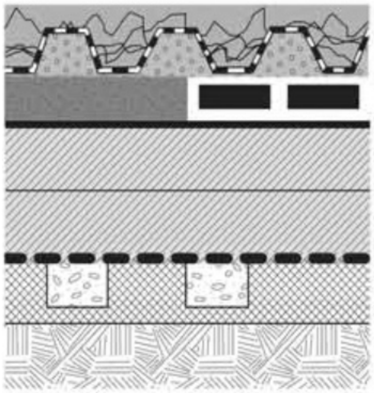



**Figure 2.10: Class C Landfill (Government Gazette, No. 36784, 2013)**

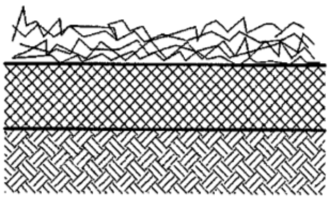



**Figure 2.11: Class D Landfill (Government Gazette, No. 36784, 2013)**

This dissertation was based on the analysis of the containment barrier designs as contained in the new National Norms and Standards for Disposal of Waste to Landfill, as the landfill liner designs previously prescribed by the Minimum Requirements for Waste Disposal by Landfill have been superseded.

It should be noted however, that although the landfill liner designs have been superseded by the containment barrier designs, the Minimum Requirements for Waste Disposal by Landfill still prescribes the specifications of the barrier design elements as these have not been amended by the new National Norms and Standards for Disposal of Waste to Landfill, and is applicable to both gentle and/or steep slopes.

The Mariannhill Landfill Site case study was based on the lining system as prescribed by the Minimum Requirements for Waste Disposal by Landfill, as that was the legislated lining system during the design of the Mariannhill Landfill Site in 2010.

## 2.2 Specification of Prescribed Lining System Elements

As can be seen in the above figures, every containment barrier design is made up of a series of liner components. The purpose of a containment barrier is to prevent pollution by leachate of the adjacent ground water and surface water and each liner component has a specific function. The detail and variation associated with each liner component is described below (DWAF, 1998) and is currently applicable, as it has not been amended by the National Norms and Standards for Disposal of Waste to Landfill:

Base Preparation Layer: The base preparation layer comprises of a compacted layer of reworked in-situ soil with a minimum thickness of 150mm and constructed to the same compaction standards as the clay liner layer. Where the permeability of a base preparation layer can be proven to be of the same standard the clay liner layer, it may replace the lowest clay liner layer.

Clay Liner Layer: Comprises of a 150mm thick compacted clay liner layer. This layer must be compacted to a minimum density of 95% Standard Proctor maximum dry density at a water content of Proctor optimum to optimum +2%. Permeabilities must be such that the outflow rates must not exceed 3 x $10^{-7}$ cm/s and 1 x $10^{-7}$ cm/s respectively for a Class A landfill and is dependent on the receiving waste type, and 1 x $10^{-6}$ cm/s for Class B, Class C and Class D landfills. Interfaces between the clay liner layers must be lightly scarified to assist in bonding the layers together.

Geomembrane Liner: A 1.5mm HDPE geomembrane liner for Class A, Class B and Class C landfills. As well as an additional 2.0mm HDPE geomembrane liner for a Class A landfill which must be laid in direct contact with the upper surface of a compacted clay liner layer.

The geomembrane thickness specified shall be minimum thickness, as measured in accordance with the SABS Specification 1526 test method.

Protection Layer: This is a cushion of 100mm of fine to medium sand or similar suitable material which is placed immediately above any geomembrane liner layer to protect it from mechanical damage. A geotextile of equivalent performance may be used.

Leachate Collection Layer: A leachate collection layer comprising a layer of single-sized gravel or crushed stone having a size of between 38mm and 50mm. The thickness of the leachate collection layer varies from 200mm thick for a Class A landfill, 150mm thick for a Class B landfill and a 300mm thick finger drain of geotextile covered aggregate for a Class C landfill. A Class D landfill does not contain a leachate collection layer.

Geotextile Filter: The geotextile filter is placed above the leachate collection layer and/or leachate detection system to prevent excessive clogging (Koerner, 2005).

Leakage Detection System: Applicable to Class A landfills only and comprises of a 150mm thick single-sized gravel or crushed stone having a size of between 38mm and 50mm.
A geosynthetic equivalent may be used.

Under Drainage and Monitoring System: Applicable to Class B and Class C landfills only and may comprise of finger drains within the base preparation layer.

A few of the above containment barrier components may be replaced with alternative elements of proven performance (Government Gazette, No. 36784, 2013), such as the replacement of:

i) Granular filters or drains with geosynthetic filters or drains

ii) Protective soil layers with geosynthetics

iii) Clay components with geomembranes or geosynthetic clay liners

The use of the above alternatives raises the concept of Equivalency and will be discussed in 2.4 below.

## 2.3 Introduction and Description of Applicable Geosynthetics

Geosynthetics is defined as a planar product manufactured from polymetric material used with soil, rock, earth, or other geotechnical related material as an integral part of a human-made project, structure or system (ASTM D4439).

Geosynthetic materials perform five major functions (Koerner, 2005):

1) Separation
2) Reinforcement
3) Filtration
4) Drainage
5) Containment (of liquid and/or gas)

The use of geosynthetics has basically two aims: (1) to perform better (e.g., with no deterioration of material or excessive leakage) and (2) to be more economical than using traditional materials and solutions) either through lower initial costs or through greater durability and longer life, thus reducing maintenance and replacement costs) (Koerner, 2005).

There are currently eight types of geosynthetics available namely, geomembranes, geosynthetic clay liners, geotextiles, geonets, geogrids, geopipes, geofoam and geocomposites.

The use of a single geosynthetic or a multitude of geosynthetics for a specific function or a combination of functions is vital to the design of containment barrier systems and is even more vital for the design of containment barrier systems on steep slopes.

A brief description and the function of the geosynthetics that were tested are listed below:

**a)** **Geotextiles** are permeable fabrics which, when used in association with soil, have the ability to separate, filter, reinforce, protect, or drain. Typically made from polypropylene or polyester. Geotextile fabrics come in three basic forms: woven, needle punched or heat bonded (Wikipedia, accessed 21/11/13).

**Figure 2.12: Examples of Geotextiles**

**b)** **Geosynthetic clay liners (GCLs)** are factory-manufactured hydraulic barriers comprising of a thin layer of bentonite (or other very low permeability material) supported by geotextiles and/or geomembranes, being mechanically held together by needling, stitching, or chemical adhesives (Koerner, 2005).

**Figure 2.13: Examples of GCLs**

**c)** A **Geomembrane** is defined as a very low permeability synthetic membrane liner or barrier used with any geotechnical engineering related material so as to control fluid (or gas) migration in a human-made project, structure, or system (ASTM D4439).

Geomembranes are made from relatively thin continuous polymeric sheets, but they can also be made from the impregnation of geotextiles with asphalt, elastomer or

Polymer sprays, or as multilayered bitumen geocomposites. In this research, we will focus on continuous polymer sheet geomembranes since they are, by far, the most common (Wikipedia, accessed 21/11/13).

**Figure 2.14: Examples of Geomembranes**

## 2.4 Equivalency Issues

Most international regulations allow for the replacement of certain lining system components if the alternative component is technically equivalent. The regulations however, rarely illustrate or provide sufficient criteria as to how technical equivalency is to be justified.

In South Africa, the following alternative lining system components of proven equivalent performance is allowed (Government Gazette, No. 36784, 2013):

i) Replacement of granular filters or drains with geosynthetic filters or drains
ii) Replacement of protective soil layers with geosynthetics
iii) Replacement of clay components with geomembranes or geosynthetic clay liners

It is therefore here that the Design-by-Function concept, with the establishment of adequate factors of safety, was applied.

### 2.4.1 Geonets

The function of granular filters or drains is in-plane drainage of liquids or gases and could be replaced with the use of geonets. Since the primary function of granular filters or drains and geonets on landfill sites is to convey liquid within the plane of its structure, the in-plane hydraulic flow rate, or transmissivity is of paramount importance (Williams et al., 1984).

For geonets, where flow rate is the primary function, the factor of safety takes the following form as detailed by Koerner (2005):

$$FS = \frac{q_{allow}}{q_{required}} \quad (2\text{-}1)$$

where

FS = Factor of safety (to handle unknown loading conditions or uncertainties in the design and testing methods),

$q_{allow}$ = Allowable flow rate as obtained from laboratory testing, and

$q_{required}$ = Required flow rate as obtained from design of the actual system

Alternatively, we could work from transmissivity to obtain the equivalent relationship. It should be emphasized however, that *flow rates per unit width* values are not *transmissivity* values. To convert flow rate per unit width to transmissivity θ, Darcy's formula may be used (assuming saturated conditions and laminar flow):

$$q = kiA$$

$$q = ki\,(W \times t)$$

$$q/W = i\,(k \times t)$$

$$kt = \theta = \frac{q}{iW}$$

where

q = Volumetric flow rate ($m^3/s$)

k = Coefficient of permeability (m/s)

i = Hydraulic gradient (dimensionless)

A = Flow cross-sectional area ($m^2$)

$\theta =$ Transmissivity ($m^2/s$)

W = Width (m)

t = Thickness (m)

The q value developed using Darcy's formula is applicable to both the $q_{allow}$ and $q_{required}$ mentioned in equation (2-1) above, and may be used for conversion purposes.

For granular filters or drains, Darcy's law constitutive equation may be used to calculate the flow of a fluid through a porous medium.

It should be noted that although geonets are mentioned, they have not been tested during this research due to their larger aperture sizes, scale effects and the limitations of the ring shear apparatus.

### 2.4.2 Geotextiles as a Protection Layer

Protective soils may be replaced by an appropriate geotextile. Since the primary function of the protective soil is to protect the HDPE geomembrane liner from damage and/or puncture, the key properties for the use of a geotextile as a protection layer are Burst Resistance, Tensile Strength, Puncture Resistance and Impact (Tear) Resistance.

The design-by-function equation formulated by Koerner (2005) for the use of geotextiles is as follows:

$$\text{factor of safety (FS)} = \frac{\text{allowable (test) property}}{\text{required (design) property}} \tag{2-3}$$

where

allowable property = a numeric value based on a laboratory test that models the actual situation or is adjusted accordingly

required property = a numeric value obtained from a design method that models the actual situation

factor of safety (FS) = FS against unknown loads and/or uncertainties in the analytic or testing process, sometimes called a global factor of safety

Burst Resistance

The equations to calculate burst resistance are as follows (Giroud, 1984):

$$T_{reqd} = 0.5\ p'\ d_v\ [\ f\ (\ \in\ )\ ] \qquad (2\text{-}4)$$

where

$T_{reqd}$ = required geotextile strength (kPa)
p' = stress on the geotextile, which is slightly less than p, the tire inflation pressure at the ground surface (Pa)
$d_v$ = maximum void diameter of the stone @ $0.33d_a$ (m)
$d_a$ = the average stone diameter (m)
f(∈) = strain function of the deformed geotextile,

$$= \frac{1}{4}\left[\frac{2y}{b} + \frac{b}{2y}\right] \text{, in which} \qquad (2\text{-}5)$$

b = width of opening (or void) (m)
y = deformation in the opening (or void) (m)

Tensile Strength

The equation to calculate the tensile strength is as follows (Giroud, 1984):

$T_{allow}$ = maximum grab strength of geotextile with cumulative reduction factors

$$T_{reqd} = p'\ d_v^2\ [\ f\ (\ \in\ )\ ] \qquad (2\text{-}6)$$

where

$T_{reqd}$ = required grab tensile force (N)
p' = applied pressure (Pa)
$d_v$ = maximum void diameter of the stone @ $0.33d_a$ (m)
$d_a$ = the average stone diameter (m)
f(∈) = strain function of the deformed geotextile,

$$= \frac{1}{4}\left[\frac{2y}{b} + \frac{b}{2y}\right] \text{, in which}$$

| | | |
|---|---|---|
| b | = | width of stone void (m) |
| y | = | deformation into stone void (m) |

Puncture Resistance

The equation to calculate the puncture resistance is as follows (Koerner, 2005):

$F_{allow}$ = ultimate puncture strength according to ASTM D4833

$$F_{reqd} = p' \; d_a^2 \; S_1 \; S_2 \; S_3 \quad (2\text{-}7)$$

where

| | | |
|---|---|---|
| $F_{reqd}$ | = | required vertical puncturing force to be resisted (N) |
| p' | = | pressure exerted on the geotextile (approximately 100% of tire inflation pressure at the ground surface for thin covering thicknesses) (Pa) |
| $d_a$ | = | average diameter of the puncturing aggregate or sharp object (m) |
| $S_1$ | = | protrusion factor of the puncturing object (dimensionless) |
| $S_2$ | = | scale factor to adjust the ASTM D4833 puncture test value that uses a 8mm diameter puncture probe to the actual puncturing object (dimensionless) |
| $S_3$ | = | shape factor to adjust the ASTM D4833 flat puncture probe to the actual shape of the puncturing object (dimensionless) |

Impact (Tear) Resistance

The resistance to impact of a geotextile is a survivability function as well as a protection and separation function. An object will rarely be intentionally dropped on an exposed geotextile with additional force, so only gravitational energy will be assumed.

The equation to calculate the energy developed due to the mass of an object due to acceleration by gravity is as follows (Koerner, 2005):

$E_{allow}$ = geotextile allowable impact strength

$$E_{reqd} = m \; g \; h \quad (2.8)$$
$$= (V \; x \; \rho \;) \; g \; h$$

$$= [V \times (\rho_w G_s)]\, gh$$

$$= \left[ \frac{\pi(d_o / 1000)^3}{6} \right] \left[ \frac{1000kg}{m^3} \right] (2.6)\,(9.81)\, h$$

$$= 13.35 \times 10^{-6}\, d_o^3\, h$$

where

| | | |
|---|---|---|
| E | = | energy developed dependant on diameter of object and height of fall and (Joules) |
| m | = | mass of the falling object (kg) |
| g | = | acceleration due to gravity ($m/sec^2$) |
| h | = | height of fall (m) |
| V | = | volume of the object ($m^3$) |
| $\rho$ | = | density of the object ($kg/m^3$) |
| $\rho_w$ | = | density of water ($kg/m^3$) |
| $G_s$ | = | specific gravity of the object (dimensionless) |
| $d_o$ | = | diameter of the object (mm) |

$E_{reqd}$ is a calculated required value to calculate the factor of safety for impact (tear) resistance.

### 2.4.3 Geosynthetic Clay Liner

The technical equivalency between compacted clay liners (CCLs) and geosynthetic clay liners (GCLs) is often based on the flow rate or flux through the competitive materials using Darcy's formula. This parameter however, is only the beginning of a complete equivalency comparison as various issues such as construction issues, hydraulic issues and physical/mechanical issues need to be assessed.

A complete set of equivalency issues that often require analysis is shown in Table 2.2.

**Table 2.2: Generalised Technical Equivalency Assessment for GCL Liners Beneath Landfills and Surface Impoundments (Koerner et al., 1993)**

| Category | Criterion for Evaluation | Probably Superior | Probably Equivalent | Probably Not Equivalent | Equivalency Depends on Site or Product |
|---|---|---|---|---|---|
| Hydraulic issues | Steady flux of water | | ✓ | | |
| | Steady solute flux | | ✓ | | |
| | Chemical adsorption capacity | | | ✓ | |
| | Breakout time | | | | |
| | Water | | | | ✓ |
| | Soluble | | | | ✓ |
| | Horizontal flow in seams and lifts | | ✓ | | |
| | Horizontal flow beneath geomembrane | | ✓ | | |
| | Generation of consolidation water | | ✓ | | |
| | | | | | |
| Physical / Mechanical issues | Freeze-thaw behaviour | | ✓ | | |
| | Total settlement | | | ✓ | |
| | Differential settlement | | ✓ | | |
| | Stability on slopes | | | | ✓ |
| | Squeezing or bearing stability | | | ✓ | |
| | | | | | |
| Construction issues | Puncture resistance | | | ✓ | |
| | Subgrade conditions | | | ✓ | |
| | Ease of placement | ✓ | | | |
| | Speed of construction | ✓ | | | |
| | Availability of materials | ✓ | | | |
| | Requirements for water | ✓ | | | |
| | Air pollution effects | ✓ | | | |
| | Weather constraints | | | | ✓ |
| | Quality assurance considerations | ✓ | | | |

Although the above table highlights equivalencies, the decision on whether to use CCLs or GCLs is very site specific, and in most cases, also budget dependant.

### 2.4.4 Summary of Equivalent Landfill Lining Components and Factors Adopted to Prove Equivalency

A summary of the prescribed lining system components and the corresponding alternative lining system components with the relevant equivalency factors that were assessed during this research are highlighted in Table 2.3.

**Table 2.3: Summary of Equivalent Landfill Lining Components and Factors Adopted to Prove Equivalency**

| | Prescribed Lining System Component | Alternative Lining System Component | Factors to Prove Equivalence | Comments |
|---|---|---|---|---|
| **1** | Under drainage and monitoring system | Geosynthetic filter (Geonets) | Hydraulic flow rate or transmissivity | Equation (2-1) or Darcy's formula (Geonets have not been tested in this research due to the limitations on the ring shear apparatus used) |
| **2** | 100mm Protection layer of silty sand | Geotextiles | Burst resistance, Tensile strength, Puncture resistance and Impact (tear) resistance | Equation (2-5), Equation (2-6), Equation (2-7) and Equation (2-8) |
| **3** | Compacted clay liner | Geosynthetic clay liners | Hydraulic, Physical/Mechanical and Construction issues | As per Table 2.1 |

In addition to the prescribed lining system components used for this research, the alternative landfill lining system components were adopted and tested during this research to assist in achieving an acceptable factor of safety of greater than 1.5 on steep slopes. This is due to the limitations and instability of the mineral layers on the steep slopes.

## 2.5 Landfill Stability

The stability of landfills has been a major concern for past and present environmental geotechnical engineers as both the short term and long term stability is vital to the performance as a containment barrier system for leachate.

The stability of a landfill is controlled by the following factors (Oweiss, 1992):

- The properties of the supporting soil (strength and bearing characteristic).
- The strength characteristics and the weight of the refuse (density, cohesion and friction angles).
- **The inclination of the slope.**
- Leachate levels and movements within the landfill (affecting pore pressures, effective stress and interface friction).
- The type of cover (soil, soil-geomembrane).
- Cover resistance to erosion.

All of the above factors are vital to landfill stability, however the inclination of the slope is highlighted as it relates directly to this research.

From above, it can be seen that the inclination of the slope is a major factor that affects overall landfill stability and therefore the design and construction of legislative compliant lining systems on steep slopes are a major challenge.

### 2.5.1 Methods of Stability Analysis

Currently in South Africa and internationally the limit state approach is the accepted geotechnical engineering design practice. Using this approach to analysis, there are two states in which failure can occur (Dixon et al., 2003):

> **Ultimate** limit state where there is a complete loss of stability or function (example, slope failure), and
> **Serviceability** limit state such that the function of a structure is impaired (example, stressing of a landfill liner leading to increased permeability).

In the context of landfill lining system design (Dixon et al., 2003):

> **Stability** of the lining system is the ultimate limit state; and
> **Integrity** of the lining system is the serviceability limit state.

Due to the difference between the ultimate limit state and the serviceability limit state, different methods of analysis for the two limit states are required.

Serviceability limit state, relates to the stresses, strains and deformations, in the system and within defined liner components, and this type of analysis requires analytical techniques such as **finite difference** and **finite element** formulations that require the use of computer programmes for analysis.

The analysis of ultimate limit state (example, slope instability) can be done by using the **limit equilibrium** concepts on an assumed circular arc failure plane or alternatively on a **two-part wedge analysis** for a finite length slope analysis as shown in Figure 2.15. Deformations and stresses that are encountered in the serviceability limit state can be controlled in the limit equilibrium analysis by increasing the factor of safety, however it is difficult to determine the stress and strain relationship with a given factor of safety.

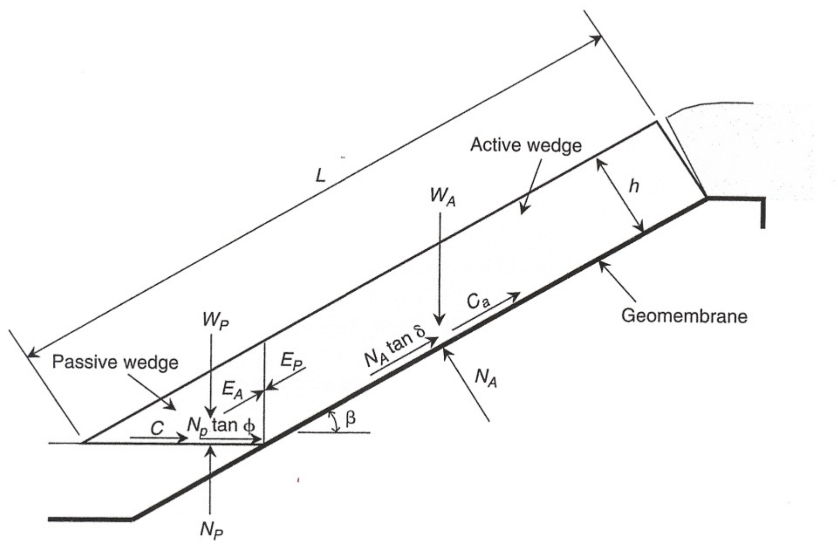



**Figure 2.15: Limit Equilibrium forces involved in a finite length slope analysis for a uniformly thick cover soil (After Koerner and Soong, 1998)**

The driving forces creating the instability in the two-part wedge analysis are the gravitational forces, equipment loads, surcharge loads, seepage forces and/or seismic forces. Each must be carefully considered in the context of site-specific conditions.

In Figure 2.15, two discreet zones can be visualised. There is a small passive wedge near the toe of the slope resisting a long thin active wedge extending the length of the finite slope. This method of analysis also assumes that the continuity is broken with the remaining cover soil at the crest.

By taking free bodies of the active and passive wedges with the appropriate forces being applied, the formulation of the factor of safety results. The resulting equation is not an explicit solution for the factor of safety, and must be solved using the quadratic equation.

For the above analysis in Figure 2.15, the resulting factor of safety value is obtained from the following equation (Koerner, 2005) and the complete development of the equation is given by Koerner and Soong (1998):

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \qquad (2.9)$$

where

$$a = (W_A - N_A \cos\beta)\cos\beta \qquad (2.10)$$

$$b = -[(W_A - N_A \cos\beta)\sin\beta\tan\phi + (N_A \tan\delta + C_a)\sin\beta\cos\beta + \sin\beta(C + W_p \tan\phi)], \text{ and} \qquad (2.11)$$

$$c = (N_A \tan\delta + C_a)\sin^2 \tan\phi \qquad (2.12)$$

and where

$W_A$ = total weight of the active wedge
$W_P$ = total weight of the passive wedge
$N_A$ = effective force normal to the failure plane of the active wedge
$N_P$ = effective force normal to the failure plane of the passive wedge
$\gamma$ = unit weight of the cover soil
h = thickness of the cover soil
L = length of slope measured along the geomembrane
$\beta$ = soil slope angle beneath the geomembrane
$\phi$ = friction angle of the cover soil
$\delta$ = interface friction angle between the cover soil and geomembrane
$C_a$ = adhesion force between cover soil and the active wedge and the geomembrane
$c_a$ = adhesion between cover soil of the active wedge and the geomembrane
C = cohesion force along the failure plane of the passive wedge
c = cohesion of the cover soil
$E_A$ = interwedge force acting on the active wedge from the passive wedge
$E_P$ = interwedge force acting on the passive wedge form the active wedge
FS = factor of safety against cover soil sliding on the geomembrane

In addition

Back slope - refers to the side slopes of the landfill which have generally steep slopes
Front slope - refers to the basal / base areas of a landfill which have generally gentle slopes

In the above two-part wedge method, the direction of the interwedge force is assumed to be parallel to either the back slope or the front slope (U.S Army Corps of Engineers, 1960). In the new approach of the two-part wedge method developed by Qian and Koerner in 2003 and updated by Qian and Koerner in 2004, 2005 and 2007 and by Qian in 2006 and 2008, the interwedge forces, $E_A$ and $E_P$, are assumed to be inclined at an unknown angle ($\omega$) to the normal direction of the interface between the active and passive wedges, and each of them is divided into two components, as seen in Figure 2.16, where $E_{HA}$ and $E_{VA}$ are the two components of $E_A$, $E_{HP}$ and $E_{VP}$ are the two components of $E_P$, $U_{HA}$ and $U_{HP}$ are the resultants of the pore water pressures acting on the interface between the active and passive wedges, $U_{NA}$ and $U_{NP}$ are the resultants of the pore water pressures acting on the bottom of the active and passive wedges, $N_A$ and $N_P$ are the normal forces acting on the bottom of the active and passive wedges, $W_A$ and $W_P$ are the weights of the active and passive wedges, $F_A$ and $F_P$ are the frictional forces acting on the bottom of the active and passive wedges, $B$ is the top width of the waste mass, and $H$ is the height of the back slope. In order to meet the waste shear failure criteria at the interface between the active and passive wedges, the average shear stress on the interface must be less than the average shear strength of the waste at the interface. Considering the equilibrium of the whole waste mass, the factor of safety at the interface between active and passive wedges, $FS_V$, should not be less than the factor of safety for the entire solid waste mass, $FS$. $FS$ is assumed to be the same at all points on the failure surface. (Qian, 2008)

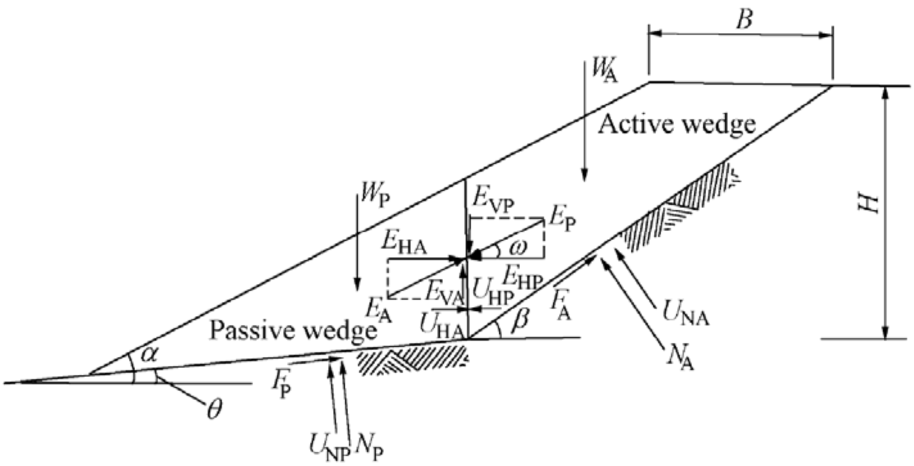



**Figure 2.16: Forces acting on two adjacent wedges of a waste mass in a landfill cell (Qian, 2008)**

The force equilibrium equation for the resulting factor of safety can be expressed as follows (Qian, 2008):

$$FS = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{2.13}$$

where

$$A = (W_T\, m_{SW} \sin\beta \sin\theta + W_A \sin\beta \cos\theta + W_P \cos\beta \sin\theta - n_{SW} \sin(\beta - \theta) + U_H\, m_{SW} \sin(\beta - \theta)$$

$$B = -[W_T (\sin\beta \cos\theta \tan\delta_P + \cos\beta \sin\theta \tan\delta_A)\, m_{SW} - (W_A \tan\delta_P + W_P \tan\delta_A) \sin\beta \sin\theta + (W_A \tan\delta_A + W_P \tan\delta_P) \cos\beta \cos\theta - n_{SW} (\tan\delta_A - \tan\delta_P) \cos(\beta - \theta) + C_A \cos\theta + C_P \cos\beta + (C_A \sin\theta + C_P \sin\beta)\, m_{SW} - U_{NA} \cos\theta \tan\delta_A - U_{NP} \cos\beta \tan\delta_P - (U_{NA} \sin\theta \tan\delta_A + U_{NP} \sin\beta \tan\delta_P)\, m_{SW} + U_H \cos(\beta - \theta) (\tan\delta_A - \tan\delta_P)\, m_{SW}]$$

$$C = W_T\, m_{SW} \cos\beta \cos\theta \tan\delta_A \tan\delta_P - (W_A \cos\beta \sin\theta + W_P \sin\beta \cos\theta) \tan\delta_A \tan\delta_P - n_{SW} \tan\delta_A \tan\delta_P \sin(\beta - \theta) - C_A \sin\theta \tan\delta_P - C_P \sin\beta \tan\delta_A + (C_A \cos\theta \tan\delta_P + C_P \cos\beta \tan\delta_A)\, m_{SW} + (U_{NA} \sin\theta + U_{NP} \sin\beta) \tan\delta_A \tan\delta_P - (U_{NA} \cos\theta + U_{NP} \cos\beta)\, m_{SW} \tan\delta_A \tan\delta_P + U_H \sin(\beta - \theta)\, m_{SW} \tan\delta_A \tan\delta_P$$

$$m_{SW} = \tan\phi_{SW} / FS_V$$

$$n_{SW} = C_{SW} / FS_V$$

The use of the above limit equilibrium tools is site specific and vital to the stability analysis of landfill lining systems.

Another key element for stability calculations is the selection of design values and their possible ranges, for the controlling actions. This includes (Dixon et al., 2003):

- Slope geometry
- Material properties (example, unit weight of liner components and waste properties)
- Water pressures
- Gas pressures
- Construction plant forces
- Actions relating to the method of construction

### 2.5.2 Factors of Safety

The definition of a Factor of Safety is the numerical expression of the degree of confidence that exists, for a given set of conditions, against a particular failure mechanism occurring (Dixon et al., 2003).

The factor of safety is based on the limit equilibrium condition and is commonly expressed as follows (Koerner, 2005) :

$$FS = \frac{\text{resisting forces}}{\text{driving forces}}$$

$$= \frac{F}{W \sin \beta}$$

$$= \frac{N \tan \delta}{W \sin \beta}$$

$$= \frac{W \cos \beta \tan \delta}{W \sin \beta}$$

$$FS = \frac{\tan \delta}{\tan \beta} \quad (2.14)$$

where

$\beta$ = slope angle
$\delta$ = friction angle between the geomembrane and its cover soil

Although based on the limit equilibrium condition, the factor of safety above refers specifically to the general relationship between the slope angle and friction angle of an infinite slope consisting of cohesionless interfaces with no seepage and is not based on the two-part wedge method of analyses. This factor of safety may be used only as a first guide to determine the friction angle required for a given slope angle. The two-part wedge method, or your selected method of analysis, and site specific testing must still be carried out.

The debate on what appropriate factors of safety for all considerations has been an endless one. Various international Directives and a commonly accepted value for the factor of safety in geotechnical engineering slope stability analysis is FS ≥ 1.5 for most conditions and is deemed acceptable (Thiel, 2001).

The DWAF Minimum Requirements for Waste Disposal to Landfill specifies a factor of safety of at least 1.5 for the slipping of the geomembrane liner on its underlying compacted soil layer.

The selection of an appropriate factor of safety that is required by a specific design, must also reflect the issues related to the consequences of failure namely, the risks to the environment and/or persons and the ease and cost of remedial actions.

It is therefore vital that an experienced geotechnical engineer using past experience to develop engineering judgement be consulted.

## 2.6 Test Methods

The material properties of the various lining components used in a lining system and their interface shear are critically important for the proper design of geomembrane lined side slopes of landfill. In the past, South Africa had no standard on definition of geosynthetics, no standard on geosynthetic testing, out of date standards and no standard guidelines on geosynthetic materials. Therefore, the use of international standards for the testing of material properties and interface shear has been the norm in South Africa. Only until recently, within the past two years, the South African National Standards (SANS) has been aligned with the International Organisation for Standardisation (ISO) and have adopted twelve (12) ISO standards to be used as SANS standards. Although South Africa is a long way from promulgating all applicable geosynthetic test standards, it is a start.

### 2.6.1 Material Properties

The current SANS that are applicable in South Africa to geosynthetics and the tests to determine their material properties are:

**General:**

| | | |
|---|---|---|
| 1. SANS 10318 | – | Geosynthetics – Terms and definitions |
| 2. SANS 9862 | – | Sampling and preparation of test specimens |

**Geotextiles and Geotextile related products:**

| | | |
|---|---|---|
| 3. SANS 9863-1 | – | Determination of thickness at specified pressures |
| 4. SANS 9864 | – | Determination of mass per unit area of geotextiles […] |
| 5. SANS 1525 | – | Wide-width tensile test |
| 6. SANS 11058 | – | Determination of water permeability […] |
| 7. SANS 12236 | – | Static puncture test (CBR test) |
| 8. SANS 12956 | – | Determination of the characteristic opening size |
| 9. SANS 13433 | – | Dynamic perforation test |
| 10. DDS circulated | – | UV Resistance |
| 11. SANS 13431 | – | Determination of tensile creep and creep rupture behaviour |
| 12. SANS TR 20432 | – | Guidelines for the determination of the long-term strength of the geosynthetics for soil reinforcement |

For all other test methods, international standards will continue to be used.

### 2.6.2 Interface Shear

The interface shear forces in a lining system are critical to stability and may be complex, as shown in Figure 2.17 for a double composite liner system, and must be carefully considered.

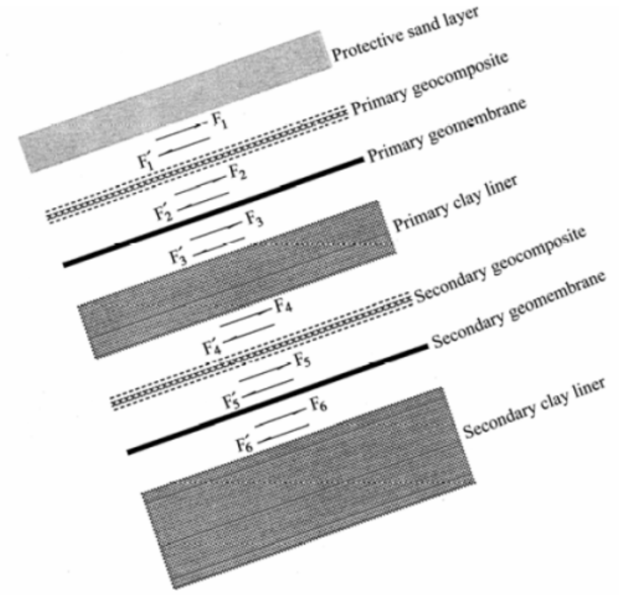



**Figure 2.17: Interface shear forces in a double composite liner system (Qian, 2008)**

The study of landfill liner interface parameters for stability calls for detail and comprehensive study of the following (Saravanan et al. 2006):

i) Landfill liner components and their interface properties.
ii) Geosynthetic liner materials and their physical properties.
iii) The compacted clay liner (CCLs) interface properties with geomembrane and geosynthetic clay liners (GCLs).
iv) The interface properties of compacted clay liners (CCLs) and geosynthetic clay liners (GCLs) with native soils.
v) Interface properties between CCLs, GCLs, non-woven geotextile and geomembrane.
vi) Study the suitable configuration of composite liner system which could improve the liner stability without neglecting the hydraulic conductivity requirement.

vii) Conduct detail stability analysis study of various configurations of landfill liner using laboratory data by limit equilibrium method.

viii) Propose recommendation for landfill stability design and installation guide for landfill liner and landfill cover to improve overall stability of landfill site by providing sufficient strain compatibility within component members

The test method used to determine the interface shear is a test adopted from the geotechnical engineering direct shear test for determining soil-to-soil friction. The size of the shear test apparatus must also be carefully considered. For geomembranes against sands, silts or clays a 100mm x 100mm square shear box is recommended by Koerner (2005) and for geosynthetic-to-soil and geosynthetic-to-geosynthetic a 300mm x 300mm square shear box is recommended (unless it can be justified that a smaller size is suitable) (ASTM D5321).

The use of the ring shear device of 180mm outside diameter and 25mm sample width, adopted for this research, would provide accurate analyses results on condition that all interfaces are tested using the same apparatus.

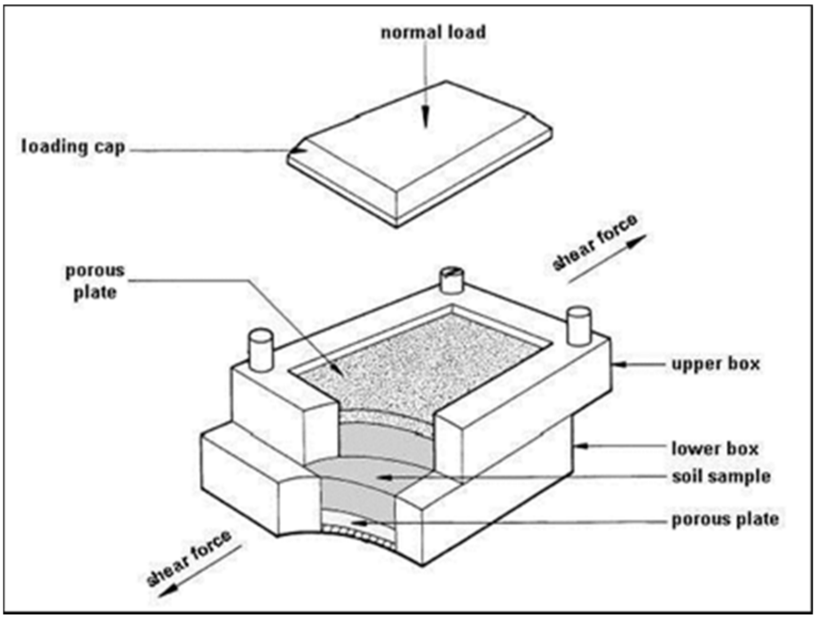



**Figure 2.18: Sketch of a typical shear box (www.tonygraham.co.uk/)**

The Standard Test Method for Torsional Ring Shear Test to Determine Drained Residual Shear Strength of Cohesive Soils, may also be used as it is suited to the relatively rapid determination of drained residual shear strength because of the short drainage path through the thin specimen, and the capability of testing one specimen under different normal stresses to quickly obtain a shear strength envelope. The test results are primarily applicable to assess the shear strength in slopes that contain a pre-existing shear surface, such as old landslides, soliflucted slopes, and sheared bedding planes, joints, or faults (ASTM D6467 – 13).

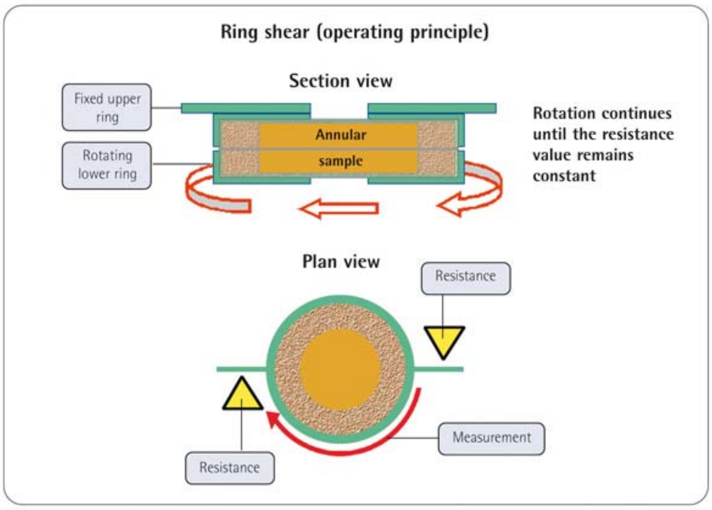



**Figure 2.19: Sketch of a typical ring shear apparatus (http://www.controls-group.com/eng/soil-mechanics-testing-equipment/bromhead-ring-shear-apparatus.php)**

The ASTM test methods are straightforward and the test method to be used must be based on site specific conditions. Although the direct shear test method is globally accepted, the current challenges are as follows:

i) Fixity or edge restraints.
ii) In the case of GCLs and geocomposites, the mid-pane or interface.
iii) Calibration in terms of the internal reference material
iv) Normal pressure validation.
v) Saturation.
vi) Consolidation.
vii) Strain rate.
viii) Friction correction.
ix) Adequate shear displacement to ensure adequate post peak value is reached.

The above test methods result in the shear strength parameters, for the materials tested, as illustrated in Figure 2.20 and Figure 2.21.

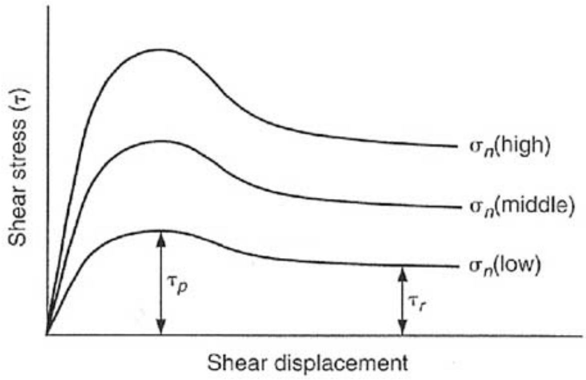



**Figure 2.20: Direct shear test data (Koerner, 2005)**

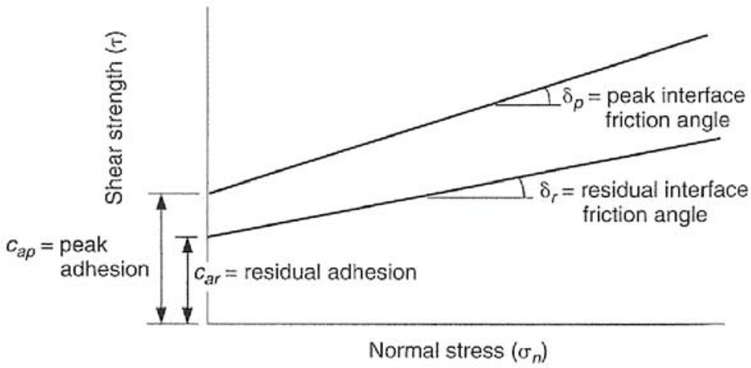



**Figure 2.21: Mohr-Coulomb failure envelopes (Koerner, 2005)**

### 2.7 Peak Shear Strength Versus Residual Shear Strength

The resultant peak shear strength and residual shear strength often leaves the designer in a dilemma. The residual shear strength is often much lower than the peak shear strength and the use of each, or a combination, results in different factors of safety. Although the use of the peak, residual or a combination of shear strength will continue to be debated, recent research recommends the following (Thiel, 2001):

- Using peak shear strengths on the landfill base, and residual shear strengths on the side slopes appears to be a successful state-of-the-practice in many situations.

- Designers should consider evaluating all facilities for stability using the residual shear strength along the geosynthetic interface that has the lowest peak strength. This would be an advisable risk-management practice for designers, even if the FS under these conditions is simply greater than unity.

## 2.8 Literature Review Conclusion

The DWAF Minimum Requirements for Waste Disposal Second Edition was applicable since 1998 and prescribed the lining systems for all landfill in South Africa. In August 2013, the prescribed lining systems were superseded by the Landfill Classification and Containment Barrier Designs as contained in the new National Norms and Standards for Disposal of Waste to Landfill. This change in legislation directly impacted the dissertation research and the research was redirected to assess the new prescribed lining systems. Therefore, this dissertation assesses the lining of steep slopes in South Africa and the applicability of the new National Norms and Standards for Disposal of Waste to Landfill.

The concept of landfill bottom liner stability design, has of recently, been well researched in South Africa and internationally, however the lining of steep slopes is still a major challenge and concern. The use of alternative lining components in the form of geosynthetics may help in improving stability, however the issues of equivalency must be addressed.

Various analytical tools, such as limit equilibrium analysis and finite element analysis, are available to assess the stability of landfill lining systems and the acceptable factors of safety, however each landfill lining system must be designed on site specific conditions using site specific materials and site specific test methods.

# CHAPTER 3

# METHODOLOGY

Chapter Three presents the methodology used for assessing the stability of the lining system on various slopes and calculating the corresponding factors of safety. Where the factors of safety were found unacceptable and where there were construction limitations, various alternative lining components were substituted to determine the effect on the stability. The selection of the relevant test methods, the alternative lining system components and the stability analyses are explained and were based on international accepted standards.

## 3.1 Introduction

The objectives of the investigation were to assess the legislated lining systems in South Africa and to determine the stability of the lining systems on various slopes and to determine whether the use of alternative geotextiles would help improved stability on steep slopes.

The various methods used to assess the stability of the lining system were considered and discussed in the literature review and were selected in the stability assessment methodology.

The design on steep side slope lining systems must also consider stability and integrity failure modes both during construction (unconfined) and in the long term following waste placement (confined). The design issues, controlling factors and analysis methods used for self-supporting and waste supported lining systems are shown in Figure 3.1 (Dixon et al., 2003).

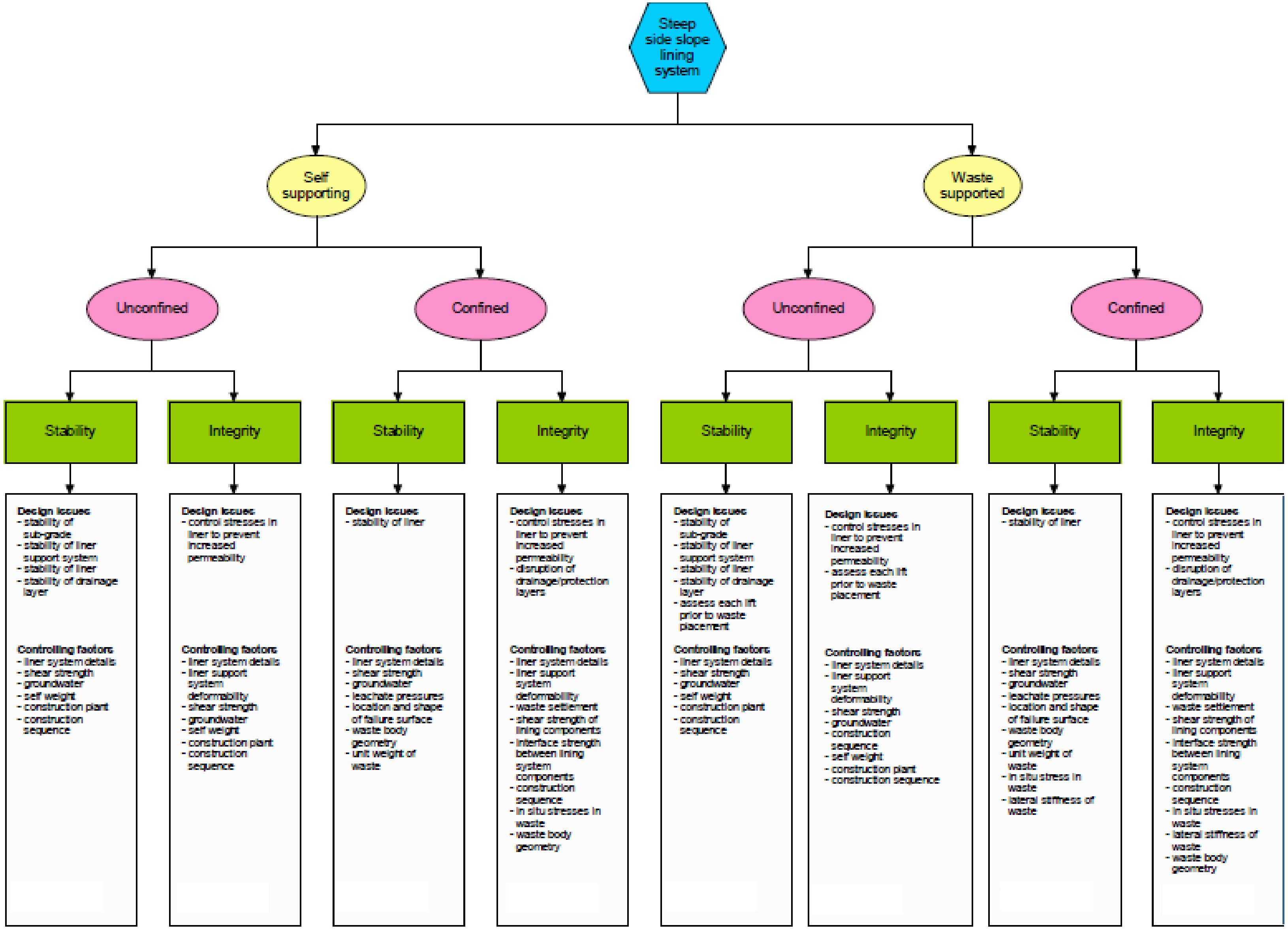



**Figure 3.1: Design flow chart: Steep side slope lining system (Dixon et al., 2003)**

This research was based on Figure 3.1 and the stability of the lining system was carried out accordingly.

The methodology also discusses the selection of the following parameters required to carry out this research:

1) The lining system to be used for assessment.
2) The equivalent lining system components.
3) The direct shear apparatus.
4) The various slope angles.
5) The accepted factors of safety.

## 3.2 Stability Analysis Approach

According to Qian (2008), calculating the factor of safety along the same interface at both the back slope and base may result in an unsafe result as the critical interfaces with the minimum factor of safety are generally at different interfaces along the back slope and along the base.

To achieve the objectives of this research, angle ($\omega$) was assumed to be constant for all selected liner configurations and the two-part wedge method, where the direction of the interwedge force is assumed to be parallel to either the back slope or the front slope, is currently globally accepted and was used. Therefore, the analysis of ultimate limit state using the limit equilibrium concepts based on a two-part wedge analysis, shown in Figure 2.15, for a finite slope length was adopted for this research.

## 3.3 Selection of Lining System to be Assessed

The major difference between the landfill liner designs based on the Minimum Requirements for Waste Disposal by Landfill and the containment barrier designs specified by the National Norms and Standards for Disposal of Waste to Landfill is the introduction of a composite lining system.

The advantage of a composite lining system is the inherent redundancy in the system and the significant reduction in leachate leakage.

Due to the replacement of the landfill liner designs based on the Minimum Requirements for Waste Disposal by Landfill with the containment barrier designs specified by the National Norms and Standards for Disposal of Waste to Landfill, a representative lining system was selected from the National Norms and Standards for Disposal of Waste to Landfill. However, the selection of a representative lining system to be used for the assessment was difficult.

Ideally a Class A landfill lining system as prescribed by the National Norms and Standards for Disposal of Waste to Landfill, which comprises of a double composite liner, would have been useful as it contains all the possible interface interactions. However, due to the possible assessment of a geocomposite leakage detection system, which comprises of a geonet between two geotextiles, the Class A landfill lining system was not selected. The ring shear apparatus used was unable to determine the interface shear of a geonet against a geotextile due to the large aperture/opening size of the geonet. Therefore a Class B landfill lining system was selected to assess the lining of steep landfill slopes. A Class B landfill lining system, when compared to a Class A landfill lining system, contains all the interface interactions that were encountered except for the following:

i) A geotextile filter layer against a clay liner
ii) A clay liner against a 2mm thick HDPE geomembrane

For the purpose of this research a Class B landfill lining system would therefore be acceptable and is again shown below.

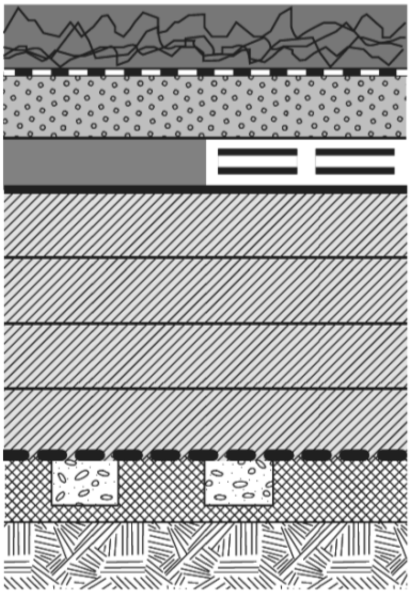



**Figure 3.2: Class B Landfill (Government Gazette, No. 36784, 2013)**

From the above Class B landfill lining system adopted for this research, the interfaces that were analysed and tested are shown in Table 3.1.

**Table 3.1: Lining system interfaces analysed and tested**

| Interface No. | Interface | | |
|---|---|---|---|
| 1 | HDPE geomembrane - makro spike | vs | Protection geotextile Bidim A10 (fluffy) |
| 2 | HDPE geomembrane - micro spike | vs | Protection geotextile Bidim A10 (fluffy) |
| 3 | HDPE geomembrane - smooth | vs | Protection geotextile Bidim A10 (fluffy) |
| 4 | HDPE geomembrane - makro pike | vs | GCL X1000 nonwoven |
| 5 | HDPE geomembrane - micro spike | vs | GCL X1000 nonwoven |
| 6 | HDPE geomembrane - smooth | vs | GCL X1000 nonwoven |

### 3.4 Equivalent Lining System Components

As landfill side slopes get steeper, construction limitations and material limitations, makes it impossible and unsafe to construct certain of the prescribed lining system components. Therefore it is necessary to replace certain of the lining system components with geosynthetics of equal performance. As discussed in the literature review, this raises the concern of equivalency. The lining system components, as specified by the containment barrier designs, which may require replacement are detailed below.

### 3.4.1 Under Drainage and Monitoring System

The under drainage and monitoring system usually comprises of a 150mm thick single sized gravel or crushed stone having a size of between 38mm and 50mm. The limiting factor would be the angle of repose of the gravel or crushed stone and the construction thereof on steep slopes.

Angle of Repose

Angle of repose may be defined as is the steepest angle of descent or dip of the slope relative to the horizontal plane when material on the slope face is on the verge of sliding (http://en.wikipedia.org/wiki/Angle_of_repose) and is illustrated in Figure 3.3.


**Figure 3.3: Angle of repose**

The angle of repose of single sized gravel or crushed stone is between 25$^o$ to 30$^o$ (http://en.wikipedia.org/wiki/Angle_of_repose) and is therefore the limiting factor. However, the construction of single sized gravel or crushed stone on slopes steeper than 1V:3H with machinery is not safe and not practical. Therefore the overall limiting factor was selected as 1V:3H (18,4$^o$) for this research.

The under drainage and monitoring system may be replaced with a composite geosynthetic leakage detection system that comprises of a geonet with geotextiles on either side. However, as discussed in 3.3 above, the use of a composite geosynthetic leakage detection system is outside the scope of this research.

For the purpose of this research, it is assumed that the under drainage and monitoring system is located in the interim anchor trenches that drains by gravity to leachate detection manholes.

### 3.4.2 Compacted Clay Liner

Most compacted clay soils with a firm to stiff consistency and constructed in horizontal layers will have sufficient shear strength to support slope angles of 1V:2H ($27^{o}$) for banks up to about 4m high. Another method is to construct the layers by working up and down batter slopes. Some compaction equipment will have difficulty safely negotiating the steep slopes while still sufficiently compacting the clay. A flatter batter of 1V:3H, or even 1V:4H ($14^{o}$) will provide a much higher percentage compaction if this method is adopted (IPENZ Practice Note 21, 2013).

The construction of a compacted clay liner on a landfill slope is shown in Figure 3.4 below. The thickness of the compacted clay liner is consistently parallel to the underlying layer.


**Figure 3.4: Construction of a compacted clay liner on a landfill slope**

The limitation for the construction of compacted clay liners (CCLs) is therefore the slope angle for the construction, to attain the specified compaction to achieve the required hydraulic conductivity. Construction of CCLs on slopes steeper than 1V:3H with machinery is also a safety hazard and therefore not practical. Therefore, on slopes steeper that 1V:3H the CCL was replaced with a geosynthetic clay liner (GCL). The selection of the GCL was based on the equivalency issues as discussed in Section 2.4.3.

The selected GCL that was used for this research was the enviroFIX X1000 that is manufactured locally and was supplied by Kaytech Engineered Fabrics. The Technical Data Sheet for the enviroFIX X1000 is attached in Appendix A.

### 3.4.3 HDPE Geomembrane Protection

The protection of the HDPE geomembrane may be achieved by a 100mm thick layer of silty sand or a geotextile of equivalent performance (DWAF, 1998).

The limiting factor for the 100mm thick layer of silty sand would be the angle of repose of the silty sand and the construction thereof on steep slopes.

The angle of repose of silty sand is 1V:1.55H ($34^o$) (http://en.wikipedia.org/wiki/Angle_of_repose) and is therefore the limiting factor. However, the construction of silty sand on slopes steeper than 1V:3H with machinery is not safe and not practical. The construction of silty sand on slopes steeper than 1V:3H with labour may be considered. However, the overall limiting factor of 1V:3H ($18{,}4^o$) was selected for this research.

The use of geotextiles as a protection layer may be considered and has been discussed in Section 2.4.2. The 150mm thick stone leachate collection system above the protection geotextile is of vital importance for the correct selection. The selection of the protection geotextile was determined by the burst resistance, tensile strength, puncture resistance and impact (tear) strength and is summarised in Table 3.2. The calculations of the factors of safety for the above parameters for a Bidim A10 nonwoven polyester geotextile may be found in Appendix B.

**Table 3.2: Factors of safety for a Bidim A10 nonwoven polyester geotextile to be used as a protection layer**

| Parameter | Factor of Safety (FS) |
|---|---|
| Burst Resistance | 1.90 |
| Tensile Strength | 14.84 |
| Puncture Resistance | 5.16 |
| Impact (Tear) Resistance | 2.13 |

All of the above factors of safety are above 1.5 and therefore the Bidim A10 nonwoven polyester geotextile was used as a protection geotextile in this research. The Technical Data Sheet for the Bidim A10 is attached in Appendix A.

## 3.5 Selection of HDPE Geomembranes

The HDPE geomembranes selected for this research are as follows:

1) 2.0mm double-sided textured HDPE
   - Processed from flat die process (cast sheet)
   - Method of texturing was by structuring or patterning
   - Asperity height - makro spike ≤ 0.9mm
   - - micro spike ≤ 0.4mm

2) 2.0mm single-sided textured HDPE
   - Processed from flat die process (cast sheet)
   - Method of texturing was by structuring or patterning
   - Asperity height - ≤ 0.9mm

Although there are other processes of manufacturing HDPE geomembranes, like circular die (blown sheet), and other methods of texturing like coextrusion, impingement and lamination, the sample chosen to be tested for this research was based on current industry trends and personal past design experience.

Both the above 2.0mm double-sided textured HDPE and the 2.0mm single-sided textured HDPE was used for the direct shear testing for this research. The use of the above two 2.0mm HDPE geomembranes for this research, instead of a 1.5mm HDPE geomembrane recommended, by the National Norms and Standards, was due to product availability, as the HDPE geomembrane was imported from Germany. The 2.0mm HDPE geomembrane was used consistently throughout this research and therefore the overall results would not be affected.

The Technical Data Sheets for the HDPE geomembranes used is attached in Appendix A.

### 3.6 Direct Shear Apparatus

The interface shear and interface frictional properties between the various lining system components for a Class B landfill was determined by the use of a ring shear apparatus. The large scale 180mm outside diameter ring shear was used at the University of Kwa-Zulu Natal, Howard College. The test method used to carry out the testing was based on ASTM D6467 – 13, The Standard Test Method for Torsional Ring Shear Test to Determine Drained Residual Shear Strength of Cohesive Soils. The ring shear apparatus that was used is shown in Figure 3.5, Figure 3.6 and Figure 3.7.

**Figure 3.5: Ring shear apparatus (UKZN)**

**Figure 3.6: Ring shear apparatus showing geosynthetics**

**Figure 3.7: Geosynthetics after a ring shear test**

Based on ASTM D6467 – 13, The Standard Test Method for Torsional Ring Shear Test, the general testing procedures involved:

- A ring shear device of 180mm outside diameter and 25mm sample width
- The rate of displacement was set to 1mm/min before the tests commenced. Displacement indicators were used to check for internal movement in the GCL
- The geosynthetic materials were secured using adhesive
- Tests were performed at vertical normal stresses of 50, 100, 200 and 400 kPa. The vertical stresses were controlled using weights and lever arms
- The geosynthetic materials were hydrated and submerged during the duration of the tests
- Shearing loads were measured using two load cells mounted symmetrically about the central axis. The shear load was taken to be the sum of two load cell readings. The calibration of the load cells was checked before the tests commenced.

- All soils to geosynthetic materials interfaces adopted for this research from external sources, given in Table 4.3, were obtained using the same ring shear device and test method above.

The general procedure above is illustrated in Figure 2.19.

## 3.7 Selection of Slope Angles

In order to determine the effects of steep slopes on the stability of a Class B landfill lining system, four (4) slopes angles were chosen for this research. The reasons for the selection of these four (4) slopes angles are explained in Table 3.3.

**Table 3.3: Selection of slope angles**

| Slope (V:H) | Slope Angle | Reason for selection |
|---|---|---|
| 1 : 4 | $14.04^o$ | Recommended by the new National Norms and Standards for Disposal of Waste to Landfill |
| 1 : 3 | $18.43^o$ | Recommended by the Minimum Requirements for Waste Disposal, Second Edition, DWAF 1998 |
| 1 : 2 | $26.57^o$ | Adopted for this research |
| 1 : 1 | $45.00^o$ | Adopted for this research |

The slope angles selected were required for the calculation of the various factors of safety using the limit equilibrium concepts on the selected two-part wedge analysis.

Slopes steeper than 1:1 were not selected for this research as the selected definition of a steep slope lining system, detailed in Section 1.1, would have been compromised. Slopes steeper than 1:1 would not be naturally stable without additional loads from the waste mass, anchorage or engineered support structures.

## 3.8 Selection of Factor of Safety

As discussed under literature review, a commonly accepted value for the factor of safety in slope stability analysis is $FS \geq 1.5$ and was adopted for this research.

## 3.9 Summary of Methodology

After a detailed study of the research topic which included the applicable South African Standards, the various lining system components, the apparatus available for direct shear testing, stability analysis tools, equivalency issues, lining system components and the relevant factors of safety, all the parameters for this research were chosen. The parameters chosen had to adequately investigate the objectives of this research.

The methodology adopted for this research is shown in Figure 3.8.

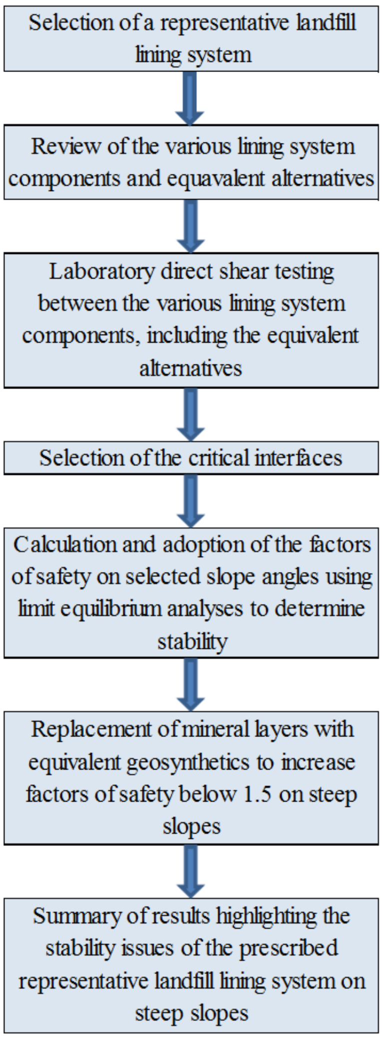



**Figure 3.8: Methodology adopted for this research**

It must be noted that although the methodology may be used for steep slopes as well as gentle slopes, the selection of different test materials and geosynthetics will affect the overall results. It is therefore strongly recommended that site specific tests be carried out.

# CHAPTER 4

# RESULTS AND DISCUSSIONS

Chapter Four presents the results obtained from the ring shear tests and the stability analyses for the prescribed lining system components as well as the alternative geosynthetics used to help improve the stability. The design approach for the various combinations of liner components to increase stability is highlighted. The self-weights of the various lining system components are also assessed. The use of geogrids as veneer reinforcement is analysed. Finally, the factors that were not considered for this investigation are discussed.

## 4.1 Presentation of Results

The results presented in this chapter are summaries of all the calculations carried out to achieved the objectives of this research. All calculations are attached in Appendix C and are indexed accordingly and will be cross referenced in this chapter.

The results are discussed in the order that the analyses were performed.

## 4.2 Selection of Lining System Interfaces for Investigation

The initial lining system interfaces were dictated by the selected Class B landfill lining system and the critical interfaces tested were listed in Table 3.1 above and are repeated in Table 4.1 for ease of reference.

**Table 4.1: Lining system interfaces tested**

| Interface No. | Interface | | |
|---|---|---|---|
| 1 | HDPE geomembrane - makro spike | vs | Protection geotextile Bidim A10 (fluffy) |
| 2 | HDPE geomembrane - micro spike | vs | Protection geotextile Bidim A10 (fluffy) |
| 3 | HDPE geomembrane - smooth | vs | Protection geotextile Bidim A10 (fluffy) |
| 4 | HDPE geomembrane - makro pike | vs | GCL X1000 nonwoven |
| 5 | HDPE geomembrane - micro spike | vs | GCL X1000 nonwoven |
| 6 | HDPE geomembrane - smooth | vs | GCL X1000 nonwoven |

The raw data from the ring shear tests are attached in Appendix C.1 and the corresponding graphical shear strength parameters are as follows:

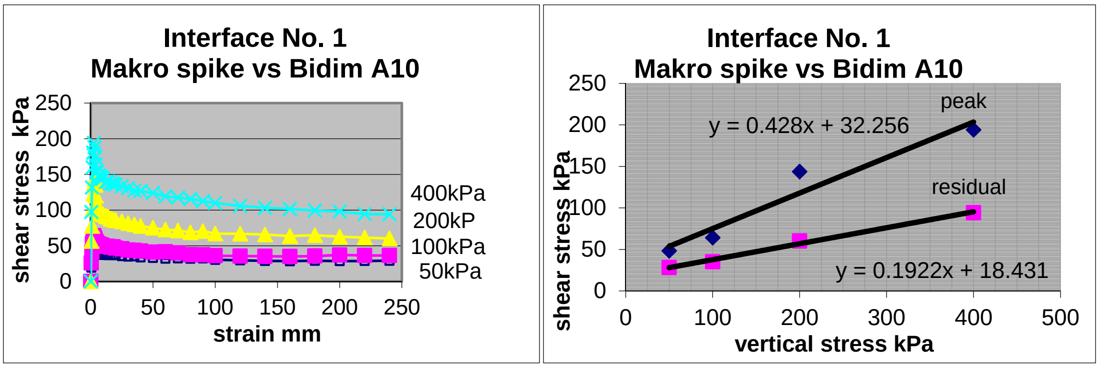



**Figure 4.1: Interface No. 1 shear strength parameters**

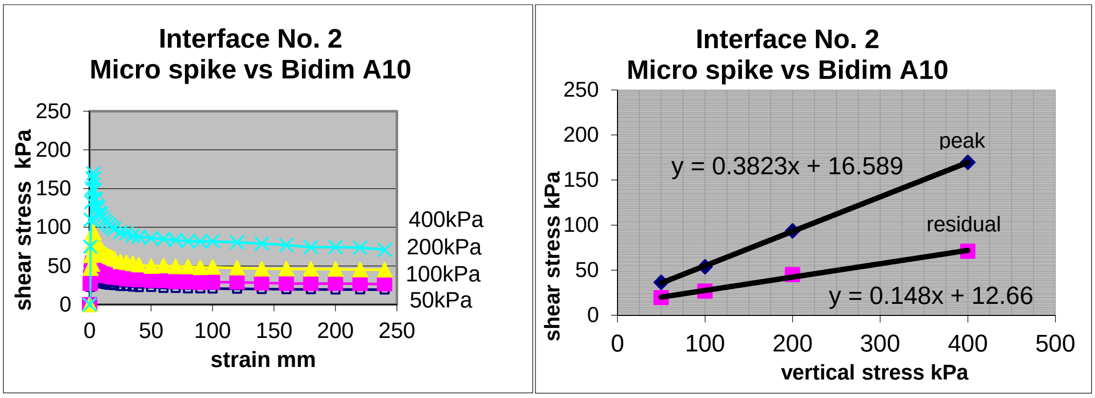



**Figure 4.2: Interface No. 2 shear strength parameters**

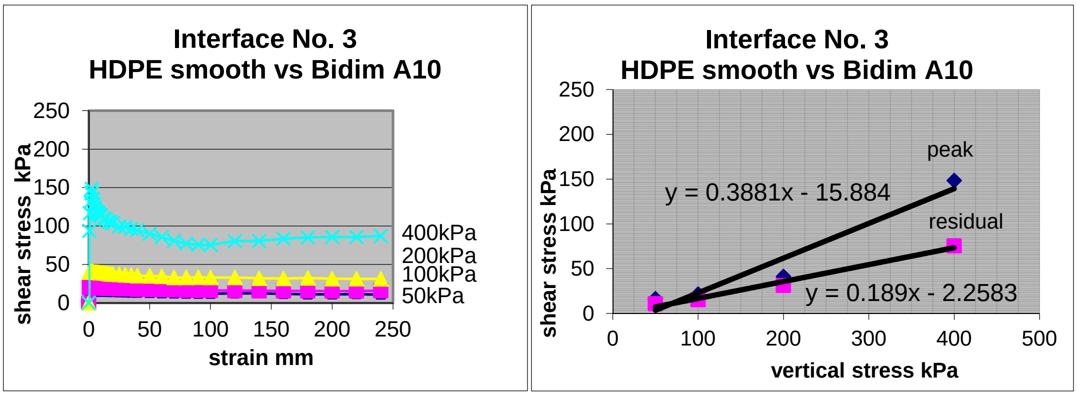



**Figure 4.3: Interface No. 3 shear strength parameters**

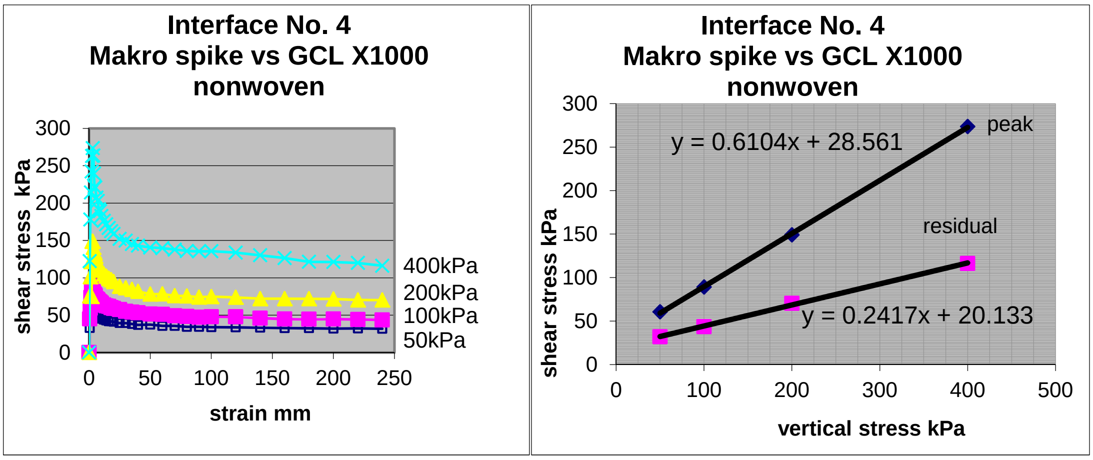



Figure 4.4: Interface No. 4 shear strength parameters

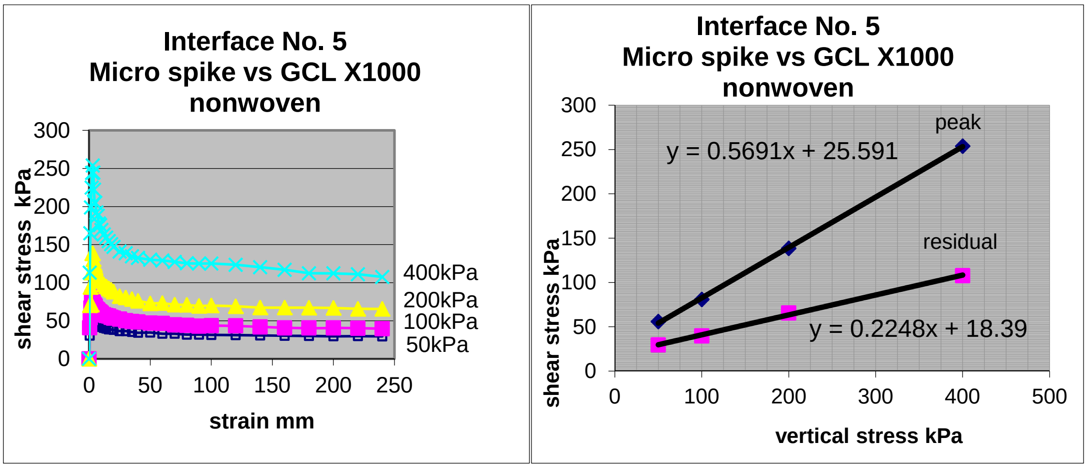



Figure 4.5: Interface No. 5 shear strength parameters

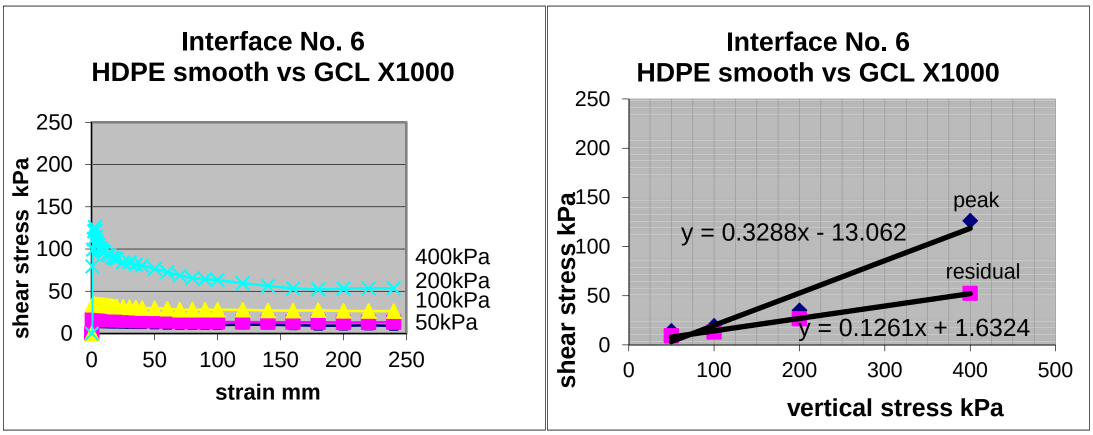



Figure 4.6: Interface No. 6 shear strength parameters

Therefore, from the above ring shear tests carried out, the peak and residual interface friction angles and their corresponding peak and residual adhesion values are given in Table 4.2.

**Table 4.2: Friction angles and adhesion values from ring shear tests carried out**

| **HDPE Geomembrane** | | Peak Friction Angle (δ) (Degrees) | Peak Adhesion ($c_a$) (kPa) | Residual Friction Angle (δ) (Degrees) | Residual Adhesion ($c_a$) (kPa) |
|---|---|---|---|---|---|
| Makro spike vs | Protection geotextile | 23.17 | 32.26 | 10.88 | 18.43 |
| Micro spike vs | Protection geotextile | 20.92 | 16.59 | 8.42 | 12.66 |
| Smooth vs | Protection geotextile | 18.68 | 0.00 | 10.70 | 0.00 |
| **HDPE Geomembrane** | | | | | |
| Makro spike vs | GCL | 31.40 | 28.56 | 13.59 | 20.13 |
| Micro spike vs | GCL | 29.64 | 25.59 | 12.67 | 18.39 |
| Smooth vs | GCL | 18.20 | 0.00 | 7.19 | 0.00 |

From the ring shear tests carried out, Interface No. 3 and Interface No. 6 have resulted in negative adhesion values. The negative adhesion value may be the result of the following conditions:

- The points at higher stresses were run too fast resulting in an artificially higher strength.
- The points at higher stresses were run on a higher strength material than the lower point.
- There is potential that there is a nonlinear strength envelope, even though a linear strength envelope is specified.

Since the negative adhesion values are small, it is norm to typically assume the adhesion values to be zero. Therefore, the negative adhesion values obtained at Interface No. 3 and Interface No. 6 are reflected as zero in Table 4.2 above.

Additional friction angles and adhesion values considered for this research are given in Table 4.3. The values given in Table 4.3 were obtained from the same ring shear apparatus used for the values given in Table 4.2 above, and therefore the values were used in parallel without corrections.

**Table 4.3: Additional friction angles and adhesion values**

| HDPE Geomembrane | | Peak Friction Angle (δ) (Degrees) | Peak Adhesion ($c_a$) (kPa) | Residual Friction Angle (δ) (Degrees) | Residual Adhesion ($c_a$) (kPa) | Notes |
|---|---|---|---|---|---|---|
| Makro spike vs | Protection layer of stabilised river sand (3% cement) | 35.05 | 6.62 | 31.77 | 17.67 | *a |
| Micro spike vs | Protection layer of stabilised river sand (3% cement) | 31.33 | 5.86 | 26.45 | 17.92 | *b |
| Smooth vs | Protection layer of stabilised river sand (5% cement) | 19.10 | 5.80 | 17.40 | 0.00 | *c |
| Makro spike vs | Clayey silt | 36.00 | 0.00 | 29.20 | 0.00 | *d |
| Smooth vs | Clayey silt | 25.90 | 0.00 | 12.70 | 0.00 | *e |
| **HDPE Geomembrane** | | | | | | |
| Makro spike vs | CCL | 22.60 | 16.80 | 17.60 | 13.20 | *f |
| Smooth vs | CCL | 13.20 | 3.10 | 6.90 | 4.70 | *g |

Notes: *a, *b - Representative data courtesy of PDNA.

*c, *d, *e - Representative data courtesy of Thekweni GeoCivils and Drennan, Maud & Partners.

*f, *g - Representative data courtesy of Jones & Wagener.

## 4.3 Effects of Slope Angle

As discussed under literature review, various slopes were chosen for this research. The slopes, the corresponding slope angles and the recommended minimum peak friction angles for each slope angle are shown in Table 4.4.

**Table 4.4: Selected slope angles showing recommended minimum peak friction angles**

| Vertical:Horizontal | Slope angle (β) | Recommended minimum peak friction angle (δ) |
|---|---|---|
| 1:4 | 14.04 | 14.04 |
| 1:3 | 18.43 | 18.43 |
| 1:2 | 26.57 | 26.57 |
| 1:1 | 45.00 | 45.00 |

If all of the interface shear strengths (interface friction angles) are greater than the slope angle, stability is achieved and the only deformation involved is a small amount to achieve elastic equilibrium (Wilson-Fahmy et al., 1993). However, if any interface shear strengths (interface friction angles) are lower than the slope angle, wide-width tensile stresses are induced into the overlying geosynthetics. This can cause the failure of the geosynthetics or pull-out from the anchor trench, or it can result in quasistability via tensile reinforcement. If the last is the case, we can refer to the overlying geosynthetics as acting as nonintentional reinforcement (Koerner, 2005). The use of geosynthetics acting as nonintentional reinforcement is not ideal and should be avoided.

It was also important to position the critical slip plane above the primary liner and/or geomembrane. Therefore attempts were made in the lining systems configurations to ensure that the friction angle below the geomembrane was higher than the friction angle above. This ensures that the geomembrane is not compromised should there be a failure.

The peak shear strengths were used for this research as the use of the residual shear strengths of the materials tested resulted in most of the factors of safety being below 1.5. The objectives of this research were still met using the peak shear strengths.

Due to the large number of variables for the assessment of a multilined side slope, the following assumptions were made in order to achieve the objectives of this research:

a) The subgrade of all lining system configurations are considered to be stable.
b) The liner support systems are considered to be stable and were positioned at 10m vertical height lifts resulting in different lengths of geosynthetic on the slopes as shown in Table 4.5.

**Table 4.5: Slope length of geosynthetics on selected slope angles**

| Vertical:Horizontal | Slope angle (β) | Elevation difference (h) | Slope Length of geosynthetics (l) |
|---|---|---|---|
| 1:4 | 14.04 | 10 | 41 |
| 1:3 | 18.43 | 10 | 32 |
| 1:2 | 26.57 | 10 | 22 |
| 1:1 | 45.00 | 10 | 14 |

c) Adhesion values obtained from the laboratory testing were adopted for all computations as this would produce a more accurate design approach.

d) Slopes of 1:4 and 1:3 takes into consideration equipment loads. Slopes of 1:2 and 1:1 were considered with and without equipment loads to achieve the objectives of this research.

e) On slopes of 1:2 and 1:1, the leachate collection layer will be placed in lifts ahead of waste placement to ensure stability. However, the effects of the leachate collection layer on these slopes were considered, to achieve the objectives of this research.

### 4.4 Selection of Critical Interfaces

The critical interfaces selected for this research were based on the following criteria:

- The interface shear strengths obtained from laboratory direct shear tests were greater than the slope angle to achieve stability.
- The lowest interface shear strength obtained from laboratory direct shear tests was selected as that interface would govern the overall landfill lining system stability.
- The critical slip plane was positioned above the primary liner and/or geomembrane to ensure that the friction angle below the geomembrane was higher than the friction angle above.

Therefore, using the above criteria, and the limiting factors discussed under literature review, the lining system components and configurations were chosen in line with a Class B landfill lining system and will be used as inputs to the theoretical design adopted for this research.

## 4.5 Configuration No. 1

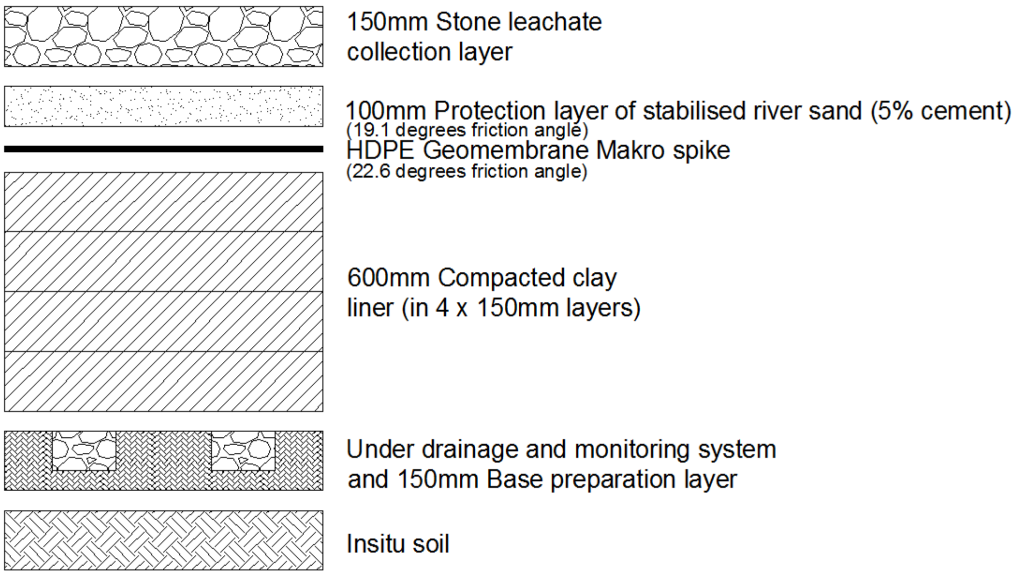



**Figure 4.7: Configuration No. 1**

The factors of safety for Configuration No. 1 are shown in Table 4.6 and are graphically represented in Figure 4.8. The calculations are attached as Appendix C.2.

**Table 4.6: Configuration No. 1 factors of safety**

| **Configuration No. 1**<br>Critical Interface: HDPE Geomembrane Makro Spike vs<br>100mm Protection layer of stabilised sand (5% cement) | | | | |
|---|---|---|---|---|
| **Factor of Safety** | **Slope** | | | |
| | 1:4 | 1:3 | 1:2 | 1:1 |
| Uniform Cover Soil and Stone Layer Thickness | 5.91 | 4.52 | 3.16 | 1.93 |
| Uniform Cover Soil Thickness and Stone Layer Thickness with Equipment Loads | 4.61 | 3.32 | 2.09 | 1.07 |

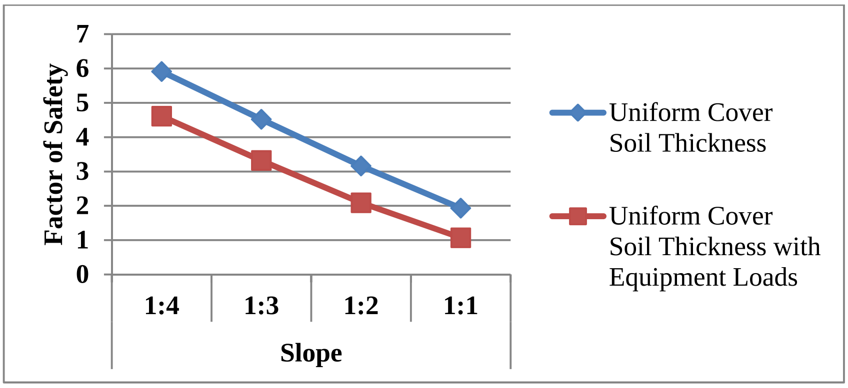



**Figure 4.8: Graphical presentation of Configuration No. 1 factors of safety**

From the CCL, the HDPE geomembrane makro spike and the protection layer of stabilised sand tested in Configuration No. 1, the factors of safety with the equipment loads on slopes 1:4 and 1:3 are greater than 1.5 and are acceptable. Although the factor of safety on the 1:2 slope is acceptable, the CCL has a construction limitation and is not practical on a slope of 1:2 and was not considered further. The CCL was replaced with a GCL for all slopes steeper than 1:3. The factor of safety on the 1:1 slope with the equipment loads is less than 1.5 and is not acceptable.

It can also been seen that the curve connecting the factors of safety without the equipment loads is almost parallel to the curve connecting the factors of safety with the equipment loads and is exponentially lower.

Another key parameter was the interface adhesion ( $c_a$ ) of 5.8kPa. This adhesion value is considered to be high and is a resultant of using stabilised sand. Adhesion values of less than 0.15 would result in all factors of safety being ≤ 1.5.

Other combinations for Configuration No. 1 were assessed and could have been chosen, however any other combination with the CCL, results with a higher friction angle above the HDPE geomembrane liner, and wide width tensile stresses are induced in the geomembrane which could result in failure from anchor trench pull-out or quasistability via tensile reinforcement. The geomembrane therefore acts as nonintentional veneer reinforcement which is not recommended. The use of an additional geosynthetic, such as a geogrid, would have to be considered.

Integrity of the HDPE Geomembrane

The integrity of the HDPE geomembrane was calculated by comparing the self-weight of the HDPE geomembrane with its yield strength assuming the worst case scenario of no frictional support from the underlying layer. The factors of safety for integrity of the HDPE geomembrane for the acceptable slopes are listed in Table 4.7. The calculations of the HDPE geomembrane integrity factors of safety are attached as Appendix C.3.

**Table 4.7: Factor of safety for HDPE geomembrane integrity**

| | 1:4 Slope | 1:3 Slope |
|---|---|---|
| Factor of Safety | 43.55 | 55.80 |

The integrity of the HDPE geomembrane on the 1:4 and 1:3 slopes are acceptable.

## 4.6 Configuration No. 2

From the materials and geosynthetics tested, many combinations were available for Configurations No. 2. The combination that was selected was based on industry norm where a single sided textured HDPE geomembrane is used, with the textured surface in contact with a GCL and the smooth surface in contact with either a mineral protection layer or a geosynthetic protection layer. The geosynthetic protection layer option was chosen for this research configuration since the friction angle was less than the friction angle against the stabilised sand layer that was tested. Configurations No. 2 is illustrated in Figure 4.9.

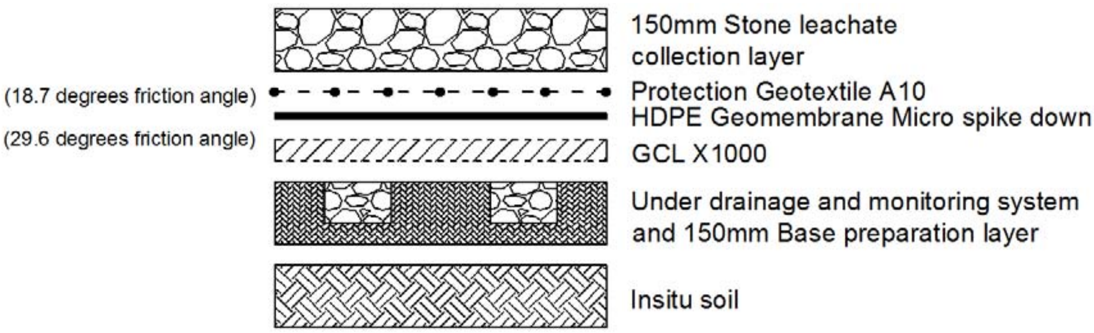



**Figure 4.9: Configuration No. 2**

Since Configuration No. 2 includes a GCL, the Hydraulic issues, Physical/Mechanical issues and Construction issues are again highlighted. Table 2.1 in Chapter 2 details the concerns. For the GCL used, the peak friction angle is $34.6^{o}$ and the adhesion is 99kPa. The interface friction test report and peel test is attached in Appendix A. The stability calculations, when using the GCL, assumes that the configurations do not fail due to internal shear of the GCL.

The factors of safety for Configuration No. 2 are shown in Table 4.8 and are graphically represented in Figure 4.10. The calculations are attached as Appendix C.4.

The use of the HDPE geomembrane single sided texture with the smooth surface in contact with the protection geotextile resulted in all factors of safety < 1.5. It was therefore necessary to use veneer reinforcement. The stability calculations were therefore extended to include for veneer reinforcement for Configuration No. 2. Various strengths of veneer reinforcement were assessed and the strengths of the veneer reinforcement required to achieve factors of safety ≥ 1.5 are also shown in Table 4.8.

**Table 4.8: Configuration No. 2 factors of safety**

| **Configuration No. 2**<br>Critical Interface: HDPE Geomembrane Smooth Upper vs Protection Geotextile A10 | | | | |
|---|---|---|---|---|
| **Factor of Safety** | **Slope** | | | |
| | 1:4 | 1:3 | 1:2 | 1:1 |
| Uniform Stone Layer Thickness | 1.39 | 1.05 | 0.72 | 0.87 |
| Uniform Stone Layer Thickness with Equipment Loads | 1.38 | 1.03 | 0.70 | 0.59 |
| Uniform Stone Layer Thickness with Veneer Reinforcement (Rock Grid PC strength required) | 1.72 (50/50) | 1.68 (100/100) | 3.30 (200/200) | 1.75 (200/200) |

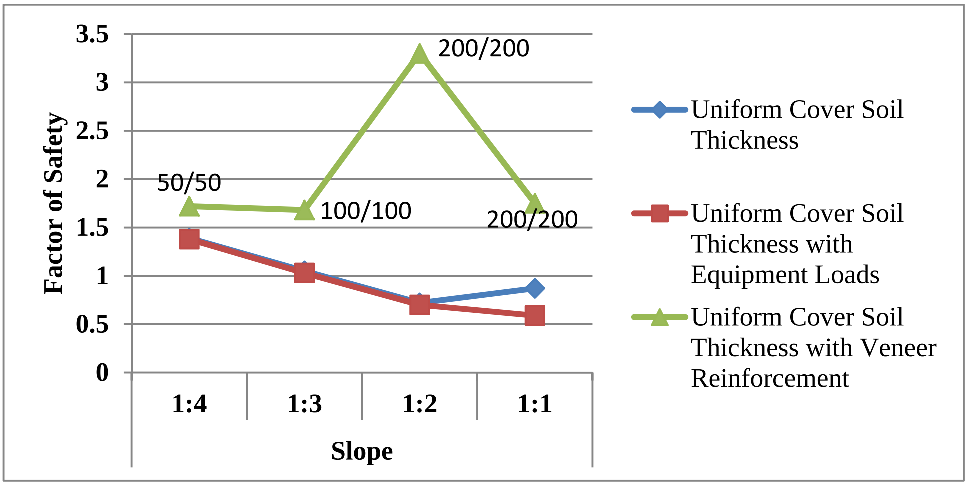



**Figure 4.10: Graphical presentation of Configuration No. 2 factors of safety**

From the GCL, the HDPE geomembrane micro spike and the protection geotextile tested in Configuration No. 2, the factors of safety with the uniform stone layer thickness and the equipment loads on slopes 1:4, 1:3, 1:2 and 1:1 are all less than 1.5 and are not acceptable. The minimal increase of factor of safety from a 1:2 slope to a 1:1 slope may be attributed to the reduced slope length and the assistance from the loading of the stone leachate collection layer on the shorter slope.

The equipment loads have a minimal effect on Configuration No.2 with regards to the factors of safety. Although the factors of safety with the equipment loads have a minimal difference than those without the equipment loads, there is still an exponential relationship with the factors of safety for the various slopes.

In order to achieve acceptable factors of safety for Configuration No. 2, veneer reinforcement was required. The addition of veneer reinforcement creates another interface that needs to be assessed. The addition of veneer reinforcement also creates another component for the inclusion in Configuration No. 2 which has significant cost implications and is not ideal. The large increase in the factor of safety from the 1:3 slope to the 1:2 slope was due to a higher tensile strength reinforcing grid selected on the 1:2 slope. The selection of a 200kN/m reinforcing grid on the 1:2 slope, instead of the 100kN/m reinforcing grid selected on the 1:3 slope, was due to the fact that the 100kN/m reinforcing grid resulted in a factor of safety lower than 1.5 on the 1:2 slope.

As shown above, a way of increasing a given slope's factor of safety is to reinforce it with a geosynthetic material. Such reinforcement can be either intentional or non-intentional. By intentional, we mean to include a reinforcing grid or high strength geotextile within the cover soil to purposely reinforce the system against instability. Depending on the type and amount of reinforcement, the majority, or even all, of the driving, or mobilizing, stresses can be supported by the reinforcing grid resulting in major increase in the factor of safety value.

Other combinations for Configuration No. 2 were also assessed and were not chosen to prevent the HDPE geomembrane acting as nonintentional veneer reinforcement as discussed previously.

Integrity of the GCL, Protection Geotextile and Veneer Reinforcement

The integrity of the HDPE geomembrane was checked in Section 4.5 above and was considered acceptable.

The integrity of the GCL, protection geotextile and veneer reinforcement was calculated by comparing the self-weight of the geosynthetics with its yield strength assuming the worst case scenario of no frictional support from the underlying layer. The factors of safety for integrity of the geosynthetics for the various slopes are listed in Table 4.9. The calculations of the geosynthetics integrity factors of safety are attached as Appendix C.5. It must be noted that the factors of safety listed in Table 4.9 are only applicable with the use of the veneer reinforcement tensile strengths used, as Configuration No. 2 factors of safety without veneer reinforcement is unacceptable.

**Table 4.9: Factors of safety for geosynthetics integrity**

| Factor of Safety with the use of Veneer Reinforcement | 1:4 Slope | 1:3 Slope | 1:2 Slope | 1:1 Slope |
|---|---|---|---|---|
| GCL | 4.83 | 6.19 | 9.01 | 14.16 |
| Protection Geotextile | 188.96 | 242.10 | 352.15 | 553.37 |
| Veneer Reinforcement | 430.95 | 1104.32 | 3243.44 | 5096.84 |

The factors of safety for the integrity of the GCL, protection geotextile and veneer reinforcement on the various slopes are more than adequate.

## 4.7 Configuration No. 3

The selection of the lining system components for the final configuration, Configuration No. 3, was based on using the highest friction angles attained from the geosynthetics that were tested, whilst still ensuring that the friction angle below the HDPE geomembrane was greater that the friction angle above the HDPE geomembrane and the internal shear of the GCL was greater than the highest friction angles used. Configurations No. 3 is illustrated in Figure 4.11.

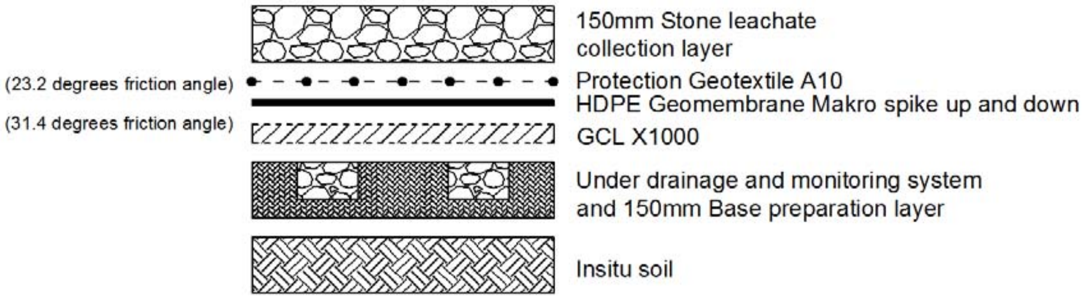



**Figure 4.11: Configuration No. 3**

The factors of safety for Configuration No. 3 are shown in Table 4.10 and are graphically represented in Figure 4.12. The calculations are attached as Appendix C.6.

**Table 4.10: Configuration No. 3 factors of safety**

| **Configuration No. 3**<br>Critical Interface: HDPE Geomembrane Makro Spike Upper vs Protection Geotextile A10 | | | | |
|---|---|---|---|---|
| **Factor of Safety** | **Slope** | | | |
| | 1:4 | 1:3 | 1:2 | 1:1 |
| Uniform Stone Layer Thickness | 40.30 | 30.91 | 21.82 | 13.74 |
| Uniform Stone Layer Thickness with Equipment Loads | 25.43 | 17.71 | 10.51 | 5.23 |

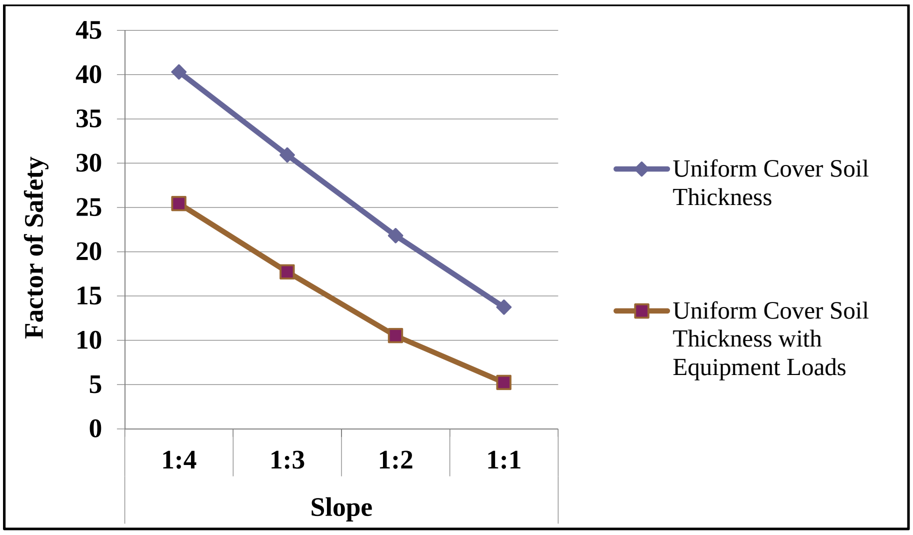



**Figure 4.12: Graphical presentation of Configuration No. 3 factors of safety**

The use of a double sided textured HDPE geomembrane has significantly increased the factors of safety for both the conditions. All the factors of safety are significantly above 1.5 and are acceptable. The factors of safety with the equipment loads are almost parallel to the factors of safety without the equipment loads. The relationship between the factors of safety without the equipment loads appears to be linear. The relationship between the factors of safety with the equipment loads appears to be exponential, as previously seen.

Integrity of the GCL, HDPE Geomembrane and Protection Geotextile

The integrity of the HDPE geomembrane, GCL and protection geotextile was checked in Section 4.4 and 4.5 above and is acceptable.

### 4.8 Factors Not Included in Above Analyses

The following factors have not been considered in the above analyses and/or in this research:

a) The effects of thermal increases on the characteristics of geosynthetics.
b) The effects of leachate head on the factors of safety.
c) The effects of using the methods of coextrusion, impingement or lamination for the texturing of the HDPE geomembrane.
d) Slopes steeper than 1 in 1.

e) The effects of Seismic forces.
f) A cost analyses between the use of mineral lining system components and/or geosynthetic lining system components.

## 4.9 Correlation of Results

Various ring shear tests were carried out to determine the friction angles and adhesion values of the selected geosynthetics. These shear strength parameter results were then used to check the stability by means of calculating the factors of safety of selected liner configurations.

Three lining system Configurations were then selected to try to achieve the objectives of this research.

Configuration No. 1, that was based directly on a Class B landfill lining system, has shown that on slopes of 1:4 and 1:3, the selected CCL and mineral protection layer have acceptable factors of safety. On steeper slopes of 1:2 and 1:1, due to construction issues and stability issues showing low factors of safety, the Class B landfill lining system using mineral layers on slopes steeper than 1:3 is not acceptable.

In Configuration No. 2, the mineral layers investigated from the Class B landfill lining system was replaced with equivalent geosynthetics. However, the smooth surface of the single sided HDPE geomembrane against the protection geotextile showed unacceptable factors of safety on all slopes i.e. 1:4, 1:3, 1:2 and 1:1. The use of various tensile strengths of veneer reinforcement, on appropriate slope angles, was needed to increase the factors of safety to the acceptable norm of above 1.5 on all slopes.

Configuration No. 3 was selected by using the highest appropriate friction angles, from the geosynthetics tested, to try to achieve acceptable factors of safety without using veneer reinforcement. The use of a double sided textured HDPE geomembrane increased all the factors of safety above 1.5 on all the slopes.

The three lining system configurations selected have shown various factors of safety for the selected slope angles. However, there is a consistent relationship between the factors of safety and the slope angles. It was found that the steeper the slope, the factors of safety reduced exponentially. Therefore, the relationship between the slope angle and factor of safety is exponential.

The selection of Configuration No. 3 and the factors of safety achieved, clearly shows that the interfaces, and lining system components, of any steep slope lining system can be made stable by using appropriate geosynthetics, using site specific conditions and appropriate testing.

# CHAPTER 5

# CASE STUDY

Chapter Five presents the case study used for this dissertation. The case study aims to assess the lining system constructed on a steep valley side slope at the Mariannhill Landfill site. The reasons for the selection of this site are discussed. The lining system constructed at the Mariannhill Landfill site is analysed and the factor of safety is checked. Finally, comments are given on the constructed lining system and the checked factor of safety.

## 5.1 Introduction

The Mariannhill Landfill site, located in Durban, was selected as the appropriate case study. Mariannhill Landfill site is classified as a $GLB^{+}$ site as per the DWAF Minimum Requirements for Waste Disposal by Landfill and the landfills cells were designed accordingly. Construction of the Mariannhill Landfill site commenced in 1998. The site is located in a long narrow valley with varying gradients of 1 in 8 in the valley base , 1 in 3 on the side slopes, up to an elevation of 290 above mean seal level, and 1 in 2 on the upper side slopes.

The geology of the site comprises of shallow sandstone bedrock outcropping at < 1.0, depth on the steeper side slopes becoming deeper between 3m to 4m depth beneath a hillwash / colluvium profile in the valley base. Since that are no thick soils on the side slopes and the sandstone bedrock is fairly horizontally bedded, there were no slope stability problems on shaping and trimming of the side slopes.

The Mariannhill Landfill site landfill cells were constructed using a cellular phased approached. Due to the varying design principles, availability of materials and landfill lining systems progression over the years, different geomembrane liners and lining systems have been used for construction of the various landfill cells at the site. The construction sequence of the landfill cells and the geomembrane liners used are shown in Table 5.1.

**Table 5.1: Cell construction sequence showing geomembrane liners used**

| Landfill Cell Name | Year Constructed | Geomembrane Liner |
|---|---|---|
| Cell 1 | 1998 | FPP monotextured |
| Cell 2 | 1998 | FPP monotextured |
| Cell 3 | 1999 | FPP monotextured |
| Cell 4 Phase 1 | 2001 | FPP monotextured |
| Cell 4 Phase 2 | 2002 | FPP monotextured |
| Cell 3 Phase 2 | 2003 | FPP monotextured and LLDPE double sided textured |
| Cell 3 Phase 3 | 2007 | HDPE monotextured |
| Cell 4 Phase 3 | 2011 | HDPE double sided textured |

More specifically, Cell 4 Phase 3 at Mariannhill Landfill site was chosen as the case study for this dissertation. The reason for the selection of Cell 4 Phase 3 was due to the complexity of the landfill cell. The landfill cell was above landfill Cell 4 Phase 2 which was constructed with FPP monotextured geomembrane and the side slopes varied from 1 in 4 to 1 in 2. The position of Cell 4 Phase 3 is shown in the Planning Phases Site Plan (courtesy of PDNA) attached in Appendix D.1. The construction layout plan of Cell 4 Phase 3 (courtesy of PDNA) is also attached in Appendix D.1.

The difference between the gentle slopes and steep slopes during construction are shown in Figures 5.1 and 5.2.

**Figure 5.1: Lining of gentle slope**

**Figure 5.2: Earthworks showing steep slope**

## 5.2 Lining System

The lining system constructed for Cell 4 Phase 3 was different for the varying slopes and is detailed below:

a) Slopes of 1 in 4 to 1in 3 - Type A
b) Slopes of 1 in 3 to 1 in 2.5 - Type B
c) Slopes of 1in 2.5 to 1 in 2 - Type C

Type A, Type B and Type C lining system details are illustrated in Figure 5.3, Figure 5.4 and Figure 5.5 respectively.

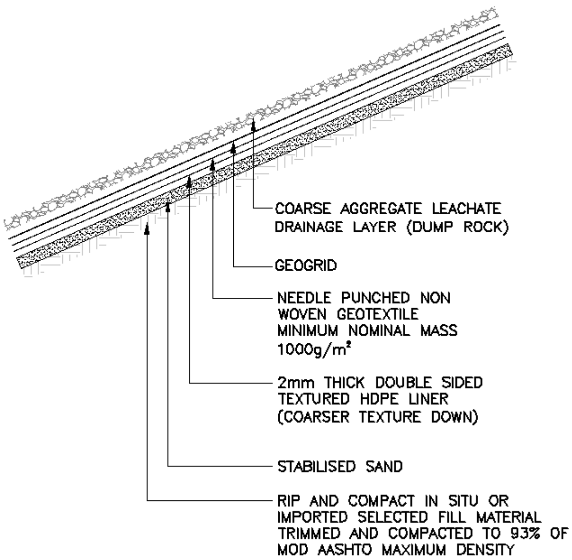



**Figure 5.3: Type A lining system**

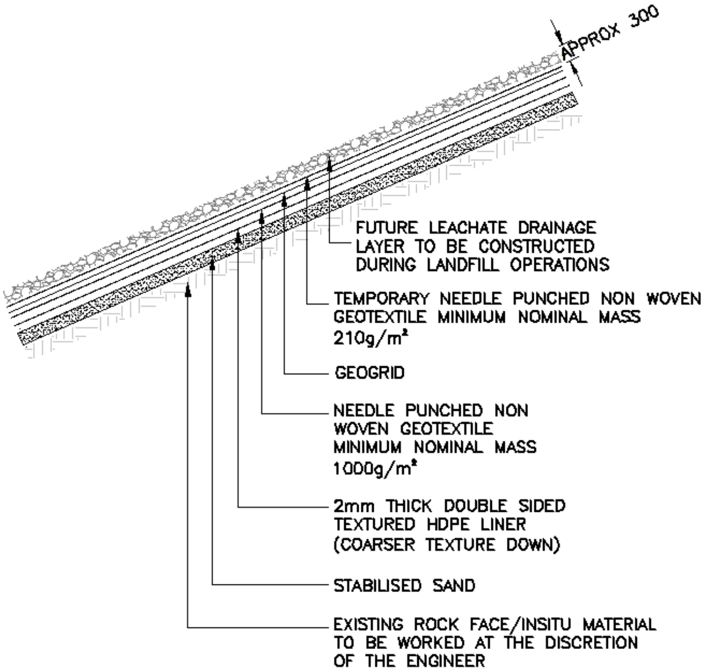



**Figure 5.4: Type B lining system**

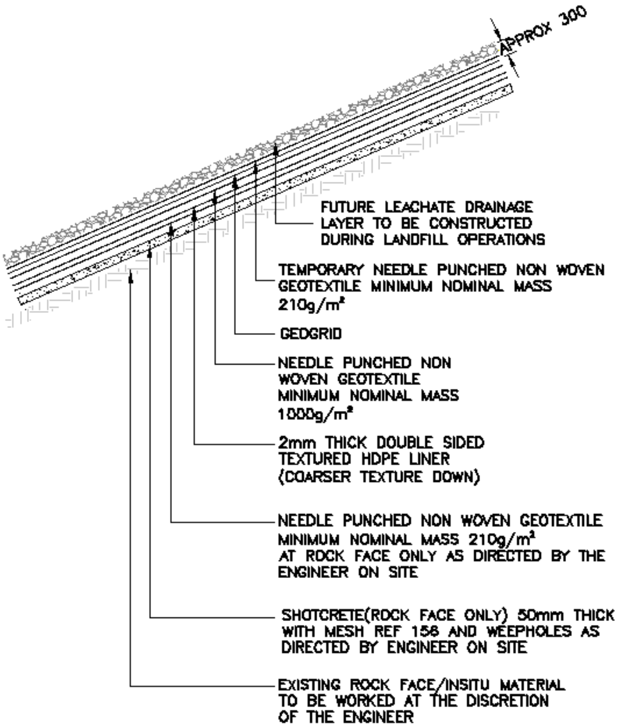



**Figure 5.5: Type C lining system**

## 5.3 Lining System Interfaces

The lining system interfaces for the above lining systems are listed in Table 5.2.

**Table 5.2: Lining system interfaces**

| Interface No. | Interface | | |
|---|---|---|---|
| 1a | Insitu material | vs | Stabilised sand (3% cement) |
| 2a | Shotcrete | vs | Non-woven geotextile |
| 3a | Stabilised sand (3% cement) | vs | HDPE geomembrane - makro spike |
| 4a | Non-woven geotextile | vs | HDPE geomembrane - makro spike |
| 5a | HDPE geomembrane - micro spike | vs | Protection geotextile |
| 6a | Protection geotextile | vs | Veneer reinforcement (Securgrid 120/40) |

Ring shear tests were carried out at UKZN, using a ring shear device of 180mm OD and a 25mm sample width. The raw data from the ring shear tests are attached in Appendix D.2 and the corresponding graphical shear strength parameters are as follows:

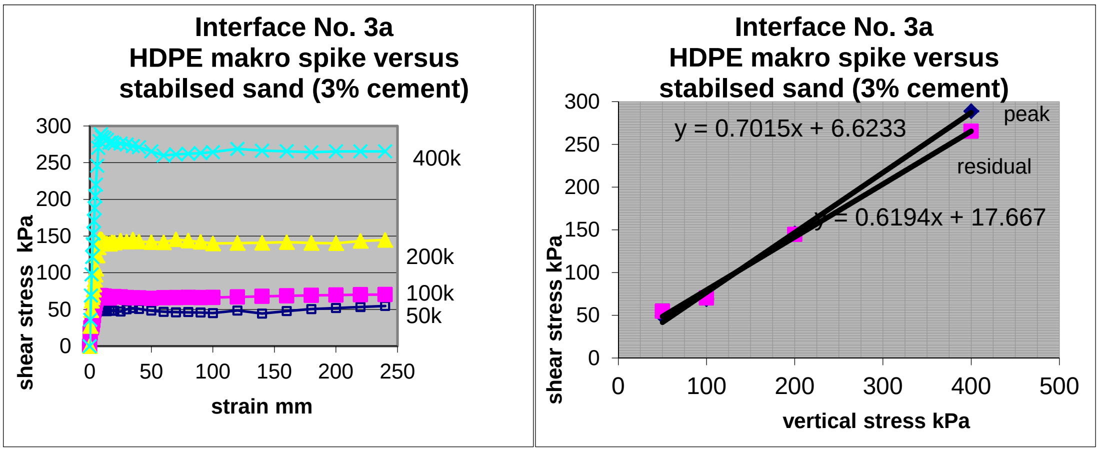



**Figure 5.6: Interface No. 3a shear strength parameters**

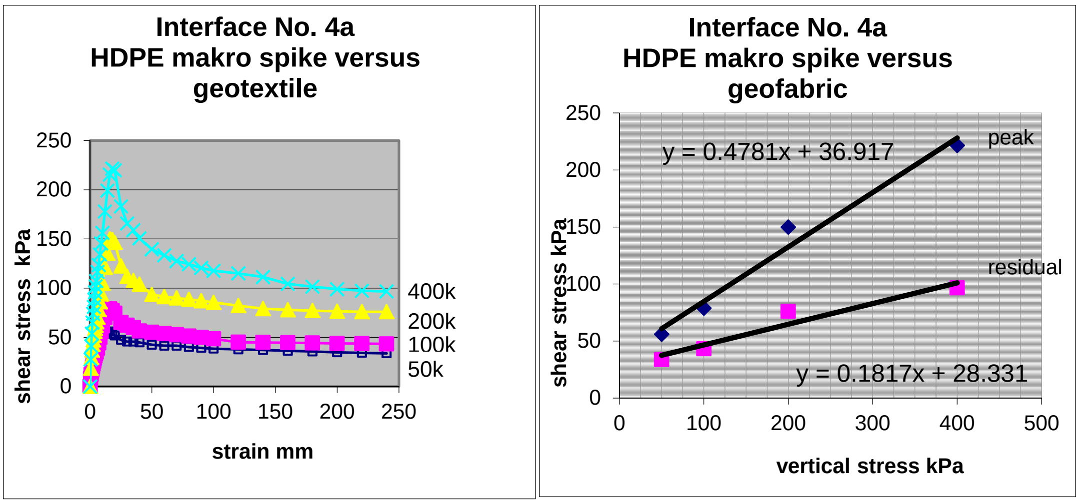



**Figure 5.7: Interface No. 4a shear strength parameters**

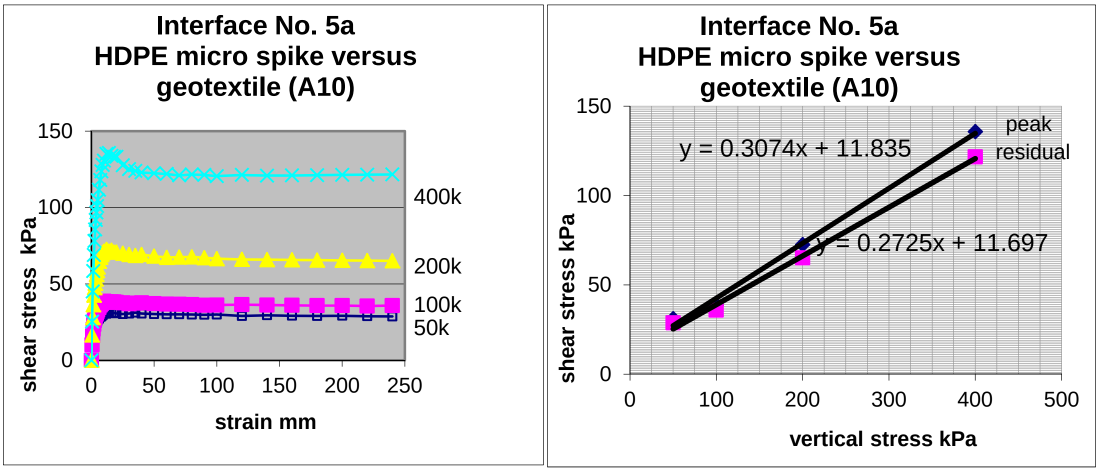



**Figure 5.8: Interface No. 5a shear strength parameters**

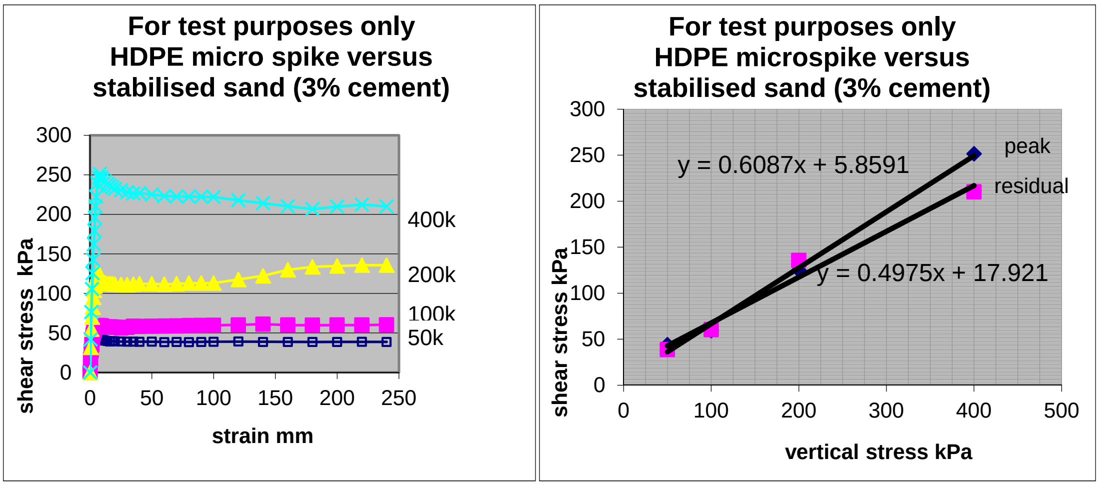



**Figure 5.9: Shear strength parameters for test purposes**

Interface 1a was only applicable to slopes of 1 in 4 to 1 in 2.5 and was considered stable. Interface 2a was only applicable to slopes of 1 in 2.5 to 1 in 2 and was also considered stable.

Interface 6a could not be tested locally due to the large aperture size of the geogrid (Secugrid 120/40) and the limitations of the ring shear device and other shear box devices in South Africa. All representative materials were sent to Naue, Germany for the testing. A 300mm x 300mm shear box device was used and the materials were hydrated for the direct shear test. Normal stresses of 50kPa, 100kPa and 200kPa were used. The test results are attached in Appendix D.3 and are included in Table 5.3.

Therefore, from the above ring shear tests carried out locally and internationally, the peak and residual interface friction angles and their corresponding peak and residual adhesion values are given in Table 5.3.

**Table 5.3: Friction angles and adhesion values from direct shear tests**

| **HDPE Geomembrane** | | Peak Friction Angle (δ) (Degrees) | Peak Adhesion ($c_a$) (kPa) | Residual Friction Angle (δ) (Degrees) | Residual Adhesion ($c_a$) (kPa) |
|---|---|---|---|---|---|
| Stabilised sand (3% cement) vs | Makro spike | 35.05 | 6.62 | 31.77 | 17.67 |
| Protection geotextile vs | Makro spike | 25.55 | 36.92 | 10.30 | 28.33 |
| Micro spike vs | Protection geotextile | 17.09 | 11.84 | 15.24 | 11.70 |
| Protection geotextile vs | Veneer Reinforcement | 26.68 | 2.22 | 22.56 | 3.39 |

The weakest interface for configurations Type A, Type B and Type C was the same for all configurations. The weakest interface was:

| | | | | | |
|---|---|---|---|---|---|
| Micro spike vs | Protection geotextile | 17.09 | 11.84 | 15.24 | 11.70 |

The factors of safety for the configurations of the Type A, Type B and Type C were checked and are shown in Table 5.4 and are graphically represented in Figure 5.10. The factor of safety calculations were based on the residual shear strength parameters and are attached as Appendix D.4.

**Table 5.4: Mariannhill Landfill site factors of safety of the weakest interface**

| **Mariannhill Landfill Site – Cell 4 Phase 3**<br>Critical Interface: HDPE Geomembrane Micro Spike vs Protection Geotextile for Type A, Type B and Type C | | | |
|---|---|---|---|
| **Factor of Safety** | **Slopes up to** | | |
| | 1:3 | 1:2.5 | 1:2 |
| Uniform Stone Layer Thickness | 8.91 | 7.58 | 6.28 |
| Uniform Stone Layer Thickness with Equipment Loads | 5.37 | 4.34 | 3.29 |

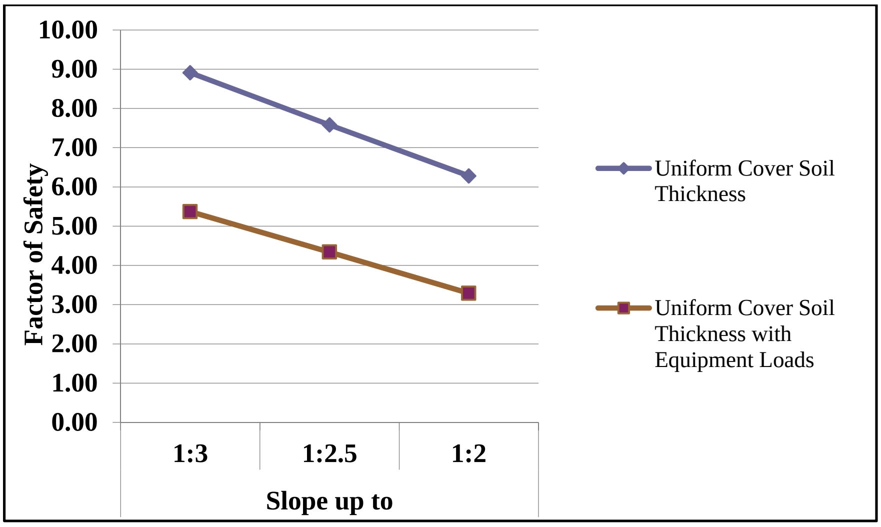



**Figure 5.10: Graphical presentation of Mariannhill Landfill Site Cell 4 Phase 3 factors of safety**

All the factors of safety for Cell 4 Phase 3 are above 1.5 and are acceptable. The use of veneer reinforcement was not needed for the construction stage of the landfill cell, however it will be needed during the settlement of the waste, when the landfill cell is filled, to prevent tensile stresses in the underlying geosynthetic lining system components. The factors of safety with the equipment loads are almost parallel to the factors of safety without the equipment loads. The relationship between the factors of safety appear to be linear.

Integrity of the HDPE Geomembrane, Protection Geotextile and Veneer Reinforcement

The integrity of the HDPE geomembrane, protection geotextile and veneer reinforcement was calculated by comparing the self-weight of the geosynthetics with its yield strength assuming the worst case scenario of no frictional support from the underlying layer. The factors of safety for integrity of the geosynthetics for the various slopes are listed in Table 5.5. The calculations of the geosynthetics integrity factors of safety are attached as Appendix D.5.

**Table 5.5: Integrity factors of safety**

| Factor of Safety | Up to 1:3 Slope | Up to 1:2.5 Slope | Up to 1:2 Slope |
|---|---|---|---|
| HDPE Geomembrane | 71.42 | 89.28 | 119.03 |
| Protection Geotextile | 309.89 | 387.36 | 516.48 |
| Veneer Reinforcement | 843.61 | 1054.52 | 1406.02 |

The factors of safety for the integrity of the HDPE geomembrane, protection geotextile and veneer reinforcement on the various slopes were found to be more than acceptable.

## 5.4 Assessment by Appointed Geotechnical Engineer

Due to the complexity of Mariannhill Landfill site Cell 4 Phase 3, external Consulting Civil Engineers and Engineering Geologists were appointed to assess the stability of the landfill Cell 3 Phase 4. A 2D Limit State Equilibrium programme called PC STABL5 was used to analyse the various modes of failure.

The recommendation by the external Consultant was to ensure that the interface with the weakest shear strength has a residual friction angle > 9 degrees, which would result in a stable landfill. The letter of recommendation is attached in Appendix D.6. The residual friction angle of the weakest interface was 15.24 degrees as shown in Table 5.3.

These analyses are in-line with the analyses carried out above and therefore should result in a stable landfill. Figure 5.12 shows the landfill Cell 4 Phase 3 upon completion.

## 5.5 Comments on the Case Study

The planning and construction of the Mariannhill Landfill site commenced in the late 1990's and even at that stage it was known that steep valley side slopes of 1 in 2 would be encountered in the final cell lifts of the landfill site. However, the conventional lining system for a $GLB^+$ site, as recommended by the DWAF Minimum Requirements for Waste Disposal by Landfill, could not be applied due to stability issues. The lining system design had to be adapted to ensure that an environmentally acceptable landfill site is still constructed whilst ensuring stability and integrity of the lining system. The difference between the lining system specified for a $GLB^+$ site and the lining system used at Mariannhill Landfill site are shown in Figure 5.11.

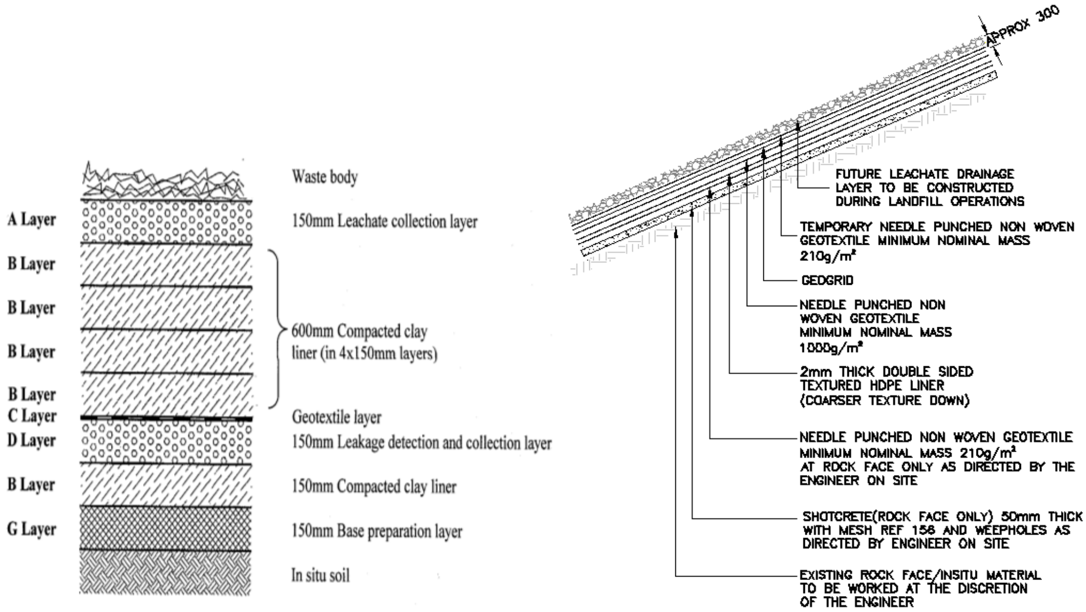



**Figure 5.11: Difference between GLB+ site prescribed lining system and the lining system used at Mariannhill Landfill site on the steepest slope of 1 in 2**

Various lining systems were incorporated into the various landfill cells, and of interest was the stability and integrity of the lining system on the steep slopes of 1 in 2 due to the complexity of the site.

As can be seen from the stability analyses above, a stable landfill cell, Cell 4 Phase 3, has been constructed on slopes up to 1 in 2 with factors of safety in excess of 1.5. This case study highlights that the specified lining system for a GLB+ site could not applied. However, a stable lining system is achievable on steep landfill side slopes as long as the appropriate lining system components are chosen, tested and analysed using site specific conditions.

Figure 5.12 shows the landfill Cell 4 Phase 3 upon completion.

**Figure 5.12: Cell 4 Phase 3 upon completion**

# CHAPTER 6

# SUMMARY AND CONCLUSIONS

Chapter Six presents a summary of the dissertation. The summary highlights the three objectives that were set at the beginning of this dissertation and the methodology used to try to achieve the objectives. This chapter also presents a summary of the results obtained from the limit state equilibrium analyses for the various factors of safety on different slope angles using the prescribed lining system and alternative geosynthetics. The conclusions from the dissertation and the recommendations for further study are presented.

## 6.1 Introduction

South Africa has been following closely behind the global progression of waste management and in 1994 the Waste Management Series, which comprised of the Minimum Requirements for Waste Disposal by Landfill, was published. The Second Edition of the Waste Management Series was published in 1998 for acceptance and use in the waste management industry. From 1998 to August 2013, the lining systems to be used for different classifications of landfill sites in South Africa were specified. In August 2013 the lining systems prescribed by the Minimum Requirements for Waste Disposal by Landfill was superseded by R636 National Norms and Standards for Disposal of Waste to Landfill. Since the change in prescribed lining systems occurred during the research for this dissertation, the lining systems prescribed by the Minimum Requirements for Waste Disposal by Landfill is discussed only and the lining systems specified by the National Norms and Standards for Disposal of Waste to Landfill were analysed.

Although waste minimisation, recycling and treatment is being promoted globally and in South Africa, there is, and always will be, the need for landfill sites in the foreseeable future. As land for landfill sites become more scarce and in an attempt to maximise each landfill site with regards to storage capacity, the use of land with slopes greater than 1 in 4 and 1 in 3 become more commercially viable. However, the lining of steep landfill slopes provides new design challenges.

The objectives of this dissertation were to assess the newly prescribed lining system components, to determine the stability and integrity of a selected lining system on various slopes and to determine whether the use of alternative geosynthetics would help improve stability on steep slopes.

## 6.2 Methodological Approach Used To Achieve Objectives

The methodological approach used to achieve the objectives of this research is summated by the key questions highlighted below.

*What are the fundamental changes with regards to the previously prescribed lining systems and the now prescribed lining systems?*

All classes of landfills, as per the National Norms and Standards for Disposal of Waste to Landfill, must have composite lining systems whereas only hazardous waste landfills were specified to have a composite lining system, as per the Minimum Requirements for Waste Disposal by Landfill.

The mineral lining system components characteristics are the same, however the mineral lining system components may now be replaced with equivalent geosynthetic alternatives. However, the use of equivalent geosynthetics as an alternative must be proven.

*How was the objective of determining the stability and integrity of lining systems on steep slopes achieved?*

The current tools available for stability analyses were researched. Currently 2-D limit equilibrium and 3-D finite-element analyses are available. A 2-D limit-equilibrium analysis was selected as it is currently industry norm and gives results that are more conservative by giving factors of safety that are equal to or less than 3-D finite element analyses (Thiel, 2001).

A Class B landfill lining system and slopes of 1 in 4, 1 in 3, 1 in 2, and 1 in 1 were selected to analyse the factors of safety.

Direct shear tests were carried out using a 180mm outside diameter circular ring shear device, at UKZN, to determine the various interface shear strength properties.

Using 2-D limit equilibrium analyses the factors of safety for the various lining systems on the various slope angles using equivalent geosynthetics, where required, were calculated. The integrity of the geosynthetics was also checked. The relationship between the stability and the slope angles were thereafter determined.

A case study to determine the effects of the slope angle in relation to the factor of safety was investigated. Mariannhill Landfill site was selected as the case study due to the steep valley side slopes and the overall complexity of the site. The results found for Mariannhill Landfill site was compared to the results from this dissertation to determine whether the results are consistent with current industry applications.

## 6.3 Summary of Results

A summary of the various lining systems analysed with their corresponding factors of safety are shown in Table 6.1 and the factors of safety for Mariannhill Landfill site are shown in Table 6.2. The factors of safety below 1.5 are highlighted with red, the lining system components with factors of safety higher than 1.5 but have construction limitations are highlighted in green and the factors of safety above 1.5 are highlighted in yellow. The factors of safety in Table 6.1 and 6.2 are based on:

i) the weakest interface
ii) the various slopes
iii) the worst case scenario which includes equipment loads

**Table 6.1: Summary of factors of safety for analysed lining systems**

| Lining System Name | Slope | | | | Comments |
|---|---|---|---|---|---|
| | 1:4 | 1:3 | 1:2 | 1:1 | |
| Configuration No. 1 **(Figure 34)** | 4.61 | 3.32 | 2.09 | 1.07 | Based on a Class B landfill |
| Configuration No. 2 **(Figure 36)** without veneer reinforcement | 1.38 | 1.03 | 0.70 | 0.59 | Using geosynthetics with mono textured HDPE geomembrane |
| Configuration No. 2 **(Figure 36)** with varying veneer reinforcement strengths *(tensile strength)* | 1.72 *(50/50)* | 1.68 *(100/100)* | 3.0 *(200/200)* | 1.75 *(200/200)* | Using geosynthetics with mono textured HDPE geomembrane and veneer reinforcement |
| Configuration No. 3 **(Figure 38)** | 25.43 | 17.71 | 10.51 | 5.23 | Using geosynthetics with double sided textured HDPE geomembrane |

**Table 6.2: Factors of safety for Mariannhill Landfill Site**

| Lining System Name | Slopes up to | | | Comments |
|---|---|---|---|---|
| | 1:3 | 1:2.5 | 1:2 | |
| Mariannhill Landfill Site - Cell 4 Phase 3 **(Figures 42, 43 and 44)** | 5.37 | 4.34 | 3.29 | Using geosynthetics with double sided textured geomembrane |

The factors of safety for the integrity of all the lining system configurations were checked and were found to be acceptable.

## 6.4 Conclusions

In South Africa and globally there is, and will be, the need for landfill sites in the foreseeable future. Land for these landfill sites become scarcer and land with slopes greater than 1 in 4 become more commercially viable. However, the design of lining systems on steep slopes has greater technical challenges.

From the results of Configuration No. 1 and from the materials and geosynthetics tested and used for this dissertation, it can be seen that the lining systems that are prescribed by the National Norms and Standards for Disposal of Waste to Landfill in South Africa will not be suitable on slopes steeper than 1 in 3 due to construction limitations and stability, unless geosynthetics of equal performance are considered.

Even though equivalent geosynthetic materials may be used on steeper slopes, the equivalency must be proven and the design-by-function properties of the geosynthetics must be considered.

The use of geosynthetics on gentle slopes as well as on steep slopes does not necessarily mean that the lining system stability and integrity will be achieved and must be analysed thoroughly with the stability assessment tools available. The geosynthetics used for Configuration No. 2 was based on a mono textured HDPE geomembrane liner inducing a greater friction angle below the liner, which is required, with the smooth surface of the liner in contact with a protection geotextile. Configuration No. 2 still has factors of safety below 1.5 on all the slopes i.e. 1 in 4, 1 in 3. 1 in 2 and 1 in 1, although geosynthetics were used. It is however, possible to increase these factors of safety with the use of other geosynthetics in the form of veneer reinforcement, as can been seen in the research.

The selection of the correct equivalent geosynthetic materials is a vital part of achieving acceptable factors of safety for stability on steep slopes. Configuration No. 3 comprises of a double sided textured HDPE geomembrane liner and the factors of safety on all the slopes are well above 1.5.

The trending of the factors of safety for the various lining system configurations, tested for this dissertation, clearly shows a relationship between the slope angle and the factor of safety. The relationship appears to be exponential where the factor of safety exponentially decreases as the slope angle increases.

The Mariannhill Landfill site case study selected, shows factors of safety well above 1.5 indicating that the lining system design was conservative due to the complexity of the site. The factors of safety for the varying slopes, follows a similar trend to the results obtained from this dissertation.

From the title of this dissertation "The Lining of Steep Slopes in South Africa and the Applicability of the Minimum Requirements for Waste Disposal by Landfill by the Department of Water Affairs and Forestry", the following brief conclusions are made:

- The Minimum Requirements for Waste Disposal by Landfill was superseded by R636 National Norms and Standards for Disposal of Waste to Landfill and a representative Class B landfill lining system from the National Norms and Standards for Disposal of Waste to Landfill was selected to achieve the aims of this dissertation.

- The landfill lining systems specified by the National Norms and Standards for Disposal of Waste to Landfill are not applicable for steep slopes due to the low factors of safety achieved from the materials and geosynthetics analysed for this dissertation.

- It is possible to achieve acceptable factors of safety above 1.5 for stability on steep slopes with the selection of suitable geosynthetics of equal performance. It must be noted however, that site specific testing must be carried out.

### 6.5 Suggestions for Further Research

Due to the large number of variables required for the analyses of lining systems, various factors have not been taken into consideration for this dissertation. During the literature review process for this dissertation, many of these variables were also discussed briefly in the literature available but no in-depth research was available or found. Suggestions for further research include the following:

a) The effects of thermal increases on steep slope lining systems.

b) The use of geosynthetic drainage systems for the replacement of the mineral leakage detection layer on steep slopes.

c) Compilation of interface shear strength parameters for geotextile-geonet composites, for the use as geosynthetic drainage systems, and for geogrids-geotextile interfaces. This cannot be adequately researched in South Africa due to the limitations of the direct shear test apparatus available in South Africa. Ideally these interfaces should be tested in a shear box larger than the 300mm x 300mm shear box currently available in South Africa, due to their large aperture sizes.

d) The effects of using the methods of coextrusion, impingement or lamination for the texturing of the HDPE geomembrane for the lining of steep slopes.

# REFERENCES

ASTM D5321–02. Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method. Annual Book of ASTM Standards, Volume: 04.13.

ASTM D6467–13. Standard Test Method for Torsional Ring Shear Test to Determine Drained Residual Shear Strength of Cohesive Soils. Annual Book of ASTM Standard, Volume: 04.09.

ASTM D4439-11. Standard Terminology for Geosynthetics. Annual Book of ASTM Standards Volume: 04.13.

Blumel W., Stoewahse C., Dixon N., Kamugisha P., Jones D.R.V. British-German Cooperative Research on Geosynthetic Friction Testing Methods.

Cilliers C. and Msiza J. (2009). Case Studies: The design and construction elements that arise when hazardous waste lagoons incorporate steep side slopes. Proceedings from GIGSA GeoAfrica 2009 Conference, Cape Town, South Africa.

Dixon N. and Jones D.R.V. (2003). Stability of Landfill Lining Systems: Report No. 2 Guidance. R&D Technical Report P1-385/TR2, p. 4, 39, 153-165. Environment Agency, Bristol.

Dixon N., Ng'ambi S. and Jones D.R.V. (July 2004). Structural Performance of a Steep Slope Landfill Lining System, Proceedings of the Institution of Civil Engineers, Paper 13567: p. 115-125

Elton D.J. and Peggs I. (2002). Geomembrane Research Needs. Geosynthetics International, Vol 9, No. 3: p. 289-290

Fowmes G.J. (2007). Analysis of Steep Sided Landfill Lining Systems. EngD Thesis.

German Geotechnical Society. (2011). Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcement. Translation of 2nd German Edition. Ernst & Sohn GmbH & Co. KG. p. 142-149

Giroud J.P. (1984). Geotextiles and Geomembranes, Definitions, Properties and Design, Vol 1. p. 5-40

GSE Environmental. (2013). Technical Note Hydraulic Equivalency Comparison: CFR Prescriptive Liner System vs. Coal Ash Barrier System, TN46 Rev22APR2013.

IPENZ Practice Note 21 ISSN 1176–0907 Version 2, March 2013. Farm Dairy Effluent Pond Design and Construction.

Jones D.R.V. and Dixon N. Landfill Engineering: A Technical Challenge or Old Hat. Golder Associates (UK) Ltd., Stanton-on-the-Wolds, UK.

Koerner R.M. (2005). Designing with Geosynthetics, Fifth Edition. Pearson Prentice Hall, NJ, USA.

Koerner R.M. An Overview of Geogrids. Geosynthetic Institute, Folsom, PA.

Koerner R.M. (2003). Selected Papers on the Design Decision of using Peak Versus Residual Shear Strengths. GRI Report No. 29.

Koerner R.M. and Daniel D.E. (1993). Technical Equivalency Assessment of GCLs to CCLs. *Proceedings of the 7th Geosynthetic Research Institute Seminar*. Philadelphia, PA.

Koerner R.M. and Soong T.Y. (1998). Analysis and Design of Veneer Cover Soils. Proceedings of the 6th IGS Conference. p. 1-26

Koerner G.R. (2013). Geosynthetic Barriers Short Course Notes. *Proceedings of Landfill Interest Group 2013*, Muldersdrift, Johannesburg.

National Solid Wastes Management Association (2008). Modern Landfill: A Far Cry from the Past. Washington, DC.

Oweis, I.S. (1992). Stability of Landfills. "In Geotechnical Practice for Waste Disposal", Chapman and Hall, London.

Qian, X., Koerner, R. M., and Gray, D. H. 2003. Translational failure analysis of landfills. Journal of Geotechnical and Geoenvironmental Engineering, 129(6), 506-519.

Qian, X., Gray, D. H., and Koerner, R. M. 2004. Estimation of maximum liquid head over landfill barriers. Journal of Geotechnical and Geoenvironmental Engineering, 130(5), 488-497.

Qian, X., and Koerner, R. M. 2004. Effect of apparent cohesion on translational failure analyses of landfills. Journal of Geotechnical and Geoenvironmental Engineering, 130(1), 71-80.

Qian, X., and Koerner, R. M. 2005. A new method to analyze for, and design against, translational failures of geosynthetic lined landfills. Ling, H. I., Kaliakin, V. N., and Leshchinsky, D., eds., Geosynthetics and Geosynthetic-Engineered Structures (McMat Conference), 61-98. Baton Rouge: ASME/ASCE/SES.

Qian, X. 2006. Translational failures of geosynthetic lined landfills under difference leachate buildup conditions. Lu, N., Hoyos, L. R., and Reddi, L., eds., Advances in Unsaturated Soil, Seepage, and Environmental Geotechnics, Proceedings of Sessions of GeoShanghai. ASCE Geotechnical Special Publication 148, 278-289. Reston: ASCE/GEO Institute.

Qian, X., and Koerner, R. M. 2007. Translational Failure Analysis of Solid Waste Landfills Including Seismicity and Leachate Head Calculations, GRI Report 33. Folsom: Geosynthetic Research Institute.

Qian, X. 2008. Limit equilibrium analysis for translational failure of landfills under different leachate buildup conditions. Water Science and Engineering, 1(1), 44-62.

Regulation Gazette No. 10008. (2013). R634 National Environmental Management: Waste Act (59/2008): Waste Classification and Management Regulations. Department of Environmental Affairs, Republic of South Africa.

Regulation Gazette No. 10008. (2013). R635 National Norms and Standards for the assessment of Waste for Landfill Disposal. Department of Environmental Affairs, Republic of South Africa.

Regulation Gazette No. 10008. (2013). R636 National Norms and Standards for Disposal of Waste to Landfill. Department of Environmental Affairs, Republic of South Africa.

Saravanan M., Kamon M., Faisal H. A., Katsumi T., Akai T., Inui T., Matsumoto A. (2006) Landfill Stability Assessment Using Interface Parameters, Proceeding of the 6th Japan-Korea-France Joint Seminar on Geoenvironmental Engineering, 2006, Japan. 137-146.

Stark T.D. and Eid H.T. (1996). Shear Behaviour Reinforced Geosynthetic Clay Liners. Geosynthetics International Vol 3 No. 6. Industrial Fabrics Association International, Minnesota, USA.

The Physics Factbook. Pressure in a Truck Tire. [Internet]. Available from http://hypertextbook.com/facts/2003/AlexandraKanonik.shtml. [Accessed 25 November 2013].

Thiel, R.S. (2001) "Peak vs. Residual Shear Strength for Landfill Bottom Liner Stability Analyses" Proceedings of the 15th Annual GRI Conference Hot Topics in Geosynthetics – II, presented in Houston, TX, Dec. 13, 2001, Geosynthetics Institute, Folsom, PA, pp. 40-70.

TRH14. (1985). Guidelines for Road Construction Materials. National Institute for Transport and Road Research, Pretoria, South Africa. p. 13-26.

Vajirkar M.M. (2004). Slope Stability Analysis of Class I Landfills with Co Disposal of Bio solids Using Field Test Data. MSc Thesis

Willaims N., Giroud J.P., and Bonaparte R. (1984). Properties of Plastic Nets for Liquid and Gas Drainage Associated with Geomembranes. Proceedings of the international Conference on Geomembranes. IFAI, p. 399-404.

Wilson-Fahmy R.F., Narejo D. and Koerner R.M. (1996). Puncture Protection of Geomembranes, Part I: Theory. Geosynthetics International, Vol 3 No. 5. p. 605-628

Xuede Q. (2008). Critical interfaces in Geosynthetic Multilayer Liner System of a Landfill. Water Science and Engineering Vol.1 No.4, p. 22-35

# APPENDICES

# Appendix A: Technical Data Sheets

GCL Data Sheet

GCL Interface Friction Test Report

GCL Tensile Strength

Geotextile Data Sheet

HDPE Data Sheet

Rock Grid PC Data Sheet

Secugrid Data Sheet

GCL Data Sheet

KAYTECH
ENGINEERED FABRICS

Johannesburg +27 (0)11 922 3300
Pinetown +27 (0)31 717 2300
Cape Town +27 (0)21 531 8110
East London +27 (0)43 727 1055
www.kaytech.co.za

## TECHNICAL DATA SHEET

| | |
|---|---|
| Product Name | enviroFIX™ X 1000 |
| Reference No: | DS WAST 0497-08/2013 |
| Date of Issue | 06 August 2013 |
| Description | Envirofix is a geosynthetic clay liner |

| | | | MARV (min average roll value) | Factory QC Test Frequency ($m^2$) | |
|---|---|---|---|---|---|
| Geotextile Cover Layer | PP nonwoven, white | $g/m^2$ | 200 | 4 000 | ASTM D5261 |
| Geotextile Carrier Layer | PP slit film, woven | $g/m^2$ | 110 | 4 000 | ASTM D5261 |
| | PP nonwoven, white | $g/m^2$ | N/A | | |
| | Composite | $g/m^2$ | N/A | | |
| Bentonite Layer (bentonite mass at 0% moisture content) | Quality | Montmorillonite content > 75 %, Sodium Cation $Na^+$ > 60 % | | | |
| | Sodium Bentonite Powder | $g/m^2$ | 4 000 | 4 000 | ASTM D5993 |
| | Swell Index (minimum) | mℓ/2 g | ≥ 24 | 35 tonnes | ASTM D5890 |
| GCL Mass per Unit Area | | $g/m^2$ | 4 310 | 4 000 | ASTM D5993 |
| Bonding Process | | Needlepunched and Thermal Lock™ | | | |
| Grab Strength | MD | N | 600 | 4 000 | ASTM D4632 |
| | XD | N | 600 | | |
| CBR Burst | Strength | N | 1 600 | 20 000 | ISO 12236 |
| | Elongation | % | ≥ 15 | | |
| Hydraulic Conductivity (maximum) | | m/s | $\leq 1.85 \times 10^{-11}$ | 25 000 | ASTM D5887 |
| Index Flux (pre-hydration thickness 4.5 mm) | | $m^3/m^2/s$ | $4.0 \times 10^{-9}$ | 25 000 | ASTM D5887 |
| Peel Strength (excl Edge Treatment) | | N/m | > 360 | 4 000 | ASTM D6496 |
| Edge Treatment | | 800 $g/m^2$ x 300 mm self-sealing bentonite edge enhancement | | | |
| Roll Size (standard) | width x length | m | 5.35 x 35 | 1 % tolerance on width and length | |
| | diameter | cm | 60 | Nominal | |
| | Average roll mass | kg | 970 | Typical | |

Manufactured by Kaytech to the ISO 9001:2000 Quality Management System Standard
PP = Polypropylene MD = Machine Direction XD = Cross Direction

GCL Interface Friction Test Report

TRI/ENVIRONMENTAL, INC.
*A Texas Research International Company*

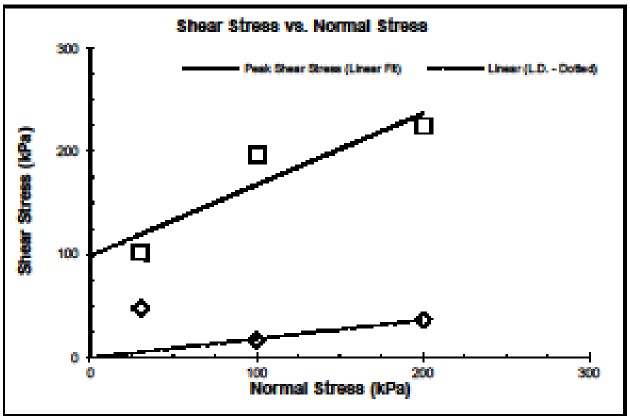
## Interface Friction Test Report

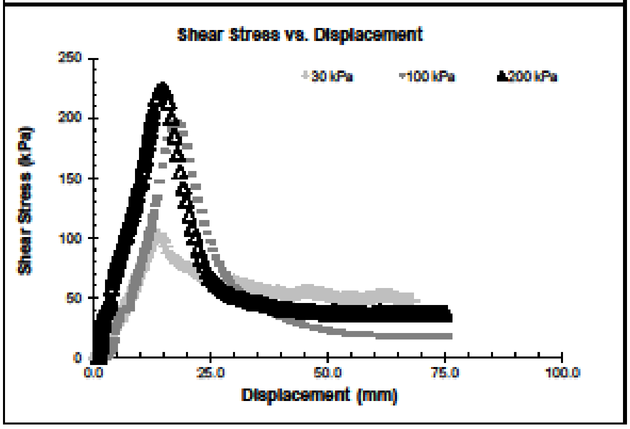
Client: **Kaytech - Kaymac Group**
Project: **GCL Shear Strength Program**
Test Date: 03/28/12-03/29/05

TRI Log#: E2365-07-08
Test Method: ASTM D 6243

John M. Allen, P.E., 03/30/2012
Quality Review/Date

### Tested Interface: Internal Shear of Envirofix X1000 GCL




| Test Results | | |
|---|---|---|
| | Peak | Large Displacement (@ 75 mm) |
| Friction Angle (degrees): | 34.6 | 10.3 |
| Y-intercept or Adhesion (kPa): | 99 | 0 |

The GCL sheared internally under the 100 & 200 kPa loads. The large displacement friction angle is fit through the 100 and 200 kPa loads only. The GCL did not shear internally under the 30 kPa load. The specimens were gripped using the gripping plates

Upper Box & Envirofix X1000 GCL

Lower Box Envirofix X1000 GCL

Box Dimensions: 305 mm x 305 mm x 102 mm

Interface Conditioning: Interface soaked and loading applied for a minimum of 24 hours prior to shear.

Test Condition: Wet

Shearing Rate: 0.1 mm/minute

**Test Data**

| Specimen No. | 1 | 2 | 3 |
|---|---|---|---|
| Bearing Slide Resistance (kPa) | 0.7 | 1.3 | 2.3 |
| Normal Stress (kPa) | 30 | 100 | 200 |
| Corrected Peak Shear Stress (kPa) | 103 | 197 | 225 |
| Corrected Large Displacement Shear Stress (kPa) | 48 | 17 | 37 |
| Peak Secant Angle (degrees) | 73.7 | 63.1 | 48.3 |
| Large Displacement Secant Angle (degrees) | 58.1 | 9.8 | 10.6 |



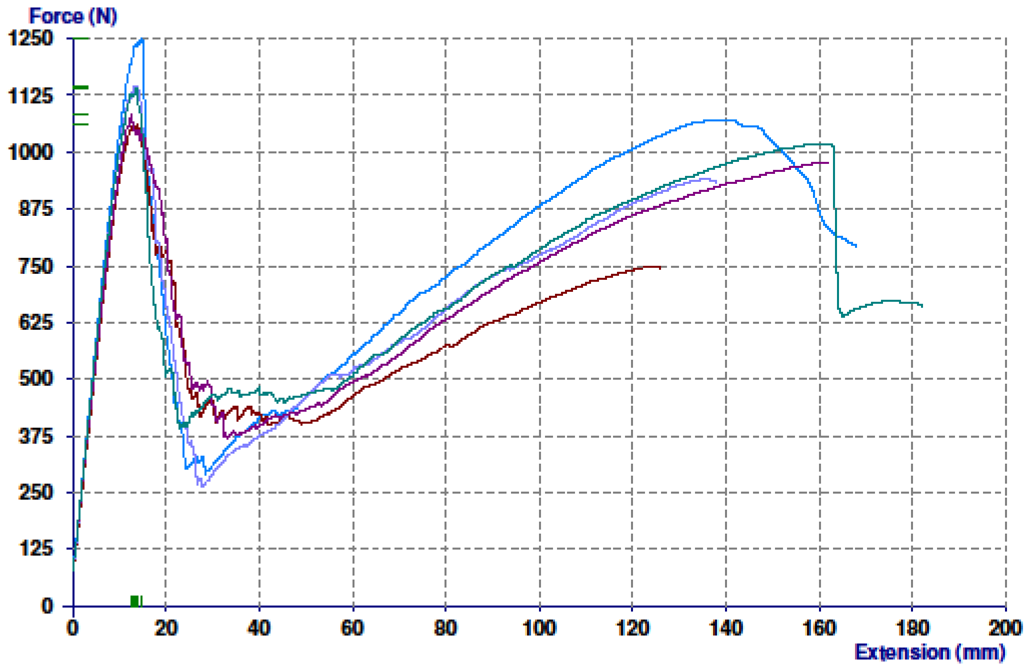
9063 Bee Caves Road □ Austin, TX 78733-6201 □ (512) 263-2101 □ (512) 263-2558 □ 1-800-880-TEST

GCL Tensile Strength Test

## GCL TENSILE ASTM D6768 R02

| | | | |
|---|---|---|---|
| **Product** | : BCL10CPHT535035(ZEBRA) | **Load Range** | : 5000 N |
| **Batch** | : 13110574 | **Extension Range** | : 100 mm |
| **Date** | : 2013/11/15 | **Test Speed** | : 300 mm/min |
| **Operator** | : BULL | **Preload** | : 75 N |

| Specimen | Width mm | Maximum N/mm | Strain at Max % | Force/Dimension @8% N/mm |
|---|---|---|---|---|
| 1 | 100.0 | 12.49 | 14.60 | 8.76 |
| 2 | 100.0 | 10.60 | 13.80 | 7.97 |
| 3 | 100.0 | 11.45 | 13.05 | 8.49 |
| 4 | 100.0 | 10.84 | 12.60 | 8.10 |
| 5 | 100.0 | 11.39 | 13.60 | 8.55 |
| Mean | | 11.35 | 13.53 | 8.38 |
| Std. Dev. | | 0.730 | 0.761 | 0.3275 |
| Coe. Var. | | 6.43 | 5.63 | 3.911 |
| Maximum | | 12.49 | 14.60 | 8.76 |
| Minimum | | 10.60 | 12.60 | 7.98 |




- Page 1 -

QMat 5.35 / Q4160 - Kaytech Engineered Fabrics (Pty) Ltd.

H25KT/130 - 5000N / [ QW00-012.HTW - 1.0 ] - GCL TENSILE ASTM D6768 R02

Geotextile Data Sheet

KAYTECH
ENGINEERED FABRICS

Johannesburg +27 (0)11 922 3300
Pinetown +27 (0)31 717 2300
Cape Town +27 (0)21 531 8110
East London +27 (0)43 727 1055
www.kaytech.co.za

## TECHNICAL DATA SHEET

| | |
|---|---|
| Product Name | **bidim** |
| Reference No: | DS FLTR 0472-06/2013 Rev2 |
| Date of Issue | 11 June 2013 |
| Description | Nonwoven, Continuous Filament, Needle Punched, Polyester Geotextile |

| | | | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mass | Nominal | g/m² | 130 | 150 | 180 | 210 | 270 | 340 | 550 | 750 | 1000 | SANS 10221-2007 |
| Thickness | Thickness under 2 kPa | mm | 1.2 | 1.6 | 1.8 | 2.0 | 2.5 | 3.2 | 4.4 | 6.1 | 6.9 | SANS 10221-2007 |
| Throughflow | @ 100mm head | ℓ/s/m² | 320 | 265 | 230 | 215 | 185 | 170 | 110 | 60 | 46 | SANS 10221-2007 |
| Permittivity | | $s^{-1}$ | 3.2 | 2.6 | 2.3 | 2.1 | 1.8 | 1.7 | 1.1 | 0.7 | 0.5 | Calc |
| Permeability | @ $1 \times 10^{-3}$ | m/sec | 3.8 | 4.2 | 4.1 | 4.3 | 4.6 | 5.4 | 4.8 | 4.3 | 3.2 | SANS 10221-2007 |
| Tensile Strength | Machine | kN/m | 8 | 11 | 13 | 16 | 22 | 30 | 49 | 62 | 76 | SANS 10221-2007 |
| | Across | kN/m | 7 | 9 | 11 | 14 | 20 | 27 | 43 | 57 | 67 | |
| | Elongation | % | 40 - 60 | | | | | | | | | |
| Penetration Load | CBR | kN | 1.4 | 1.8 | 2.2 | 2.6 | 3.7 | 4.7 | 7.2 | 9.2 | 11.4 | SANS 10221-2007 |
| Porosity | | % | 92 | 93 | 93 | 93 | 93 | 92 | 90 | 90 | 87 | GTS |

**The above results represent laboratory averages**

**Nonwoven Continuous Filament Needlepunched Polyester Geotextile**
Nonwoven – High throughflow and excellent filtration
Continuous Filament – High isotropic strength
Needlepunched – High elongation
Polyester – Superior chemical resistance

HDPE Data Sheet

NAUE GmbH & Co. KG
Windmühlenweg 4, 47906 Kempen
Germany
fon: +49 2845 808 - 155
fax: +49 2845 808 - 116
www.naue.com
info@naue.com

**Technical Data 2177**
**Carbofol® 406 Karo-Noppe/Megakron**

**Values tested in structured area**

dated: 18.04.2007

| Property | Test Method | Unit | | | | |
|---|---|---|---|---|---|---|
| Thickness nominal | ASTM D 5199 | mm | 1,50 | 2,00 | 2,50 | 3,00 |
| Thickness lowest individual value | ASTM D 5199 | mm | 1,42 | 1,90 | 2,38 | 2,85 |
| Width | / | mm | 5100 | 5100 | 5100 | 5100 |
| Density | ASTM D 1505<br>ASTM D 792 | g/cm³ | 0,942 | 0,942 | 0,942 | 0,942 |
| Melt flow index | ASTM D 1238 Cond. P 190/5 | g/10 min | < 3,0 | < 3,0 | < 3,0 | < 3,0 |
| Melt flow index | ASTM D 1238 Cond. E 190/2,16 | g/10 min | < 1,0 | < 1,0 | < 1,0 | < 1,0 |
| Tensile strength at yield | ASTM D 6693 | N/mm<br>MPA | 25<br>16 | 33<br>16 | 42<br>16 | 50<br>16 |
| Elongation at yield | ASTM D 6693 | % | 12 | 12 | 12 | 12 |
| Tensile strength at break | ASTM D 6693 | N/mm<br>MPA | > 26<br>> 18 | > 35<br>> 18 | > 47<br>> 18 | > 54<br>> 18 |
| Elongation at break | ASTM D 6693 | % | 400 | 400 | 400 | 400 |
| Carbon black content | ASTM D 1603 | % | 2 | 2 | 2 | 2 |
| Carbon black dispersion | ASTM D 5596 | Category | 1-2 | 1-2 | 1-2 | 1-2 |
| Tear resistance | ASTM D 1004 | N | 200 | 280 | 350 | 400 |
| Cold bending at -20°C | ASTM D 2136 | --- | passed | passed | passed | passed |
| Multi axial elongation | Based on DIN 53861 / EN 14151 | % | 15 | 15 | 15 | 15 |
| ESCR *1 | ASTM D 1693 | hours | 2000 | 2000 | 2000 | 2000 |
| Perforation resistance | DIN 16726 | mm | 800 | 1200 | 1600 | 2000 |
| Dimensional stability after warm storage 1h/100°C | ASTM D 1204 | % | ≤ 2 | ≤ 1 | ≤ 1 | ≤ 1 |
| NCTL – Test *1 | ASTM D 5397 app. | hours | > 300 | > 300 | > 300 | > 300 |
| OIT | ASTM D 3895 | min | 70 | 70 | 70 | 70 |
| Puncture resistance | ASTM D 4833<br>EN ISO 12236 | N | 500<br>4000 | 700<br>5400 | 820<br>6700 | 960<br>7400 |

file: 2177 - 406 kn-mk struc. Rev.2 eng.doc

*1 Measurement within the outside edge welding zones

The a.m.technical data are average values gained from measurings over the production width. These data are guiding values achieved in our aboratories and/or independent testing institutes. Our products can be subject to change without prior notice.

Rock Grid PC Data Sheet

KAYTECH
ENGINEERED FABRICS

Johannesburg +27 (0)11 922 3300
Pinetown +27 (0)31 717 2300
Cape Town +27 (0)21 531 8110
East London +27 (0)43 727 1055
www.kaytech.co.za

## TECHNICAL DATA SHEET

| | |
|---|---|
| Product Name | ROCK PC |
| Reference No: | DS REIN 0455-01/2013 |
| Date of Issue | 21 December 2012 |
| Description | High strength composite geotextile offering high modulus characteristics for reinforcement applications, with the additional benefits of in-plane capacity and high installation survivability |

| | | | 50/50 | 100/100 | 200/200 | |
|---|---|---|---|---|---|---|
| Material | | | Polyester, staple fibre 150 g/m² needle punched, nonwoven / high strength polyester yarns | | | |
| Short Term Tensile Strength ($T_u$) | Machine | kN/m | 50 | 100 | 200 | ISO 10319 |
| | Across | kN/m | 50 | 100 | 200 | |
| | Elongation | % | 10 | 10 | 10 | |
| Long Term Design Strength (LTDS*) 120 Years | | kN/m | 26 | 52 | 105 | ISO 10319 |
| Creep Limited Strength 120 Years | | kN/m | 30 | 60 | 120 | ISO 13431 |
| Water Flow Rate | Normal to Plane | ℓ/s/m² | 150 | | | ISO 11058 |
| | In Plane 20 kPa | ℓ/s/m/hr | 20 | | | ISO 12958 |
| Roll Dimensions | | m | 5 x 100 | | | ISO 12958 |

$$LTDS = \frac{T_u}{f_c.f_d.f_e.f_m}$$

$f_c$ (creep) = 1.65 (120 years)
$f_d$ (damage) = 1.05 (sand, silt, clay, yarn facing soil)
$f_e$ (environment) = 1.10 (pH 4-9)
$f_m$ (material) = 1.00

**The above results represent laboratory averages**
Kaytech reserves the right to make technical modifications to its products

Secugrid Data Sheet

# Geogrid

## Secugrid® R (PES/PET)

NAUE GmbH & Co. KG
Gewerbestrasse 2
32339 Espelkamp-Fiestel, Germany
Phone: +49 5743 41-0 · Fax: +49 5743 41-240
E-Mail: info@naue.com · Internet: www.naue.com

0799-CPD-20

**Product description:** Laid geogrid made of stretched, monolithic polyester (PET) flat or profile bars with welded junctions used for the reinforcement in many fields of civil engineering including landfill engineering, road construction and hydraulic engineering

| Property | Test method* | Unit | 60/20 R6 | 80/20 R6 | 120/40 R6 | 200/40 R6 | 400/40 R6 |
|---|---|---|---|---|---|---|---|
| Raw material | - | - | polyester/PET, transparent | | | | |
| Mass per unit area | EN ISO 9864 | g/m² | 380 | 360 | 580 | 810 | 1,420 |
| Max. tensile strength, md / cmd** | EN ISO 10319 | kN/m | ≥ 60 / ≥ 20 | ≥ 80 / ≥ 20 | ≥ 120 / ≥ 40 | ≥ 200 / ≥ 40 | ≥ 400 / ≥ 40 |
| Elongation at nominal strength, md / cmd** | EN ISO 10319 | % | ≤ 8 / ≤ 8 | | | | |
| Tensile strength at 2% elongation, md** | EN ISO 10319 | kN/m | 21 | 28 | 42 | 70 | 140 |
| Tensile strength at 5% elongation, md** | EN ISO 10319 | kN/m | 36 | 48 | 72 | 120 | 240 |
| Aperture size, md x cmd** | - | mm x mm | approx. 73 x 31 | approx. 73 x 30 | approx. 71 x 28 | approx. 71 x 25 | approx. 70 x 14 |
| UV-resistance (remaining tensile strength) | EN 12224 | % | 96.3 | | | | |
| Weather resistance | FGSV | class | high | | | | |
| Production specific elongation | - | % | 0 | | | | |
| Roll dimensions, width x length | - | m x m | 4.75 x 100 | | | | 4.75 50 |

*based on, **md = machine direction, cmd = cross machine direction

The listed technical values are guiding values, achieved in our laboratories and/or independent testing institutes. Our products are subject to changes without prior notice.

13 July 2009 N-Std Secugrid.XLS 60'80-20 120'200'400-40 R6_en Rev. 11

# Appendix B: Geotextile Equivalency Calculations for HDPE Protection Layer

**BURST RESISTANCE**

$T_{reqd}$ = $0.5\, p'\, d_v\, [\, f\, (\in)\, ]$

where

| | | |
|---|---|---|
| $T_{reqd}$ | = | required geotextile strength |
| p' | = | stress on the geotextile, which is slightly less than p, the tire inflation pressure at the ground surface |
| $d_v$ | = | maximum void diameter of the stone ≅ $0.33d_a$ |
| $d_a$ | = | the average stone diameter |
| f(∈) | = | strain function of the deformed geotextile, |

$$= \frac{1}{4}\left[\frac{2y}{b}+\frac{b}{2y}\right]$$ , in which

| | | |
|---|---|---|
| b | = | width of opening (or void) |
| y | = | deformation in the opening (or void) |

$$FS = \frac{60.6\, p_{test}}{p'\, d_a}$$

= **1.90** (>1.5 therefore Bidim A10 OK)

| | | | |
|---|---|---|---|
| $p_{test}$ | 1100 | kPa | -ultimate burst strength from Figure 2.30 (Koerner, 2005) |
| p' | 700 | kPa | - tire inflation pressure from http://hypertextbook.com/facts/2003 |
| $d_a$ | 50 | mm | -maximum stone size from DWAF, 1998 |

**TENSILE STRENGTH**

$T_{allow}$ = maximum grab strength of geotextile

$T_{reqd}$ = p' $d_v^2$ [ f ( ∈ ) ]

where

$T_{reqd}$ = required grab tensile force
p' = applied pressure
$d_v$ = maximum void diameter of the stone ≅ $0.33d_a$
$d_a$ = the average stone diameter
f(∈) = strain function of the deformed geotextile,

$$= \frac{1}{4}\left[\frac{2y}{b}+\frac{b}{2y}\right]$$ , in which

b = width of stone void
y = deformation into stone void

---

$T_{reqd}$ = p' $d_v^2$ [f(∈)] -maximum grab strength of geotextile
= 99.75

| | | | | |
|---|---|---|---|---|
| p' | = | 700 | kPa | -tire inflation pressure from http://hypertextbook.com/facts/2003 |
| $d_v$ | = | 16.5 | mm | -0.33 $d_a$ (Koerner, 2005) |
| $d_a$ | = | 50 | mm | -maximum stone size from DWAF, 1998 |
| f(∈) | = | 0.52 | | -strain function of deformed geotextile (Koerner, 2005) |

$T_{allow}$ = $\frac{\text{Max grab strength}}{\text{Reduction factors}}$
= 1480 N

| | | | |
|---|---|---|---|
| = | 3700 | N | -maximum grab strength of Bidim A10 (from kaytech Data Sheet) |
| | 2.5 | | -reduction factors (Koerner, 2005) |

FS = $\frac{T_{allow}}{T_{reqd}} = \frac{1480}{99.75}$

= **14.84** (>1.5 therefore Bidim A10 OK)

**PUNCTURE RESISTANCE**

$F_{allow}$ = ultimate puncture strength according to ASTM D4833

$F_{reqd}$ = p' $d_a^2$ $S_1$ $S_2$ $S_3$

where

$F_{reqd}$ = required vertical puncturing force to be resisted
p' = pressure exerted on the geotextile (approximately 100% of tire inflation pressure at the ground surface for thin covering thicknesses)
$d_a$ = average diameter of the puncturing aggregate or sharp object
$S_1$ = protrusion factor of the puncturing object
$S_2$ = scale factor to adjust the ASTM D4833 puncture test value that uses a 8mm diameter puncture probe to the actual puncturing object
$S_3$ = shape factor to adjust the ASTM D4833 flat puncture probe to the actual shape of the puncturing object

| | | | | |
|---|---|---|---|---|
| $F_{reqd}$ | = | p' $d_a^2$ S1 S2 S3 | | -required vertical puncturing force to be resisted |
| | = | 1134 | N | |
| p' | = | 700 | kPa | -tire inflation pressure from http://hypertextbook.com/facts/2003 |
| $d_a$ | = | 50 | mm | -average diameter of the puncturing aggregate (DWAF, 1998) |
| $S_1$ | = | 0.9 | | -protrusion factor of the puncturing object (Table 2.13, Koerner, 2005) |
| $S_2$ | = | 0.8 | | -scale factor (Table 2.13, Koerner, 2005) |
| $S_3$ | = | 0.9 | | -shape factor (Table 2.13, Koerner, 2005) |

$F_{allow}$ = $\frac{\text{Ult puncture strength}}{\text{Reduction factors}}$

= 5850 N

| | | | | |
|---|---|---|---|---|
| | = | 11700 | N | -ultimate puncture strength of Bidim A10 (from Kaytech Data Sheet) |
| | | 2 | | -reduction factors (Koerner, 2005) |

FS = $\frac{F_{allow}}{F_{reqd}}$ = $\frac{5850}{1134}$

= 5.16 (>1.5 therefore Bidim A10 OK)

**IMPACT (TEAR) RESISTANCE**

$E_{allow}$ = geotextile allowable impact strength

$E_{reqd}$ = m g h

= (V x ρ ) g h

= $[V \times (\rho_w G_s)]\, gh$

= $\left[\frac{\pi(d_a/1000)^3}{6}\right]\left[\frac{1000kg}{m^3}\right]$ (2.6) (9.81) h

= $13.35 \times 10^{-6}\, d_a^{\ 3}\, h$

where

E = energy developed (Joules)

m = mass of the flling object (kg)

g = acceleration due to gravity (m/sec$^2$)

h = height of fall (m)

V = volume of the object (m$^3$)

ρ = density of the object (kg/m$^3$)

$\rho_w$ = density of water (kg/m$^3$)

$G_s$ = specific gravity of the object (dimensionless)

$d_a$ = diameter of the object (mm)

---

$E_{max}$ = $13.35 \times 10^{-6}\, d_a^{\ 3}\, h$

= 67.6 J

$d_a$ = 150 mm -diameter of the object (mm) (assumed)

h = 1.5 m -height of fall (m) (assumed)

$E_{reqd}$ = $\frac{E_{max}}{\text{Reduction facctor}}$

= 8.45 J

Red. fact = 8 -based on Figure 2.34 (Koerner, 2005)

assumed CBR value of 10

$E_{allow}$ = 18 J -allowable impact strength of Bidim A10 (from Kaytech Data Sheet)

FS = $\frac{E_{allow}}{E_{reqd}} = \frac{18}{8}$

= 2.13 (>1.5 therefore Bidim A10 OK)

# Appendix C: Stability Calculations

C.1. Ring Shear Tests – Raw Data and Graphs

C.2. Configuration No. 1 Factors of Safety

C.3. Factors of Safety for HDPE Geomembrane Integrity

C.4. Configuration No. 2 Factors of Safety

C.5. Factors of Safety for GCL, Protection Geotextile and Veneer Reinforcement Integrity

C.6. Configuration No. 3 Factors of Safety

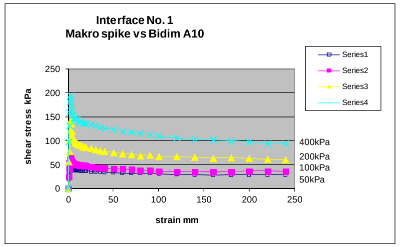
## C.1. Ring Shear Tests – Raw Data and Graphs

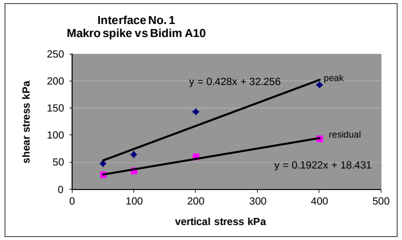
**Mr A.S Dookhi** **MSc Eng** **RING SHEAR TESTING** started **October 2013**

**Interface No. 1** **HDPE geomembrane - makro spike vs Protection geotextile Bidim A10 (fluffy)** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 65 | 130 | 57 | 114 | 99 | 198 | 64 | 128 | 230 | 460 | 127 | 254 | 388 | 776 | 227 | 454 |
| 1 | 99 | 198 | 75 | 150 | 166 | 332 | 93 | 186 | 309 | 618 | 181 | 362 | 456 | 912 | 375 | 750 |
| 1.5 | 132 | 264 | 92 | 184 | 223 | 446 | 116 | 232 | 391 | 782 | 250 | 500 | 522 | 1044 | 487 | 974 |
| 2 | 165 | 330 | 109 | 218 | 261 | 522 | 129 | 258 | 463 | 926 | 310 | 620 | 578 | 1156 | 562 | 1124 |
| 2.5 | 184 | 368 | 116 | 232 | 271 | 542 | 134 | 268 | 514 | 1028 | 353 | 706 | 616 | 1232 | 609 | 1218 |
| 3 | 190 | 380 | 115 | 230 | 262 | 524 | 129 | 258 | 535 | 1070 | 372 | 744 | 605 | 1210 | 582 | 1164 |
| 3.5 | 186 | 372 | 111 | 222 | 250 | 500 | 126 | 252 | 510 | 1020 | 344 | 688 | 566 | 1132 | 533 | 1066 |
| 4 | 171 | 342 | 104 | 208 | 235 | 470 | 120 | 240 | 454 | 908 | 304 | 608 | 535 | 1070 | 498 | 996 |
| 4.5 | 161 | 322 | 101 | 202 | 230 | 460 | 119 | 238 | 421 | 842 | 273 | 546 | 504 | 1008 | 476 | 952 |
| 5 | 155 | 310 | 98 | 196 | 222 | 444 | 116 | 232 | 403 | 806 | 259 | 518 | 498 | 996 | 470 | 940 |
| 6 | 151 | 302 | 96 | 192 | 219 | 438 | 114 | 228 | 391 | 782 | 247 | 494 | 478 | 956 | 456 | 912 |
| 7 | 146 | 292 | 93 | 186 | 214 | 428 | 112 | 224 | 383 | 766 | 243 | 486 | 476 | 952 | 458 | 916 |
| 8 | 150 | 300 | 95 | 190 | 212 | 424 | 112 | 224 | 374 | 748 | 233 | 466 | 471 | 942 | 451 | 902 |
| 9 | 143 | 286 | 92 | 184 | 209 | 418 | 110 | 220 | 369 | 738 | 227 | 454 | 464 | 928 | 444 | 888 |
| 10 | 143 | 286 | 92 | 184 | 206 | 412 | 108 | 216 | 368 | 736 | 226 | 452 | 463 | 926 | 448 | 896 |
| 12 | 144 | 288 | 91 | 182 | 203 | 406 | 107 | 214 | 359 | 718 | 221 | 442 | 443 | 886 | 436 | 872 |
| 14 | 140 | 280 | 92 | 184 | 203 | 406 | 108 | 216 | 355 | 710 | 218 | 436 | 444 | 888 | 442 | 884 |
| 16 | 142 | 284 | 93 | 186 | 198 | 396 | 105 | 210 | 346 | 692 | 208 | 416 | 434 | 868 | 433 | 866 |
| 18 | 139 | 278 | 95 | 190 | 200 | 400 | 106 | 212 | 342 | 684 | 206 | 412 | 430 | 860 | 434 | 868 |
| 20 | 138 | 276 | 94 | 188 | 191 | 382 | 104 | 208 | 344 | 688 | 197 | 394 | 427 | 854 | 432 | 864 |
| 25 | 131 | 262 | 93 | 186 | 186 | 372 | 103 | 206 | 338 | 676 | 193 | 386 | 416 | 832 | 427 | 854 |
| 30 | 127 | 254 | 93 | 186 | 177 | 354 | 101 | 202 | 326 | 652 | 189 | 378 | 405 | 810 | 421 | 842 |
| 35 | 126 | 252 | 96 | 192 | 175 | 350 | 100 | 200 | 317 | 634 | 187 | 374 | 390 | 780 | 413 | 826 |
| 40 | 121 | 242 | 92 | 184 | 169 | 338 | 100 | 200 | 309 | 618 | 181 | 362 | 387 | 774 | 413 | 826 |
| 50 | 117 | 234 | 92 | 184 | 161 | 322 | 99 | 198 | 287 | 574 | 188 | 376 | 374 | 748 | 409 | 818 |
| 60 | 112 | 224 | 89 | 178 | 159 | 318 | 103 | 206 | 267 | 534 | 192 | 384 | 353 | 706 | 400 | 800 |
| 70 | 115 | 230 | 89 | 178 | 149 | 298 | 103 | 206 | 255 | 510 | 196 | 392 | 349 | 698 | 394 | 788 |
| 80 | 114 | 228 | 87 | 174 | 138 | 276 | 99 | 198 | 238 | 476 | 196 | 392 | 348 | 696 | 382 | 764 |
| 90 | 116 | 232 | 88 | 176 | 137 | 274 | 98 | 196 | 237 | 474 | 208 | 416 | 343 | 686 | 368 | 736 |
| 100 | 110 | 220 | 82 | 164 | 134 | 268 | 94 | 188 | 222 | 444 | 201 | 402 | 340 | 680 | 354 | 708 |
| 120 | 108 | 216 | 79 | 158 | 132 | 264 | 92 | 184 | 215 | 430 | 207 | 414 | 342 | 684 | 326 | 652 |
| 140 | 104 | 208 | 78 | 156 | 130 | 260 | 93 | 186 | 230 | 460 | 185 | 370 | 353 | 706 | 299 | 598 |
| 160 | 101 | 202 | 78 | 156 | 131 | 262 | 90 | 180 | 235 | 470 | 166 | 332 | 362 | 724 | 279 | 558 |
| 180 | 104 | 208 | 79 | 158 | 142 | 284 | 83 | 166 | 246 | 492 | 163 | 326 | 353 | 706 | 274 | 548 |
| 200 | 99 | 198 | 81 | 162 | 156 | 312 | 78 | 156 | 244 | 488 | 152 | 304 | 337 | 674 | 281 | 562 |
| 220 | 97 | 194 | 84 | 168 | 153 | 306 | 77 | 154 | 240 | 480 | 148 | 296 | 312 | 624 | 284 | 568 |
| 240 | 99 | 198 | 84 | 168 | 152 | 304 | 77 | 154 | 238 | 476 | 143 | 286 | 295 | 590 | 300 | 600 |

| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 244 | 326 | 714 | 1230 | 50 | 610 | 358 | 0.01263 | 48.30 | 28.35 | 19.32 | 25.81 | 56.53 | 97.39 | 0.5 |
| 1 | 348 | 518 | 980 | 1662 | 100 | 810 | 442 | 0.01263 | 64.13 | 35.00 | 27.55 | 41.01 | 77.59 | 131.59 | 1 |
| 1.5 | 448 | 678 | 1282 | 2018 | 200 | 1814 | 762 | 0.01263 | 143.63 | 60.33 | 35.47 | 53.68 | 101.50 | 159.78 | 1.5 |
| 2 | 548 | 780 | 1546 | 2280 | 400 | 2450 | 1190 | 0.01263 | 193.98 | 94.22 | 43.39 | 61.76 | 122.41 | 180.52 | 2 |
| 2.5 | 600 | 810 | 1734 | 2450 | | | | 0.01263 | | | 47.51 | 64.13 | 137.29 | 193.98 | 2.5 |
| 3 | 610 | 782 | 1814 | 2374 | | | | 0.01263 | | | 48.30 | 61.92 | 143.63 | 187.97 | 3 |
| 3.5 | 594 | 752 | 1708 | 2198 | | | | 0.01263 | | | 47.03 | 59.54 | 135.23 | 174.03 | 3.5 |
| 4 | 550 | 710 | 1516 | 2066 | | | | 0.01263 | | | 43.55 | 56.22 | 120.03 | 163.58 | 4 |
| 4.5 | 524 | 698 | 1388 | 1960 | | | | 0.01263 | | | 41.49 | 55.27 | 109.90 | 155.19 | 4.5 |
| 5 | 506 | 676 | 1324 | 1936 | | | | 0.01263 | | | 40.06 | 53.52 | 104.83 | 153.29 | 5 |
| 6 | 494 | 666 | 1276 | 1868 | | | | 0.01263 | | | 39.11 | 52.73 | 101.03 | 147.90 | 6 |
| 7 | 478 | 652 | 1252 | 1868 | | | | 0.01263 | | | 37.85 | 51.62 | 99.13 | 147.90 | 7 |
| 8 | 490 | 648 | 1214 | 1844 | | | | 0.01263 | | | 38.80 | 51.31 | 96.12 | 146.00 | 8 |
| 9 | 470 | 638 | 1192 | 1816 | | | | 0.01263 | | | 37.21 | 50.51 | 94.38 | 143.78 | 9 |
| 10 | 470 | 628 | 1188 | 1822 | | | | 0.01263 | | | 37.21 | 49.72 | 94.06 | 144.26 | 10 |
| 12 | 470 | 620 | 1160 | 1758 | | | | 0.01263 | | | 37.21 | 49.09 | 91.84 | 139.19 | 12 |
| 14 | 464 | 622 | 1146 | 1772 | | | | 0.01263 | | | 36.74 | 49.25 | 90.74 | 140.30 | 14 |
| 16 | 470 | 606 | 1108 | 1734 | | | | 0.01263 | | | 37.21 | 47.98 | 87.73 | 137.29 | 16 |
| 18 | 468 | 612 | 1096 | 1728 | | | | 0.01263 | | | 37.05 | 48.46 | 86.78 | 136.82 | 18 |
| 20 | 464 | 590 | 1082 | 1718 | | | | 0.01263 | | | 36.74 | 46.71 | 85.67 | 136.03 | 20 |
| 25 | 448 | 578 | 1062 | 1686 | | | | 0.01263 | | | 35.47 | 45.76 | 84.09 | 133.49 | 25 |
| 30 | 440 | 556 | 1030 | 1652 | | | | 0.01263 | | | 34.84 | 44.02 | 81.55 | 130.80 | 30 |
| 35 | 444 | 550 | 1008 | 1606 | | | | 0.01263 | | | 35.15 | 43.55 | 79.81 | 127.16 | 35 |
| 40 | 426 | 538 | 980 | 1600 | | | | 0.01263 | | | 33.73 | 42.60 | 77.59 | 126.68 | 40 |
| 50 | 418 | 520 | 950 | 1566 | | | | 0.01263 | | | 33.10 | 41.17 | 75.22 | 123.99 | 50 |
| 60 | 402 | 524 | 918 | 1506 | | | | 0.01263 | | | 31.83 | 41.49 | 72.68 | 119.24 | 60 |
| 70 | 408 | 504 | 902 | 1486 | | | | 0.01263 | | | 32.30 | 39.90 | 71.42 | 117.66 | 70 |
| 80 | 402 | 474 | 868 | 1460 | | | | 0.01263 | | | 31.83 | 37.53 | 68.73 | 115.60 | 80 |
| 90 | 408 | 470 | 890 | 1422 | | | | 0.01263 | | | 32.30 | 37.21 | 70.47 | 112.59 | 90 |
| 100 | 384 | 456 | 846 | 1388 | | | | 0.01263 | | | 30.40 | 36.10 | 66.98 | 109.90 | 100 |
| 120 | 374 | 448 | 844 | 1336 | | | | 0.01263 | | | 29.61 | 35.47 | 66.83 | 105.78 | 120 |
| 140 | 364 | 446 | 830 | 1304 | | | | 0.01263 | | | 28.82 | 35.31 | 65.72 | 103.25 | 140 |
| 160 | 358 | 442 | 802 | 1282 | | | | 0.01263 | | | 28.35 | 35.00 | 63.50 | 101.50 | 160 |
| 180 | 366 | 450 | 818 | 1254 | | | | 0.01263 | | | 28.98 | 35.63 | 64.77 | 99.29 | 180 |
| 200 | 360 | 468 | 792 | 1236 | | | | 0.01263 | | | 28.50 | 37.05 | 62.71 | 97.86 | 200 |
| 220 | 362 | 460 | 776 | 1192 | | | | 0.01263 | | | 28.66 | 36.42 | 61.44 | 94.38 | 220 |
| 240 | 366 | 458 | 762 | 1190 | | | | 0.01263 | | | 28.98 | 36.26 | 60.33 | 94.22 | 240 |




Peak Friction Angle (δ) = 23.17 deg    Peak Cohesion (c) = 32.26 kPa

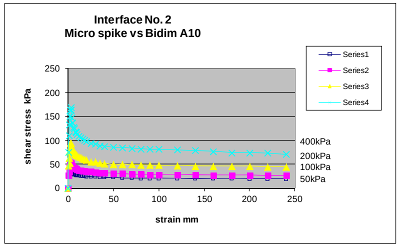
Residual Friction Angle (δ) = 10.88 deg    Residual Cohesion (c) = 18.43 kPa

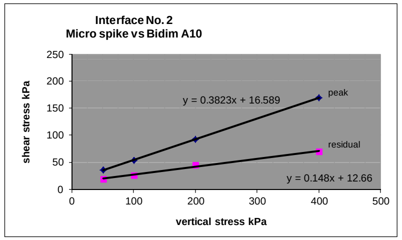
**Mr A.S Dookhi** **MSc Eng** started **October 2013**

**Interface No. 2** **HDPE geomembrane - micro spike vs Protection geotextile Bidim A10 (fluffy)** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 90 | 180 | 54 | 108 | 89 | 178 | 83 | 165 | 143 | 287 | 153 | 306 | 255 | 510 | 218 | 435 |
| 1 | 100 | 200 | 69 | 138 | 122 | 244 | 103 | 206 | 183 | 366 | 218 | 435 | 356 | 712 | 337 | 674 |
| 1.5 | 122 | 244 | 82 | 164 | 147 | 294 | 134 | 267 | 215 | 430 | 268 | 536 | 418 | 836 | 419 | 837 |
| 2 | 137 | 275 | 91 | 182 | 166 | 332 | 157 | 314 | 24 | 48 | 307 | 614 | 472 | 943 | 476 | 951 |
| 2.5 | 139 | 278 | 91 | 182 | 176 | 353 | 163 | 326 | 260 | 521 | 330 | 660 | 507 | 1014 | 523 | 1046 |
| 3 | 129 | 258 | 86 | 171 | 176 | 352 | 154 | 308 | 264 | 528 | 326 | 653 | 528 | 1056 | 542 | 1085 |
| 3.5 | 116 | 232 | 79 | 158 | 167 | 334 | 140 | 281 | 253 | 506 | 303 | 606 | 511 | 1021 | 521 | 1041 |
| 4 | 113 | 227 | 77 | 155 | 161 | 323 | 137 | 273 | 245 | 491 | 288 | 576 | 469 | 937 | 467 | 933 |
| 4.5 | 114 | 228 | 77 | 155 | 159 | 318 | 135 | 270 | 242 | 485 | 281 | 561 | 433 | 865 | 432 | 864 |
| 5 | 112 | 223 | 76 | 152 | 156 | 312 | 133 | 266 | 235 | 470 | 273 | 546 | 429 | 858 | 434 | 869 |
| 6 | 112 | 224 | 77 | 153 | 148 | 295 | 126 | 252 | 221 | 443 | 258 | 516 | 407 | 814 | 402 | 804 |
| 7 | 105 | 210 | 74 | 149 | 145 | 289 | 125 | 249 | 214 | 428 | 252 | 504 | 397 | 794 | 395 | 789 |
| 8 | 104 | 209 | 73 | 146 | 141 | 282 | 120 | 240 | 208 | 416 | 242 | 485 | 377 | 755 | 371 | 741 |
| 9 | 101 | 203 | 71 | 143 | 138 | 276 | 119 | 237 | 202 | 403 | 238 | 476 | 373 | 745 | 366 | 732 |
| 10 | 101 | 203 | 73 | 146 | 135 | 270 | 116 | 231 | 199 | 398 | 236 | 473 | 361 | 721 | 352 | 704 |
| 12 | 98 | 196 | 71 | 141 | 131 | 262 | 110 | 221 | 188 | 376 | 227 | 455 | 350 | 701 | 336 | 672 |
| 14 | 95 | 191 | 69 | 138 | 128 | 256 | 109 | 218 | 183 | 366 | 221 | 443 | 339 | 678 | 330 | 660 |
| 16 | 92 | 185 | 68 | 135 | 126 | 252 | 108 | 216 | 178 | 355 | 216 | 432 | 331 | 661 | 319 | 638 |
| 18 | 92 | 185 | 68 | 135 | 122 | 245 | 105 | 210 | 174 | 348 | 212 | 423 | 323 | 646 | 310 | 620 |
| 20 | 91 | 181 | 67 | 134 | 120 | 240 | 104 | 207 | 169 | 338 | 206 | 413 | 317 | 635 | 300 | 600 |
| 25 | 87 | 174 | 64 | 128 | 116 | 233 | 102 | 204 | 156 | 312 | 195 | 390 | 305 | 610 | 287 | 573 |
| 30 | 87 | 174 | 64 | 128 | 110 | 221 | 99 | 198 | 150 | 300 | 194 | 389 | 303 | 606 | 278 | 557 |
| 35 | 85 | 169 | 62 | 123 | 107 | 214 | 99 | 198 | 146 | 293 | 189 | 378 | 296 | 592 | 268 | 536 |
| 40 | 82 | 163 | 60 | 120 | 105 | 210 | 98 | 195 | 142 | 284 | 183 | 366 | 295 | 589 | 260 | 519 |
| 50 | 83 | 166 | 60 | 120 | 102 | 204 | 95 | 189 | 127 | 253 | 187 | 374 | 296 | 593 | 246 | 492 |
| 60 | 79 | 158 | 57 | 114 | 101 | 203 | 93 | 186 | 116 | 232 | 202 | 404 | 303 | 606 | 233 | 467 |
| 70 | 79 | 158 | 57 | 114 | 97 | 193 | 91 | 182 | 105 | 210 | 206 | 411 | 308 | 616 | 218 | 437 |
| 80 | 76 | 151 | 56 | 113 | 94 | 187 | 91 | 182 | 101 | 203 | 209 | 417 | 307 | 614 | 211 | 422 |
| 90 | 76 | 151 | 56 | 113 | 92 | 184 | 89 | 177 | 100 | 199 | 204 | 408 | 310 | 620 | 205 | 410 |
| 100 | 75 | 150 | 55 | 110 | 92 | 184 | 92 | 183 | 104 | 209 | 201 | 402 | 311 | 622 | 205 | 410 |
| 120 | 74 | 149 | 55 | 110 | 91 | 182 | 92 | 183 | 109 | 217 | 191 | 383 | 306 | 612 | 203 | 405 |
| 140 | 74 | 148 | 53 | 107 | 85 | 170 | 92 | 183 | 108 | 216 | 184 | 368 | 291 | 582 | 206 | 413 |
| 160 | 73 | 145 | 53 | 105 | 82 | 164 | 90 | 180 | 107 | 215 | 185 | 369 | 271 | 541 | 216 | 432 |
| 180 | 72 | 144 | 53 | 105 | 81 | 162 | 91 | 182 | 107 | 215 | 184 | 368 | 254 | 509 | 215 | 429 |
| 200 | 71 | 142 | 52 | 104 | 81 | 162 | 92 | 183 | 108 | 216 | 182 | 363 | 248 | 497 | 221 | 443 |
| 220 | 71 | 142 | 53 | 105 | 80 | 161 | 90 | 180 | 106 | 212 | 179 | 357 | 245 | 491 | 220 | 440 |
| 240 | 70 | 140 | 52 | 104 | 79 | 158 | 89 | 177 | 107 | 214 | 177 | 354 | 247 | 494 | 200 | 401 |

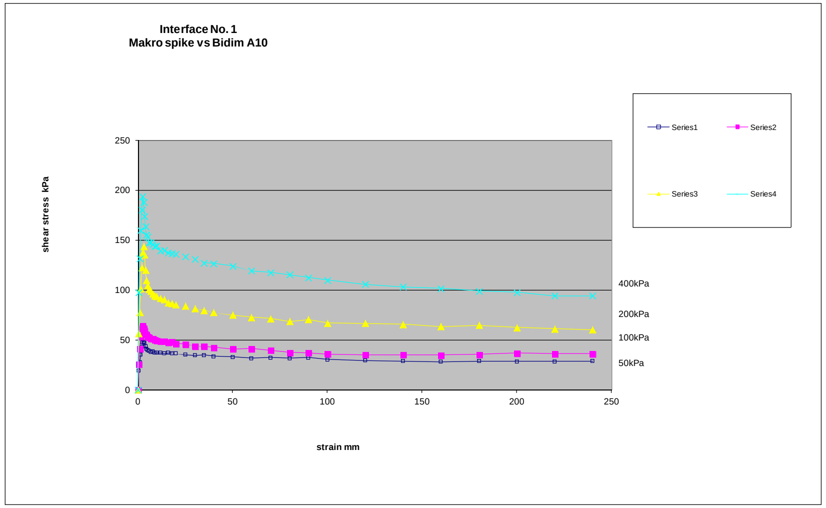
| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 288 | 343 | 593 | 945 | 50 | 460 | 244 | 0.01263 | 36.41 | 19.31 | 22.80 | 27.13 | 46.94 | 74.82 | 0.5 |
| 1 | 338 | 449 | 801 | 1385 | 100 | 678 | 335 | 0.01263 | 53.71 | 26.56 | 26.79 | 35.56 | 63.42 | 109.67 | 1 |
| 1.5 | 407 | 561 | 965 | 1673 | 200 | 1181 | 568 | 0.01263 | 93.47 | 44.94 | 32.23 | 44.42 | 76.41 | 132.49 | 1.5 |
| 2 | 456 | 646 | 662 | 1894 | 400 | 2141 | 895 | 0.01263 | 169.48 | 70.86 | 36.13 | 51.14 | 52.38 | 149.98 | 2 |
| 2.5 | 460 | 678 | 1181 | 2060 | | | | 0.01263 | | | 36.41 | 53.71 | 93.49 | 163.06 | 2.5 |
| 3 | 429 | 659 | 1181 | 2141 | | | | 0.01263 | | | 33.97 | 52.19 | 93.47 | 169.48 | 3 |
| 3.5 | 389 | 614 | 1112 | 2062 | | | | 0.01263 | | | 30.81 | 48.62 | 88.08 | 163.28 | 3.5 |
| 4 | 381 | 596 | 1067 | 1870 | | | | 0.01263 | | | 30.19 | 47.17 | 84.47 | 148.08 | 4 |
| 4.5 | 383 | 588 | 1046 | 1729 | | | | 0.01263 | | | 30.29 | 46.56 | 82.80 | 136.91 | 4.5 |
| 5 | 375 | 578 | 1016 | 1727 | | | | 0.01263 | | | 29.67 | 45.72 | 80.48 | 136.70 | 5 |
| 6 | 377 | 547 | 959 | 1618 | | | | 0.01263 | | | 29.88 | 43.33 | 75.91 | 128.08 | 6 |
| 7 | 359 | 538 | 932 | 1583 | | | | 0.01263 | | | 28.38 | 42.61 | 73.82 | 125.37 | 7 |
| 8 | 354 | 522 | 901 | 1496 | | | | 0.01263 | | | 28.05 | 41.33 | 71.33 | 118.43 | 8 |
| 9 | 345 | 513 | 879 | 1477 | | | | 0.01263 | | | 27.34 | 40.62 | 69.57 | 116.96 | 9 |
| 10 | 348 | 501 | 871 | 1425 | | | | 0.01263 | | | 27.58 | 39.67 | 68.95 | 112.80 | 10 |
| 12 | 337 | 482 | 830 | 1373 | | | | 0.01263 | | | 26.65 | 38.17 | 65.72 | 108.69 | 12 |
| 14 | 329 | 473 | 809 | 1338 | | | | 0.01263 | | | 26.03 | 37.46 | 64.01 | 105.94 | 14 |
| 16 | 320 | 468 | 787 | 1299 | | | | 0.01263 | | | 25.32 | 37.05 | 62.33 | 102.83 | 16 |
| 18 | 320 | 455 | 771 | 1265 | | | | 0.01263 | | | 25.32 | 36.01 | 61.05 | 100.17 | 18 |
| 20 | 315 | 447 | 751 | 1235 | | | | 0.01263 | | | 24.92 | 35.39 | 59.45 | 97.77 | 20 |
| 25 | 302 | 437 | 702 | 1183 | | | | 0.01263 | | | 23.87 | 34.58 | 55.58 | 93.63 | 25 |
| 30 | 302 | 419 | 689 | 1163 | | | | 0.01263 | | | 23.87 | 33.16 | 54.51 | 92.04 | 30 |
| 35 | 292 | 412 | 671 | 1127 | | | | 0.01263 | | | 23.14 | 32.59 | 53.11 | 89.24 | 35 |
| 40 | 283 | 405 | 650 | 1108 | | | | 0.01263 | | | 22.42 | 32.07 | 51.50 | 87.74 | 40 |
| 50 | 286 | 393 | 627 | 1085 | | | | 0.01263 | | | 22.61 | 31.12 | 49.62 | 85.89 | 50 |
| 60 | 272 | 389 | 635 | 1073 | | | | 0.01263 | | | 21.57 | 30.78 | 50.29 | 84.92 | 60 |
| 70 | 272 | 375 | 621 | 1052 | | | | 0.01263 | | | 21.57 | 29.67 | 49.17 | 83.30 | 70 |
| 80 | 264 | 369 | 620 | 1036 | | | | 0.01263 | | | 20.88 | 29.19 | 49.07 | 82.02 | 80 |
| 90 | 264 | 361 | 607 | 1030 | | | | 0.01263 | | | 20.88 | 28.55 | 48.08 | 81.54 | 90 |
| 100 | 260 | 367 | 611 | 1031 | | | | 0.01263 | | | 20.55 | 29.03 | 48.36 | 81.64 | 100 |
| 120 | 258 | 365 | 600 | 1017 | | | | 0.01263 | | | 20.45 | 28.93 | 47.48 | 80.52 | 120 |
| 140 | 254 | 353 | 584 | 995 | | | | 0.01263 | | | 20.12 | 27.98 | 46.20 | 78.74 | 140 |
| 160 | 250 | 344 | 584 | 973 | | | | 0.01263 | | | 19.81 | 27.27 | 46.22 | 77.05 | 160 |
| 180 | 249 | 344 | 582 | 938 | | | | 0.01263 | | | 19.71 | 27.20 | 46.10 | 74.25 | 180 |
| 200 | 245 | 345 | 579 | 939 | | | | 0.01263 | | | 19.41 | 27.32 | 45.84 | 74.37 | 200 |
| 220 | 247 | 341 | 569 | 930 | | | | 0.01263 | | | 19.52 | 26.98 | 45.08 | 73.66 | 220 |
| 240 | 244 | 335 | 568 | 895 | | | | 0.01263 | | | 19.31 | 26.56 | 44.94 | 70.86 | 240 |

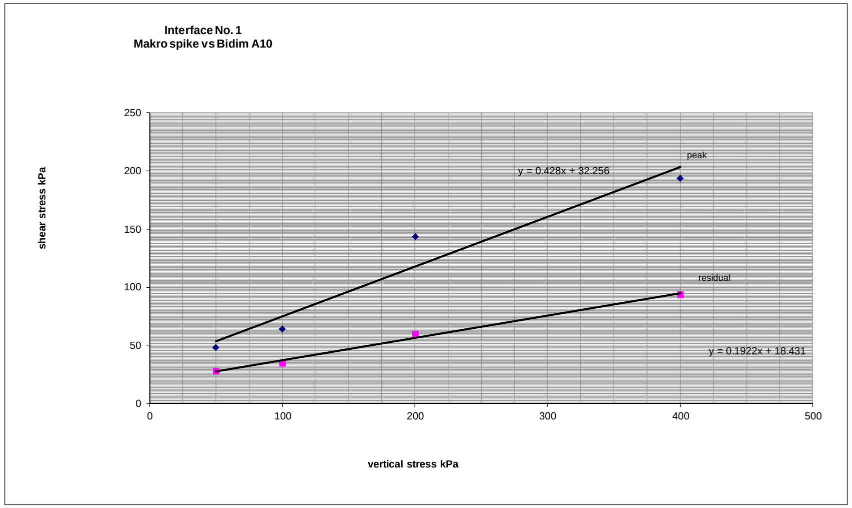


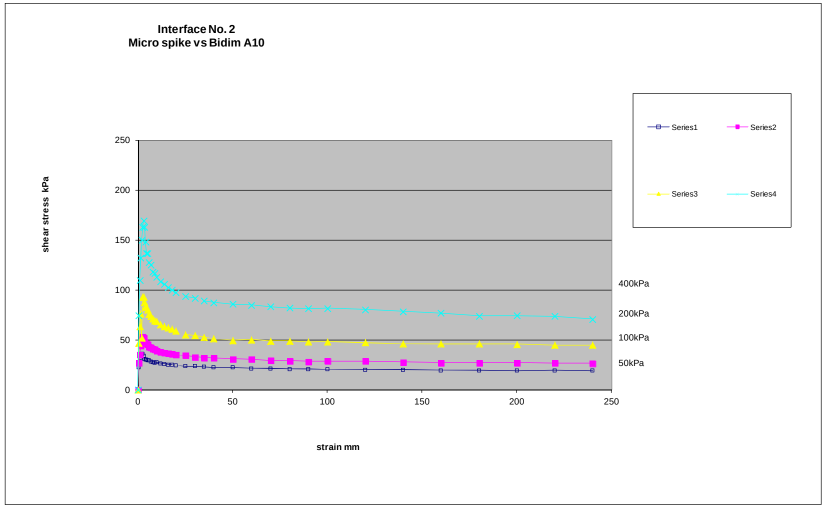



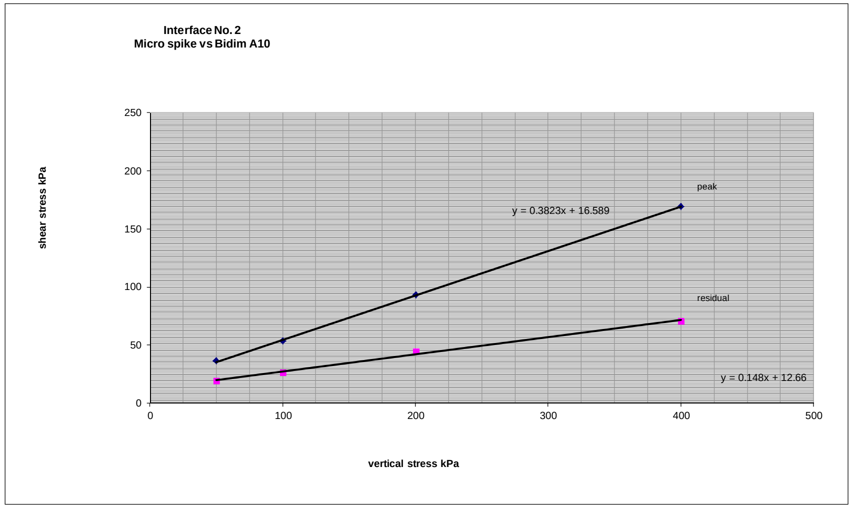

Peak Friction Angle (δ) = 20.92 deg Peak Cohesion (c) = 16.59 kPa

Residual Friction Angle (δ) = 8.42 deg Residual Cohesion (c) = 12.66 kPa


Interface No. 1
Makro spike vs Bidim A10
Series1
Series2
Series3
Series4
shear stress kPa
strain mm
400kPa
200kPa
100kPa
50kPa


Interface No. 1
Makro spike vs Bidim A10
shear stress kPa
vertical stress kPa
peak
y = 0.428x + 32.256
residual
y = 0.1922x + 18.431


Interface No. 2
Micro spike vs Bidim A10
Series1
Series2
Series3
Series4
shear stress kPa
strain mm
400kPa
200kPa
100kPa
50kPa

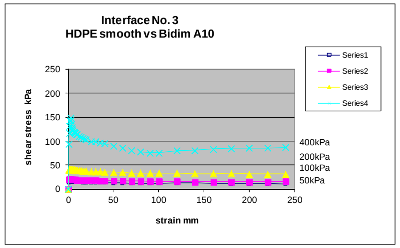

Interface No. 2
Micro spike vs Bidim A10
shear stress kPa
vertical stress kPa
peak
y = 0.3823x + 16.589
residual
y = 0.148x + 12.66

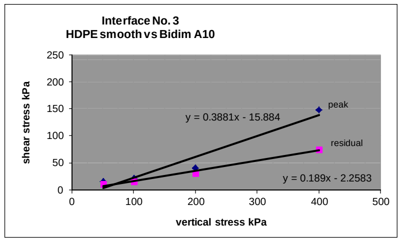
**Mr A.S Dookhi** **MSc Eng** **RING SHEAR TESTING** started **October 2013**

**Interface No. 3** **HDPE geomembrane - smooth vs Protection geotextile Bidim A10 (fluffy)** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 47 | 94 | 36 | 72 | 86 | 172 | 42 | 84 | 222 | 444 | 31 | 62 | 364 | 728 | 227 | 454 |
| 1 | 55 | 110 | 44 | 88 | 92 | 184 | 44 | 88 | 207 | 414 | 53 | 106 | 363 | 726 | 375 | 750 |
| 1.5 | 57 | 114 | 47 | 94 | 92 | 184 | 43 | 86 | 207 | 414 | 52 | 104 | 343 | 686 | 487 | 974 |
| 2 | 52 | 104 | 48 | 96 | 90 | 180 | 44 | 88 | 204 | 408 | 52 | 104 | 337 | 674 | 562 | 1124 |
| 2.5 | 50 | 100 | 48 | 96 | 89 | 178 | 42 | 84 | 204 | 408 | 51 | 102 | 328 | 656 | 609 | 1218 |
| 3 | 49 | 98 | 49 | 98 | 88 | 176 | 42 | 84 | 204 | 408 | 52 | 104 | 323 | 646 | 582 | 1164 |
| 3.5 | 48 | 96 | 49 | 98 | 88 | 176 | 42 | 84 | 203 | 406 | 52 | 104 | 319 | 638 | 533 | 1066 |
| 4 | 48 | 96 | 49 | 98 | 87 | 174 | 41 | 82 | 203 | 406 | 51 | 102 | 312 | 624 | 498 | 996 |
| 4.5 | 46 | 92 | 50 | 100 | 87 | 174 | 42 | 84 | 202 | 404 | 51 | 102 | 309 | 618 | 476 | 952 |
| 5 | 46 | 92 | 50 | 100 | 86 | 172 | 41 | 82 | 203 | 406 | 51 | 102 | 304 | 608 | 470 | 940 |
| 6 | 44 | 88 | 51 | 102 | 85 | 170 | 41 | 82 | 202 | 404 | 51 | 102 | 297 | 594 | 456 | 912 |
| 7 | 43 | 86 | 51 | 102 | 85 | 170 | 41 | 82 | 201 | 402 | 51 | 102 | 288 | 576 | 458 | 916 |
| 8 | 43 | 86 | 50 | 100 | 84 | 168 | 41 | 82 | 200 | 400 | 51 | 102 | 282 | 564 | 451 | 902 |
| 9 | 42 | 84 | 50 | 100 | 83 | 166 | 41 | 82 | 199 | 398 | 50 | 100 | 275 | 550 | 444 | 888 |
| 10 | 41 | 82 | 50 | 100 | 83 | 166 | 40 | 80 | 198 | 396 | 50 | 100 | 269 | 538 | 448 | 896 |
| 12 | 41 | 82 | 50 | 100 | 81 | 162 | 40 | 80 | 197 | 394 | 50 | 100 | 258 | 516 | 436 | 872 |
| 14 | 40 | 80 | 51 | 102 | 81 | 162 | 40 | 80 | 195 | 390 | 49 | 98 | 245 | 490 | 442 | 884 |
| 16 | 38 | 76 | 51 | 102 | 80 | 160 | 39 | 78 | 194 | 388 | 48 | 96 | 236 | 472 | 433 | 866 |
| 18 | 37 | 74 | 52 | 104 | 80 | 160 | 39 | 78 | 192 | 384 | 46 | 92 | 228 | 456 | 434 | 868 |
| 20 | 36 | 72 | 53 | 106 | 80 | 160 | 39 | 78 | 192 | 384 | 44 | 88 | 223 | 446 | 432 | 864 |
| 25 | 31 | 62 | 56 | 112 | 78 | 156 | 38 | 76 | 191 | 382 | 43 | 86 | 200 | 400 | 427 | 854 |
| 30 | 27 | 54 | 58 | 116 | 78 | 156 | 38 | 76 | 191 | 382 | 39 | 78 | 204 | 408 | 421 | 842 |
| 35 | 24 | 48 | 60 | 120 | 77 | 154 | 37 | 74 | 193 | 386 | 34 | 68 | 195 | 390 | 413 | 826 |
| 40 | 22 | 44 | 62 | 124 | 75 | 150 | 37 | 74 | 195 | 390 | 29 | 58 | 185 | 370 | 413 | 826 |
| 50 | 18 | 36 | 63 | 126 | 75 | 150 | 36 | 72 | 199 | 398 | 23 | 46 | 159 | 318 | 409 | 818 |
| 60 | 14 | 28 | 65 | 130 | 72 | 144 | 37 | 74 | 205 | 410 | 13 | 26 | 140 | 280 | 400 | 800 |
| 70 | 12 | 24 | 65 | 130 | 69 | 138 | 38 | 76 | 205 | 410 | 4 | 8 | 116 | 232 | 394 | 788 |
| 80 | 12 | 24 | 64 | 128 | 66 | 132 | 38 | 76 | 205 | 410 | 4 | 8 | 106 | 212 | 382 | 764 |
| 90 | 13 | 26 | 62 | 124 | 64 | 128 | 39 | 78 | 206 | 412 | 4 | 8 | 110 | 220 | 368 | 736 |
| 100 | 15 | 30 | 60 | 120 | 62 | 124 | 40 | 80 | 206 | 412 | 3 | 6 | 122 | 244 | 354 | 708 |
| 120 | 24 | 48 | 54 | 108 | 59 | 118 | 42 | 84 | 206 | 412 | 3 | 6 | 182 | 364 | 326 | 652 |
| 140 | 33 | 66 | 45 | 90 | 56 | 112 | 43 | 86 | 200 | 400 | 3 | 6 | 210 | 420 | 299 | 598 |
| 160 | 36 | 72 | 38 | 76 | 56 | 112 | 43 | 86 | 198 | 396 | 3 | 6 | 248 | 496 | 279 | 558 |
| 180 | 33 | 66 | 37 | 74 | 56 | 112 | 43 | 86 | 195 | 390 | 10 | 20 | 264 | 528 | 274 | 548 |
| 200 | 33 | 66 | 37 | 74 | 57 | 114 | 40 | 80 | 176 | 352 | 23 | 46 | 260 | 520 | 281 | 562 |
| 220 | 34 | 68 | 38 | 76 | 60 | 120 | 37 | 74 | 168 | 336 | 30 | 60 | 257 | 514 | 284 | 568 |
| 240 | 21 | 42 | 47 | 94 | 63 | 126 | 37 | 74 | 167 | 334 | 30 | 60 | 250 | 500 | 300 | 600 |

| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 166 | 256 | 506 | 1182 | 50 | 208 | 136 | 0.01263 | 16.47 | 10.77 | 13.14 | 20.27 | 40.06 | 93.59 | 0.5 |
| 1 | 198 | 272 | 520 | 1476 | 100 | 272 | 194 | 0.01263 | 21.54 | 15.36 | 15.68 | 21.54 | 41.17 | 116.86 | 1 |
| 1.5 | 208 | 270 | 518 | 1660 | 200 | 520 | 394 | 0.01263 | 41.17 | 31.20 | 16.47 | 21.38 | 41.01 | 131.43 | 1.5 |
| 2 | 200 | 268 | 512 | 1798 | 400 | 1874 | 952 | 0.01263 | 148.38 | 75.38 | 15.84 | 21.22 | 40.54 | 142.36 | 2 |
| 2.5 | 196 | 262 | 510 | 1874 | | | | 0.01263 | | | 15.52 | 20.74 | 40.38 | 148.38 | 2.5 |
| 3 | 196 | 260 | 512 | 1810 | | | | 0.01263 | | | 15.52 | 20.59 | 40.54 | 143.31 | 3 |
| 3.5 | 194 | 260 | 510 | 1704 | | | | 0.01263 | | | 15.36 | 20.59 | 40.38 | 134.92 | 3.5 |
| 4 | 194 | 256 | 508 | 1620 | | | | 0.01263 | | | 15.36 | 20.27 | 40.22 | 128.27 | 4 |
| 4.5 | 192 | 258 | 506 | 1570 | | | | 0.01263 | | | 15.20 | 20.43 | 40.06 | 124.31 | 4.5 |
| 5 | 192 | 254 | 508 | 1548 | | | | 0.01263 | | | 15.20 | 20.11 | 40.22 | 122.57 | 5 |
| 6 | 190 | 252 | 506 | 1506 | | | | 0.01263 | | | 15.04 | 19.95 | 40.06 | 119.24 | 6 |
| 7 | 188 | 252 | 504 | 1492 | | | | 0.01263 | | | 14.89 | 19.95 | 39.90 | 118.13 | 7 |
| 8 | 186 | 250 | 502 | 1466 | | | | 0.01263 | | | 14.73 | 19.79 | 39.75 | 116.07 | 8 |
| 9 | 184 | 248 | 498 | 1438 | | | | 0.01263 | | | 14.57 | 19.64 | 39.43 | 113.86 | 9 |
| 10 | 182 | 246 | 496 | 1434 | | | | 0.01263 | | | 14.41 | 19.48 | 39.27 | 113.54 | 10 |
| 12 | 182 | 242 | 494 | 1388 | | | | 0.01263 | | | 14.41 | 19.16 | 39.11 | 109.90 | 12 |
| 14 | 182 | 242 | 488 | 1374 | | | | 0.01263 | | | 14.41 | 19.16 | 38.64 | 108.79 | 14 |
| 16 | 178 | 238 | 484 | 1338 | | | | 0.01263 | | | 14.09 | 18.84 | 38.32 | 105.94 | 16 |
| 18 | 178 | 238 | 476 | 1324 | | | | 0.01263 | | | 14.09 | 18.84 | 37.69 | 104.83 | 18 |
| 20 | 178 | 238 | 472 | 1310 | | | | 0.01263 | | | 14.09 | 18.84 | 37.37 | 103.72 | 20 |
| 25 | 174 | 232 | 468 | 1254 | | | | 0.01263 | | | 13.78 | 18.37 | 37.05 | 99.29 | 25 |
| 30 | 170 | 232 | 460 | 1250 | | | | 0.01263 | | | 13.46 | 18.37 | 36.42 | 98.97 | 30 |
| 35 | 168 | 228 | 454 | 1216 | | | | 0.01263 | | | 13.30 | 18.05 | 35.95 | 96.28 | 35 |
| 40 | 168 | 224 | 448 | 1196 | | | | 0.01263 | | | 13.30 | 17.74 | 35.47 | 94.70 | 40 |
| 50 | 162 | 222 | 444 | 1136 | | | | 0.01263 | | | 12.83 | 17.58 | 35.15 | 89.94 | 50 |
| 60 | 158 | 218 | 436 | 1080 | | | | 0.01263 | | | 12.51 | 17.26 | 34.52 | 85.51 | 60 |
| 70 | 154 | 214 | 418 | 1020 | | | | 0.01263 | | | 12.19 | 16.94 | 33.10 | 80.76 | 70 |
| 80 | 152 | 208 | 418 | 976 | | | | 0.01263 | | | 12.03 | 16.47 | 33.10 | 77.28 | 80 |
| 90 | 150 | 206 | 420 | 956 | | | | 0.01263 | | | 11.88 | 16.31 | 33.25 | 75.69 | 90 |
| 100 | 150 | 204 | 418 | 952 | | | | 0.01263 | | | 11.88 | 16.15 | 33.10 | 75.38 | 100 |
| 120 | 156 | 202 | 418 | 1016 | | | | 0.01263 | | | 12.35 | 15.99 | 33.10 | 80.44 | 120 |
| 140 | 156 | 198 | 406 | 1018 | | | | 0.01263 | | | 12.35 | 15.68 | 32.15 | 80.60 | 140 |
| 160 | 148 | 198 | 402 | 1054 | | | | 0.01263 | | | 11.72 | 15.68 | 31.83 | 83.45 | 160 |
| 180 | 140 | 198 | 410 | 1076 | | | | 0.01263 | | | 11.08 | 15.68 | 32.46 | 85.19 | 180 |
| 200 | 140 | 194 | 398 | 1082 | | | | 0.01263 | | | 11.08 | 15.36 | 31.51 | 85.67 | 200 |
| 220 | 144 | 194 | 396 | 1082 | | | | 0.01263 | | | 11.40 | 15.36 | 31.35 | 85.67 | 220 |
| 240 | 136 | 200 | 394 | 1100 | | | | 0.01263 | | | 10.77 | 15.84 | 31.20 | 87.09 | 240 |




Peak Friction Angle (δ) = 18.68 deg Peak Cohesion (c) = 0.00 kPa

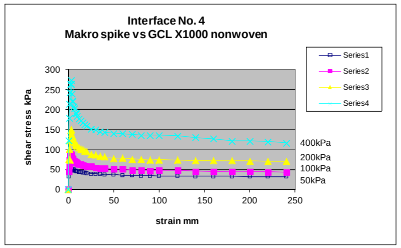
Residual Friction Angle (δ) = 10.70 deg Residual Cohesion (c) = 0.00 kPa

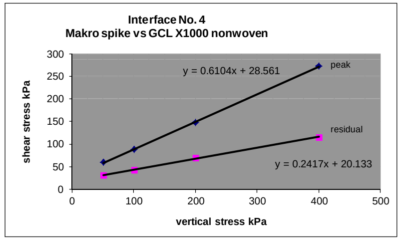
**Mr A.S Dookhi** **MSc Eng** started **October 2013**

**Interface No. 4** **HDPE geomembrane - makro spike vs GCL X1000 nonwoven** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 132 | 264 | 76 | 151 | 163 | 326 | 121 | 242 | 263 | 526 | 214 | 428 | 468 | 935 | 305 | 609 |
| 1 | 184 | 367 | 97 | 193 | 223 | 447 | 151 | 301 | 336 | 671 | 305 | 609 | 652 | 1305 | 471 | 943 |
| 1.5 | 223 | 447 | 114 | 229 | 270 | 539 | 196 | 392 | 394 | 788 | 375 | 750 | 767 | 1533 | 586 | 1172 |
| 2 | 252 | 504 | 127 | 254 | 305 | 609 | 230 | 460 | 44 | 88 | 429 | 859 | 865 | 1729 | 666 | 1331 |
| 2.5 | 255 | 510 | 127 | 254 | 323 | 647 | 239 | 477 | 477 | 955 | 462 | 924 | 930 | 1859 | 732 | 1464 |
| 3 | 237 | 473 | 120 | 239 | 322 | 645 | 226 | 451 | 484 | 968 | 457 | 914 | 968 | 1936 | 759 | 1518 |
| 3.5 | 212 | 425 | 110 | 221 | 306 | 612 | 206 | 411 | 464 | 928 | 424 | 848 | 936 | 1872 | 729 | 1457 |
| 4 | 208 | 416 | 108 | 216 | 296 | 592 | 200 | 400 | 450 | 900 | 403 | 806 | 859 | 1718 | 653 | 1306 |
| 4.5 | 209 | 418 | 108 | 216 | 292 | 583 | 198 | 396 | 444 | 889 | 393 | 785 | 793 | 1586 | 605 | 1210 |
| 5 | 205 | 409 | 106 | 212 | 286 | 572 | 195 | 389 | 431 | 862 | 382 | 764 | 787 | 1573 | 608 | 1216 |
| 6 | 206 | 411 | 107 | 214 | 271 | 541 | 185 | 370 | 406 | 812 | 361 | 722 | 746 | 1492 | 563 | 1126 |
| 7 | 193 | 385 | 104 | 208 | 265 | 530 | 183 | 365 | 393 | 785 | 353 | 706 | 728 | 1456 | 552 | 1105 |
| 8 | 191 | 383 | 102 | 204 | 259 | 517 | 176 | 352 | 382 | 763 | 339 | 678 | 692 | 1384 | 519 | 1037 |
| 9 | 186 | 372 | 100 | 200 | 253 | 506 | 174 | 348 | 370 | 739 | 333 | 666 | 683 | 1366 | 512 | 1025 |
| 10 | 186 | 372 | 102 | 204 | 248 | 495 | 169 | 339 | 365 | 730 | 331 | 662 | 661 | 1322 | 492 | 985 |
| 12 | 179 | 359 | 99 | 197 | 240 | 480 | 162 | 323 | 344 | 689 | 318 | 636 | 642 | 1285 | 470 | 941 |
| 14 | 175 | 350 | 97 | 193 | 234 | 469 | 160 | 319 | 336 | 671 | 310 | 620 | 622 | 1243 | 462 | 924 |
| 16 | 169 | 339 | 95 | 189 | 231 | 462 | 158 | 317 | 326 | 651 | 302 | 605 | 606 | 1212 | 446 | 893 |
| 18 | 169 | 339 | 95 | 189 | 224 | 449 | 154 | 308 | 319 | 638 | 296 | 592 | 592 | 1184 | 434 | 867 |
| 20 | 166 | 332 | 93 | 187 | 220 | 440 | 152 | 304 | 310 | 620 | 289 | 578 | 582 | 1164 | 420 | 840 |
| 25 | 160 | 319 | 89 | 179 | 213 | 427 | 150 | 299 | 286 | 572 | 273 | 546 | 559 | 1118 | 401 | 802 |
| 30 | 160 | 319 | 89 | 179 | 202 | 405 | 145 | 290 | 275 | 550 | 272 | 544 | 556 | 1111 | 390 | 779 |
| 35 | 155 | 310 | 86 | 172 | 196 | 392 | 145 | 290 | 268 | 537 | 265 | 529 | 542 | 1085 | 375 | 750 |
| 40 | 150 | 299 | 84 | 168 | 193 | 385 | 143 | 286 | 261 | 521 | 256 | 512 | 540 | 1080 | 363 | 727 |
| 50 | 152 | 304 | 84 | 168 | 187 | 374 | 139 | 277 | 232 | 464 | 261 | 523 | 543 | 1087 | 344 | 689 |
| 60 | 145 | 290 | 80 | 160 | 186 | 372 | 136 | 273 | 212 | 425 | 282 | 565 | 556 | 1111 | 327 | 653 |
| 70 | 145 | 290 | 80 | 160 | 177 | 354 | 133 | 266 | 193 | 385 | 288 | 575 | 564 | 1129 | 306 | 611 |
| 80 | 139 | 277 | 79 | 158 | 172 | 343 | 133 | 266 | 186 | 372 | 292 | 584 | 563 | 1126 | 295 | 590 |
| 90 | 139 | 277 | 79 | 158 | 168 | 337 | 130 | 260 | 183 | 365 | 286 | 571 | 569 | 1137 | 287 | 573 |
| 100 | 138 | 275 | 77 | 153 | 168 | 337 | 134 | 268 | 191 | 383 | 281 | 563 | 570 | 1140 | 287 | 573 |
| 120 | 136 | 273 | 77 | 153 | 167 | 334 | 134 | 268 | 199 | 398 | 268 | 536 | 561 | 1122 | 284 | 567 |
| 140 | 135 | 271 | 75 | 149 | 156 | 312 | 134 | 268 | 198 | 396 | 257 | 515 | 534 | 1067 | 289 | 578 |
| 160 | 133 | 266 | 74 | 147 | 151 | 301 | 132 | 264 | 197 | 394 | 258 | 517 | 496 | 992 | 302 | 605 |
| 180 | 132 | 264 | 74 | 147 | 149 | 297 | 133 | 266 | 197 | 394 | 257 | 515 | 466 | 933 | 300 | 601 |
| 200 | 130 | 260 | 72 | 145 | 149 | 297 | 134 | 268 | 198 | 396 | 254 | 508 | 455 | 911 | 310 | 620 |
| 220 | 130 | 260 | 74 | 147 | 147 | 295 | 132 | 264 | 195 | 389 | 250 | 500 | 450 | 900 | 308 | 615 |
| 240 | 129 | 257 | 72 | 145 | 145 | 290 | 130 | 260 | 196 | 392 | 248 | 496 | 453 | 906 | 280 | 561 |

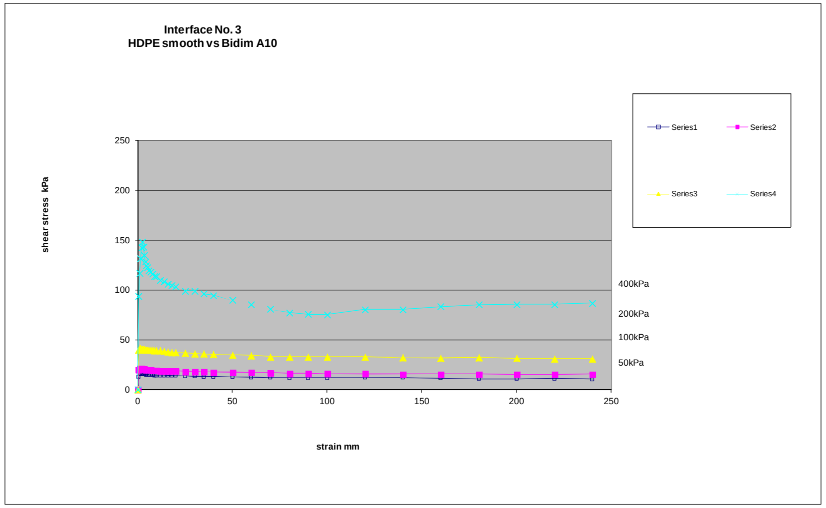
| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 415 | 568 | 954 | 1544 | 50 | 765 | 402 | 0.01263 | 60.53 | 31.85 | 32.87 | 44.94 | 75.55 | 122.25 | 0.5 |
| 1 | 561 | 748 | 1280 | 2248 | 100 | 1124 | 550 | 0.01263 | 89.01 | 43.55 | 44.39 | 59.22 | 101.35 | 177.95 | 1 |
| 1.5 | 676 | 931 | 1537 | 2705 | 200 | 1882 | 887 | 0.01263 | 148.97 | 70.25 | 53.48 | 73.68 | 121.72 | 214.19 | 1.5 |
| 2 | 758 | 1069 | 947 | 3061 | 400 | 3454 | 1467 | 0.01263 | 273.50 | 116.16 | 60.01 | 84.66 | 74.97 | 242.33 | 2 |
| 2.5 | 765 | 1124 | 1879 | 3323 | | | | 0.01263 | | | 60.53 | 89.01 | 148.76 | 263.08 | 2.5 |
| 3 | 712 | 1096 | 1882 | 3454 | | | | 0.01263 | | | 56.41 | 86.75 | 148.97 | 273.50 | 3 |
| 3.5 | 645 | 1023 | 1777 | 3330 | | | | 0.01263 | | | 51.08 | 81.00 | 140.68 | 263.63 | 3.5 |
| 4 | 632 | 992 | 1706 | 3024 | | | | 0.01263 | | | 50.05 | 78.56 | 135.09 | 239.46 | 4 |
| 4.5 | 634 | 979 | 1674 | 2796 | | | | 0.01263 | | | 50.22 | 77.51 | 132.56 | 221.36 | 4.5 |
| 5 | 621 | 961 | 1627 | 2789 | | | | 0.01263 | | | 49.19 | 76.12 | 128.80 | 220.82 | 5 |
| 6 | 626 | 911 | 1534 | 2617 | | | | 0.01263 | | | 49.53 | 72.11 | 121.47 | 207.22 | 6 |
| 7 | 593 | 895 | 1491 | 2561 | | | | 0.01263 | | | 46.94 | 70.89 | 118.05 | 202.77 | 7 |
| 8 | 587 | 869 | 1442 | 2421 | | | | 0.01263 | | | 46.44 | 68.80 | 114.15 | 191.70 | 8 |
| 9 | 571 | 854 | 1405 | 2391 | | | | 0.01263 | | | 45.23 | 67.59 | 111.24 | 189.31 | 9 |
| 10 | 576 | 834 | 1392 | 2307 | | | | 0.01263 | | | 45.57 | 66.02 | 110.21 | 182.67 | 10 |
| 12 | 556 | 803 | 1325 | 2226 | | | | 0.01263 | | | 44.02 | 63.58 | 104.90 | 176.22 | 12 |
| 14 | 543 | 788 | 1291 | 2167 | | | | 0.01263 | | | 42.99 | 62.36 | 102.18 | 171.58 | 14 |
| 16 | 528 | 779 | 1256 | 2105 | | | | 0.01263 | | | 41.79 | 61.66 | 99.45 | 166.64 | 16 |
| 18 | 528 | 757 | 1230 | 2051 | | | | 0.01263 | | | 41.79 | 59.92 | 97.40 | 162.38 | 18 |
| 20 | 519 | 744 | 1198 | 2004 | | | | 0.01263 | | | 41.10 | 58.88 | 94.85 | 158.65 | 20 |
| 25 | 498 | 726 | 1118 | 1920 | | | | 0.01263 | | | 39.39 | 57.48 | 88.52 | 152.00 | 25 |
| 30 | 498 | 695 | 1094 | 1890 | | | | 0.01263 | | | 39.39 | 55.04 | 86.61 | 149.65 | 30 |
| 35 | 482 | 682 | 1066 | 1834 | | | | 0.01263 | | | 38.19 | 54.00 | 84.40 | 145.23 | 35 |
| 40 | 467 | 671 | 1034 | 1807 | | | | 0.01263 | | | 36.99 | 53.13 | 81.85 | 143.06 | 40 |
| 50 | 472 | 651 | 987 | 1776 | | | | 0.01263 | | | 37.34 | 51.56 | 78.16 | 140.59 | 50 |
| 60 | 450 | 645 | 990 | 1764 | | | | 0.01263 | | | 35.63 | 51.04 | 78.35 | 139.68 | 60 |
| 70 | 450 | 620 | 960 | 1740 | | | | 0.01263 | | | 35.63 | 49.12 | 76.04 | 137.74 | 70 |
| 80 | 435 | 609 | 956 | 1717 | | | | 0.01263 | | | 34.42 | 48.25 | 75.66 | 135.91 | 80 |
| 90 | 435 | 596 | 936 | 1711 | | | | 0.01263 | | | 34.42 | 47.21 | 74.14 | 135.45 | 90 |
| 100 | 428 | 605 | 946 | 1713 | | | | 0.01263 | | | 33.91 | 47.90 | 74.87 | 135.62 | 100 |
| 120 | 426 | 603 | 934 | 1689 | | | | 0.01263 | | | 33.74 | 47.73 | 73.93 | 133.73 | 120 |
| 140 | 420 | 581 | 911 | 1645 | | | | 0.01263 | | | 33.23 | 45.99 | 72.09 | 130.21 | 140 |
| 160 | 413 | 565 | 910 | 1597 | | | | 0.01263 | | | 32.72 | 44.77 | 72.08 | 126.44 | 160 |
| 180 | 411 | 563 | 908 | 1533 | | | | 0.01263 | | | 32.54 | 44.59 | 71.92 | 121.41 | 180 |
| 200 | 405 | 565 | 904 | 1530 | | | | 0.01263 | | | 32.03 | 44.77 | 71.59 | 121.16 | 200 |
| 220 | 407 | 559 | 889 | 1515 | | | | 0.01263 | | | 32.19 | 44.24 | 70.40 | 119.96 | 220 |
| 240 | 402 | 550 | 887 | 1467 | | | | 0.01263 | | | 31.85 | 43.55 | 70.25 | 116.16 | 240 |

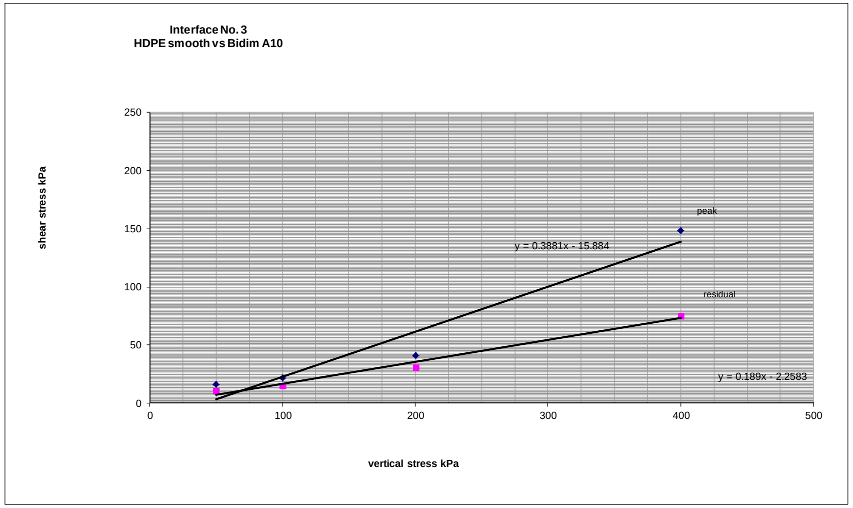


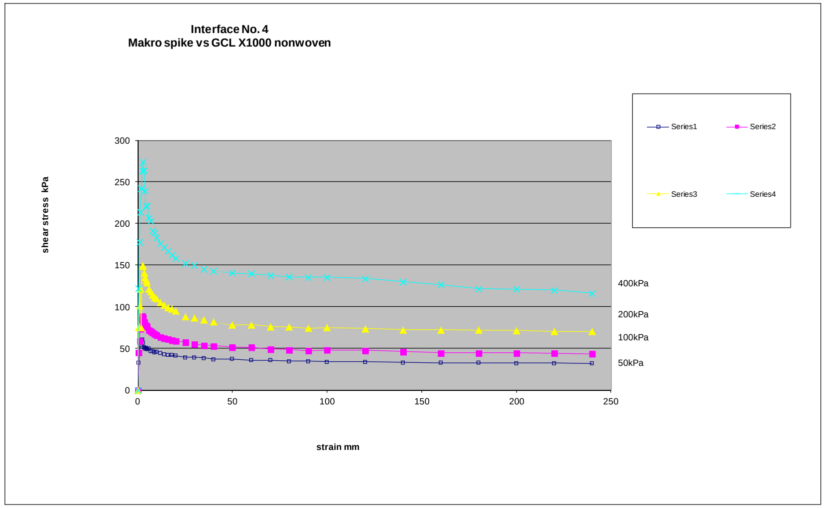



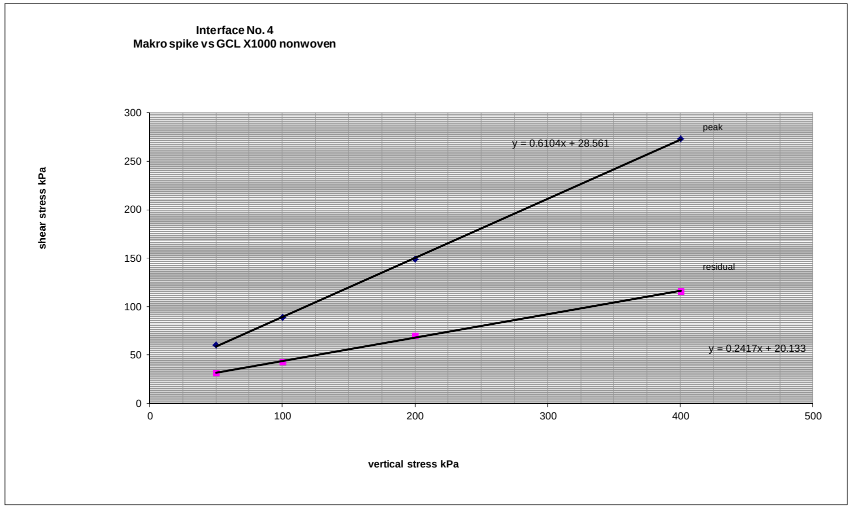

Peak Friction Angle (δ) = 31.40 deg Peak Cohesion (c) = 28.56 kPa

Residual Friction Angle (δ) = 13.59 deg Residual Cohesion (c) = 20.13 kPa


Interface No. 3
HDPE smooth vs Bidim A10
shear stress kPa
strain mm
Series1
Series2
Series3
Series4
400kPa
200kPa
100kPa
50kPa


Interface No. 3
HDPE smooth vs Bidim A10
shear stress kPa
vertical stress kPa
peak
y = 0.3881x - 15.884
residual
y = 0.189x - 2.2583


Interface No. 4
Makro spike vs GCL X1000 nonwoven
shear stress kPa
strain mm
Series1
Series2
Series3
Series4
400kPa
200kPa
100kPa
50kPa

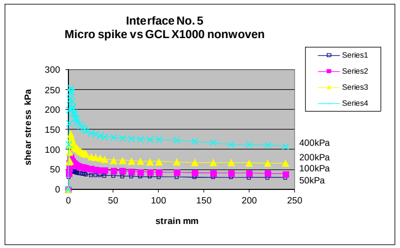

Interface No. 4
Makro spike vs GCL X1000 nonwoven
shear stress kPa
vertical stress kPa
peak
y = 0.6104x + 28.561
residual
y = 0.2417x + 20.133

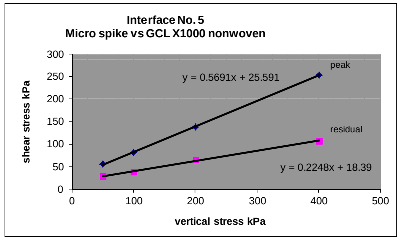
**Mr A.S Dookhi** **MSc Eng** **RING SHEAR TESTING** started **October 2013**

**Interface No. 5** **HDPE geomembrane - micro spike vs GCL X1000 nonwoven** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 120 | 240 | 72 | 144 | 148 | 296 | 110 | 220 | 239 | 478 | 204 | 408 | 425 | 850 | 290 | 580 |
| 1 | 167 | 334 | 92 | 184 | 203 | 406 | 137 | 274 | 305 | 610 | 290 | 580 | 593 | 1186 | 449 | 898 |
| 1.5 | 203 | 406 | 109 | 218 | 245 | 490 | 178 | 356 | 358 | 716 | 357 | 714 | 697 | 1394 | 558 | 1116 |
| 2 | 229 | 458 | 121 | 242 | 277 | 554 | 209 | 418 | 40 | 80 | 409 | 818 | 786 | 1572 | 634 | 1268 |
| 2.5 | 232 | 464 | 121 | 242 | 294 | 588 | 217 | 434 | 434 | 868 | 440 | 880 | 845 | 1690 | 697 | 1394 |
| 3 | 215 | 430 | 114 | 228 | 293 | 586 | 205 | 410 | 440 | 880 | 435 | 870 | 880 | 1760 | 723 | 1446 |
| 3.5 | 193 | 386 | 105 | 210 | 278 | 556 | 187 | 374 | 422 | 844 | 404 | 808 | 851 | 1702 | 694 | 1388 |
| 4 | 189 | 378 | 103 | 206 | 269 | 538 | 182 | 364 | 409 | 818 | 384 | 768 | 781 | 1562 | 622 | 1244 |
| 4.5 | 190 | 380 | 103 | 206 | 265 | 530 | 180 | 360 | 404 | 808 | 374 | 748 | 721 | 1442 | 576 | 1152 |
| 5 | 186 | 372 | 101 | 202 | 260 | 520 | 177 | 354 | 392 | 784 | 364 | 728 | 715 | 1430 | 579 | 1158 |
| 6 | 187 | 374 | 102 | 204 | 246 | 492 | 168 | 336 | 369 | 738 | 344 | 688 | 678 | 1356 | 536 | 1072 |
| 7 | 175 | 350 | 99 | 198 | 241 | 482 | 166 | 332 | 357 | 714 | 336 | 672 | 662 | 1324 | 526 | 1052 |
| 8 | 174 | 348 | 97 | 194 | 235 | 470 | 160 | 320 | 347 | 694 | 323 | 646 | 629 | 1258 | 494 | 988 |
| 9 | 169 | 338 | 95 | 190 | 230 | 460 | 158 | 316 | 336 | 672 | 317 | 634 | 621 | 1242 | 488 | 976 |
| 10 | 169 | 338 | 97 | 194 | 225 | 450 | 154 | 308 | 332 | 664 | 315 | 630 | 601 | 1202 | 469 | 938 |
| 12 | 163 | 326 | 94 | 188 | 218 | 436 | 147 | 294 | 313 | 626 | 303 | 606 | 584 | 1168 | 448 | 896 |
| 14 | 159 | 318 | 92 | 184 | 213 | 426 | 145 | 290 | 305 | 610 | 295 | 590 | 565 | 1130 | 440 | 880 |
| 16 | 154 | 308 | 90 | 180 | 210 | 420 | 144 | 288 | 296 | 592 | 288 | 576 | 551 | 1102 | 425 | 850 |
| 18 | 154 | 308 | 90 | 180 | 204 | 408 | 140 | 280 | 290 | 580 | 282 | 564 | 538 | 1076 | 413 | 826 |
| 20 | 151 | 302 | 89 | 178 | 200 | 400 | 138 | 276 | 282 | 564 | 275 | 550 | 529 | 1058 | 400 | 800 |
| 25 | 145 | 290 | 85 | 170 | 194 | 388 | 136 | 272 | 260 | 520 | 260 | 520 | 508 | 1016 | 382 | 764 |
| 30 | 145 | 290 | 85 | 170 | 184 | 368 | 132 | 264 | 250 | 500 | 259 | 518 | 505 | 1010 | 371 | 742 |
| 35 | 141 | 282 | 82 | 164 | 178 | 356 | 132 | 264 | 244 | 488 | 252 | 504 | 493 | 986 | 357 | 714 |
| 40 | 136 | 272 | 80 | 160 | 175 | 350 | 130 | 260 | 237 | 474 | 244 | 488 | 491 | 982 | 346 | 692 |
| 50 | 138 | 276 | 80 | 160 | 170 | 340 | 126 | 252 | 211 | 422 | 249 | 498 | 494 | 988 | 328 | 656 |
| 60 | 132 | 264 | 76 | 152 | 169 | 338 | 124 | 248 | 193 | 386 | 269 | 538 | 505 | 1010 | 311 | 622 |
| 70 | 132 | 264 | 76 | 152 | 161 | 322 | 121 | 242 | 175 | 350 | 274 | 548 | 513 | 1026 | 291 | 582 |
| 80 | 126 | 252 | 75 | 150 | 156 | 312 | 121 | 242 | 169 | 338 | 278 | 556 | 512 | 1024 | 281 | 562 |
| 90 | 126 | 252 | 75 | 150 | 153 | 306 | 118 | 236 | 166 | 332 | 272 | 544 | 517 | 1034 | 273 | 546 |
| 100 | 125 | 250 | 73 | 146 | 153 | 306 | 122 | 244 | 174 | 348 | 268 | 536 | 518 | 1036 | 273 | 546 |
| 120 | 124 | 248 | 73 | 146 | 152 | 304 | 122 | 244 | 181 | 362 | 255 | 510 | 510 | 1020 | 270 | 540 |
| 140 | 123 | 246 | 71 | 142 | 142 | 284 | 122 | 244 | 180 | 360 | 245 | 490 | 485 | 970 | 275 | 550 |
| 160 | 121 | 242 | 70 | 140 | 137 | 274 | 120 | 240 | 179 | 358 | 246 | 492 | 451 | 902 | 288 | 576 |
| 180 | 120 | 240 | 70 | 140 | 135 | 270 | 121 | 242 | 179 | 358 | 245 | 490 | 424 | 848 | 286 | 572 |
| 200 | 118 | 236 | 69 | 138 | 135 | 270 | 122 | 244 | 180 | 360 | 242 | 484 | 414 | 828 | 295 | 590 |
| 220 | 118 | 236 | 70 | 140 | 134 | 268 | 120 | 240 | 177 | 354 | 238 | 476 | 409 | 818 | 293 | 586 |
| 240 | 117 | 234 | 69 | 138 | 132 | 264 | 118 | 236 | 178 | 356 | 236 | 472 | 412 | 824 | 267 | 534 |

| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 384 | 516 | 886 | 1430 | 50 | 706 | 372 | 0.01263 | 55.90 | 29.45 | 30.40 | 40.86 | 70.15 | 113.22 | 0.5 |
| 1 | 518 | 680 | 1190 | 2084 | 100 | 1022 | 500 | 0.01263 | 80.92 | 39.59 | 41.01 | 53.84 | 94.22 | 165.00 | 1 |
| 1.5 | 624 | 846 | 1430 | 2510 | 200 | 1750 | 828 | 0.01263 | 138.56 | 65.56 | 49.41 | 66.98 | 113.22 | 198.73 | 1.5 |
| 2 | 700 | 972 | 898 | 2840 | 400 | 3206 | 1358 | 0.01263 | 253.84 | 107.52 | 55.42 | 76.96 | 71.10 | 224.86 | 2 |
| 2.5 | 706 | 1022 | 1748 | 3084 | | | | 0.01263 | | | 55.90 | 80.92 | 138.40 | 244.18 | 2.5 |
| 3 | 658 | 996 | 1750 | 3206 | | | | 0.01263 | | | 52.10 | 78.86 | 138.56 | 253.84 | 3 |
| 3.5 | 596 | 930 | 1652 | 3090 | | | | 0.01263 | | | 47.19 | 73.63 | 130.80 | 244.66 | 3.5 |
| 4 | 584 | 902 | 1586 | 2806 | | | | 0.01263 | | | 46.24 | 71.42 | 125.57 | 222.17 | 4 |
| 4.5 | 586 | 890 | 1556 | 2594 | | | | 0.01263 | | | 46.40 | 70.47 | 123.20 | 205.38 | 4.5 |
| 5 | 574 | 874 | 1512 | 2588 | | | | 0.01263 | | | 45.45 | 69.20 | 119.71 | 204.91 | 5 |
| 6 | 578 | 828 | 1426 | 2428 | | | | 0.01263 | | | 45.76 | 65.56 | 112.91 | 192.24 | 6 |
| 7 | 548 | 814 | 1386 | 2376 | | | | 0.01263 | | | 43.39 | 64.45 | 109.74 | 188.12 | 7 |
| 8 | 542 | 790 | 1340 | 2246 | | | | 0.01263 | | | 42.91 | 62.55 | 106.10 | 177.83 | 8 |
| 9 | 528 | 776 | 1306 | 2218 | | | | 0.01263 | | | 41.81 | 61.44 | 103.40 | 175.61 | 9 |
| 10 | 532 | 758 | 1294 | 2140 | | | | 0.01263 | | | 42.12 | 60.02 | 102.45 | 169.44 | 10 |
| 12 | 514 | 730 | 1232 | 2064 | | | | 0.01263 | | | 40.70 | 57.80 | 97.55 | 163.42 | 12 |
| 14 | 502 | 716 | 1200 | 2010 | | | | 0.01263 | | | 39.75 | 56.69 | 95.01 | 159.14 | 14 |
| 16 | 488 | 708 | 1168 | 1952 | | | | 0.01263 | | | 38.64 | 56.06 | 92.48 | 154.55 | 16 |
| 18 | 488 | 688 | 1144 | 1902 | | | | 0.01263 | | | 38.64 | 54.47 | 90.58 | 150.59 | 18 |
| 20 | 480 | 676 | 1114 | 1858 | | | | 0.01263 | | | 38.00 | 53.52 | 88.20 | 147.11 | 20 |
| 25 | 460 | 660 | 1040 | 1780 | | | | 0.01263 | | | 36.42 | 52.26 | 82.34 | 140.93 | 25 |
| 30 | 460 | 632 | 1018 | 1752 | | | | 0.01263 | | | 36.42 | 50.04 | 80.60 | 138.72 | 30 |
| 35 | 446 | 620 | 992 | 1700 | | | | 0.01263 | | | 35.31 | 49.09 | 78.54 | 134.60 | 35 |
| 40 | 432 | 610 | 962 | 1674 | | | | 0.01263 | | | 34.20 | 48.30 | 76.17 | 132.54 | 40 |
| 50 | 436 | 592 | 920 | 1644 | | | | 0.01263 | | | 34.52 | 46.87 | 72.84 | 130.17 | 50 |
| 60 | 416 | 586 | 924 | 1632 | | | | 0.01263 | | | 32.94 | 46.40 | 73.16 | 129.22 | 60 |
| 70 | 416 | 564 | 898 | 1608 | | | | 0.01263 | | | 32.94 | 44.66 | 71.10 | 127.32 | 70 |
| 80 | 402 | 554 | 894 | 1586 | | | | 0.01263 | | | 31.83 | 43.86 | 70.78 | 125.57 | 80 |
| 90 | 402 | 542 | 876 | 1580 | | | | 0.01263 | | | 31.83 | 42.91 | 69.36 | 125.10 | 90 |
| 100 | 396 | 550 | 884 | 1582 | | | | 0.01263 | | | 31.35 | 43.55 | 69.99 | 125.26 | 100 |
| 120 | 394 | 548 | 872 | 1560 | | | | 0.01263 | | | 31.20 | 43.39 | 69.04 | 123.52 | 120 |
| 140 | 388 | 528 | 850 | 1520 | | | | 0.01263 | | | 30.72 | 41.81 | 67.30 | 120.35 | 140 |
| 160 | 382 | 514 | 850 | 1478 | | | | 0.01263 | | | 30.25 | 40.70 | 67.30 | 117.02 | 160 |
| 180 | 380 | 512 | 848 | 1420 | | | | 0.01263 | | | 30.09 | 40.54 | 67.14 | 112.43 | 180 |
| 200 | 374 | 514 | 844 | 1418 | | | | 0.01263 | | | 29.61 | 40.70 | 66.83 | 112.27 | 200 |
| 220 | 376 | 508 | 830 | 1404 | | | | 0.01263 | | | 29.77 | 40.22 | 65.72 | 111.16 | 220 |
| 240 | 372 | 500 | 828 | 1358 | | | | 0.01263 | | | 29.45 | 39.59 | 65.56 | 107.52 | 240 |




Peak Friction Angle (δ) = 29.64 deg

Peak Cohesion (c) = 25.59 kPa

Residual Friction Angle (δ) = 12.67 deg

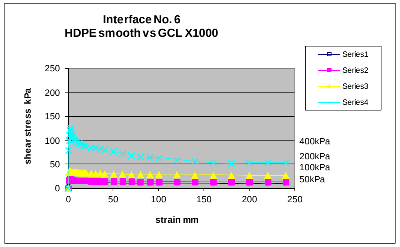
Residual Cohesion (c) = 18.39 kPa

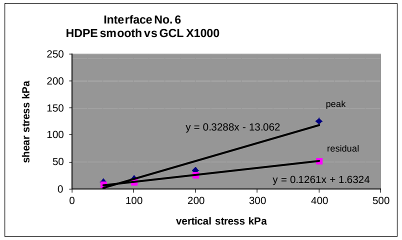
**Mr A.S Dookhi** **MSc Eng** started **October 2013**

**Interface No. 6** **HDPE geomembrane - smooth vs GCL X1000 nonwoven** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 40 | 80 | 31 | 61 | 73 | 146 | 36 | 71 | 189 | 377 | 26 | 53 | 309 | 619 | 193 | 386 |
| 1 | 47 | 94 | 37 | 75 | 78 | 156 | 36 | 72 | 176 | 352 | 45 | 90 | 309 | 617 | 319 | 638 |
| 1.5 | 48 | 97 | 40 | 80 | 78 | 156 | 37 | 73 | 176 | 352 | 44 | 88 | 292 | 583 | 414 | 828 |
| 2 | 44 | 88 | 41 | 82 | 84 | 168 | 37 | 75 | 173 | 347 | 44 | 88 | 286 | 573 | 478 | 955 |
| 2.5 | 43 | 85 | 41 | 82 | 82 | 164 | 36 | 71 | 173 | 347 | 43 | 87 | 279 | 558 | 518 | 1035 |
| 3 | 42 | 83 | 42 | 83 | 75 | 150 | 36 | 71 | 173 | 347 | 44 | 88 | 275 | 549 | 495 | 989 |
| 3.5 | 41 | 82 | 42 | 83 | 75 | 150 | 36 | 71 | 173 | 345 | 44 | 88 | 271 | 542 | 453 | 906 |
| 4 | 41 | 82 | 42 | 83 | 74 | 148 | 35 | 70 | 173 | 345 | 43 | 87 | 265 | 530 | 423 | 847 |
| 4.5 | 39 | 78 | 43 | 85 | 74 | 148 | 36 | 71 | 172 | 343 | 43 | 87 | 263 | 525 | 405 | 809 |
| 5 | 39 | 78 | 43 | 85 | 73 | 146 | 35 | 70 | 173 | 345 | 43 | 87 | 258 | 517 | 400 | 799 |
| 6 | 37 | 75 | 43 | 87 | 72 | 145 | 35 | 70 | 172 | 343 | 43 | 87 | 252 | 505 | 388 | 775 |
| 7 | 37 | 73 | 43 | 87 | 72 | 145 | 35 | 70 | 171 | 342 | 43 | 87 | 245 | 490 | 389 | 779 |
| 8 | 37 | 73 | 43 | 85 | 71 | 143 | 35 | 70 | 170 | 340 | 43 | 87 | 240 | 479 | 383 | 767 |
| 9 | 36 | 71 | 43 | 85 | 71 | 141 | 35 | 70 | 169 | 338 | 43 | 85 | 234 | 468 | 377 | 755 |
| 10 | 35 | 70 | 43 | 85 | 71 | 141 | 34 | 68 | 168 | 337 | 43 | 85 | 229 | 457 | 381 | 762 |
| 12 | 35 | 70 | 43 | 85 | 69 | 138 | 34 | 68 | 167 | 335 | 43 | 85 | 219 | 439 | 371 | 741 |
| 14 | 34 | 68 | 43 | 87 | 69 | 138 | 34 | 68 | 166 | 332 | 42 | 83 | 208 | 417 | 376 | 751 |
| 16 | 32 | 65 | 43 | 87 | 68 | 136 | 33 | 66 | 165 | 330 | 41 | 82 | 201 | 401 | 368 | 736 |
| 18 | 31 | 63 | 44 | 88 | 68 | 136 | 33 | 66 | 163 | 326 | 39 | 78 | 194 | 388 | 369 | 738 |
| 20 | 31 | 61 | 45 | 90 | 68 | 136 | 33 | 66 | 163 | 326 | 37 | 75 | 190 | 379 | 367 | 734 |
| 25 | 26 | 53 | 48 | 95 | 66 | 133 | 32 | 65 | 162 | 325 | 37 | 73 | 170 | 340 | 363 | 726 |
| 30 | 23 | 46 | 49 | 99 | 66 | 133 | 32 | 65 | 162 | 325 | 33 | 66 | 173 | 347 | 358 | 716 |
| 35 | 20 | 41 | 51 | 102 | 65 | 131 | 31 | 63 | 164 | 328 | 29 | 58 | 166 | 332 | 351 | 702 |
| 40 | 19 | 37 | 53 | 105 | 64 | 128 | 31 | 63 | 166 | 332 | 25 | 49 | 157 | 315 | 351 | 702 |
| 50 | 15 | 31 | 54 | 107 | 64 | 128 | 31 | 61 | 169 | 338 | 20 | 39 | 135 | 270 | 348 | 695 |
| 60 | 12 | 24 | 55 | 111 | 61 | 122 | 31 | 63 | 174 | 349 | 11 | 22 | 119 | 238 | 340 | 680 |
| 70 | 10 | 20 | 55 | 111 | 59 | 117 | 32 | 65 | 174 | 349 | 3 | 7 | 99 | 197 | 335 | 670 |
| 80 | 10 | 20 | 54 | 109 | 56 | 112 | 32 | 65 | 174 | 349 | 3 | 7 | 90 | 180 | 325 | 649 |
| 90 | 11 | 22 | 53 | 105 | 54 | 109 | 33 | 66 | 175 | 350 | 3 | 7 | 94 | 187 | 313 | 626 |
| 100 | 13 | 26 | 51 | 102 | 53 | 105 | 34 | 68 | 175 | 350 | 3 | 5 | 99 | 198 | 301 | 602 |
| 120 | 20 | 41 | 46 | 92 | 50 | 100 | 36 | 71 | 175 | 350 | 3 | 5 | 99 | 198 | 277 | 554 |
| 140 | 28 | 56 | 38 | 77 | 48 | 95 | 37 | 73 | 170 | 340 | 3 | 5 | 102 | 204 | 254 | 508 |
| 160 | 31 | 61 | 32 | 65 | 48 | 95 | 37 | 73 | 168 | 337 | 3 | 5 | 100 | 200 | 237 | 474 |
| 180 | 28 | 56 | 31 | 63 | 48 | 95 | 37 | 73 | 166 | 332 | 9 | 17 | 98 | 196 | 233 | 466 |
| 200 | 28 | 56 | 31 | 63 | 48 | 97 | 34 | 68 | 150 | 299 | 20 | 39 | 98 | 196 | 239 | 478 |
| 220 | 29 | 58 | 32 | 65 | 51 | 102 | 31 | 63 | 143 | 286 | 26 | 51 | 97 | 194 | 241 | 483 |
| 240 | 18 | 36 | 40 | 80 | 54 | 107 | 31 | 63 | 142 | 284 | 26 | 51 | 98 | 196 | 241 | 482 |

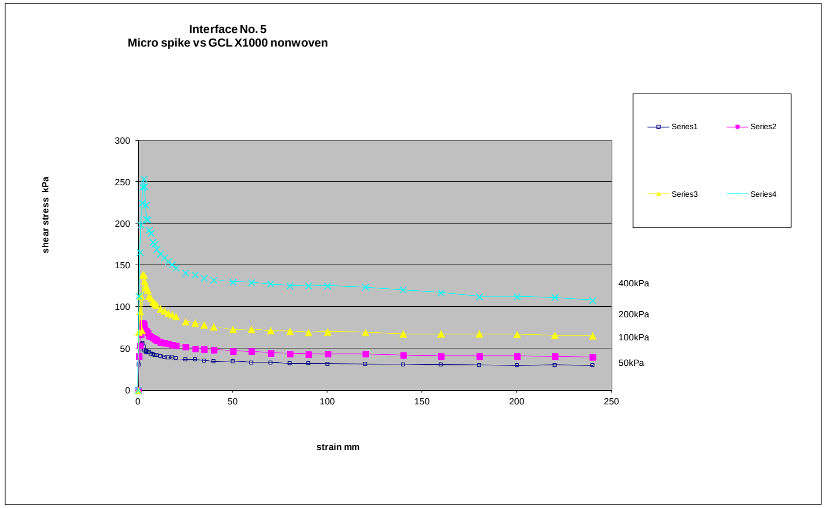
| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 141 | 218 | 430 | 1005 | 50 | 177 | 116 | 0.01263 | 14.00 | 9.15 | 11.17 | 17.23 | 34.05 | 79.55 | 0.5 |
| 1 | 168 | 228 | 442 | 1255 | 100 | 243 | 165 | 0.01263 | 19.22 | 13.06 | 13.33 | 18.08 | 35.00 | 99.33 | 1 |
| 1.5 | 177 | 230 | 440 | 1411 | 200 | 442 | 335 | 0.01263 | 35.00 | 26.52 | 14.00 | 18.17 | 34.86 | 111.72 | 1.5 |
| 2 | 170 | 243 | 435 | 1528 | 400 | 1593 | 662 | 0.01263 | 126.12 | 52.40 | 13.46 | 19.22 | 34.46 | 121.01 | 2 |
| 2.5 | 167 | 235 | 434 | 1593 | | | | 0.01263 | | | 13.19 | 18.64 | 34.32 | 126.12 | 2.5 |
| 3 | 167 | 221 | 435 | 1539 | | | | 0.01263 | | | 13.19 | 17.50 | 34.46 | 121.81 | 3 |
| 3.5 | 165 | 221 | 434 | 1448 | | | | 0.01263 | | | 13.06 | 17.50 | 34.32 | 114.68 | 3.5 |
| 4 | 165 | 218 | 432 | 1377 | | | | 0.01263 | | | 13.06 | 17.23 | 34.19 | 109.03 | 4 |
| 4.5 | 163 | 219 | 430 | 1335 | | | | 0.01263 | | | 12.92 | 17.36 | 34.05 | 105.66 | 4.5 |
| 5 | 163 | 216 | 432 | 1316 | | | | 0.01263 | | | 12.92 | 17.09 | 34.19 | 104.18 | 5 |
| 6 | 162 | 214 | 430 | 1280 | | | | 0.01263 | | | 12.79 | 16.96 | 34.05 | 101.35 | 6 |
| 7 | 160 | 214 | 428 | 1268 | | | | 0.01263 | | | 12.65 | 16.96 | 33.92 | 100.41 | 7 |
| 8 | 158 | 213 | 427 | 1246 | | | | 0.01263 | | | 12.52 | 16.83 | 33.78 | 98.66 | 8 |
| 9 | 156 | 211 | 423 | 1222 | | | | 0.01263 | | | 12.38 | 16.69 | 33.52 | 96.78 | 9 |
| 10 | 155 | 209 | 422 | 1219 | | | | 0.01263 | | | 12.25 | 16.56 | 33.38 | 96.51 | 10 |
| 12 | 155 | 206 | 420 | 1180 | | | | 0.01263 | | | 12.25 | 16.29 | 33.25 | 93.41 | 12 |
| 14 | 155 | 206 | 415 | 1168 | | | | 0.01263 | | | 12.25 | 16.29 | 32.84 | 92.47 | 14 |
| 16 | 151 | 202 | 411 | 1137 | | | | 0.01263 | | | 11.98 | 16.02 | 32.57 | 90.05 | 16 |
| 18 | 151 | 202 | 405 | 1125 | | | | 0.01263 | | | 11.98 | 16.02 | 32.03 | 89.11 | 18 |
| 20 | 151 | 202 | 401 | 1114 | | | | 0.01263 | | | 11.98 | 16.02 | 31.77 | 88.16 | 20 |
| 25 | 148 | 197 | 398 | 1066 | | | | 0.01263 | | | 11.71 | 15.61 | 31.50 | 84.39 | 25 |
| 30 | 145 | 197 | 391 | 1063 | | | | 0.01263 | | | 11.44 | 15.61 | 30.96 | 84.13 | 30 |
| 35 | 143 | 194 | 386 | 1034 | | | | 0.01263 | | | 11.31 | 15.34 | 30.55 | 81.84 | 35 |
| 40 | 143 | 190 | 381 | 1017 | | | | 0.01263 | | | 11.31 | 15.08 | 30.15 | 80.49 | 40 |
| 50 | 138 | 189 | 377 | 966 | | | | 0.01263 | | | 10.90 | 14.94 | 29.88 | 76.45 | 50 |
| 60 | 134 | 185 | 371 | 918 | | | | 0.01263 | | | 10.63 | 14.67 | 29.34 | 72.68 | 60 |
| 70 | 131 | 182 | 355 | 867 | | | | 0.01263 | | | 10.36 | 14.40 | 28.13 | 68.65 | 70 |
| 80 | 129 | 177 | 355 | 830 | | | | 0.01263 | | | 10.23 | 14.00 | 28.13 | 65.68 | 80 |
| 90 | 128 | 175 | 357 | 813 | | | | 0.01263 | | | 10.10 | 13.86 | 28.27 | 64.34 | 90 |
| 100 | 128 | 173 | 355 | 800 | | | | 0.01263 | | | 10.10 | 13.73 | 28.13 | 63.33 | 100 |
| 120 | 133 | 172 | 355 | 752 | | | | 0.01263 | | | 10.50 | 13.59 | 28.13 | 59.56 | 120 |
| 140 | 133 | 168 | 345 | 712 | | | | 0.01263 | | | 10.50 | 13.33 | 27.32 | 56.40 | 140 |
| 160 | 126 | 168 | 342 | 674 | | | | 0.01263 | | | 9.96 | 13.33 | 27.05 | 53.39 | 160 |
| 180 | 119 | 168 | 349 | 662 | | | | 0.01263 | | | 9.42 | 13.33 | 27.59 | 52.40 | 180 |
| 200 | 119 | 165 | 338 | 674 | | | | 0.01263 | | | 9.42 | 13.06 | 26.79 | 53.34 | 200 |
| 220 | 122 | 165 | 337 | 677 | | | | 0.01263 | | | 9.69 | 13.06 | 26.65 | 53.59 | 220 |
| 240 | 116 | 170 | 335 | 678 | | | | 0.01263 | | | 9.15 | 13.46 | 26.52 | 53.68 | 240 |

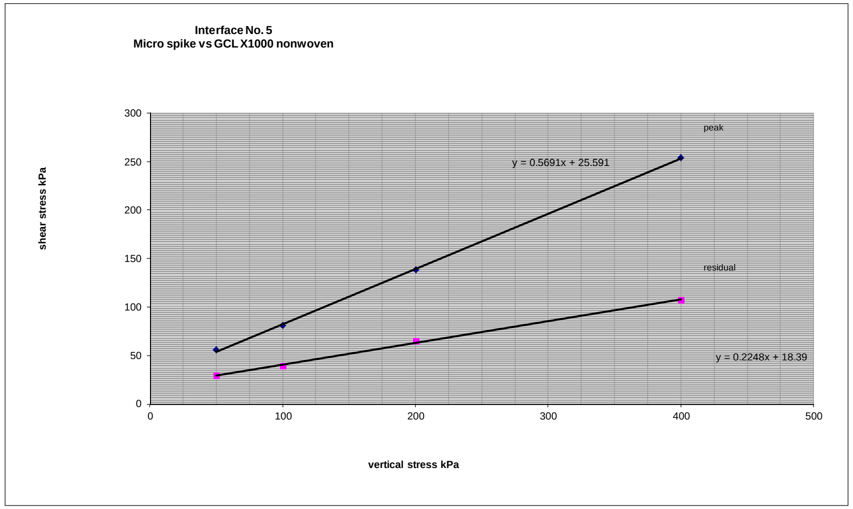


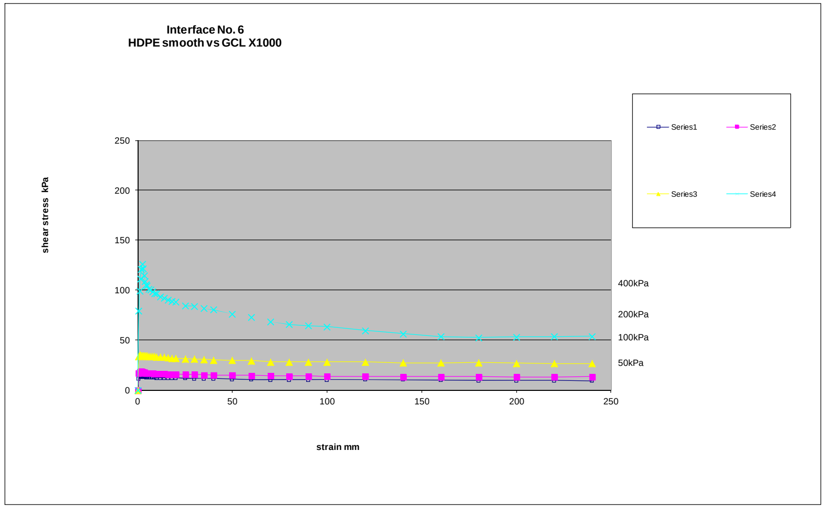



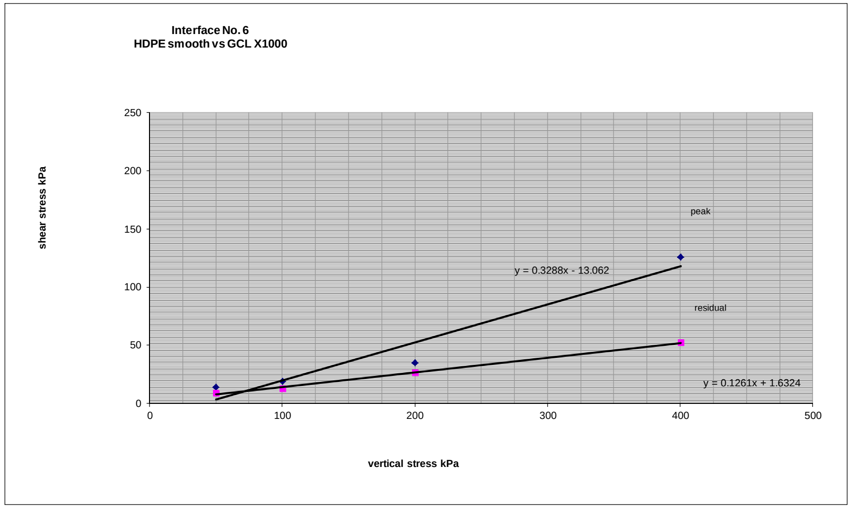

Peak Friction Angle (δ) = 18.20 deg    Peak Cohesion (c) = 0.00 kPa

Residual Friction Angle (δ) = 7.19 deg    Residual Cohesion (c) = 0.00 kPa


Interface No. 5
Micro spike vs GCL X1000 nonwoven
shear stress kPa
strain mm
Series1
Series2
Series3
Series4
400kPa
200kPa
100kPa
50kPa


Interface No. 5
Micro spike vs GCL X1000 nonwoven
shear stress kPa
vertical stress kPa
peak
y = 0.5691x + 25.591
residual
y = 0.2248x + 18.39


Interface No. 6
HDPE smooth vs GCL X1000
shear stress kPa
strain mm
Series1
Series2
Series3
Series4
400kPa
200kPa
100kPa
50kPa

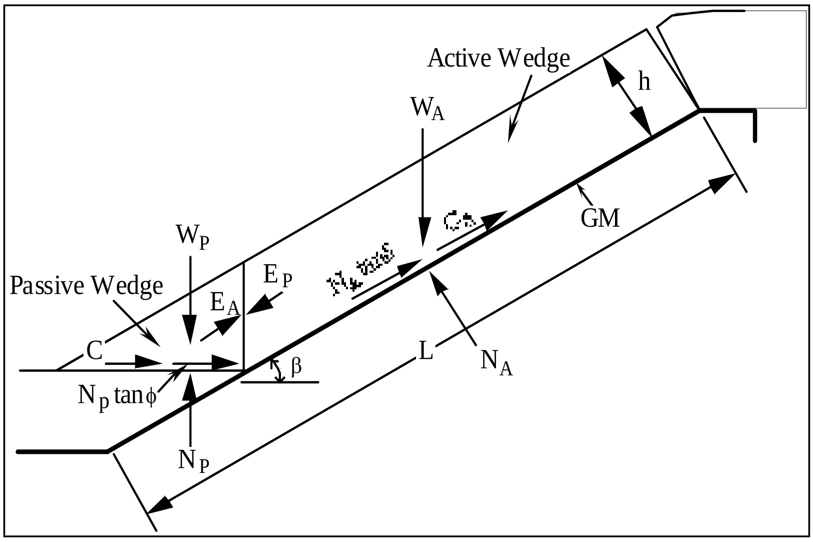

Interface No. 6
HDPE smooth vs GCL X1000
shear stress kPa
vertical stress kPa
peak
y = 0.3288x - 13.062
residual
y = 0.1261x + 1.6324

## C.2. Configuration No. 1 Factors of Safety

## Cover Soil Stability Analysis Worksheet for Configuration No. 1

### Uniform Cover Soil Thickness

**Configuration No. 1 SLOPE 1:4**




**Calculation of FS**

Active Wedge:

*Wa= 212.7 kN*

*Na= 206.3 kN*

Passive Wedge:

*Wp= 2.8 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 12.1*

*b= -74*

*c= 10.3*

**FS= 5.91**

| | | | | |
|---|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | | |
| soil slope angle beneath the geomembrane = β = | 14.0 | ° | *= 0.25 (rad.)* | |
| length of slope measured along the geomembrane = L = | 41.0 | m | | |
| unit weight of the cover soil and stone layer = γ = | 21.3 | kN/m^3 | *for stabilised sand* | |
| friction angle of the cover soil = ϕ = | 30.0 | ° | *= 0.52 (rad.)* | |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | *C= 0* | *kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* | |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | *Ca= 231.82* | *kN* |

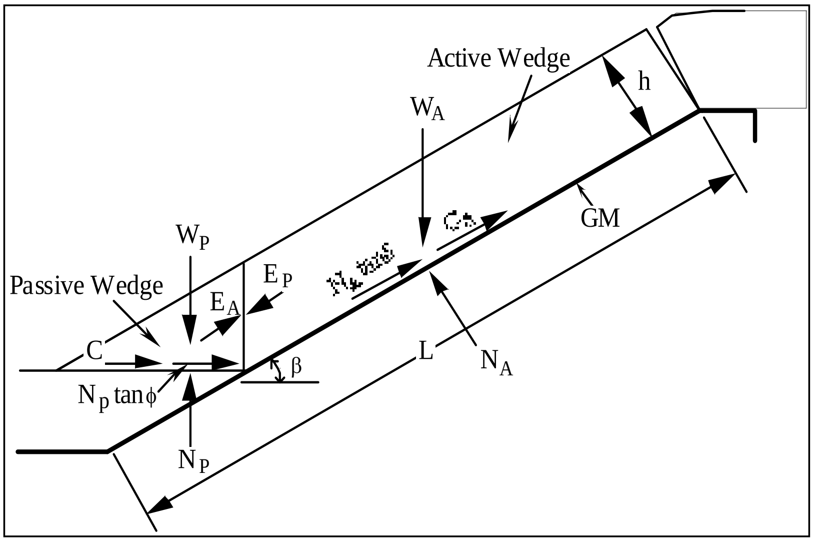
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 1

### Uniform Cover Soil Thickness

**Configuration No. 1 SLOPE 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 166.0 kN*

*Na= 157.5 kN*

Passive Wedge:

*Wp= 2.2 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 15.7*

*b= -74*

*c= 13.6*

***FS= 4.52***

| | | | | |
|---|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* | |
| length of slope measured along the geomembrane = L = | 32.0 | m | | |
| unit weight of the cover soil = γ = | 21.3 | kN/m^3 | *for stabilised sand* | |
| friction angle of the cover soil = ϕ = | 30.0 | ° | *= 0.52 (rad.)* | |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | | *C= 0 kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* | |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | | *Ca= 181.01 kN* |

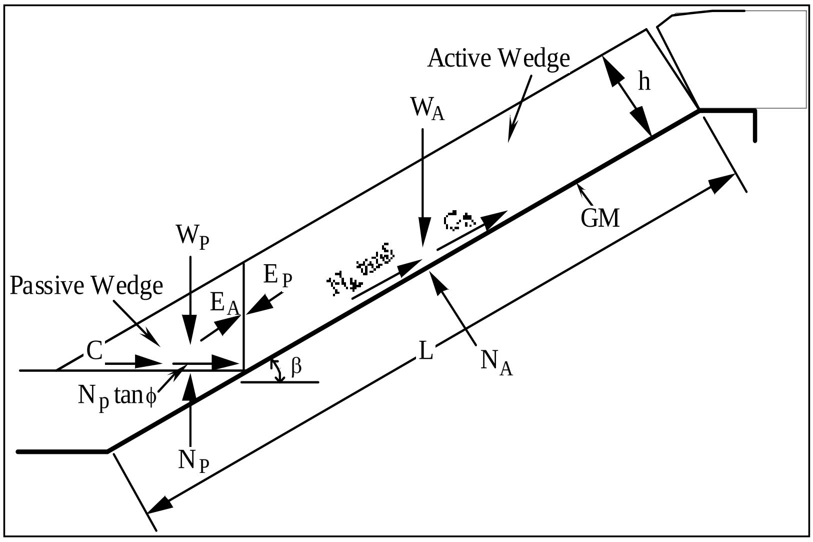
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 1

### Uniform Cover Soil Thickness

**Configuration No. 1 SLOPE 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 113.8 kN*

*Na= 101.8 kN*

Passive Wedge:

*Wp= 1.7 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 20.4*

*b= -70*

*c= 18.4*

***FS= 3.16***

| | | | |
|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the cover soil = γ = | 21.3 | kN/m^3 | *for stabilised sand* |
| friction angle of the cover soil = φ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | *Ca= 124.36 kN* |

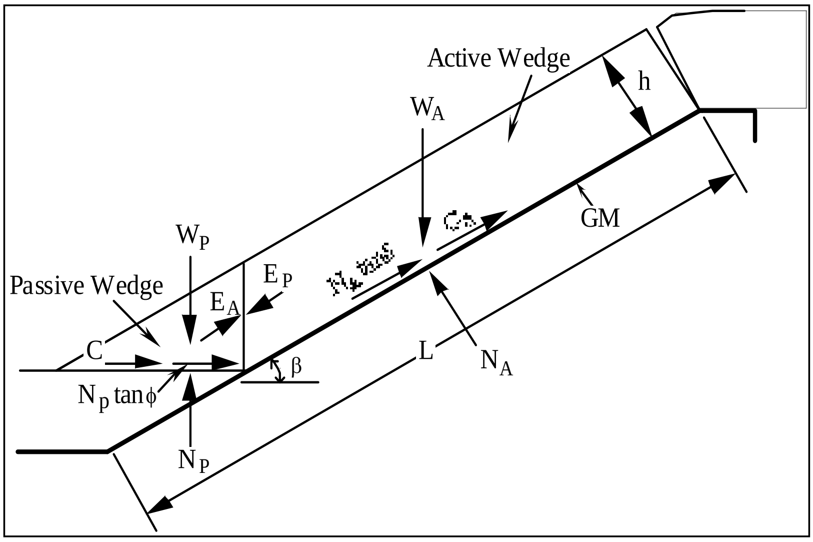
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 1

### Uniform Cover Soil Thickness

**Configuration No. 1 SLOPE 1:1**




**Calculation of FS**

Active Wedge:

*Wa= 72.0 kN*

*Na= 50.9 kN*

Passive Wedge:

*Wp= 1.3 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 25.5*

*b= -64*

*c= 27.9*

***FS= 1.93***

| | | | |
|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | |
| soil slope angle beneath the geomembrane = β = | 45.0 | ° | *= 0.79 (rad.)* |
| length of slope measured along the geomembrane = L = | 14.0 | m | |
| unit weight of the cover soil = γ = | 21.3 | kN/m^3 | *for stabilised sand* |
| friction angle of the cover soil = φ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | *Ca= 79.149 kN* |

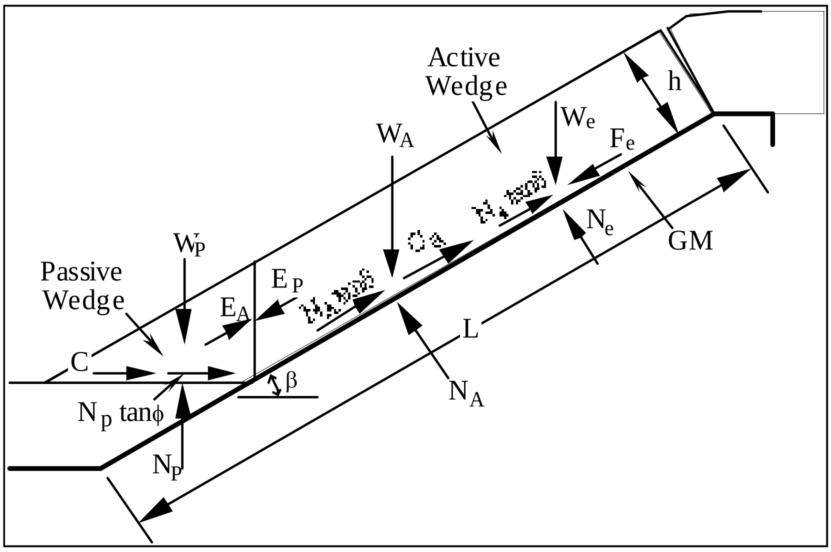
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 1

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Configuration No. No. 1 SLOPE 1:4**




**Calculation of FS**

Active Wedge:

*Wa= 212.7 kN*

*Na= 206.3 kN*

Passive Wedge:

*Wp= 2.8 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 70.4*

*b= -334*

*c= 46.5*

***FS= 4.61***

| | | | |
|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | |
| soil slope angle beneath the geomembrane = β = | 14.0 | ° | *= 0.24 (rad.)* |
| finished cover soil slope angle = ω = | 14.0 | ° | *= 0.24 (rad.)* |
| length of slope measured along the geomembrane = L = | 41.0 | m | |
| unit weight of the cover soil = γ = | 21.3 | kN/m^3 | |
| friction angle of the cover soil = ϕ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | *Ca= 232 kN* |
| thickness of cover soil = h = | 0.25 | m | *b/h= 2.4* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 84.7* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| $^{2}$ 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| $^{3}$ 1000 mm | 0.95 | 0.75 | 0.30 |

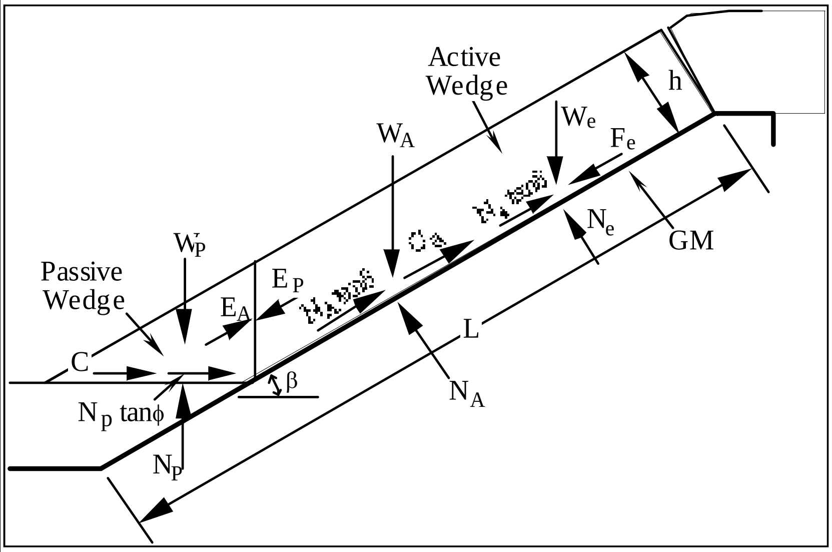
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 1

### Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)

**Configuration No. No. 1 SLOPE 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 166.0 kN*

*Na= 157.5 kN*

Passive Wedge:

*Wp= 2.2 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 76.0*

*b= -267*

*c= 48.2*

***FS= 3.32***

| | | | |
|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* |
| finished cover soil slope angle = ω = | 18.4 | ° | *= 0.32 (rad.)* |
| length of slope measured along the geomembrane = L = | 32.0 | m | |
| unit weight of the cover soil = γ = | 21.3 | kN/m^3 | |
| friction angle of the cover soil = φ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | *Ca= 181 kN* |

| | | | |
|---|---|---|---|
| thickness of cover soil = h = | 0.25 | m | *b/h= 2.4* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 82.8* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ≤ 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ≥ 1000 mm | 0.95 | 0.75 | 0.30 |

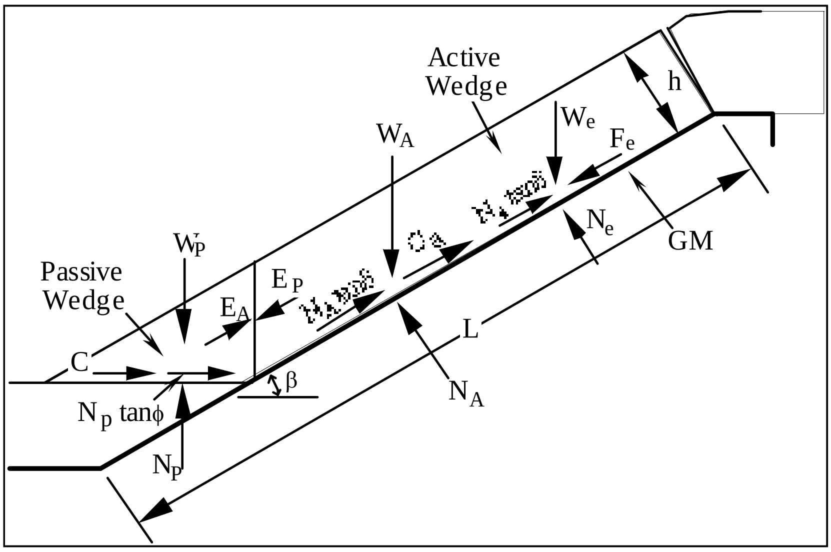
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 1

### Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)

**Configuration No. 1 SLOPE 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 113.8 kN*

*Na= 101.8 kN*

Passive Wedge:

*Wp= 1.7 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 80.5*

*b= -191*

*c= 48.2*

***FS= 2.09***

| | | | |
|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| finished cover soil slope angle = ω = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the cover soil = γ = | 21.3 | kN/m^3 | |
| friction angle of the cover soil = ϕ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | *Ca= 124 kN* |
| thickness of cover soil = h = | 0.25 | m | *b/h= 2.4* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 78.1* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| $^{2}$ 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| $^{3}$ 1000 mm | 0.95 | 0.75 | 0.30 |

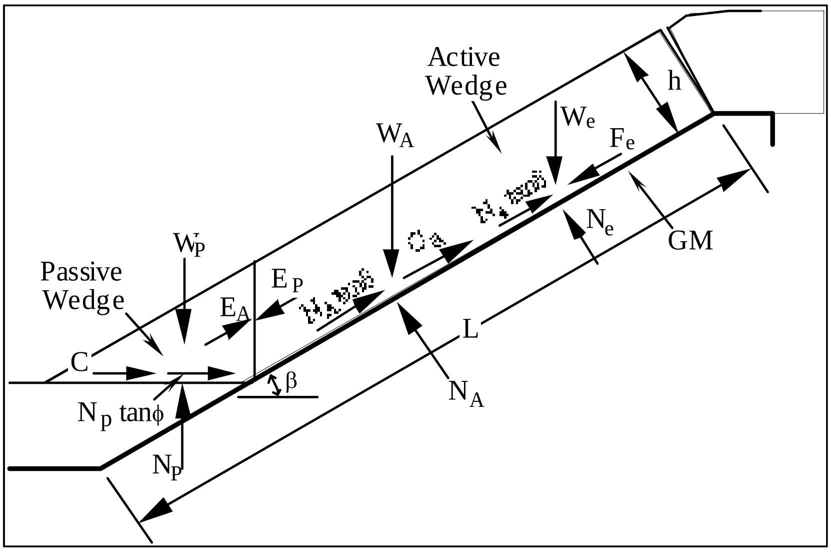
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 1

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Configuration No. 1 SLOPE 1:1**




**Calculation of FS**

Active Wedge:

*Wa= 72.0 kN*

*Na= 50.9 kN*

Passive Wedge:

*Wp= 1.3 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 79.7*

*b= -130*

*c= 48.2*

***FS= 1.07***

| | | | |
|---|---|---|---|
| thickness of cover soil and stone layer = h = | 0.25 | m | |
| soil slope angle beneath the geomembrane = β = | 45.0 | ° | *= 0.79 (rad.)* |
| finished cover soil slope angle = ω = | 45.0 | ° | *= 0.79 (rad.)* |
| length of slope measured along the geomembrane = L = | 14.0 | m | |
| unit weight of the cover soil = γ = | 21.3 | kN/m^3 | |
| friction angle of the cover soil = φ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the cover soil = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between cover soil and geomembrane = δ = | 19.1 | ° | *= 0.33 (rad.)* |
| adhesion between cover soil and geomembrane = ca = | 5.8 | kN/m^2 | *Ca= 79.1 kN* |
| thickness of cover soil = h = | 0.25 | m | *b/h= 2.4* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=We cos β= 61.7* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ² 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ³ 1000 mm | 0.95 | 0.75 | 0.30 |

Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## C.3. Factors of Safety for HDPE Geomembrane Integrity

**Integrity of HDPE Geomembrane**

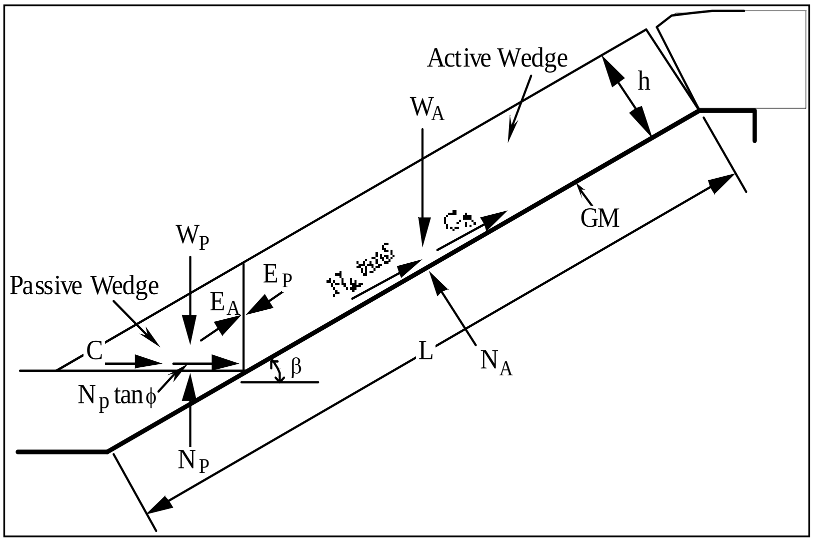
| | 1:4 Slope | | | 1:3 Slope | | | Comments |
|---|---|---|---|---|---|---|---|
| Thickness | = | 2 | mm | = | 2 | mm | Data sheet |
| Density | = | 942 | kg/m$^3$ | = | 942 | kg/m$^2$ | Data sheet |
| Mass of 1m strip | = | 41*1*0.002*942 | | = | 32*1*0.002*942 | | |
| | = | 77.24 | kg | = | 60.29 | kg | |
| Weight of 1m strip | = | 77.24 * 9.81 / 1000 | | = | 60.29 * 9.81 / 1000 | | |
| | = | 0.76 | kN/m | = | 0.59 | kN/m | |
| Tensile strength at yield | = | 33 | kN/m | = | 33 | kN/m | Data sheet |
| Factor of Safety | = | 33 / 0.76 | | = | 33 / 0.59 | | |
| | = | **43.55** | | = | **55.80** | | |

## C.4. Configuration No. 2 Factors of Safety

## Cover Soil Stability Analysis Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness

**Configuration No. 2 SLOPE 1:4**




**Calculation of FS**

Active Wedge:

*Wa= 139.3 kN*

*Na= 135.1 kN*

Passive Wedge:

*Wp= 1.1 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 8.0*

*b= -13*

*c= 2.3*

***FS= 1.39***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 14.0 | ° | *= 0.25 (rad.)* |
| length of slope measured along the geomembrane = L = | 41.0 | m | |
| unit weight of the stone layer= γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = ϕ= | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ= | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |

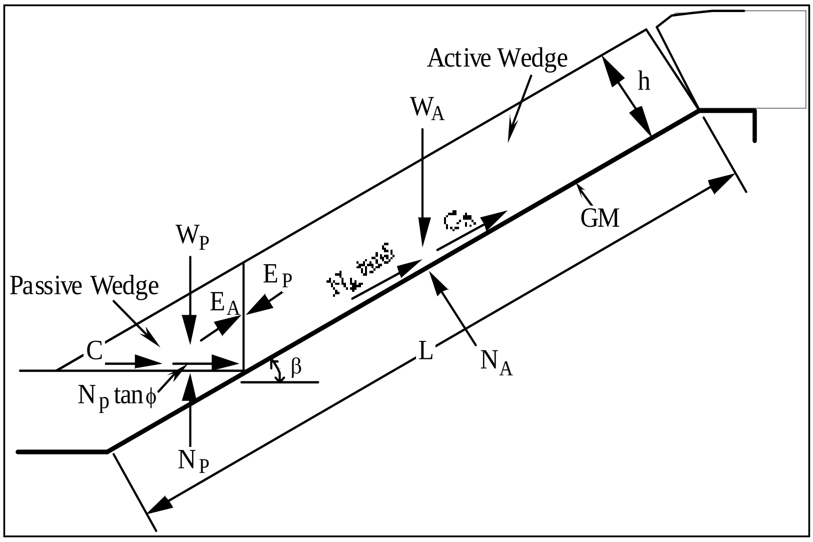
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness

**Configuration No. 2 SLOPE 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 108.7 kN*

*Na= 103.1 kN*

Passive Wedge:

*Wp= 0.9 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 10.3*

*b= -14*

*c= 2.9*

***FS= 1.05***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* |
| length of slope measured along the geomembrane = L = | 32.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = ϕ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |

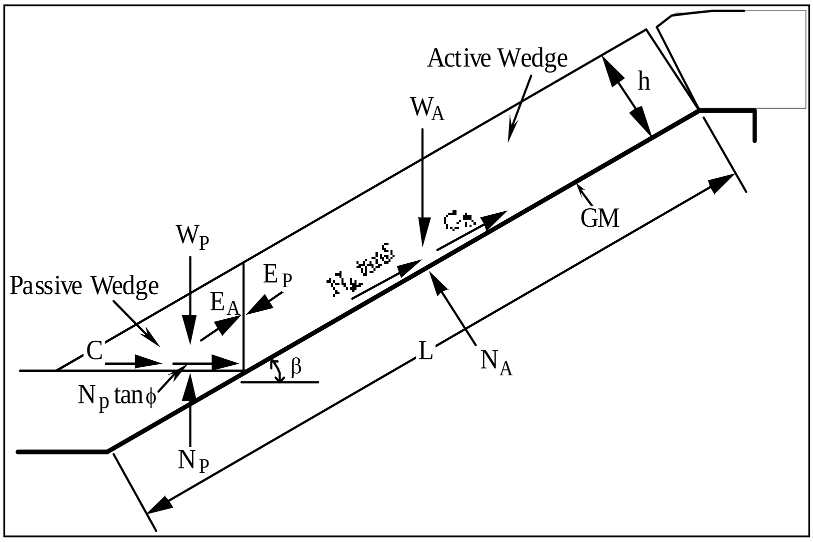
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness

**Configuration No. 2 SLOPE 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 74.6 kN*

*Na= 66.7 kN*

Passive Wedge:

*Wp= 0.6 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 13.4*

*b= -15*

*c= 3.8*

***FS= 0.72***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = ϕ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |

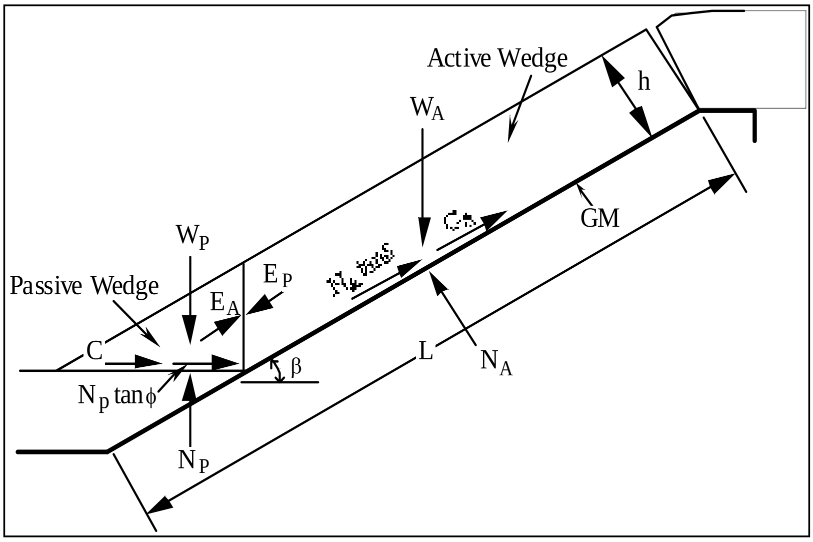
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness

**Configuration No. 2 SLOPE 1:1**




**Calculation of FS**

Active Wedge:

*Wa= 47.3 kN*

*Na= 33.5 kN*

Passive Wedge:

*Wp= 0.5 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 16.7*

*b= -20*

*c= 4.8*

***FS= 0.87***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 45.0 | ° | *= 0.79 (rad.)* |
| length of slope measured along the geomembrane = L = | 14.0 | m | |
| unit weight of the stone layer= γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = φ= | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ= | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |

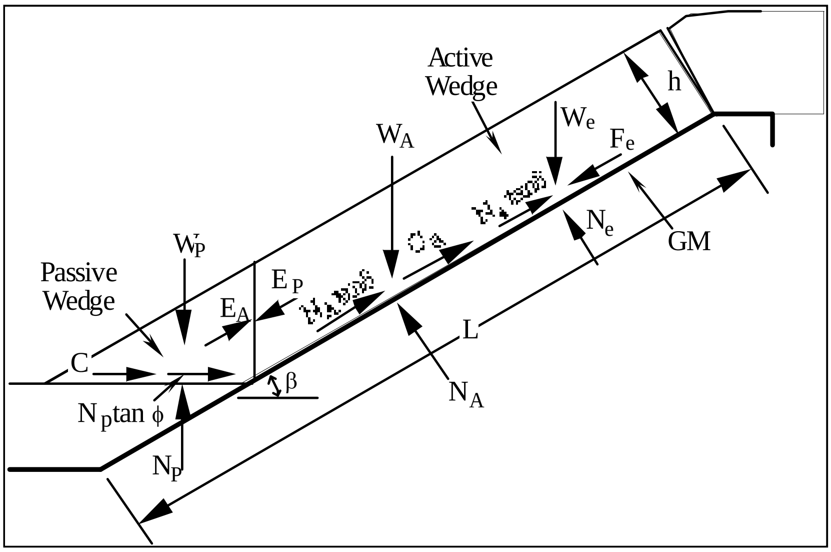
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 2

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Configuration No. 2 SLOPE 1:4**




**Calculation of FS**

Active Wedge:

*Wa= 139.2 kN*

*Na= 135.1 kN*

Passive Wedge:

*Wp= 1.1 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 53.2*

*b= -84*

*c= 15.1*

***FS= 1.38***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 14.0 | ° | *= 0.24 (rad.)* |
| finished stone layer slope angle = ω = | 14.0 | ° | *= 0.24 (rad.)* |
| length of slope measured along the geomembrane = L = | 41.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | *b/h= 4.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 84.7* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ≤ 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ≥ 1000 mm | 0.95 | 0.75 | 0.30 |

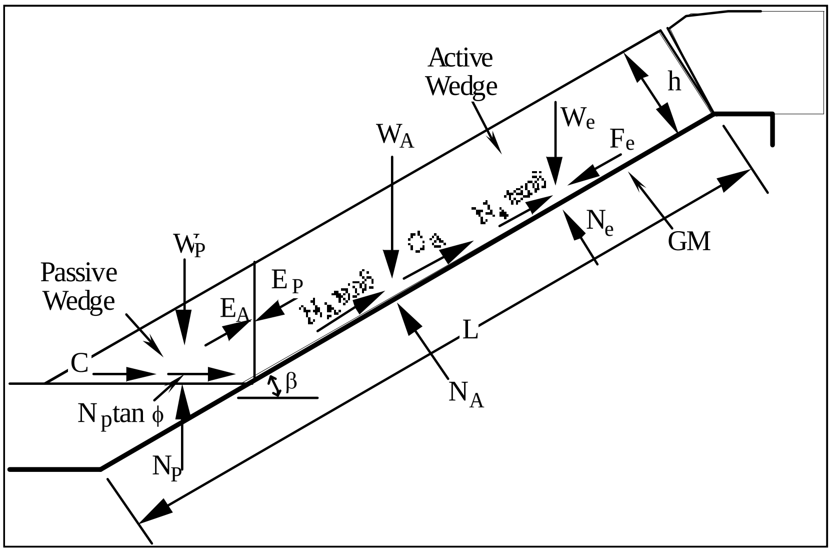
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 2

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Configuration No. 2 SLOPE 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 108.7 kN*

*Na= 103.1 kN*

Passive Wedge:

*Wp= 0.9 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 58.8*

*b= -77*

*c= 16.7*

***FS= 1.03***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* |
| finished stone layer slope angle = ω = | 18.4 | ° | *= 0.32 (rad.)* |
| length of slope measured along the geomembrane = L = | 32.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |
| thickness of stone layer = h = | 0.15 | m | *b/h= 4.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 82.8* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ≤ 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ≥ 1000 mm | 0.95 | 0.75 | 0.30 |

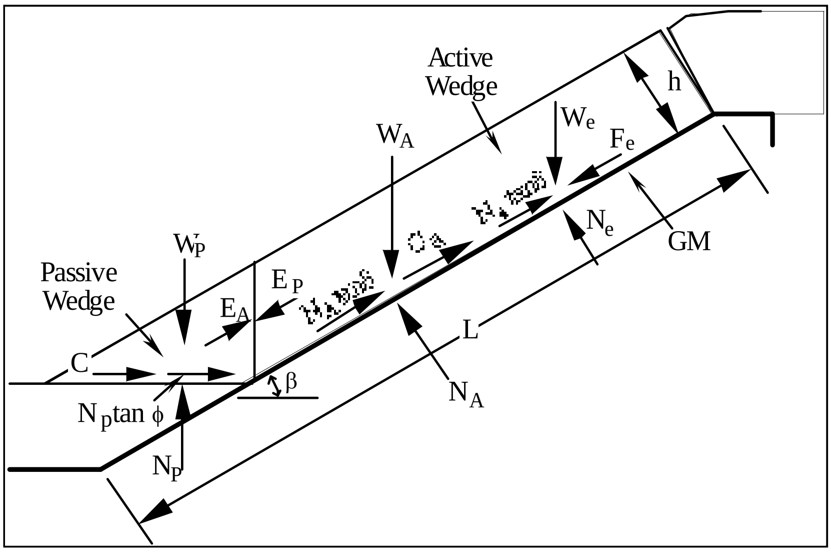
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

# Cover Soil Stability Worksheet for Configuration No. 2

## Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)

**Configuration No. 2 SLOPE 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 74.6 kN*

*Na= 66.7 kN*

Passive Wedge:

*Wp= 0.6 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 64.8*

*b= -72*

*c= 18.4*

***FS= 0.70***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| finished stone layer slope angle = ω = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | *b/h= 4.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 78.1* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ² 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ³ 1000 mm | 0.95 | 0.75 | 0.30 |

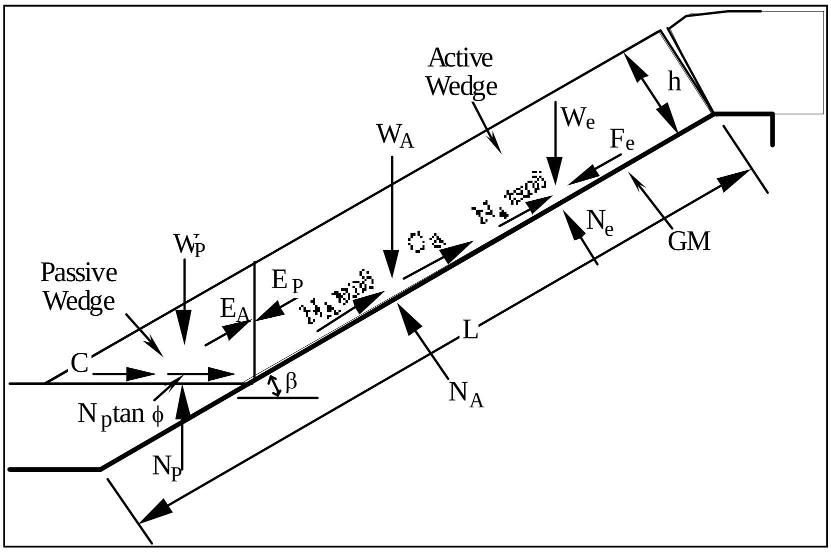
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)

**Configuration No. 2 SLOPE 1:1**




**Calculation of FS**

Active Wedge:

*Wa= 43.8 kN*

*Na= 31.0 kN*

Passive Wedge:

*Wp= 0.5 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 65.6*

*b= -60*

*c= 12.8*

***FS= 0.59***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 45.0 | ° | *= 0.79 (rad.)* |
| finished stone layer slope angle = ω = | 45.0 | ° | *= 0.79 (rad.)* |
| length of slope measured along the geomembrane = L = | 14.0 | m | |
| unit weight of the stone layer = γ = | 21.3 | kN/m^3 | |
| friction angle of the stone layer = φ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | *b/h= 4.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 61.7* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ² 300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ³ 1000 mm | 0.95 | 0.75 | 0.30 |

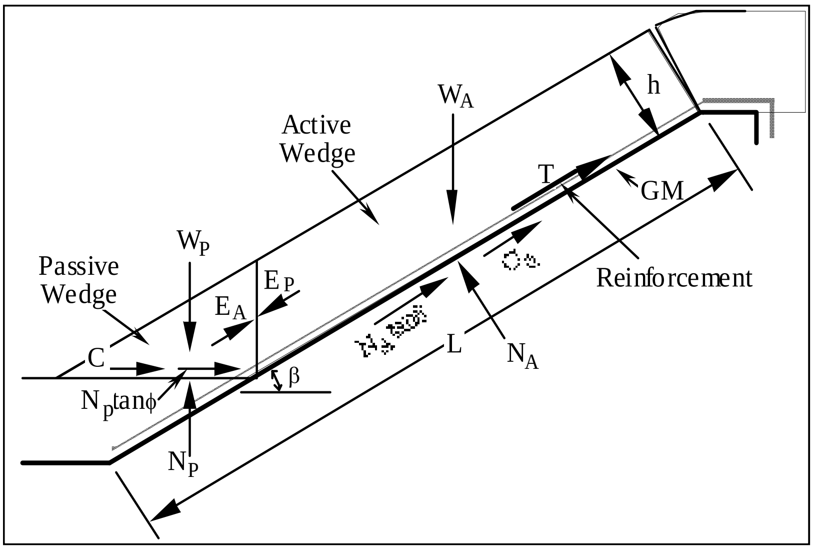
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness with Veneer Reinforcement

**Configuration No. 2 SLOPE 1:4**




**Calculation of FS**

Active Wedge:

*Wa= 139.2 kN*

*Na= 135.1 kN*

Passive Wedge:

*Wp= 1.1 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 6.4*

*b= -12*

*c= 2.2*

***FS= 1.72***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 14.0 | ° | *= 0.24 (rad.)* |
| length of slope measured along the geomembrane = L = | 41.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = ϕ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |
| ultimate (manufactured) value of reinforcement strength = Tult = | 26.0 | kN/m | |
| partial FS for installation damage = (FS)ID = | 1.3 | | |
| partial FS for creep = (FS)CR = | 2.4 | | |
| partial FS for chemical/biological degradation = (FS)CBD = | 1.3 | | *Tallow= 6.5 kN/m* |
| partial FS for seams = (FS)SM = | 1.0 | | |

Note: numbers in boxes are input values

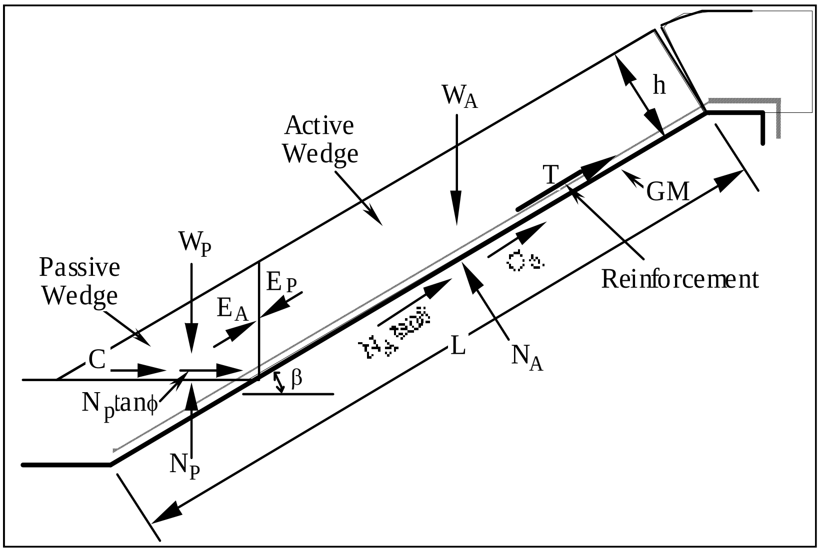
*numbers in Italics are calculated values*

Please note that Tult = LTDS for 120 years for the Rock Grid PC Reinforcement.
The Technical Data Sheet for the Rock Grid PC Reinforcement is attached in Annexure A.

## Cover Soil Stability Analysis Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness with Veneer Reinforcement

**Configuration No. 2 SLOPE 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 108.7 kN*

*Na= 103.1 kN*

Passive Wedge:

*Wp= 0.9 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 6.4*

*b= -12*

*c= 2.9*

***FS= 1.68***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* |
| length of slope measured along the geomembrane = L = | 32.0 | m | |
| unit weight of the stone layer= γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |
| ultimate (manufactured) value of reinforcement strength = Tult = | 52.0 | kN/m | |
| partial FS for installation damage = (FS)ID = | 1.3 | | |
| partial FS for creep = (FS)CR = | 2.4 | | |
| partial FS for chemical/biological degradation = (FS)CBD = | 1.3 | | *Tallow= 13.0 kN/m* |
| partial FS for seams = (FS)SM = | 1.0 | | |

Note: numbers in boxes are input values

*numbers in Italics are calculated values*

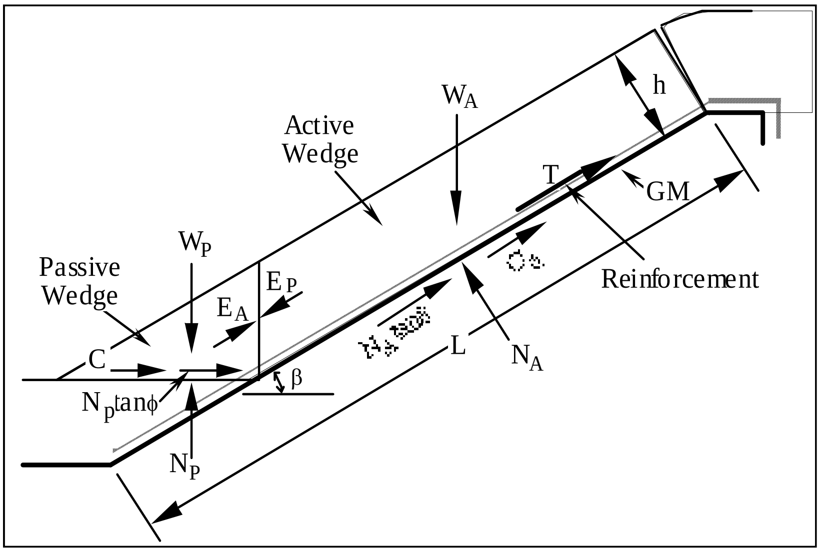
Please note that Tult = LTDS for 120 years for the Rock Grid PC Reinforcement.

The Technical Data Sheet for the Rock Grid PC Reinforcement is attached in Annexure A.

## Cover Soil Stability Analysis Worksheet for Configuration No. 2

### Uniform Cover Soil Thickness with Veneer Reinforcement

**Configuration No. 2 SLOPE 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 74.6 kN*

*Na= 66.7 kN*

Passive Wedge:

*Wp= 0.6 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 2.8*

*b= -10*

*c= 3.8*

***FS= 3.30***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the stone layer= γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |
| ultimate (manufactured) value of reinforcement strength = Tult = | 105.0 | kN/m | |
| partial FS for installation damage = (FS)ID = | 1.3 | | |
| partial FS for creep = (FS)CR = | 2.4 | | |
| partial FS for chemical/biological degradation = (FS)CBD = | 1.3 | | *Tallow= 26.3 kN/m* |
| partial FS for seams = (FS)SM = | 1.0 | | |

Note: numbers in boxes are input values

*numbers in Italics are calculated values*

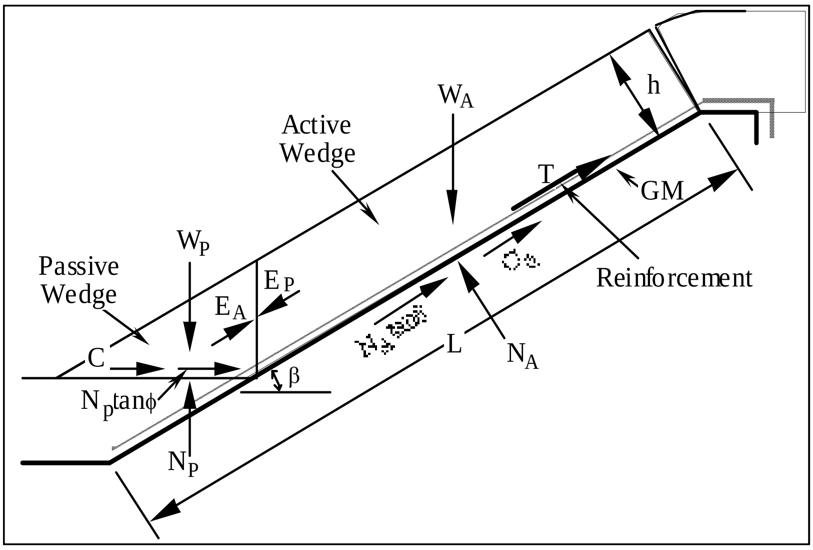
Please note that Tult = LTDS for 120 years for the Rock Grid PC Reinforcement.

The Technical Data Sheet for the Rock Grid PC Reinforcement is attached in Annexure A.

**Cover Soil Stability Analysis Worksheet for Configuration No. 2**

**Uniform Cover Soil Thickness with Veneer Reinforcement**

**Configuration No. 2 SLOPE 1:1**




**Calculation of FS**

Active Wedge:

*Wa= 47.3 kN*

*Na= 33.5 kN*

Passive Wedge:

*Wp= 0.5 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 3.6*

*b= -9*

*c= 4.8*

***FS= 1.75***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 45.0 | ° | *= 0.79 (rad.)* |
| length of slope measured along the geomembrane = L = | 14.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = ϕ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 18.7 | ° | *= 0.33 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 0.0 | kN/m^2 | *Ca= 0 kN* |
| ultimate (manufactured) value of reinforcement strength = Tult = | 105.0 | kN/m | |
| partial FS for installation damage = (FS)ID = | 1.3 | | |
| partial FS for creep = (FS)CR = | 2.4 | | |
| partial FS for chemical/biological degradation = (FS)CBD = | 1.3 | | *Tallow= 26.3 kN/m* |
| partial FS for seams = (FS)SM = | 1.0 | | |

Note: numbers in boxes are input values

*numbers in Italics are calculated values*

Please note that Tult = LTDS for 120 years for the Rock Grid PC Reinforcement.

The Technical Data Sheet for the Rock Grid PC Reinforcement is attached in Annexure A.

## C.5. Factors of Safety for GCL, Protection Geotextile and Veneer Reinforcement Integrity

**Integrity of GCL X1000**

| | 1:4 Slope | | 1:3 Slope | | 1:2 Slope | | 1:1 Slope | | Comments |
|---|---|---|---|---|---|---|---|---|---|
| Mass per unit area | = 4310 | $g/m^2$ | = 4310 | $g/m^2$ | = 4310 | $g/m^2$ | = 4310 | $g/m^2$ | Data sheet |
| Mass of 1m strip | = 41*1*4.310 | | = 32*1*4.310 | | = 22*1*4.310 | | = 14*1*4.310 | | |
| | = 176.71 | kg | = 137.92 | kg | = 94.82 | kg | = 60.34 | kg | |
| Weight of 1m strip | = 176.71 * 9.81 / 1000 | | = 137.92 * 9.81 / 1000 | | = 137.92 * 9.81 / 1000 | | = 137.92 * 9.81 / 1000 | | |
| | = 1.73 | kN/m | = 1.35 | kN/m | = 0.93 | kN/m | = 0.59 | kN/m | |
| Tensile strength at yield | = 8.38 | kN/m | = 8.38 | kN/m | = 8.38 | kN/m | = 8.38 | kN/m | Data sheet |
| Factor of Safety | = 33 / 1.73 | | = 33 / 1.35 | | = 33 / 1.35 | | = 33 / 1.35 | | |
| | = **4.83** | | = **6.19** | | = **9.01** | | = **14.16** | | |

**Integrity of Protection Geotextile A10**

| | 1:4 Slope | | 1:3 Slope | | 1:2 Slope | | 1:1 Slope | | Comments |
|---|---|---|---|---|---|---|---|---|---|
| Mass per unit area | = 1000 | $g/m^2$ | = 1000 | $g/m^2$ | = 1000 | $g/m^2$ | = 1000 | $g/m^2$ | Data sheet |
| Mass of 1m strip | = 41*1*1 | | = 32*1*1 | | = 22*1*1 | | = 14*1*1 | | |
| | = 41.00 | kg | = 32.00 | kg | = 22.00 | kg | = 14.00 | kg | |
| Weight of 1m strip | = 41 * 9.81 / 1000 | | = 32 * 9.81 / 1000 | | = 22 * 9.81 / 1000 | | = 14 * 9.81 / 1000 | | |
| | = 0.40 | kN/m | = 0.31 | kN/m | = 0.22 | kN/m | = 0.14 | kN/m | |
| Tensile strength at yield | = 76 | kN/m | = 76 | kN/m | = 76 | kN/m | = 76 | kN/m | Data sheet |
| Factor of Safety | = 76 / 0.40 | | = 76 / 0.31 | | = 76 / 0.22 | | = 76 / 0.14 | | |
| | = **188.96** | | = **242.10** | | = **352.15** | | = **553.37** | | |

**Integrity of Veneer Reinforcement - (Tensile Strength Varies)**

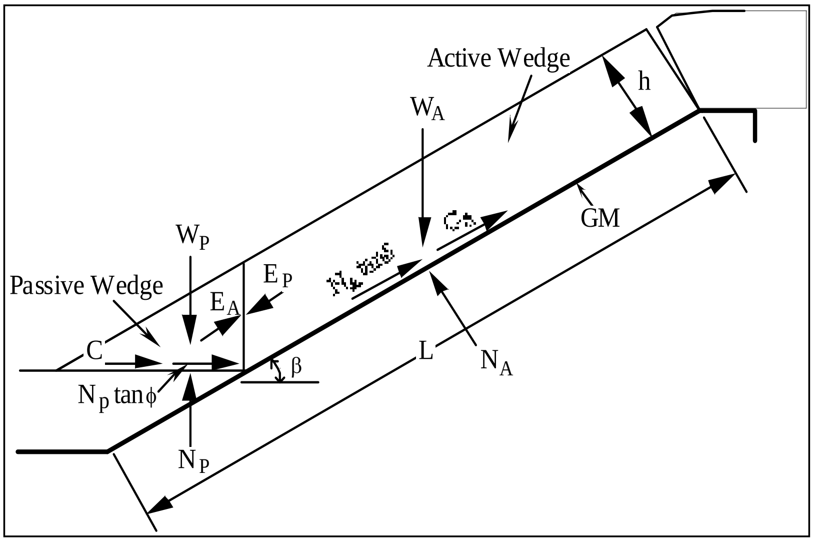
| | 1:4 Slope (50/50) | | 1:3 Slope (100/100) | | 1:2 Slope (200/200) | | 1:1 Slope (200/200) | | Comments |
|---|---|---|---|---|---|---|---|---|---|
| Mass per unit area | = 150 | $g/m^2$ | = 150 | $g/m^2$ | = 150 | $g/m^2$ | = 150 | $g/m^2$ | Data sheet |
| Mass of 1m strip | = 41*1*0.15 | | = 32*1*0.15 | | = 22*1*0.15 | | = 14*1*0.15 | | |
| | = 6.15 | kg | = 4.80 | kg | = 3.30 | kg | = 2.10 | kg | |
| Weight of 1m strip | = 6.15 * 9.81 / 1000 | | = 4.80 * 9.81 / 1000 | | = 3.30 * 9.81 / 1000 | | = 2.10 * 9.81 / 1000 | | |
| | = 0.06 | kN/m | = 0.05 | kN/m | = 0.03 | kN/m | = 0.02 | kN/m | |
| Tensile strength at yield | = 26 | kN/m | = 52 | kN/m | = 105 | kN/m | = 105 | kN/m | Data sheet |
| Factor of Safety | = 76 / 0.40 | | = 76 / 0.31 | | = 76 / 0.22 | | = 76 / 0.14 | | |
| | = **430.95** | | = **1104.32** | | = **3243.44** | | = **5096.84** | | |

## C.6. Configuration No. 3 Factors of Safety

## Cover Soil Stability Analysis Worksheet for Configuration No. 3

### Uniform Cover Soil Thickness

**Configuration No. 3 SLOPE 1:4**




**Calculation of FS**

Active Wedge:

*Wa= 139.3 kN*

*Na= 135.1 kN*

Passive Wedge:

*Wp= 1.1 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 8.0*

*b= -322*

*c= 67.2*

***FS= 40.30***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = $\beta$ = | 14.0 | ° | *= 0.25 (rad.)* |
| length of slope measured along the geomembrane = L = | 41.0 | m | |
| unit weight of the stone layer = $\gamma$ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = $\phi$ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = $\delta$ = | 23.2 | ° | *= 0.40 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 32.3 | kN/m^2 | *Ca= 1302.7 kN* |

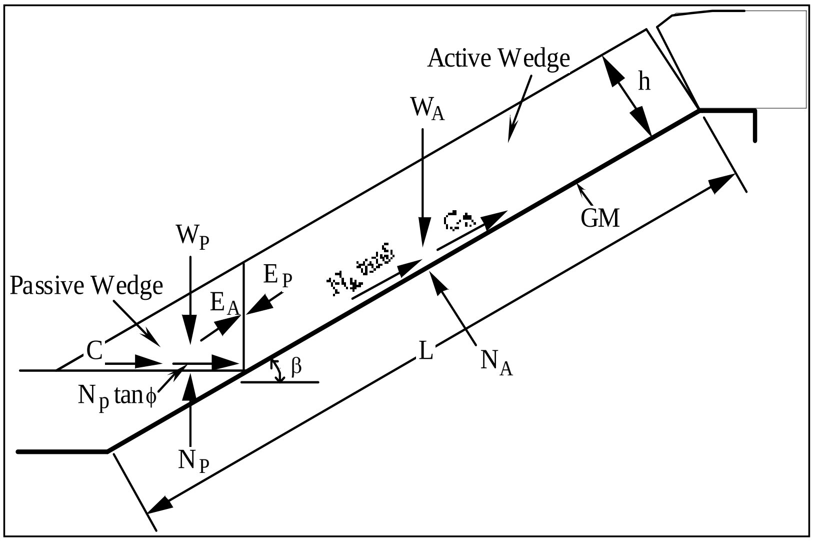
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 3

### Uniform Cover Soil Thickness

**Configuration No. 3 SLOPE 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 108.7 kN*

*Na= 103.1 kN*

Passive Wedge:

*Wp= 0.9 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 10.3*

*b= -321*

*c= 89.0*

***FS= 30.91***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* |
| length of slope measured along the geomembrane = L = | 32.0 | m | |
| unit weight of the stone layer= γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 23.2 | ° | *= 0.40 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 32.3 | kN/m^2 | *Ca= 1017 kN* |

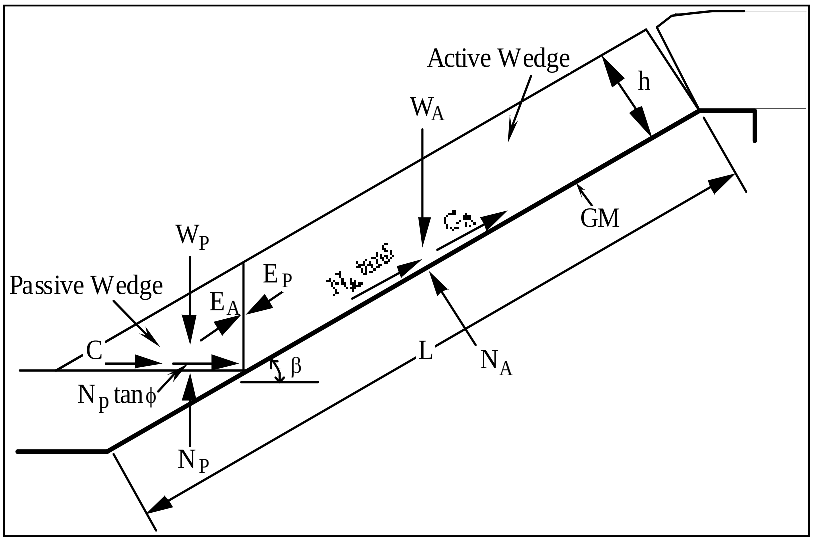
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 3

### Uniform Cover Soil Thickness

**Configuration No. 3 SLOPE 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 74.6 kN*

*Na= 66.7 kN*

Passive Wedge:

*Wp= 0.6 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 13.4*

*b= -297*

*c= 122.1*

***FS= 21.82***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = ϕ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 23.2 | ° | *= 0.40 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 32.3 | kN/m^2 | *Ca= 698.9 kN* |

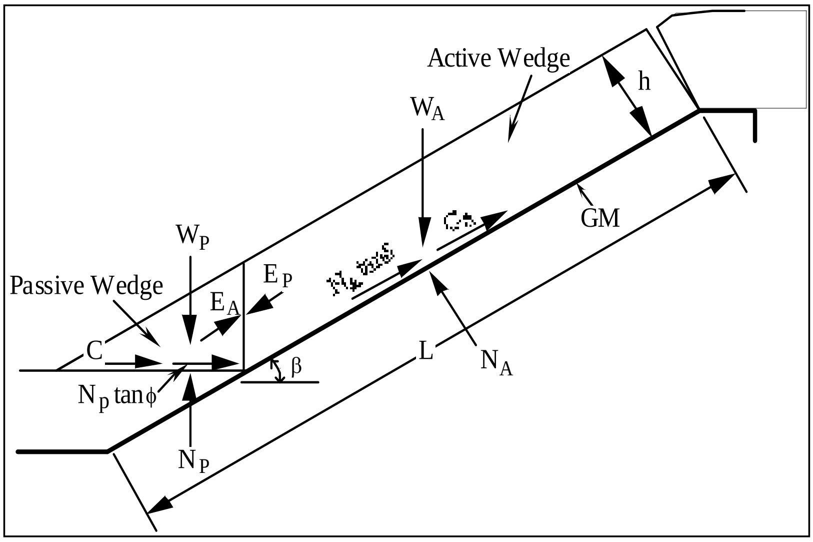
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Configuration No. 3

### Uniform Cover Soil Thickness

**Configuration No. 3 SLOPE 1:1**




**Calculation of FS**

Active Wedge:

*Wa= 47.3 kN*

*Na= 33.5 kN*

Passive Wedge:

*Wp= 0.5 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 16.7*

*b= -244*

*c= 192.6*

***FS= 13.74***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 45.0 | ° | *= 0.79 (rad.)* |
| length of slope measured along the geomembrane = L = | 14.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 23.2 | ° | *= 0.40 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 32.3 | kN/m^2 | *Ca= 444.8 kN* |

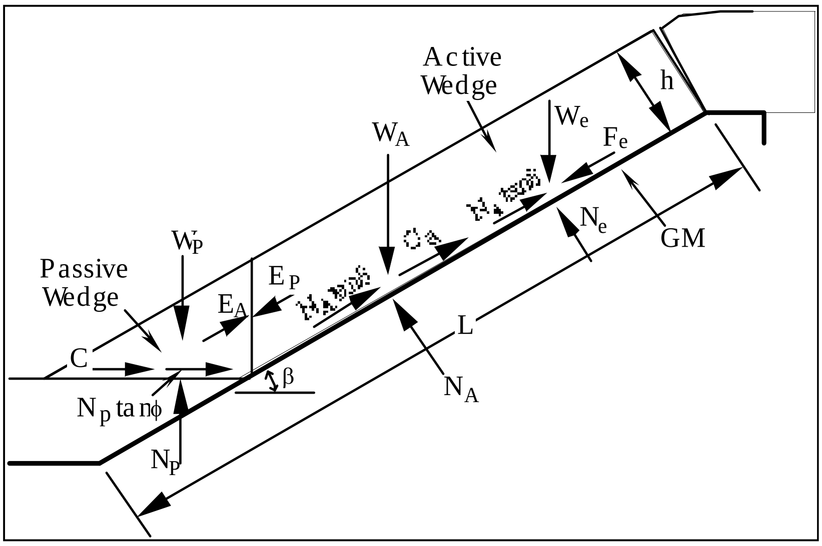
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 3

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Configuration No. 3 SLOPE 1:4**




**Calculation of FS**

Active Wedge:

*Wa= 139.2 kN*

*Na= 135.1 kN*

Passive Wedge:

*Wp= 1.1 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 53.2*

*b= -1363*

*c= 282.7*

***FS= 25.43***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 14.0 | ° | *= 0.24 (rad.)* |
| finished stone layer slope angle = ω = | 14.0 | ° | *= 0.24 (rad.)* |
| length of slope measured along the geomembrane = L = | 41.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 23.2 | ° | *= 0.40 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 32.2 | kN/m^2 | *Ca= 1299 kN* |
| thickness of stone layer = h = | 0.15 | m | *b/h= 4.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 84.7* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ≤300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ≥1000 mm | 0.95 | 0.75 | 0.30 |

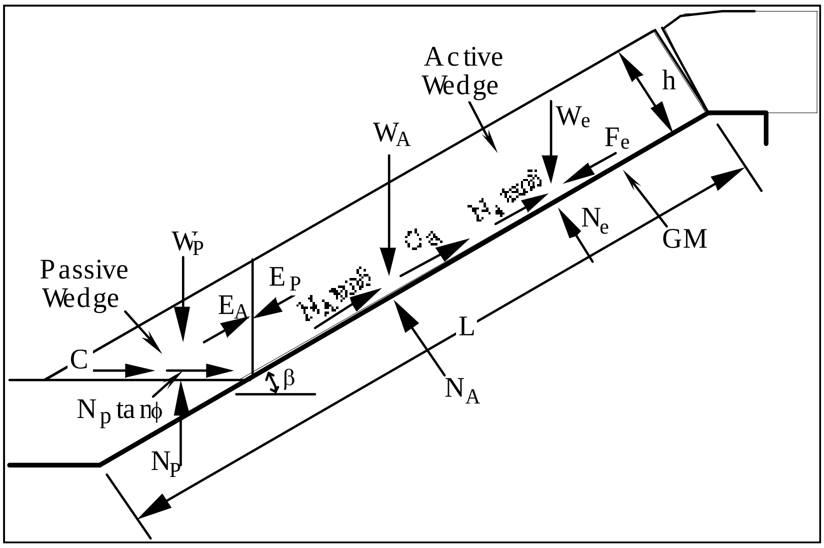
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 3

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Configuration No. 3 SLOPE 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 108.7 kN*

*Na= 103.1 kN*

Passive Wedge:

*Wp= 0.9 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 58.8*

*b= -1058*

*c= 290.9*

**FS= 17.71**

thickness of stone layer = h = 0.15 m

soil slope angle beneath the geomembrane = β = 18.4 ° *= 0.32 (rad.)*

finished stone layer slope angle = ω = 18.4 ° *= 0.32 (rad.)*

length of slope measured along the geomembrane = L = 32.0 m

unit weight of the stone layer = γ = 23.0 kN/m^3

friction angle of the stone layer = φ = 40.0 ° *= 0.70 (rad.)*

cohesion of the stone layer = c = 0.0 kN/m^2 *C= 0 kN*

interface friction angle between geotextile and geomembrane = δ = 23.2 ° *= 0.40 (rad.)*

adhesion between geotextile and geomembrane = ca = 32.3 kN/m^2 *Ca= 1017 kN*

thickness of stone layer = h = 0.15 m *b/h= 4.0*

equipment ground pressure (= wt. of equipment/(2w b)) = q = 30.0 kN/m^2 *We=q w I= 87.3*

length of each equipment track = w = 3.0 m *Ne=Wecos β= 82.8*

width of each equipment track = b = 0.6 m *Fe=We (a/g) = 0.0*

influence factor* at geomembrane interface = I = 0.97

acceleration/deceleration of the bulldozer = a = 0.00 g

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ≤300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ≥1000 mm | 0.95 | 0.75 | 0.30 |

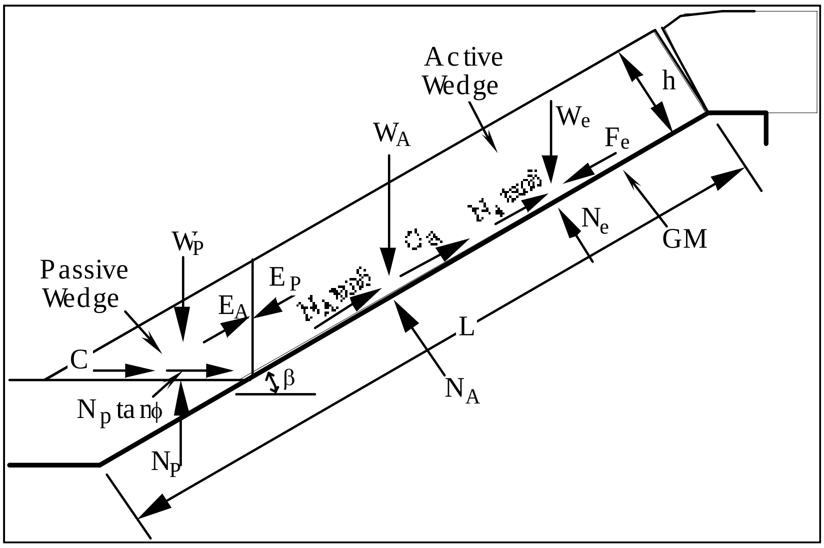
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 3

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Configuration No. 3 SLOPE 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 74.6 kN*

*Na= 66.7 kN*

Passive Wedge:

*Wp= 0.6 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 64.8*

*b= -708*

*c= 285.6*

***FS= 10.51***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| finished stone layer slope angle = ω = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = ϕ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 23.2 | ° | *= 0.40 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 32.3 | kN/m^2 | *Ca= 698.9 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | *b/h= 4.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 78.1* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ²300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ³1000 mm | 0.95 | 0.75 | 0.30 |

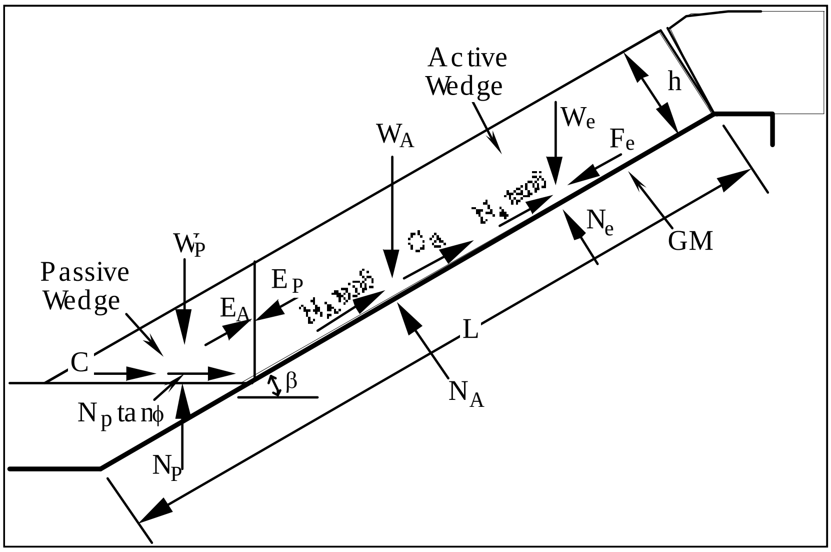
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Configuration No. 3

### Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)

**Configuration No. 3 SLOPE 1:1**




**Calculation of FS**

Active Wedge:

*Wa= 43.8 kN*

*Na= 31.0 kN*

Passive Wedge:

*Wp= 0.5 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 65.6*

*b= -381*

*c= 197.8*

***FS= 5.23***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | |
| soil slope angle beneath the geomembrane = β = | 45.0 | ° | *= 0.79 (rad.)* |
| finished stone layer slope angle = ω = | 45.0 | ° | *= 0.79 (rad.)* |
| length of slope measured along the geomembrane = L = | 14.0 | m | |
| unit weight of the stone layer = γ = | 21.3 | kN/m^3 | |
| friction angle of the stone layer = φ = | 30.0 | ° | *= 0.52 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 23.2 | ° | *= 0.40 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 32.3 | kN/m^2 | *Ca= 445 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.15 | m | *b/h= 4.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 61.7* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ²300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ³1000 mm | 0.95 | 0.75 | 0.30 |

Note: numbers in boxes are input values

*numbers in Italics are calculated values*

# Appendix D:  Case Study – Mariannhill Landfill Site

D.1. Planning Phases Site Plan and Construction Layout Plan

D.2. Ring Shear Tests – Raw Data and Graphs

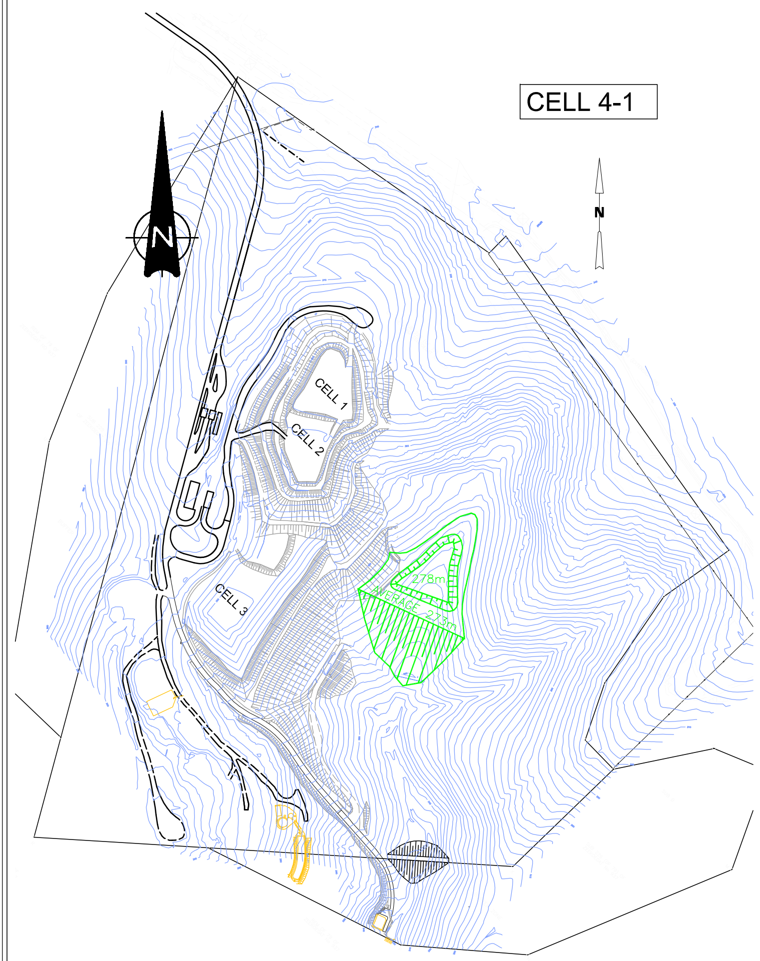
D.3. Shear Box Test – Secugrid vs Protection Geotextile

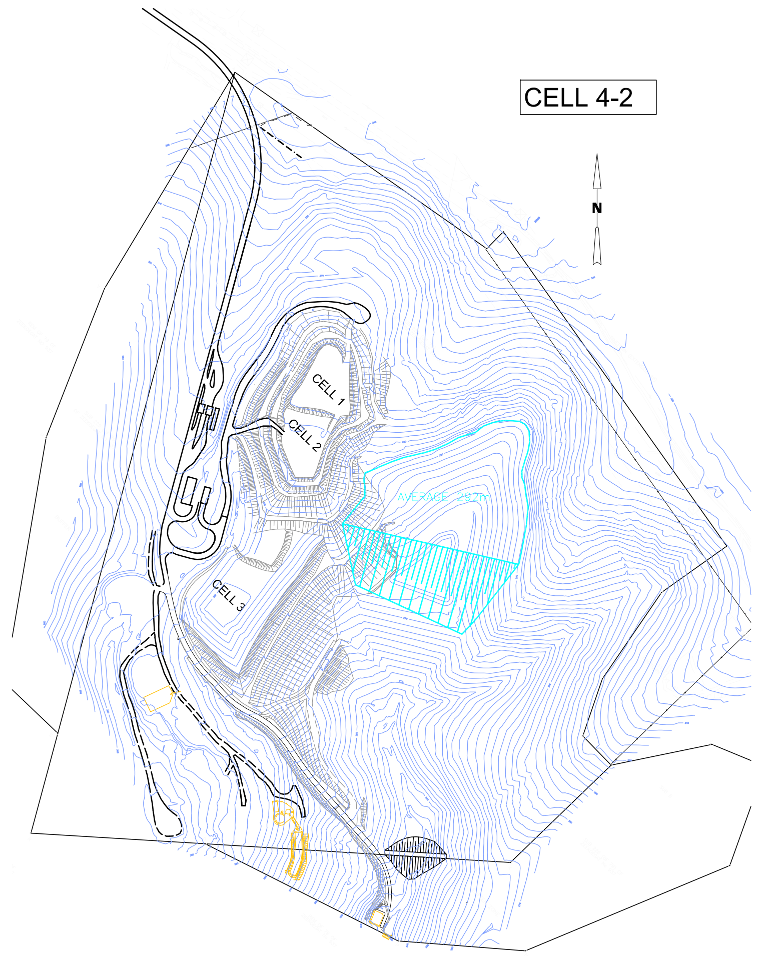
D.4. Calculation of Factors of Safety for Mariannhill Landfill Site

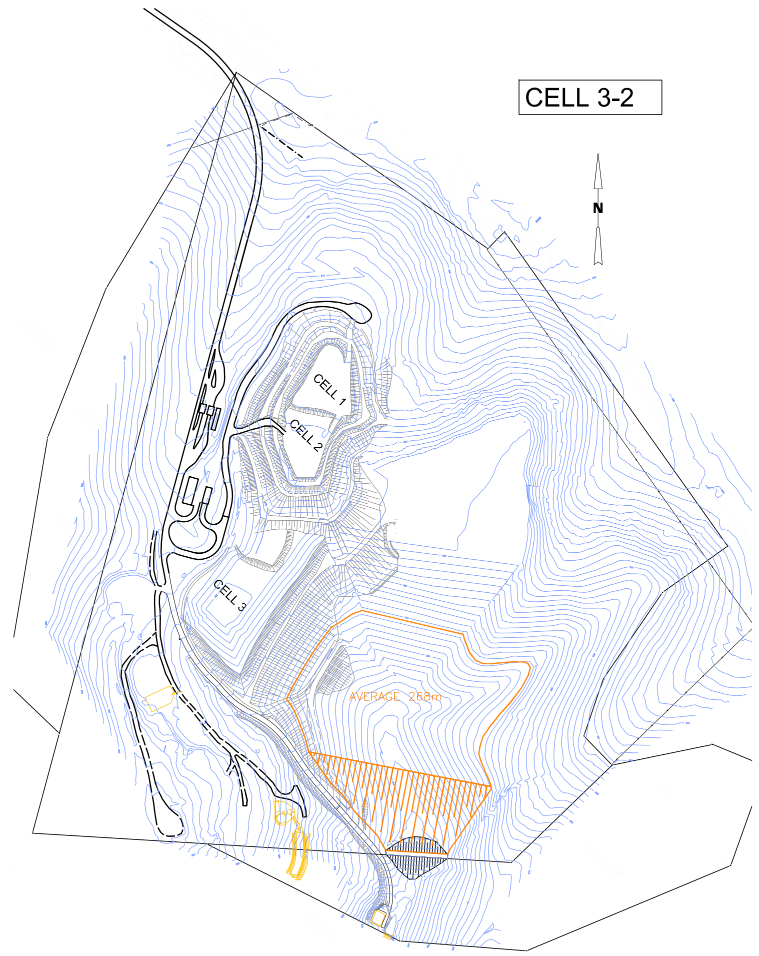
D.5. Factors of Safety for HDPE Geomembrane, Protection Geotextile and Veneer Reinforcement Integrity

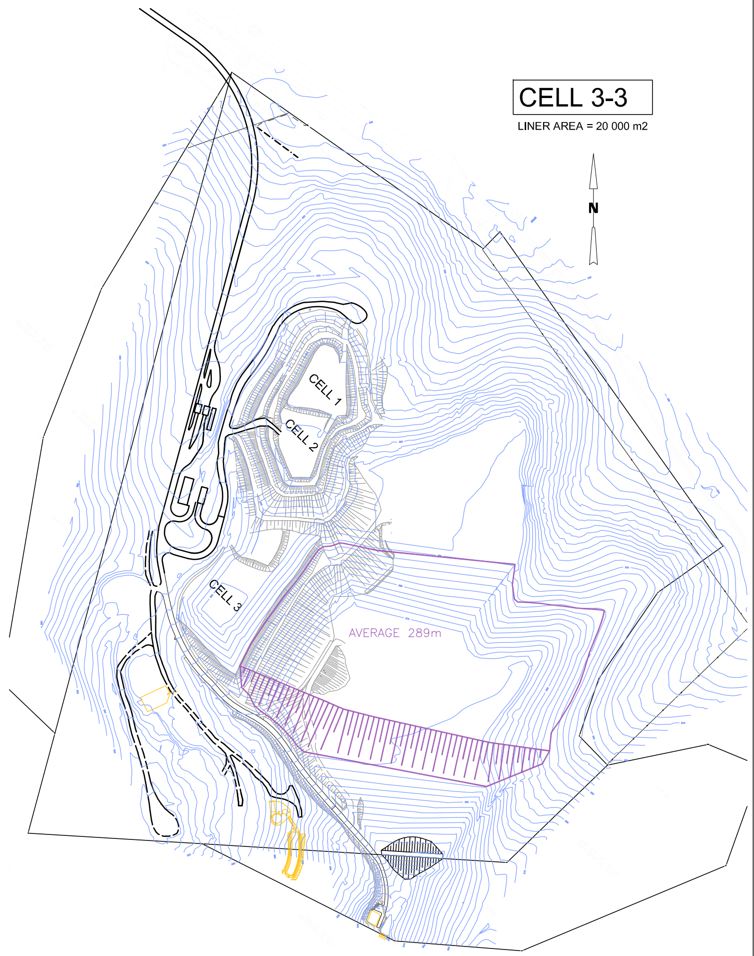
D.6. Mariannhill Landfill Cell 4 – Phase 3 – Consultant Letter

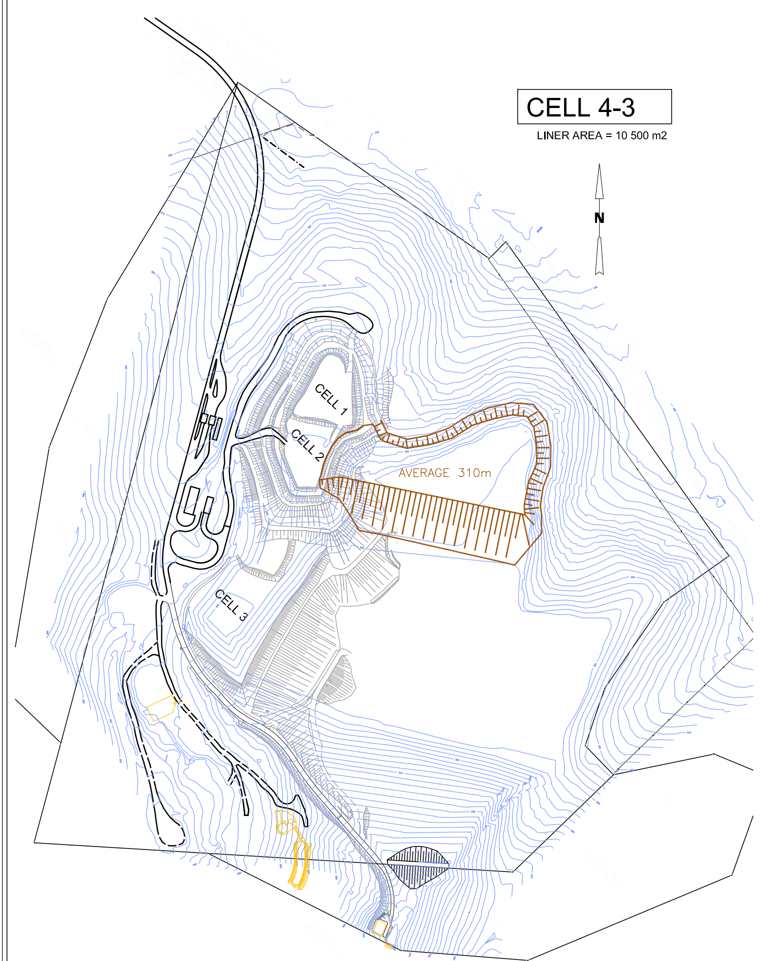
D.1. Planning Phases Site Plan and Construction Layout Plan

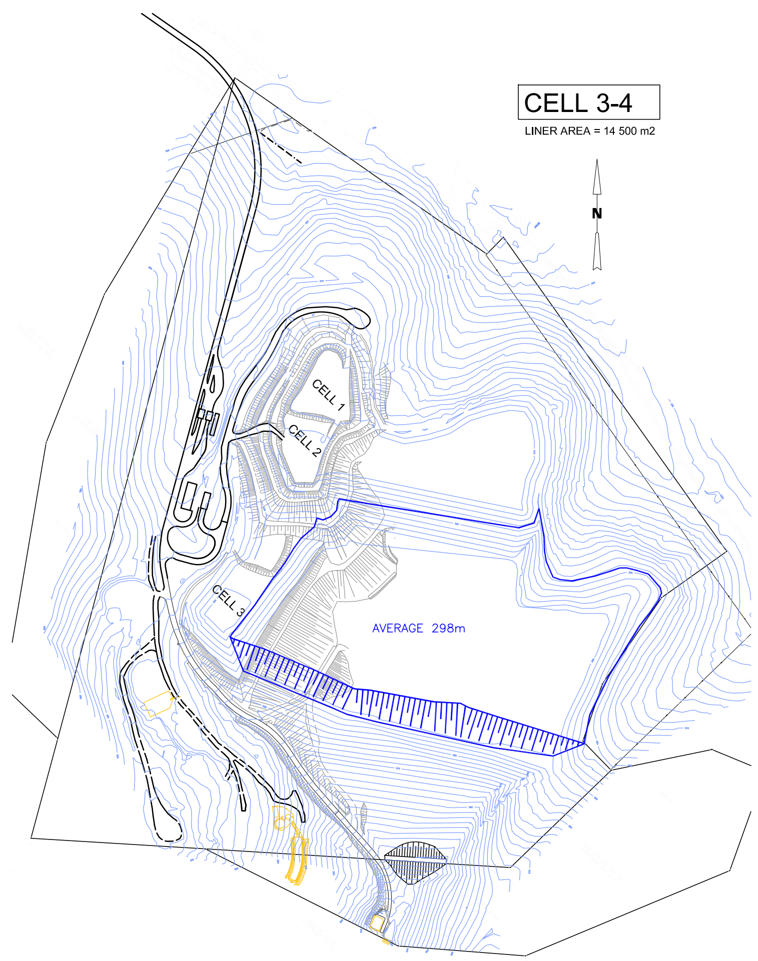


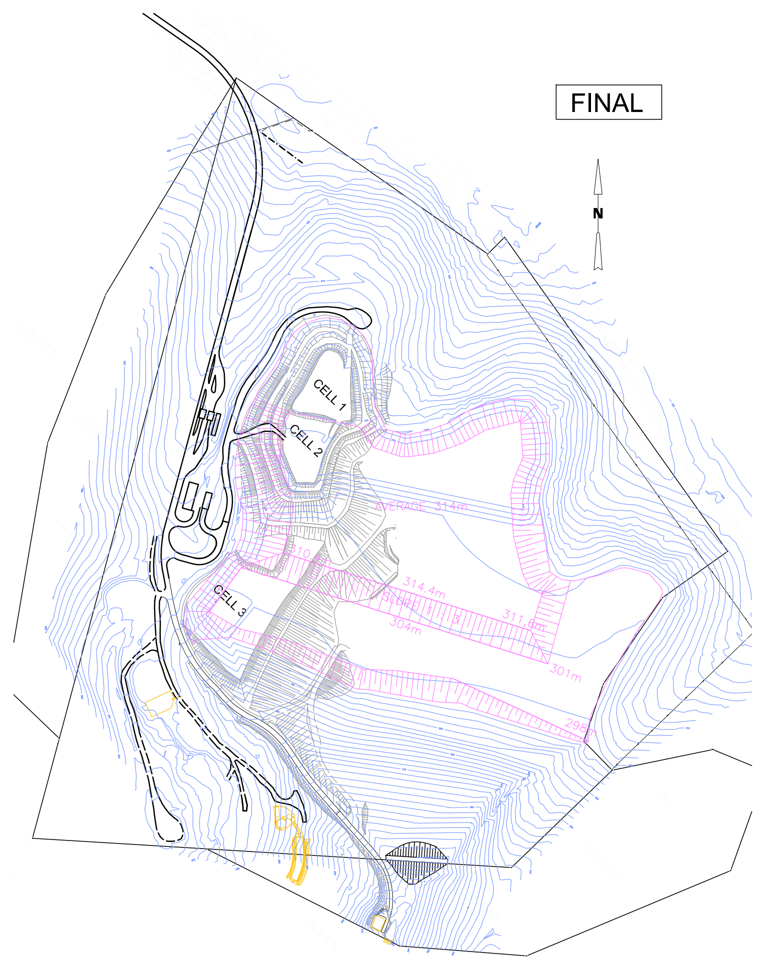




**NOTES :**

1. MAXIMUM ELEVATION = 316m
2. AIRSPACE VOLUMES

| | | |
|---|---|---|
| CELL 1 | 277 000 m3 | (21 MONTHS) |
| CELL 2 | 260 000 m3 | (20 MONTHS) |
| CELL 3–1 | 270 000 m3 | (24 MONTHS) |
| CELL 4–1 | 110 000 m3 | (10 MONTHS) |
| CELL 4–2 | 290 000 m3 | (23 MONTHS) |
| CELL 3–2 | 518 000 m3 | (41 MONTHS) |
| CELL 3–3 | 950 000 m3 | (76 MONTHS) |
| CELL 4–3 | 350 000 m3 | (28 MONTHS) |
| CELL 3–4 | 730 000 m3 | (58 MONTHS) |
| REMAINING LIFTS | 695 000 m3 | (56 MONTHS) |
| TOTAL AIRSPACE | 4 450 000 m3 | (357 MONTHS) |

3. ESTIMATED WASTE DISPOSAL RATE 150 000 m3/year INCLUDING COVER MATERIAL FROM INFILLING OF CELL 4–2.
4. NO ALLOWANCE IS MADE FOR GROWTH
5. ALL CUT AND FILL SLOPES = 1 : 3

0 10 20 30 40 50 60 70 80 90 100
100mm ORIGINAL PLAN



| REV | DATE | DRAWN | CHK'D | DESCRIPTION |
|---|---|---|---|---|
| A | 01/02/03 | AB | CD | FOR WHATEVER |


PD Naidoo & Associates (Pty) Limited Reg. No. 97/4139/07
The Sharaf House, 2 Sinembe Cres, La Lucia Ridge, 4001
P.O. Box 37659, Overport, 4067
Tel: 031 - 566 3745
Fax: 031 - 566 4381
e-mail: durban@pdna.co.za
PDNA
PD NAIDOO & ASSOCIATES
incorporating GFJ


CLIENT
CLEANSING AND SOLID WASTE
DSW

PROJECT
MARIANNHILL LANDFILL

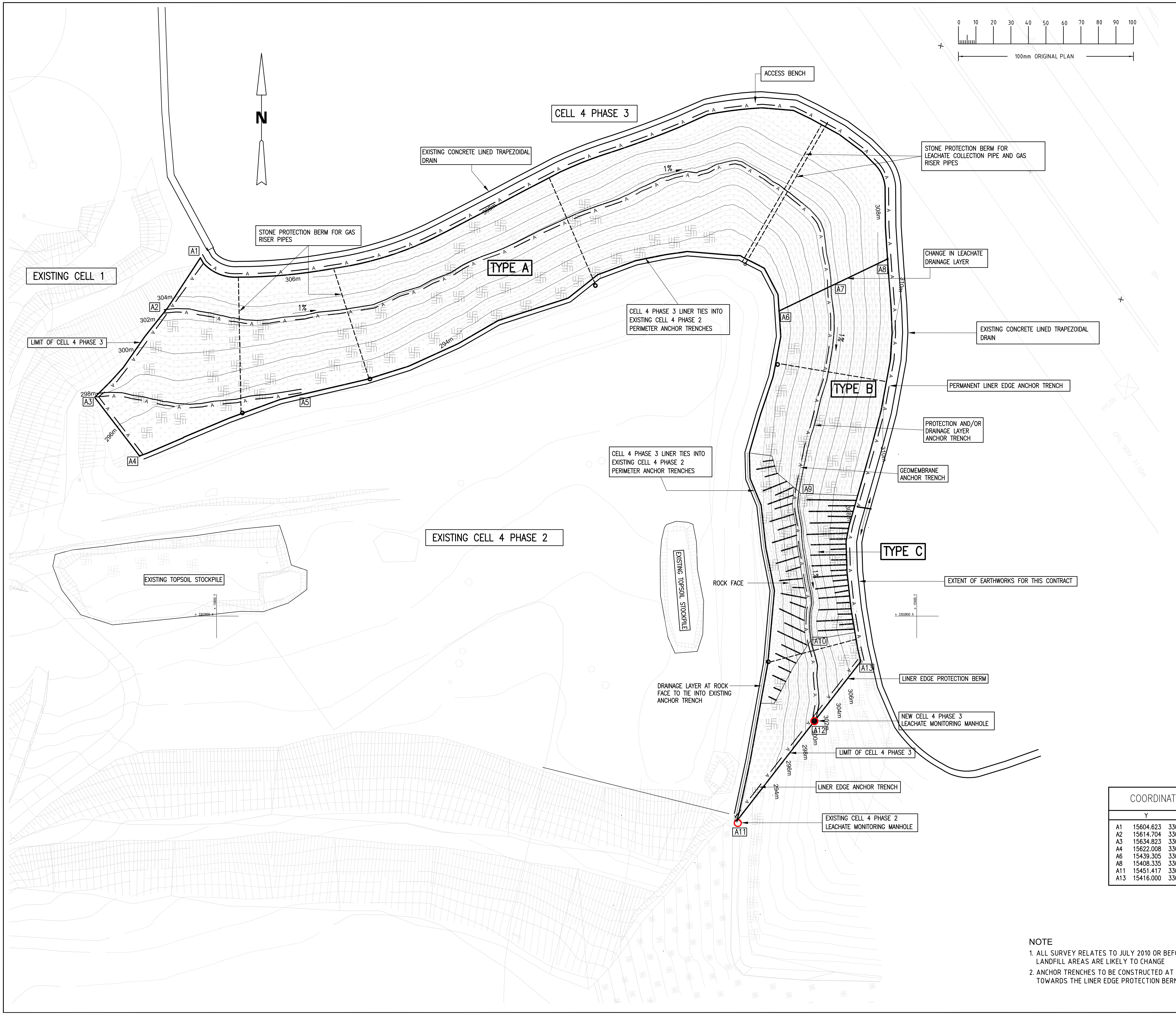
DRAWING
PLANNING PHASES
SITE PLAN

FOR DISCUSSION

| | SIGNATURE | DATE |
|---|---|---|
| DESIGNED | N. DOOKHI | 14/01/10 |
| DRAWN | S. BENNETT | 14/01/10 |
| CHECKED | J. McCALL | 14/01/10 |
| APPROVED | J. McCALL | 14/01/10 |
| SCALE | 1 : 3000 | |

| PROJECT No. | DISCPL | DRG. NUMBER | STAGE | SHEET SIZE | REVISION |
|---|---|---|---|---|---|
| EDM 98.02 | E | 07 | 0 | A0 | 01 |

| CLIENT DRAWING No. | FILE NAME AND LOCATION No. |
|---|---|
| EDM 9802-07 | \EDM9802\PLANNING\EDM9802-07.DWG |




SAFETY WARNING

The MARIANNHILL LANDFILL is an operational site and, as such, large amounts of LANDFILL GAS (containing methane) are generated within the site and leachate collection system. The Contractor and staff are warned against the risk of EXPLOSIVE ATMOSPHERES on site because of the presence of landfill gas and dissolved methane in the LANDFILL LEACHATE.

NAKED FLAMES AND SMOKING IS NOT PERMITTED anywhere on the site and due care must be taken, in compliance with all the laws, when working on the site. Operations resulting in spark, ignition, flames etc must be strictly supervised and all workmen appropriately warned of the risks.

DUE CARE AND DILIGENCE should also be exercised when work is carried out in the vicinity and/or adjacent to the disposal operations.

ALL LIQUIDS emanating from the Landfill and surroundings are deemed to be DANGEROUS. Thus no liquid may be collected or used for any purpose whatsoever.

For health and safety reasons, NO SCAVENGING of any materials deposited on the landfill will be permitted. The Contractor is to ensure that all his workers as well as his Subcontractors comply with this requirement. Failure to do so will be sufficient grounds to remove persons off site who are in contravention of any of the above.

NO ENTRY into enclosed areas without the use of a methane and oxygen monitor is allowed, due to the presence of landfill gas which can cause asphyxiation.

Extreme caution and maximum supervision is required when working in enclosed areas or trenches.

NO ENTRY into any MANHOLES on site by the Contractor or any other persons shall be permitted without the written approval by the ETHEKWINI MUNICIPALITY who must be satisfied by the abovementioned persons that all safety precautions and requirements will be complied with for working/entering these manholes.

IT SHALL BE THE CONTRACTORS RESPONSIBILITY THAT ALL STAFF IS AWARE OF THE ABOVE SAFETY WARNING. Failure to do so may be sufficient grounds to remove persons off site who are in contravention of any of the above.

LEGEND

- ANCHOR TRENCH
- STONE PROTECTION BERM
- EXISTING MANHOLE
- NEW MANHOLE
- ANCHOR TRENCH REFERENCE POINT
- EXISTING GAS WELLS
- TYPE A LINER
- TYPE B LINER
- TYPE C LINER
- EXPOSED HARD AND/OR BOULDER SURFACE

REFERENCE DRAWINGS :
100490/02A - TYPICAL DETAILS
100490/03A - PIPE LAYOUT
100490/04A - SIDE SLOPE CROSS SECTIONS

| REVISION | DATE | DESCRIPTION |
|---|---|---|
| A | DEC 2010 | FOR TENDER |

CLIENT

**CLEANSING AND SOLID WASTE DSW**

TITLE

**MARIANNHILL LANDFILL: CONSTRUCTION OF CELL 4 - PHASE 3**

**LAYOUT PLAN**

COORDINATES

| | Y | X |
|---|---|---|
| A1 | 15604.623 | 3302697.676 |
| A2 | 15614.704 | 3302712.876 |
| A3 | 15634.823 | 3302737.527 |
| A4 | 15622.008 | 3302754.242 |
| A6 | 15439.305 | 3302712.837 |
| A8 | 15408.335 | 3302697.999 |
| A11 | 15451.417 | 3302858.493 |
| A13 | 15416.000 | 3302812.970 |

PD Naidoo & Associates (Pty) Limited Reg. No. 97/4139/07
PDNA HOUSE, 16 Cranbrook Cresent, La Lucia Ridge, 4019
P.O. Box 25370 Gateway 4321
Tel: 031 - 581 6000
Fax: 031 - 566 4381
e-mail: durban@pdna.co.za
PDNA
PD NAIDOO & ASSOCIATES
incorporating

NOTE

1. ALL SURVEY RELATES TO JULY 2010 OR BEFORE AND LANDFILL AREAS ARE LIKELY TO CHANGE
2. ANCHOR TRENCHES TO BE CONSTRUCTED AT A 1% GRADIENT TOWARDS THE LINER EDGE PROTECTION BERM

| | |
|---|---|
| DESIGN : ND | SIGNATURE : DATE : |
| DRAWN : TG | DATE : DECEMBER 2010 |
| SCALE 1 : 500 | DRAWING No. 100490/01A |
| CAD FILE \\100490\DRAWINGS | |

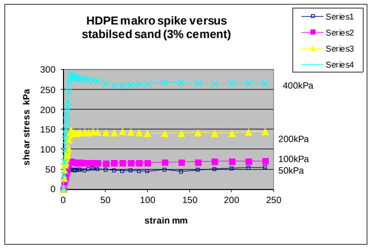
## D.2. Ring Shear Tests – Raw Data and Graphs

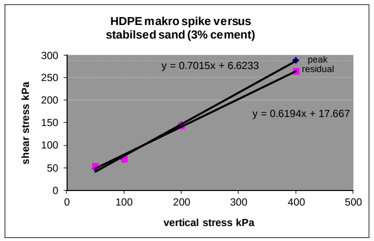
**PD NAIDOO AND ASSOCIATES** **MARIANNHILL LANDFILL** **RING SHEAR TESTING** **19th JULY 2011**

**TEST 1** **HDPE MAKRO SPIKE VERSUS SAND STABILISED WITH 3% CEMENT** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 57 | 114 | 57 | 114 | 65 | 130 | 48 | 96 | 111 | 222 | 62 | 124 | 154 | 308 | 73 | 146 |
| 1 | 89 | 178 | 70 | 140 | 95 | 190 | 63 | 126 | 214 | 428 | 96 | 192 | 312 | 624 | 124 | 248 |
| 1.5 | 87 | 174 | 58 | 116 | 99 | 198 | 59 | 118 | 277 | 554 | 114 | 228 | 427 | 854 | 190 | 380 |
| 2 | 89 | 178 | 48 | 96 | 116 | 232 | 66 | 132 | 309 | 618 | 111 | 222 | 504 | 1008 | 264 | 528 |
| 2.5 | 109 | 218 | 53 | 106 | 142 | 284 | 78 | 156 | 331 | 662 | 111 | 222 | 560 | 1120 | 318 | 636 |
| 3 | 131 | 262 | 62 | 124 | 170 | 340 | 91 | 182 | 361 | 722 | 124 | 248 | 608 | 1216 | 362 | 724 |
| 3.5 | 147 | 294 | 71 | 142 | 203 | 406 | 102 | 204 | 391 | 782 | 138 | 276 | 662 | 1324 | 415 | 830 |
| 4 | 161 | 322 | 80 | 160 | 228 | 456 | 112 | 224 | 412 | 824 | 160 | 320 | 718 | 1436 | 469 | 938 |
| 4.5 | 172 | 344 | 86 | 172 | 248 | 496 | 120 | 240 | 427 | 854 | 188 | 376 | 772 | 1544 | 520 | 1040 |
| 5 | 183 | 366 | 94 | 188 | 269 | 538 | 127 | 254 | 451 | 902 | 215 | 430 | 825 | 1650 | 565 | 1130 |
| 6 | 195 | 390 | 100 | 200 | 293 | 586 | 136 | 272 | 507 | 1014 | 273 | 546 | 912 | 1824 | 640 | 1280 |
| 7 | 200 | 400 | 103 | 206 | 296 | 592 | 137 | 274 | 539 | 1078 | 311 | 622 | 986 | 1972 | 720 | 1440 |
| 8 | 202 | 404 | 106 | 212 | 298 | 596 | 137 | 274 | 573 | 1146 | 345 | 690 | 995 | 1990 | 770 | 1540 |
| 9 | 203 | 406 | 107 | 214 | 298 | 596 | 137 | 274 | 575 | 1150 | 346 | 692 | 1002 | 2004 | 822 | 1644 |
| 10 | 201 | 402 | 106 | 212 | 295 | 590 | 137 | 274 | 574 | 1148 | 341 | 682 | 990 | 1980 | 810 | 1620 |
| 12 | 200 | 400 | 107 | 214 | 292 | 584 | 138 | 276 | 572 | 1144 | 319 | 638 | 982 | 1964 | 808 | 1616 |
| 14 | 195 | 390 | 106 | 212 | 289 | 578 | 135 | 270 | 566 | 1132 | 318 | 636 | 976 | 1952 | 800 | 1600 |
| 16 | 198 | 396 | 108 | 216 | 284 | 568 | 130 | 260 | 559 | 1118 | 321 | 642 | 966 | 1932 | 784 | 1568 |
| 18 | 196 | 392 | 110 | 220 | 290 | 580 | 133 | 266 | 566 | 1132 | 328 | 656 | 966 | 1932 | 788 | 1576 |
| 20 | 195 | 390 | 110 | 220 | 295 | 590 | 132 | 264 | 560 | 1120 | 332 | 664 | 965 | 1930 | 779 | 1558 |
| 25 | 189 | 378 | 109 | 218 | 293 | 586 | 130 | 260 | 564 | 1128 | 344 | 688 | 970 | 1940 | 774 | 1548 |
| 30 | 201 | 402 | 116 | 232 | 290 | 580 | 128 | 256 | 556 | 1112 | 342 | 684 | 969 | 1938 | 767 | 1534 |
| 35 | 209 | 418 | 119 | 238 | 289 | 578 | 126 | 252 | 564 | 1128 | 354 | 708 | 971 | 1942 | 751 | 1502 |
| 40 | 204 | 408 | 117 | 234 | 289 | 578 | 127 | 254 | 558 | 1116 | 342 | 684 | 968 | 1936 | 744 | 1488 |
| 50 | 196 | 392 | 111 | 222 | 286 | 572 | 125 | 250 | 555 | 1110 | 340 | 680 | 966 | 1932 | 710 | 1420 |
| 60 | 186 | 372 | 110 | 220 | 289 | 578 | 128 | 256 | 551 | 1102 | 342 | 684 | 960 | 1920 | 681 | 1362 |
| 70 | 184 | 368 | 107 | 214 | 289 | 578 | 129 | 258 | 559 | 1118 | 360 | 720 | 970 | 1940 | 680 | 1360 |
| 80 | 188 | 376 | 106 | 212 | 289 | 578 | 130 | 260 | 555 | 1110 | 353 | 706 | 976 | 1952 | 680 | 1360 |
| 90 | 186 | 372 | 104 | 208 | 288 | 576 | 130 | 260 | 550 | 1100 | 347 | 694 | 980 | 1960 | 681 | 1362 |
| 100 | 184 | 368 | 101 | 202 | 288 | 576 | 131 | 262 | 551 | 1102 | 333 | 666 | 987 | 1974 | 683 | 1366 |
| 120 | 199 | 398 | 108 | 216 | 290 | 580 | 134 | 268 | 556 | 1112 | 331 | 662 | 1006 | 2012 | 691 | 1382 |
| 140 | 177 | 354 | 104 | 208 | 291 | 582 | 138 | 276 | 559 | 1118 | 330 | 660 | 1009 | 2018 | 673 | 1346 |
| 160 | 190 | 380 | 112 | 224 | 293 | 586 | 140 | 280 | 558 | 1116 | 337 | 674 | 1012 | 2024 | 665 | 1330 |
| 180 | 200 | 400 | 119 | 238 | 296 | 592 | 142 | 284 | 558 | 1116 | 330 | 660 | 1016 | 2032 | 652 | 1304 |
| 200 | 207 | 414 | 121 | 242 | 297 | 594 | 143 | 286 | 554 | 1108 | 332 | 664 | 1018 | 2036 | 658 | 1316 |
| 220 | 212 | 424 | 125 | 250 | 298 | 596 | 145 | 290 | 564 | 1128 | 341 | 682 | 1020 | 2040 | 656 | 1312 |
| 240 | 216 | 432 | 130 | 260 | 298 | 596 | 146 | 292 | 569 | 1138 | 345 | 690 | 1022 | 2044 | 654 | 1308 |

| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 228 | 226 | 346 | 454 | 50 | 620 | 692 | 0.01263 | 49.09 | 54.79 | 18.05 | 17.89 | 27.40 | 35.95 | 0.5 |
| 1 | 318 | 316 | 620 | 872 | 100 | 870 | 888 | 0.01263 | 68.88 | 70.31 | 25.18 | 25.02 | 49.09 | 69.04 | 1 |
| 1.5 | 290 | 316 | 782 | 1234 | 200 | 1842 | 1828 | 0.01263 | 145.84 | 144.73 | 22.96 | 25.02 | 61.92 | 97.70 | 1.5 |
| 2 | 274 | 364 | 840 | 1536 | 400 | 3648 | 3352 | 0.01263 | 288.84 | 265.40 | 21.69 | 28.82 | 66.51 | 121.62 | 2 |
| 2.5 | 324 | 440 | 884 | 1756 | | | | 0.01263 | | | 25.65 | 34.84 | 69.99 | 139.03 | 2.5 |
| 3 | 386 | 522 | 970 | 1940 | | | | 0.01263 | | | 30.56 | 41.33 | 76.80 | 153.60 | 3 |
| 3.5 | 436 | 610 | 1058 | 2154 | | | | 0.01263 | | | 34.52 | 48.30 | 83.77 | 170.55 | 3.5 |
| 4 | 482 | 680 | 1144 | 2374 | | | | 0.01263 | | | 38.16 | 53.84 | 90.58 | 187.97 | 4 |
| 4.5 | 516 | 736 | 1230 | 2584 | | | | 0.01263 | | | 40.86 | 58.27 | 97.39 | 204.59 | 4.5 |
| 5 | 554 | 792 | 1332 | 2780 | | | | 0.01263 | | | 43.86 | 62.71 | 105.46 | 220.11 | 5 |
| 6 | 590 | 858 | 1560 | 3104 | | | | 0.01263 | | | 46.71 | 67.93 | 123.52 | 245.76 | 6 |
| 7 | 606 | 866 | 1700 | 3412 | | | | 0.01263 | | | 47.98 | 68.57 | 134.60 | 270.15 | 7 |
| 8 | 616 | 870 | 1836 | 3530 | | | | 0.01263 | | | 48.77 | 68.88 | 145.37 | 279.49 | 8 |
| 9 | 620 | 870 | 1842 | 3648 | | | | 0.01263 | | | 49.09 | 68.88 | 145.84 | 288.84 | 9 |
| 10 | 614 | 864 | 1830 | 3600 | | | | 0.01263 | | | 48.61 | 68.41 | 144.89 | 285.04 | 10 |
| 12 | 614 | 860 | 1782 | 3580 | | | | 0.01263 | | | 48.61 | 68.09 | 141.09 | 283.45 | 12 |
| 14 | 602 | 848 | 1768 | 3552 | | | | 0.01263 | | | 47.66 | 67.14 | 139.98 | 281.24 | 14 |
| 16 | 612 | 828 | 1760 | 3500 | | | | 0.01263 | | | 48.46 | 65.56 | 139.35 | 277.12 | 16 |
| 18 | 612 | 846 | 1788 | 3508 | | | | 0.01263 | | | 48.46 | 66.98 | 141.57 | 277.75 | 18 |
| 20 | 610 | 854 | 1784 | 3488 | | | | 0.01263 | | | 48.30 | 67.62 | 141.25 | 276.17 | 20 |
| 25 | 596 | 846 | 1816 | 3488 | | | | 0.01263 | | | 47.19 | 66.98 | 143.78 | 276.17 | 25 |
| 30 | 634 | 836 | 1796 | 3472 | | | | 0.01263 | | | 50.20 | 66.19 | 142.20 | 274.90 | 30 |
| 35 | 656 | 830 | 1836 | 3444 | | | | 0.01263 | | | 51.94 | 65.72 | 145.37 | 272.68 | 35 |
| 40 | 642 | 832 | 1800 | 3424 | | | | 0.01263 | | | 50.83 | 65.87 | 142.52 | 271.10 | 40 |
| 50 | 614 | 822 | 1790 | 3352 | | | | 0.01263 | | | 48.61 | 65.08 | 141.73 | 265.40 | 50 |
| 60 | 592 | 834 | 1786 | 3282 | | | | 0.01263 | | | 46.87 | 66.03 | 141.41 | 259.86 | 60 |
| 70 | 582 | 836 | 1838 | 3300 | | | | 0.01263 | | | 46.08 | 66.19 | 145.53 | 261.28 | 70 |
| 80 | 588 | 838 | 1816 | 3312 | | | | 0.01263 | | | 46.56 | 66.35 | 143.78 | 262.23 | 80 |
| 90 | 580 | 836 | 1794 | 3322 | | | | 0.01263 | | | 45.92 | 66.19 | 142.04 | 263.02 | 90 |
| 100 | 570 | 838 | 1768 | 3340 | | | | 0.01263 | | | 45.13 | 66.35 | 139.98 | 264.45 | 100 |
| 120 | 614 | 848 | 1774 | 3394 | | | | 0.01263 | | | 48.61 | 67.14 | 140.46 | 268.73 | 120 |
| 140 | 562 | 858 | 1778 | 3364 | | | | 0.01263 | | | 44.50 | 67.93 | 140.78 | 266.35 | 140 |
| 160 | 604 | 866 | 1790 | 3354 | | | | 0.01263 | | | 47.82 | 68.57 | 141.73 | 265.56 | 160 |
| 180 | 638 | 876 | 1776 | 3336 | | | | 0.01263 | | | 50.51 | 69.36 | 140.62 | 264.13 | 180 |
| 200 | 656 | 880 | 1772 | 3352 | | | | 0.01263 | | | 51.94 | 69.68 | 140.30 | 265.40 | 200 |
| 220 | 674 | 886 | 1810 | 3352 | | | | 0.01263 | | | 53.37 | 70.15 | 143.31 | 265.40 | 220 |
| 240 | 692 | 888 | 1828 | 3352 | | | | 0.01263 | | | 54.79 | 70.31 | 144.73 | 265.40 | 240 |



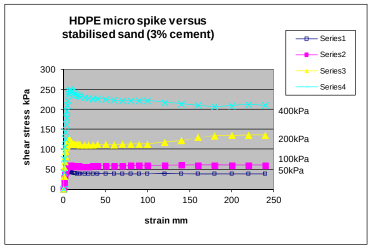

| | | | |
|---|---|---|---|
| peak | 35.05 | cohesion | 6.62 |
| residual | 31.77 | cohesion | 17.67 |

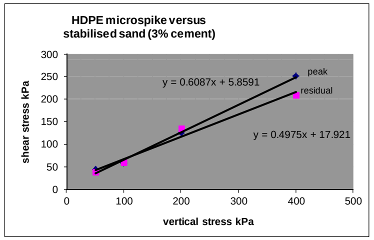
**PD NAIDOO AND ASSOCIATES** **MARIANNHILL LANDFILL** **RING SHEAR TESTING** **19th JULY 2011**

**TEST 2** **HDPE MICRO SPIKE VERSUS SAND STABILISED WITH 3% CEMENT** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 62 | 124 | 53 | 106 | 60 | 120 | 46 | 92 | 130 | 260 | 71 | 142 | 175 | 350 | 89 | 178 |
| 1 | 84 | 168 | 72 | 144 | 106 | 212 | 67 | 134 | 237 | 474 | 109 | 218 | 339 | 678 | 144 | 288 |
| 1.5 | 98 | 196 | 81 | 162 | 145 | 290 | 80 | 160 | 308 | 616 | 134 | 268 | 448 | 896 | 219 | 438 |
| 2 | 114 | 228 | 88 | 176 | 180 | 360 | 89 | 178 | 368 | 736 | 154 | 308 | 517 | 1034 | 277 | 554 |
| 2.5 | 122 | 244 | 91 | 182 | 207 | 414 | 96 | 192 | 418 | 836 | 182 | 364 | 572 | 1144 | 329 | 658 |
| 3 | 133 | 266 | 95 | 190 | 228 | 456 | 100 | 200 | 454 | 908 | 203 | 406 | 638 | 1276 | 387 | 774 |
| 3.5 | 143 | 286 | 100 | 200 | 241 | 482 | 103 | 206 | 476 | 952 | 216 | 432 | 691 | 1382 | 441 | 882 |
| 4 | 150 | 300 | 103 | 206 | 253 | 506 | 106 | 212 | 492 | 984 | 227 | 454 | 741 | 1482 | 496 | 992 |
| 4.5 | 154 | 308 | 105 | 210 | 257 | 514 | 106 | 212 | 506 | 1012 | 234 | 468 | 790 | 1580 | 538 | 1076 |
| 5 | 161 | 322 | 108 | 216 | 262 | 524 | 107 | 214 | 516 | 1032 | 243 | 486 | 834 | 1668 | 569 | 1138 |
| 6 | 167 | 334 | 111 | 222 | 268 | 536 | 107 | 214 | 534 | 1068 | 256 | 512 | 890 | 1780 | 622 | 1244 |
| 7 | 168 | 336 | 110 | 220 | 269 | 538 | 105 | 210 | 532 | 1064 | 256 | 512 | 910 | 1820 | 644 | 1288 |
| 8 | 165 | 330 | 109 | 218 | 268 | 536 | 104 | 208 | 524 | 1048 | 250 | 500 | 929 | 1858 | 659 | 1318 |
| 9 | 158 | 316 | 107 | 214 | 270 | 540 | 103 | 206 | 512 | 1024 | 235 | 470 | 914 | 1828 | 641 | 1282 |
| 10 | 155 | 310 | 107 | 214 | 267 | 534 | 101 | 202 | 504 | 1008 | 225 | 450 | 908 | 1816 | 634 | 1268 |
| 12 | 150 | 300 | 105 | 210 | 268 | 536 | 98 | 196 | 497 | 994 | 220 | 440 | 898 | 1796 | 627 | 1254 |
| 14 | 148 | 296 | 104 | 208 | 264 | 528 | 97 | 194 | 492 | 984 | 218 | 436 | 887 | 1774 | 620 | 1240 |
| 16 | 144 | 288 | 104 | 208 | 266 | 532 | 98 | 196 | 493 | 986 | 218 | 436 | 880 | 1760 | 614 | 1228 |
| 18 | 146 | 292 | 104 | 208 | 266 | 532 | 97 | 194 | 492 | 984 | 217 | 434 | 873 | 1746 | 607 | 1214 |
| 20 | 146 | 292 | 103 | 206 | 264 | 528 | 97 | 194 | 488 | 976 | 217 | 434 | 865 | 1730 | 601 | 1202 |
| 25 | 144 | 288 | 104 | 208 | 260 | 520 | 96 | 192 | 485 | 970 | 218 | 436 | 856 | 1712 | 601 | 1202 |
| 30 | 142 | 284 | 104 | 208 | 263 | 526 | 97 | 194 | 484 | 968 | 218 | 436 | 847 | 1694 | 594 | 1188 |
| 35 | 142 | 284 | 104 | 208 | 268 | 536 | 101 | 202 | 481 | 962 | 224 | 448 | 842 | 1684 | 588 | 1176 |
| 40 | 141 | 282 | 104 | 208 | 266 | 532 | 102 | 204 | 484 | 968 | 225 | 450 | 846 | 1692 | 588 | 1176 |
| 50 | 143 | 286 | 104 | 208 | 266 | 532 | 103 | 206 | 477 | 954 | 231 | 462 | 832 | 1664 | 590 | 1180 |
| 60 | 140 | 280 | 103 | 206 | 265 | 530 | 105 | 210 | 468 | 936 | 237 | 474 | 828 | 1656 | 582 | 1164 |
| 70 | 140 | 280 | 104 | 208 | 266 | 532 | 106 | 212 | 466 | 932 | 243 | 486 | 827 | 1654 | 579 | 1158 |
| 80 | 140 | 280 | 103 | 206 | 268 | 536 | 107 | 214 | 464 | 928 | 250 | 500 | 822 | 1644 | 583 | 1166 |
| 90 | 140 | 280 | 104 | 208 | 268 | 536 | 108 | 216 | 456 | 912 | 258 | 516 | 821 | 1642 | 583 | 1166 |
| 100 | 140 | 280 | 105 | 210 | 268 | 536 | 109 | 218 | 448 | 896 | 266 | 532 | 820 | 1640 | 582 | 1164 |
| 120 | 142 | 284 | 106 | 212 | 270 | 540 | 110 | 220 | 442 | 884 | 301 | 602 | 796 | 1592 | 580 | 1160 |
| 140 | 140 | 280 | 104 | 208 | 274 | 548 | 112 | 224 | 436 | 872 | 336 | 672 | 773 | 1546 | 579 | 1158 |
| 160 | 139 | 278 | 105 | 210 | 269 | 538 | 110 | 220 | 428 | 856 | 392 | 784 | 750 | 1500 | 578 | 1156 |
| 180 | 139 | 278 | 105 | 210 | 269 | 538 | 109 | 218 | 398 | 796 | 446 | 892 | 730 | 1460 | 576 | 1152 |
| 200 | 140 | 280 | 104 | 208 | 268 | 536 | 111 | 222 | 368 | 736 | 483 | 966 | 736 | 1472 | 589 | 1178 |
| 220 | 140 | 280 | 105 | 210 | 269 | 538 | 110 | 220 | 360 | 720 | 497 | 994 | 729 | 1458 | 612 | 1224 |
| 240 | 139 | 278 | 105 | 210 | 270 | 540 | 111 | 222 | 351 | 702 | 506 | 1012 | 717 | 1434 | 610 | 1220 |

| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 230 | 212 | 402 | 528 | 50 | 556 | 488 | 0.01263 | 44.02 | 38.64 | 18.21 | 16.79 | 31.83 | 41.81 | 0.5 |
| 1 | 312 | 346 | 692 | 966 | 100 | 750 | 762 | 0.01263 | 59.38 | 60.33 | 24.70 | 27.40 | 54.79 | 76.48 | 1 |
| 1.5 | 358 | 450 | 884 | 1334 | 200 | 1580 | 1714 | 0.01263 | 125.10 | 135.71 | 28.35 | 35.63 | 69.99 | 105.62 | 1.5 |
| 2 | 404 | 538 | 1044 | 1588 | 400 | 3176 | 2654 | 0.01263 | 251.46 | 210.13 | 31.99 | 42.60 | 82.66 | 125.73 | 2 |
| 2.5 | 426 | 606 | 1200 | 1802 | | | | 0.01263 | | | 33.73 | 47.98 | 95.01 | 142.68 | 2.5 |
| 3 | 456 | 656 | 1314 | 2050 | | | | 0.01263 | | | 36.10 | 51.94 | 104.04 | 162.31 | 3 |
| 3.5 | 486 | 688 | 1384 | 2264 | | | | 0.01263 | | | 38.48 | 54.47 | 109.58 | 179.26 | 3.5 |
| 4 | 506 | 718 | 1438 | 2474 | | | | 0.01263 | | | 40.06 | 56.85 | 113.86 | 195.88 | 4 |
| 4.5 | 518 | 726 | 1480 | 2656 | | | | 0.01263 | | | 41.01 | 57.48 | 117.18 | 210.29 | 4.5 |
| 5 | 538 | 738 | 1518 | 2806 | | | | 0.01263 | | | 42.60 | 58.43 | 120.19 | 222.17 | 5 |
| 6 | 556 | 750 | 1580 | 3024 | | | | 0.01263 | | | 44.02 | 59.38 | 125.10 | 239.43 | 6 |
| 7 | 556 | 748 | 1576 | 3108 | | | | 0.01263 | | | 44.02 | 59.22 | 124.78 | 246.08 | 7 |
| 8 | 548 | 744 | 1548 | 3176 | | | | 0.01263 | | | 43.39 | 58.91 | 122.57 | 251.46 | 8 |
| 9 | 530 | 746 | 1494 | 3110 | | | | 0.01263 | | | 41.96 | 59.07 | 118.29 | 246.24 | 9 |
| 10 | 524 | 736 | 1458 | 3084 | | | | 0.01263 | | | 41.49 | 58.27 | 115.44 | 244.18 | 10 |
| 12 | 510 | 732 | 1434 | 3050 | | | | 0.01263 | | | 40.38 | 57.96 | 113.54 | 241.49 | 12 |
| 14 | 504 | 722 | 1420 | 3014 | | | | 0.01263 | | | 39.90 | 57.17 | 112.43 | 238.64 | 14 |
| 16 | 496 | 728 | 1422 | 2988 | | | | 0.01263 | | | 39.27 | 57.64 | 112.59 | 236.58 | 16 |
| 18 | 500 | 726 | 1418 | 2960 | | | | 0.01263 | | | 39.59 | 57.48 | 112.27 | 234.36 | 18 |
| 20 | 498 | 722 | 1410 | 2932 | | | | 0.01263 | | | 39.43 | 57.17 | 111.64 | 232.15 | 20 |
| 25 | 496 | 712 | 1406 | 2914 | | | | 0.01263 | | | 39.27 | 56.37 | 111.32 | 230.72 | 25 |
| 30 | 492 | 720 | 1404 | 2882 | | | | 0.01263 | | | 38.95 | 57.01 | 111.16 | 228.19 | 30 |
| 35 | 492 | 738 | 1410 | 2860 | | | | 0.01263 | | | 38.95 | 58.43 | 111.64 | 226.44 | 35 |
| 40 | 490 | 736 | 1418 | 2868 | | | | 0.01263 | | | 38.80 | 58.27 | 112.27 | 227.08 | 40 |
| 50 | 494 | 738 | 1416 | 2844 | | | | 0.01263 | | | 39.11 | 58.43 | 112.11 | 225.18 | 50 |
| 60 | 486 | 740 | 1410 | 2820 | | | | 0.01263 | | | 38.48 | 58.59 | 111.64 | 223.28 | 60 |
| 70 | 488 | 744 | 1418 | 2812 | | | | 0.01263 | | | 38.64 | 58.91 | 112.27 | 222.64 | 70 |
| 80 | 486 | 750 | 1428 | 2810 | | | | 0.01263 | | | 38.48 | 59.38 | 113.06 | 222.49 | 80 |
| 90 | 488 | 752 | 1428 | 2808 | | | | 0.01263 | | | 38.64 | 59.54 | 113.06 | 222.33 | 90 |
| 100 | 490 | 754 | 1428 | 2804 | | | | 0.01263 | | | 38.80 | 59.70 | 113.06 | 222.01 | 100 |
| 120 | 496 | 760 | 1486 | 2752 | | | | 0.01263 | | | 39.27 | 60.17 | 117.66 | 217.89 | 120 |
| 140 | 488 | 772 | 1544 | 2704 | | | | 0.01263 | | | 38.64 | 61.12 | 122.25 | 214.09 | 140 |
| 160 | 488 | 758 | 1640 | 2656 | | | | 0.01263 | | | 38.64 | 60.02 | 129.85 | 210.29 | 160 |
| 180 | 488 | 756 | 1688 | 2612 | | | | 0.01263 | | | 38.64 | 59.86 | 133.65 | 206.81 | 180 |
| 200 | 488 | 758 | 1702 | 2650 | | | | 0.01263 | | | 38.64 | 60.02 | 134.76 | 209.82 | 200 |
| 220 | 490 | 758 | 1714 | 2682 | | | | 0.01263 | | | 38.80 | 60.02 | 135.71 | 212.35 | 220 |
| 240 | 488 | 762 | 1714 | 2654 | | | | 0.01263 | | | 38.64 | 60.33 | 135.71 | 210.13 | 240 |



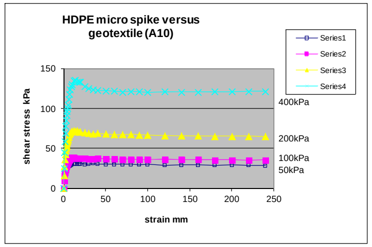

| | | | |
|---|---|---|---|
| peak | 31.33 | cohesion | 5.86 |
| residual | 26.45 | cohesion | 17.92 |

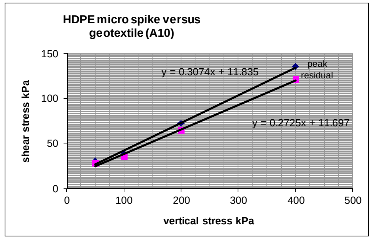
**PD NAIDOO AND ASSOCIATES** **MARIANNHILL LANDFILL** **RING SHEAR TESTING** **19th JULY 2011**

**TEST 3** **HDPE MICRO SPIKE VERSUS GEOFABRIC** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 30 | 60 | 32 | 64 | 31 | 62 | 33 | 66 | 60 | 120 | 44 | 88 | 105 | 210 | 55 | 110 |
| 1 | 50 | 100 | 43 | 86 | 56 | 112 | 45 | 90 | 110 | 220 | 66 | 132 | 196 | 392 | 88 | 176 |
| 1.5 | 62 | 124 | 48 | 96 | 74 | 148 | 54 | 108 | 147 | 294 | 82 | 164 | 259 | 518 | 110 | 220 |
| 2 | 72 | 144 | 52 | 104 | 87 | 174 | 61 | 122 | 174 | 348 | 95 | 190 | 306 | 612 | 129 | 258 |
| 2.5 | 79 | 158 | 54 | 108 | 97 | 194 | 67 | 134 | 195 | 390 | 105 | 210 | 344 | 688 | 149 | 298 |
| 3 | 84 | 168 | 56 | 112 | 105 | 210 | 71 | 142 | 206 | 412 | 112 | 224 | 364 | 728 | 177 | 354 |
| 3.5 | 90 | 180 | 58 | 116 | 111 | 222 | 75 | 150 | 217 | 434 | 119 | 238 | 380 | 760 | 200 | 400 |
| 4 | 95 | 190 | 59 | 118 | 115 | 230 | 78 | 156 | 229 | 458 | 125 | 250 | 394 | 788 | 217 | 434 |
| 4.5 | 99 | 198 | 60 | 120 | 120 | 240 | 81 | 162 | 239 | 478 | 131 | 262 | 406 | 812 | 231 | 462 |
| 5 | 104 | 208 | 61 | 122 | 124 | 248 | 84 | 168 | 249 | 498 | 136 | 272 | 419 | 838 | 243 | 486 |
| 6 | 109 | 218 | 63 | 126 | 130 | 260 | 88 | 176 | 265 | 530 | 144 | 288 | 441 | 882 | 264 | 528 |
| 7 | 114 | 228 | 65 | 130 | 136 | 272 | 92 | 184 | 275 | 550 | 150 | 300 | 462 | 924 | 283 | 566 |
| 8 | 115 | 230 | 66 | 132 | 139 | 278 | 95 | 190 | 281 | 562 | 155 | 310 | 480 | 960 | 301 | 602 |
| 9 | 118 | 236 | 68 | 136 | 142 | 284 | 97 | 194 | 286 | 572 | 159 | 318 | 493 | 986 | 314 | 628 |
| 10 | 122 | 244 | 70 | 140 | 145 | 290 | 99 | 198 | 289 | 578 | 162 | 324 | 503 | 1006 | 322 | 644 |
| 12 | 122 | 244 | 70 | 140 | 143 | 286 | 99 | 198 | 292 | 584 | 166 | 332 | 519 | 1038 | 334 | 668 |
| 14 | 124 | 248 | 71 | 142 | 140 | 280 | 99 | 198 | 288 | 576 | 163 | 326 | 524 | 1048 | 333 | 666 |
| 16 | 124 | 248 | 71 | 142 | 141 | 282 | 100 | 200 | 290 | 580 | 165 | 330 | 518 | 1036 | 327 | 654 |
| 18 | 125 | 250 | 71 | 142 | 141 | 282 | 100 | 200 | 284 | 568 | 163 | 326 | 520 | 1040 | 321 | 642 |
| 20 | 124 | 248 | 70 | 140 | 139 | 278 | 100 | 200 | 286 | 572 | 161 | 322 | 520 | 1040 | 321 | 642 |
| 25 | 121 | 242 | 70 | 140 | 137 | 274 | 100 | 200 | 283 | 566 | 159 | 318 | 502 | 1004 | 304 | 608 |
| 30 | 122 | 244 | 71 | 142 | 134 | 268 | 99 | 198 | 279 | 558 | 158 | 316 | 494 | 988 | 296 | 592 |
| 35 | 125 | 250 | 72 | 144 | 136 | 272 | 100 | 200 | 277 | 554 | 156 | 312 | 491 | 982 | 292 | 584 |
| 40 | 121 | 242 | 72 | 144 | 136 | 272 | 101 | 202 | 280 | 560 | 157 | 314 | 488 | 976 | 288 | 576 |
| 50 | 120 | 240 | 71 | 142 | 134 | 268 | 100 | 200 | 275 | 550 | 155 | 310 | 487 | 974 | 286 | 572 |
| 60 | 120 | 240 | 70 | 140 | 133 | 266 | 99 | 198 | 273 | 546 | 152 | 304 | 485 | 970 | 285 | 570 |
| 70 | 119 | 238 | 71 | 142 | 132 | 264 | 99 | 198 | 274 | 548 | 152 | 304 | 484 | 968 | 280 | 560 |
| 80 | 118 | 236 | 71 | 142 | 132 | 264 | 98 | 196 | 274 | 548 | 153 | 306 | 484 | 968 | 284 | 568 |
| 90 | 117 | 234 | 71 | 142 | 130 | 260 | 97 | 194 | 272 | 544 | 152 | 304 | 484 | 968 | 282 | 564 |
| 100 | 118 | 236 | 71 | 142 | 131 | 262 | 97 | 194 | 270 | 540 | 150 | 300 | 480 | 960 | 281 | 562 |
| 120 | 113 | 226 | 70 | 140 | 132 | 264 | 98 | 196 | 268 | 536 | 149 | 298 | 482 | 964 | 284 | 568 |
| 140 | 115 | 230 | 71 | 142 | 131 | 262 | 97 | 194 | 267 | 534 | 149 | 298 | 480 | 960 | 283 | 566 |
| 160 | 114 | 228 | 70 | 140 | 131 | 262 | 96 | 192 | 267 | 534 | 148 | 296 | 480 | 960 | 284 | 568 |
| 180 | 112 | 224 | 71 | 142 | 130 | 260 | 96 | 192 | 266 | 532 | 148 | 296 | 482 | 964 | 283 | 566 |
| 200 | 113 | 226 | 71 | 142 | 131 | 262 | 95 | 190 | 265 | 530 | 148 | 296 | 480 | 960 | 286 | 572 |
| 220 | 112 | 224 | 70 | 140 | 130 | 260 | 94 | 188 | 265 | 530 | 147 | 294 | 480 | 960 | 287 | 574 |
| 240 | 111 | 222 | 70 | 140 | 132 | 264 | 94 | 188 | 264 | 528 | 147 | 294 | 480 | 960 | 288 | 576 |

| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 124 | 128 | 208 | 320 | 50 | 392 | 362 | 0.01263 | 31.04 | 28.66 | 9.82 | 10.13 | 16.47 | 25.34 | 0.5 |
| 1 | 186 | 202 | 352 | 568 | 100 | 488 | 452 | 0.01263 | 38.64 | 35.79 | 14.73 | 15.99 | 27.87 | 44.97 | 1 |
| 1.5 | 220 | 256 | 458 | 738 | 200 | 916 | 822 | 0.01263 | 72.53 | 65.08 | 17.42 | 20.27 | 36.26 | 58.43 | 1.5 |
| 2 | 248 | 296 | 538 | 870 | 400 | 1714 | 1536 | 0.01263 | 135.71 | 121.62 | 19.64 | 23.44 | 42.60 | 68.88 | 2 |
| 2.5 | 266 | 328 | 600 | 986 | | | | 0.01263 | | | 21.06 | 25.97 | 47.51 | 78.07 | 2.5 |
| 3 | 280 | 352 | 636 | 1082 | | | | 0.01263 | | | 22.17 | 27.87 | 50.36 | 85.67 | 3 |
| 3.5 | 296 | 372 | 672 | 1160 | | | | 0.01263 | | | 23.44 | 29.45 | 53.21 | 91.84 | 3.5 |
| 4 | 308 | 386 | 708 | 1222 | | | | 0.01263 | | | 24.39 | 30.56 | 56.06 | 96.75 | 4 |
| 4.5 | 318 | 402 | 740 | 1274 | | | | 0.01263 | | | 25.18 | 31.83 | 58.59 | 100.87 | 4.5 |
| 5 | 330 | 416 | 770 | 1324 | | | | 0.01263 | | | 26.13 | 32.94 | 60.97 | 104.83 | 5 |
| 6 | 344 | 436 | 818 | 1410 | | | | 0.01263 | | | 27.24 | 34.52 | 64.77 | 111.64 | 6 |
| 7 | 358 | 456 | 850 | 1490 | | | | 0.01263 | | | 28.35 | 36.10 | 67.30 | 117.97 | 7 |
| 8 | 362 | 468 | 872 | 1562 | | | | 0.01263 | | | 28.66 | 37.05 | 69.04 | 123.67 | 8 |
| 9 | 372 | 478 | 890 | 1614 | | | | 0.01263 | | | 29.45 | 37.85 | 70.47 | 127.79 | 9 |
| 10 | 384 | 488 | 902 | 1650 | | | | 0.01263 | | | 30.40 | 38.64 | 71.42 | 130.64 | 10 |
| 12 | 384 | 484 | 916 | 1706 | | | | 0.01263 | | | 30.40 | 38.32 | 72.53 | 135.08 | 12 |
| 14 | 390 | 478 | 902 | 1714 | | | | 0.01263 | | | 30.88 | 37.85 | 71.42 | 135.71 | 14 |
| 16 | 390 | 482 | 910 | 1690 | | | | 0.01263 | | | 30.88 | 38.16 | 72.05 | 133.81 | 16 |
| 18 | 392 | 482 | 894 | 1682 | | | | 0.01263 | | | 31.04 | 38.16 | 70.78 | 133.17 | 18 |
| 20 | 388 | 478 | 894 | 1682 | | | | 0.01263 | | | 30.72 | 37.85 | 70.78 | 133.17 | 20 |
| 25 | 382 | 474 | 884 | 1612 | | | | 0.01263 | | | 30.25 | 37.53 | 69.99 | 127.63 | 25 |
| 30 | 386 | 466 | 874 | 1580 | | | | 0.01263 | | | 30.56 | 36.90 | 69.20 | 125.10 | 30 |
| 35 | 394 | 472 | 866 | 1566 | | | | 0.01263 | | | 31.20 | 37.37 | 68.57 | 123.99 | 35 |
| 40 | 386 | 474 | 874 | 1552 | | | | 0.01263 | | | 30.56 | 37.53 | 69.20 | 122.88 | 40 |
| 50 | 382 | 468 | 860 | 1546 | | | | 0.01263 | | | 30.25 | 37.05 | 68.09 | 122.41 | 50 |
| 60 | 380 | 464 | 850 | 1540 | | | | 0.01263 | | | 30.09 | 36.74 | 67.30 | 121.93 | 60 |
| 70 | 380 | 462 | 852 | 1528 | | | | 0.01263 | | | 30.09 | 36.58 | 67.46 | 120.98 | 70 |
| 80 | 378 | 460 | 854 | 1536 | | | | 0.01263 | | | 29.93 | 36.42 | 67.62 | 121.62 | 80 |
| 90 | 376 | 454 | 848 | 1532 | | | | 0.01263 | | | 29.77 | 35.95 | 67.14 | 121.30 | 90 |
| 100 | 378 | 456 | 840 | 1522 | | | | 0.01263 | | | 29.93 | 36.10 | 66.51 | 120.51 | 100 |
| 120 | 366 | 460 | 834 | 1532 | | | | 0.01263 | | | 28.98 | 36.42 | 66.03 | 121.30 | 120 |
| 140 | 372 | 456 | 832 | 1526 | | | | 0.01263 | | | 29.45 | 36.10 | 65.87 | 120.82 | 140 |
| 160 | 368 | 454 | 830 | 1528 | | | | 0.01263 | | | 29.14 | 35.95 | 65.72 | 120.98 | 160 |
| 180 | 366 | 452 | 828 | 1530 | | | | 0.01263 | | | 28.98 | 35.79 | 65.56 | 121.14 | 180 |
| 200 | 368 | 452 | 826 | 1532 | | | | 0.01263 | | | 29.14 | 35.79 | 65.40 | 121.30 | 200 |
| 220 | 364 | 448 | 824 | 1534 | | | | 0.01263 | | | 28.82 | 35.47 | 65.24 | 121.46 | 220 |
| 240 | 362 | 452 | 822 | 1536 | | | | 0.01263 | | | 28.66 | 35.79 | 65.08 | 121.62 | 240 |



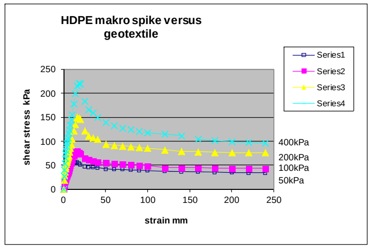

| | | | |
|---|---|---|---|
| peak | 17.09 | cohesion | 11.84 |
| residual | 15.24 | cohesion | 11.70 |

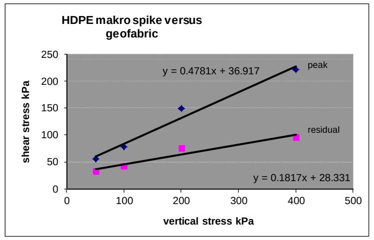
**PD NAIDOO AND ASSOCIATES** **MARIANNHILL LANDFILL** **RING SHEAR TESTING** **19th JULY 2011**

**TEST 4** **HDPE MAKRO SPIKE VERSUS GEOFABRIC** **Shearing rate : 1,0 mm/minute**

| Time min. | 50kPa v/s sh. str. N. A | corr.sh. str. N. A | 50kPa v/s sh. str. N. B | corr. sh. str. N. B | 100kPa v/s sh. str.N. A | corr. sh. str. N. A | 100kPav/s sh. str. N. B | corr. sh. str. N. B | 200kPa v/s sh.str.N. A | corr sh. str. N. A | 200kPa v/s sh.str. N. B | corr. sh. str. N. B | 400kPav/s sh.str.N. A | corr. sh. str. N. A | 400kPav/s sh.str. N. B | corr. sh. str. N. B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 42 | 84 | 23 | 46 | 24 | 48 | 27 | 54 | 74 | 148 | 43 | 86 | 116 | 232 | 57 | 114 |
| 1 | 63 | 126 | 37 | 74 | 41 | 82 | 37 | 74 | 123 | 246 | 63 | 126 | 180 | 360 | 78 | 156 |
| 1.5 | 75 | 150 | 48 | 96 | 56 | 112 | 47 | 94 | 158 | 316 | 76 | 152 | 242 | 484 | 98 | 196 |
| 2 | 85 | 170 | 57 | 114 | 69 | 138 | 56 | 112 | 184 | 368 | 86 | 172 | 296 | 592 | 114 | 228 |
| 2.5 | 95 | 190 | 64 | 128 | 80 | 160 | 65 | 130 | 205 | 410 | 95 | 190 | 339 | 678 | 128 | 256 |
| 3 | 104 | 208 | 69 | 138 | 87 | 174 | 75 | 150 | 226 | 452 | 102 | 204 | 372 | 744 | 139 | 278 |
| 3.5 | 111 | 222 | 73 | 146 | 94 | 188 | 86 | 172 | 245 | 490 | 108 | 216 | 404 | 808 | 154 | 308 |
| 4 | 118 | 236 | 76 | 152 | 101 | 202 | 94 | 188 | 260 | 520 | 113 | 226 | 430 | 860 | 175 | 350 |
| 4.5 | 127 | 254 | 80 | 160 | 108 | 216 | 100 | 200 | 275 | 550 | 117 | 234 | 450 | 900 | 193 | 386 |
| 5 | 135 | 270 | 84 | 168 | 115 | 230 | 105 | 210 | 293 | 586 | 122 | 244 | 469 | 938 | 208 | 416 |
| 6 | 153 | 306 | 92 | 184 | 132 | 264 | 113 | 226 | 318 | 636 | 127 | 254 | 502 | 1004 | 234 | 468 |
| 7 | 170 | 340 | 99 | 198 | 154 | 308 | 125 | 250 | 357 | 714 | 136 | 272 | 527 | 1054 | 253 | 506 |
| 8 | 187 | 374 | 106 | 212 | 176 | 352 | 139 | 278 | 397 | 794 | 147 | 294 | 570 | 1140 | 278 | 556 |
| 9 | 201 | 402 | 111 | 222 | 193 | 386 | 158 | 316 | 429 | 858 | 165 | 330 | 613 | 1226 | 305 | 610 |
| 10 | 209 | 418 | 115 | 230 | 208 | 416 | 181 | 362 | 470 | 940 | 193 | 386 | 652 | 1304 | 334 | 668 |
| 12 | 220 | 440 | 118 | 236 | 231 | 462 | 211 | 422 | 523 | 1046 | 244 | 488 | 727 | 1454 | 397 | 794 |
| 14 | 231 | 462 | 121 | 242 | 255 | 510 | 235 | 470 | 568 | 1136 | 288 | 576 | 800 | 1600 | 458 | 916 |
| 16 | 232 | 464 | 121 | 242 | 260 | 520 | 238 | 476 | 611 | 1222 | 336 | 672 | 850 | 1700 | 511 | 1022 |
| 18 | 223 | 446 | 116 | 232 | 256 | 512 | 231 | 462 | 600 | 1200 | 344 | 688 | 860 | 1720 | 539 | 1078 |
| 20 | 214 | 428 | 113 | 226 | 248 | 496 | 222 | 444 | 584 | 1168 | 340 | 680 | 842 | 1684 | 546 | 1092 |
| 25 | 193 | 386 | 106 | 212 | 217 | 434 | 193 | 386 | 492 | 984 | 282 | 564 | 700 | 1400 | 457 | 914 |
| 30 | 184 | 368 | 104 | 208 | 209 | 418 | 184 | 368 | 457 | 914 | 249 | 498 | 644 | 1288 | 403 | 806 |
| 35 | 182 | 364 | 106 | 212 | 199 | 398 | 178 | 356 | 441 | 882 | 239 | 478 | 624 | 1248 | 380 | 760 |
| 40 | 178 | 356 | 105 | 210 | 188 | 376 | 168 | 336 | 428 | 856 | 229 | 458 | 593 | 1186 | 358 | 716 |
| 50 | 168 | 336 | 100 | 200 | 184 | 368 | 164 | 328 | 392 | 784 | 198 | 396 | 555 | 1110 | 326 | 652 |
| 60 | 164 | 328 | 98 | 196 | 179 | 358 | 159 | 318 | 385 | 770 | 192 | 384 | 536 | 1072 | 306 | 612 |
| 70 | 163 | 326 | 99 | 198 | 175 | 350 | 156 | 312 | 380 | 760 | 188 | 376 | 516 | 1032 | 290 | 580 |
| 80 | 156 | 312 | 97 | 194 | 171 | 342 | 152 | 304 | 376 | 752 | 184 | 368 | 503 | 1006 | 282 | 564 |
| 90 | 153 | 306 | 95 | 190 | 166 | 332 | 149 | 298 | 371 | 742 | 179 | 358 | 489 | 978 | 272 | 544 |
| 100 | 149 | 298 | 94 | 188 | 161 | 322 | 145 | 290 | 366 | 732 | 174 | 348 | 482 | 964 | 261 | 522 |
| 120 | 145 | 290 | 93 | 186 | 148 | 296 | 136 | 272 | 356 | 712 | 163 | 326 | 474 | 948 | 252 | 504 |
| 140 | 142 | 284 | 92 | 184 | 147 | 294 | 136 | 272 | 342 | 684 | 158 | 316 | 462 | 924 | 241 | 482 |
| 160 | 138 | 276 | 91 | 182 | 146 | 292 | 135 | 270 | 340 | 680 | 152 | 304 | 439 | 878 | 220 | 440 |
| 180 | 135 | 270 | 90 | 180 | 145 | 290 | 134 | 268 | 337 | 674 | 150 | 300 | 429 | 858 | 212 | 424 |
| 200 | 130 | 260 | 89 | 178 | 144 | 288 | 132 | 264 | 335 | 670 | 148 | 296 | 419 | 838 | 206 | 412 |
| 220 | 128 | 256 | 88 | 176 | 144 | 288 | 131 | 262 | 333 | 666 | 147 | 294 | 413 | 826 | 202 | 404 |
| 240 | 126 | 252 | 87 | 174 | 143 | 286 | 130 | 260 | 333 | 666 | 147 | 294 | 410 | 820 | 200 | 400 |

| Time min. | 50Kpa v/s sh.str. | 100kPav/s sh.str. | 200kPav/s sh.str. | 400kPav/s sh.str. | vertical str. kPa | peak sh. stress N. | residual stress N. | interface area m^ | peak sh. stress kPa. | residual sh. stress kPa. | 50 kPa v/s sh.str. kPa. | 100kPav/s sh.str. kPa. | 200kPav/s sh.str. kPa. | 400kPav/s sh.str. kPa. | strain mm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | | | | | | | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 130 | 102 | 234 | 346 | 50 | 706 | 426 | 0.01263 | 55.90 | 33.73 | 10.29 | 8.08 | 18.53 | 27.40 | 0.5 |
| 1 | 200 | 156 | 372 | 516 | 100 | 996 | 546 | 0.01263 | 78.86 | 43.23 | 15.84 | 12.35 | 29.45 | 40.86 | 1 |
| 1.5 | 246 | 206 | 468 | 680 | 200 | 1894 | 960 | 0.01263 | 149.96 | 76.01 | 19.48 | 16.31 | 37.05 | 53.84 | 1.5 |
| 2 | 284 | 250 | 540 | 820 | 400 | 2798 | 1220 | 0.01263 | 221.54 | 96.60 | 22.49 | 19.79 | 42.76 | 64.92 | 2 |
| 2.5 | 318 | 290 | 600 | 934 | | | | 0.01263 | | | 25.18 | 22.96 | 47.51 | 73.95 | 2.5 |
| 3 | 346 | 324 | 656 | 1022 | | | | 0.01263 | | | 27.40 | 25.65 | 51.94 | 80.92 | 3 |
| 3.5 | 368 | 360 | 706 | 1116 | | | | 0.01263 | | | 29.14 | 28.50 | 55.90 | 88.36 | 3.5 |
| 4 | 388 | 390 | 746 | 1210 | | | | 0.01263 | | | 30.72 | 30.88 | 59.07 | 95.80 | 4 |
| 4.5 | 414 | 416 | 784 | 1286 | | | | 0.01263 | | | 32.78 | 32.94 | 62.07 | 101.82 | 4.5 |
| 5 | 438 | 440 | 830 | 1354 | | | | 0.01263 | | | 34.68 | 34.84 | 65.72 | 107.21 | 5 |
| 6 | 490 | 490 | 890 | 1472 | | | | 0.01263 | | | 38.80 | 38.80 | 70.47 | 116.55 | 6 |
| 7 | 538 | 558 | 986 | 1560 | | | | 0.01263 | | | 42.60 | 44.18 | 78.07 | 123.52 | 7 |
| 8 | 586 | 630 | 1088 | 1696 | | | | 0.01263 | | | 46.40 | 49.88 | 86.14 | 134.28 | 8 |
| 9 | 624 | 702 | 1188 | 1836 | | | | 0.01263 | | | 49.41 | 55.58 | 94.06 | 145.37 | 9 |
| 10 | 648 | 778 | 1326 | 1972 | | | | 0.01263 | | | 51.31 | 61.60 | 104.99 | 156.14 | 10 |
| 12 | 676 | 884 | 1534 | 2248 | | | | 0.01263 | | | 53.52 | 69.99 | 121.46 | 177.99 | 12 |
| 14 | 704 | 980 | 1712 | 2516 | | | | 0.01263 | | | 55.74 | 77.59 | 135.55 | 199.21 | 14 |
| 16 | 706 | 996 | 1894 | 2722 | | | | 0.01263 | | | 55.90 | 78.86 | 149.96 | 215.52 | 16 |
| 18 | 678 | 974 | 1888 | 2798 | | | | 0.01263 | | | 53.68 | 77.12 | 149.49 | 221.54 | 18 |
| 20 | 654 | 940 | 1848 | 2776 | | | | 0.01263 | | | 51.78 | 74.43 | 146.32 | 219.79 | 20 |
| 25 | 598 | 820 | 1548 | 2314 | | | | 0.01263 | | | 47.35 | 64.92 | 122.57 | 183.21 | 25 |
| 30 | 576 | 786 | 1412 | 2094 | | | | 0.01263 | | | 45.61 | 62.23 | 111.80 | 165.80 | 30 |
| 35 | 576 | 754 | 1360 | 2008 | | | | 0.01263 | | | 45.61 | 59.70 | 107.68 | 158.99 | 35 |
| 40 | 566 | 712 | 1314 | 1902 | | | | 0.01263 | | | 44.81 | 56.37 | 104.04 | 150.59 | 40 |
| 50 | 536 | 696 | 1180 | 1762 | | | | 0.01263 | | | 42.44 | 55.11 | 93.43 | 139.51 | 50 |
| 60 | 524 | 676 | 1154 | 1684 | | | | 0.01263 | | | 41.49 | 53.52 | 91.37 | 133.33 | 60 |
| 70 | 524 | 662 | 1136 | 1612 | | | | 0.01263 | | | 41.49 | 52.41 | 89.94 | 127.63 | 70 |
| 80 | 506 | 646 | 1120 | 1570 | | | | 0.01263 | | | 40.06 | 51.15 | 88.68 | 124.31 | 80 |
| 90 | 496 | 630 | 1100 | 1522 | | | | 0.01263 | | | 39.27 | 49.88 | 87.09 | 120.51 | 90 |
| 100 | 486 | 612 | 1080 | 1486 | | | | 0.01263 | | | 38.48 | 48.46 | 85.51 | 117.66 | 100 |
| 120 | 476 | 568 | 1038 | 1452 | | | | 0.01263 | | | 37.69 | 44.97 | 82.19 | 114.96 | 120 |
| 140 | 468 | 566 | 1000 | 1406 | | | | 0.01263 | | | 37.05 | 44.81 | 79.18 | 111.32 | 140 |
| 160 | 458 | 562 | 984 | 1318 | | | | 0.01263 | | | 36.26 | 44.50 | 77.91 | 104.35 | 160 |
| 180 | 450 | 558 | 974 | 1282 | | | | 0.01263 | | | 35.63 | 44.18 | 77.12 | 101.50 | 180 |
| 200 | 438 | 552 | 966 | 1250 | | | | 0.01263 | | | 34.68 | 43.71 | 76.48 | 98.97 | 200 |
| 220 | 432 | 550 | 960 | 1230 | | | | 0.01263 | | | 34.20 | 43.55 | 76.01 | 97.39 | 220 |
| 240 | 426 | 546 | 960 | 1220 | | | | 0.01263 | | | 33.73 | 43.23 | 76.01 | 96.60 | 240 |




| | | | |
|---|---|---|---|
| peak | 25.55 | cohesion | 36.92 |
| residual | 10.30 | cohesion | 28.33 |

## D.3. Shear Box Test – Secugrid vs Protection Geotextile

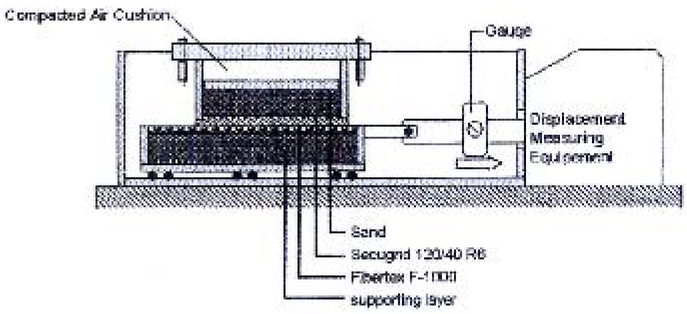
## Direct Shear Test

059-11 | Mariannhill Landfill Site, Southafrica | Page 1 of 2

Test set-up: Sand
Secugrid 120/40 R6
Fibertex F-1000
supporting layer

Remarks: because of technical reasons it was not possible to run the test with the highest loading of 400 kPa
water content of the soil at installation: 6.5 %

In the direct shear test, the frictional behaviour of the test sample is determined using a standard shear box apparatus. The sample material is placed into the shear box and a uniform normal load is applied via compacted air cushion to the apparatus.

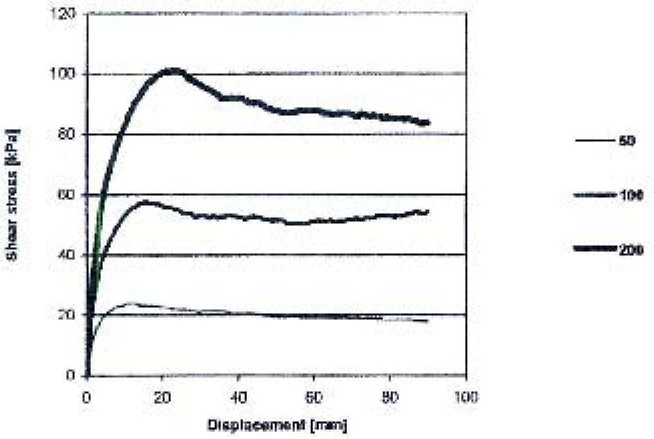


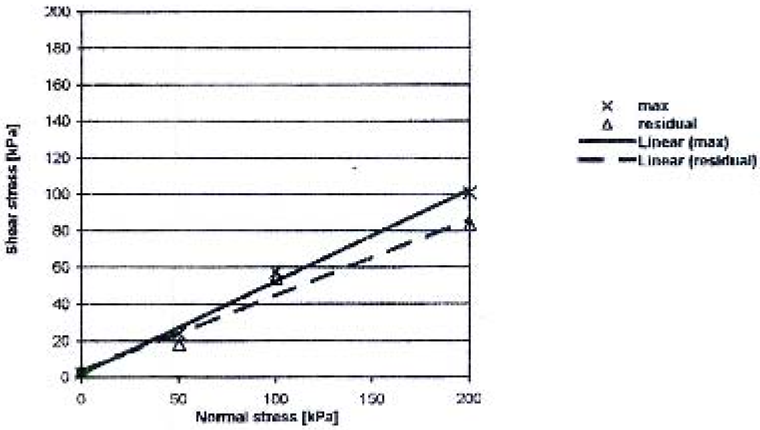

A shear force is induced by the displacement of the lower section of the shear box apparatus. The force is plotted against the displacement for different normal stress loading conditions.

**Test:**
Shear plane: Secugrid 120/40 and sand vs. Fibertex F-1000
Area [cm²]: 900
Rate of strain [mm/h]: 10
Shear plane: under water
Consolidation: yes, under water

| | | | |
|---|---|---|---|
| Normal stress [kPa] | 50 | 100 | 200 |
| Consolidation stress [kPa] | 50 | 100 | 200 |
| Time of consolidation [h] | 1 | 1 | 1 |

059-11 Mariannhill Landfill Site, Southafrica Page 2 of 2




**Regression Line at $\tau_{max}$:** $2.22 + \sigma * \tan 26.68°$
**Regession Line at $\tau_{residual}$:** $3.39 + \sigma * \tan 22.56°$

The use of the results and the appropriate application is the responsibility of the engineer and must take into consideration all aspects of the proposed construction and local soil conditions.

Espelkamp-Fiestel 10/10/2011

H. Ehrenberg K. Knost

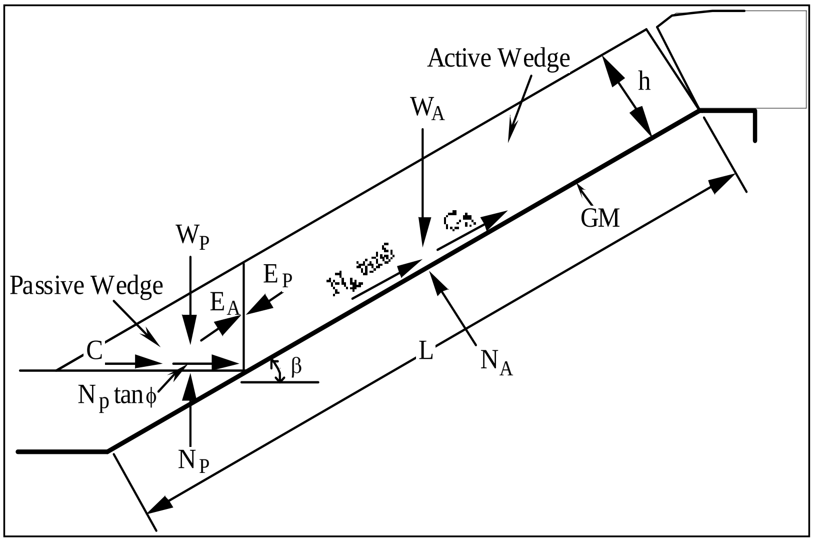
**Shear Box Testing of Secugrid against a geotextile protection layer, Naue, Germany**

## D.4. Calculation of Factors of Safety for Mariannhill Landfill Site

## Cover Soil Stability Analysis Worksheet for Mariannhill Landfill site

### Uniform Cover Soil Thickness

**Slopes up to 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 111.9 kN*

*Na= 106.2 kN*

Passive Wedge:

*Wp= 1.5 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 10.6*

*b= -98*

*c= 26.3*

***FS= 8.91***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.20 | m | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* |
| length of slope measured along the geomembrane = L = | 25.0 | m | |
| unit weight of the stone layer= γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = φ= | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ= | 15.2 | ° | *= 0.27 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 11.7 | kN/m^2 | *Ca= 285.1 kN* |

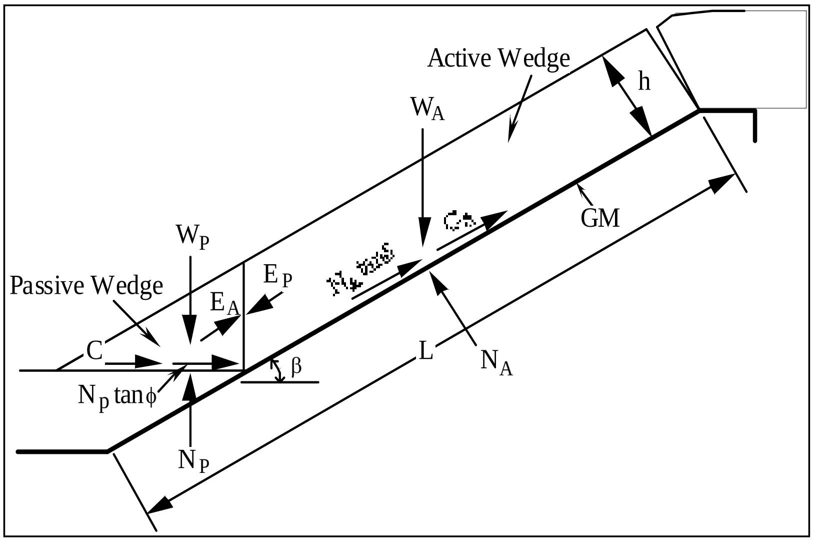
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Mariannhill Landfill site

### Uniform Cover Soil Thickness

**Slopes up to 1:2.5**




**Calculation of FS**

Active Wedge:

*Wa= 98.5 kN*

*Na= 91.5 kN*

Passive Wedge:

*Wp= 1.3 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 12.6*

*b= -100*

*c= 31.9*

***FS= 7.58***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.20 | m | |
| soil slope angle beneath the geomembrane = β = | 21.8 | ° | *= 0.38 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = ϕ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 15.2 | ° | *= 0.27 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 11.7 | kN/m^2 | *Ca= 251.1 kN* |

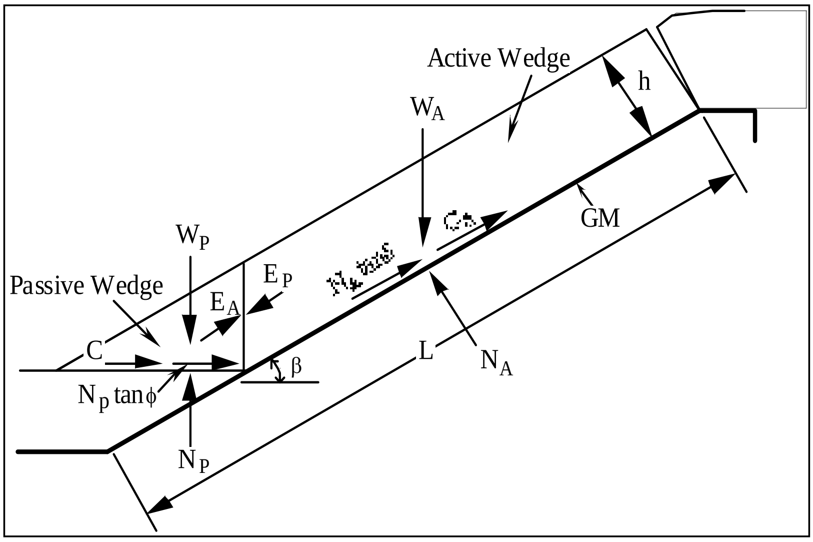
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Analysis Worksheet for Mariannhill Landfill site

### Uniform Cover Soil Thickness

**Slopes up to 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 80.5 kN*

*Na= 72.0 kN*

Passive Wedge:

*Wp= 1.1 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 14.4*

*b= -96*

*c= 37.8*

***FS= 6.28***

| | | | |
|---|---|---|---|
| thickness of cover stone layer = h = | 0.20 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 18.0 | m | |
| unit weight of the stone layer= γ = | 23.0 | kN/m^3 | *for stabilised sand* |
| friction angle of the stone layer = φ= | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ= | 15.2 | ° | *= 0.27 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 11.7 | kN/m^2 | *Ca= 205.37 kN* |

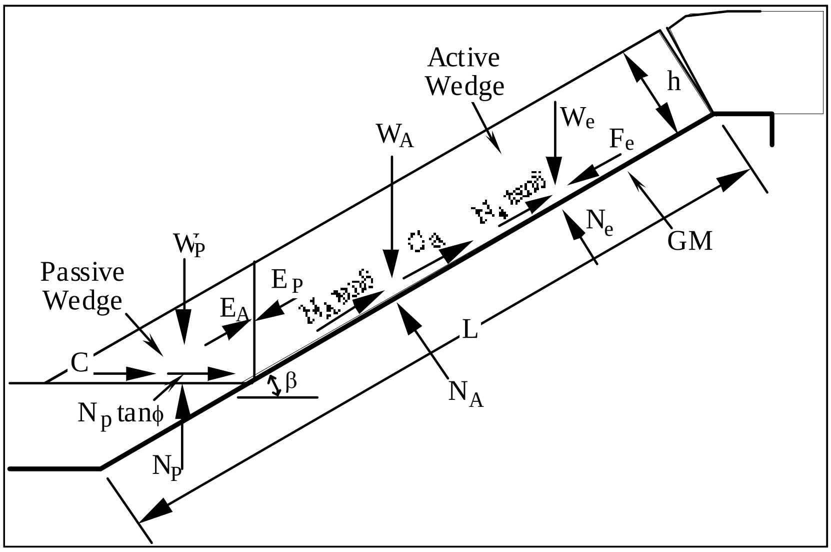
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Mariannhill Landfill Site

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Slopes up to 1:3**




**Calculation of FS**

Active Wedge:

*Wa= 111.9 kN*

*Na= 106.2 kN*

Passive Wedge:

*Wp= 1.5 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 59.8*

*b= -337*

*c= 89.3*

***FS= 5.37***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.20 | m | |
| soil slope angle beneath the geomembrane = β = | 18.4 | ° | *= 0.32 (rad.)* |
| finished stone layer slope angle = ω = | 18.4 | ° | *= 0.32 (rad.)* |
| length of slope measured along the geomembrane = L = | 25.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 15.2 | ° | *= 0.27 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 11.7 | kN/m^2 | *Ca= 285 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.20 | m | *b/h= 3.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 82.8* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ≤300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ≥1000 mm | 0.95 | 0.75 | 0.30 |

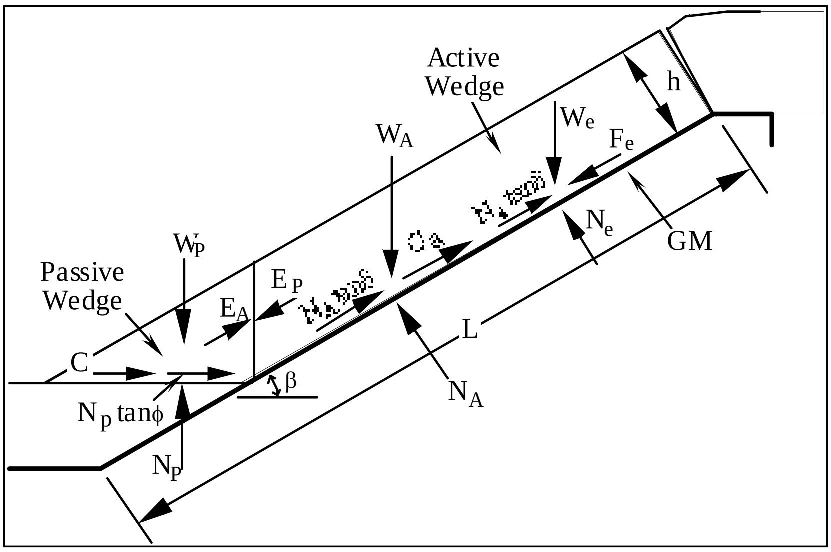
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Mariannhill Landfill Site

**Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)**

**Slopes up to 1:2.5**




**Calculation of FS**

Active Wedge:

*Wa= 98.5 kN*

*Na= 91.5 kN*

Passive Wedge:

*Wp= 1.3 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 64.1*

*b= -299*

*c= 92.9*

***FS= 4.34***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.20 | m | |
| soil slope angle beneath the geomembrane = β = | 21.8 | ° | *= 0.38 (rad.)* |
| finished stone layer slope angle = ω = | 21.8 | ° | *= 0.38 (rad.)* |
| length of slope measured along the geomembrane = L = | 22.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 15.2 | ° | *= 0.27 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 11.7 | kN/m^2 | *Ca= 251 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.20 | m | *b/h= 3.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 81.1* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ²300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ³1000 mm | 0.95 | 0.75 | 0.30 |

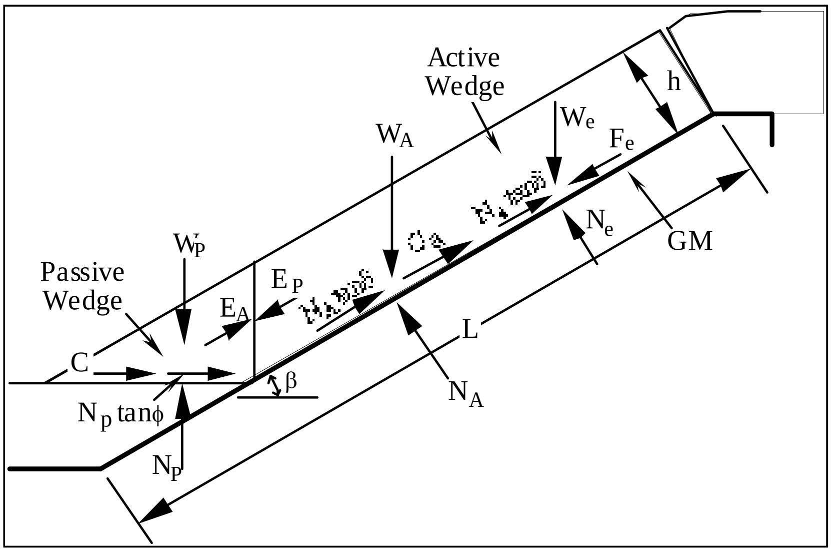
Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## Cover Soil Stability Worksheet for Mariannhill Landfill Site

### Uniform Cover Soil Thickness with the Incorporation of Equipment Loads (Moving Up or Down Slope)

**Slopes up to 1:2**




**Calculation of FS**

Active Wedge:

*Wa= 80.5 kN*

*Na= 72.0 kN*

Passive Wedge:

*Wp= 1.1 kN*

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

*a= 67.2*

*b= -249*

*c= 92.5*

***FS= 3.29***

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.20 | m | |
| soil slope angle beneath the geomembrane = β = | 26.6 | ° | *= 0.46 (rad.)* |
| finished stone layer slope angle = ω = | 26.6 | ° | *= 0.46 (rad.)* |
| length of slope measured along the geomembrane = L = | 18.0 | m | |
| unit weight of the stone layer = γ = | 23.0 | kN/m^3 | |
| friction angle of the stone layer = φ = | 40.0 | ° | *= 0.70 (rad.)* |
| cohesion of the stone layer = c = | 0.0 | kN/m^2 | *C= 0 kN* |
| interface friction angle between geotextile and geomembrane = δ = | 15.2 | ° | *= 0.27 (rad.)* |
| adhesion between geotextile and geomembrane = ca = | 11.7 | kN/m^2 | *Ca= 205 kN* |

| | | | |
|---|---|---|---|
| thickness of stone layer = h = | 0.20 | m | *b/h= 3.0* |
| equipment ground pressure (= wt. of equipment/(2w b)) = q = | 30.0 | kN/m^2 | *We=q w I= 87.3* |
| length of each equipment track = w = | 3.0 | m | *Ne=Wecos β= 78.1* |
| width of each equipment track = b = | 0.6 | m | *Fe=We (a/g) = 0.0* |
| influence factor* at geomembrane interface = I = | 0.97 | | |
| acceleration/deceleration of the bulldozer = a = | 0.00 | g | |

*Influence Factor Default Values

| Cover Soil Thickness | Equipment Track Width | | |
|---|---|---|---|
| | Very Wide | Wide | Standard |
| ≤300 mm | 1.00 | 0.97 | 0.94 |
| 300-1000 mm | 0.97 | 0.92 | 0.70 |
| ≥1000 mm | 0.95 | 0.75 | 0.30 |

Note: numbers in boxes are input values

*numbers in Italics are calculated values*

## D.5. Factors of Safety for HDPE Geomembrane, Protection Geotextile and Veneer Reinforcement Integrity

**Integrity of HDPE Geomembrane - 2.0mm double sided textured**

| | Up to 1:3 Slope | | Up to 1:2.5 Slope | | Up to 1:2 Slope | | Comments |
|---|---|---|---|---|---|---|---|
| Thickness | = 2 | mm | | | | | |
| Density | = 942 | kg/m³ | = 942 | g/m² | = 942 | g/m² | Data sheet |
| Length of slope* | = 25 | m | 20 | m | 15 | m | |
| Mass of 1m strip | = 25*1*0.002*942 | | = 20*1*0.002*942 | | = 15*1*4.310 | | |
| | = 47.10 | kg | = 37.68 | kg | = 28.26 | kg | |
| Weight of 1m strip | = 47.10 * 9.81 / 1000 | | = 37.68 * 9.81 / 1000 | | = 28.26 * 9.81 / 1000 | | |
| | = 0.46 | kN/m | = 0.37 | kN/m | = 0.28 | kN/m | |
| Tensile strength at yield | = 33 | kN/m | = 33 | kN/m | = 33 | kN/m | Data sheet |
| Factor of Safety | = 33 / 0.46 | | = 33 / 0.37 | | = 33 / 0.28 | | |
| | = **71.42** | | = **89.28** | | = **119.03** | | |

* Intermediate anchor trench constructed to assist stability and integrity

**Integrity of Protection Geotextile A10**

| | Up to 1:3 Slope | | Up to 1:2.5 Slope | | Up to 1:2 Slope | | Comments |
|---|---|---|---|---|---|---|---|
| Mass per unit area | = 1000 | g/m² | = 1000 | g/m² | = 1000 | g/m² | Data sheet |
| Mass of 1m strip | = 25*1*1 | | = 20*1*1 | | = 15*1*1 | | |
| | = 25.00 | kg | = 20.00 | kg | = 15.00 | kg | |
| Weight of 1m strip | = 25 * 9.81 / 1000 | | = 20 * 9.81 / 1000 | | = 15 * 9.81 / 1000 | | |
| | = 0.25 | kN/m | = 0.20 | kN/m | = 0.15 | kN/m | |
| Tensile strength at yield | = 76 | kN/m | = 76 | kN/m | = 76 | kN/m | Data sheet |
| Factor of Safety | = 76 / 0.25 | | = 76 / 0.20 | | = 76 / 0.15 | | |
| | = **309.89** | | = **387.36** | | = **516.48** | | |

**Integrity of Veneer Reinforcement Securgrid 120/40**

| | Up to 1:3 Slope | | Up to 1:2.5 Slope | | Up to 1:2 Slope | | Comments |
|---|---|---|---|---|---|---|---|
| Mass per unit area | = 580 | g/m² | = 580 | g/m² | = 580 | g/m² | Data sheet |
| Mass of 1m strip | = 25*1*0.58 | | = 20*1*0.58 | | = 15*1*0.58 | | |
| | = 14.50 | kg | = 11.60 | kg | = 8.70 | kg | |
| Weight of 1m strip | = 14.50 * 9.81 / 1000 | | = 11.60 * 9.81 / 1000 | | = 8.70 * 9.81 / 1000 | | |
| | = 0.14 | kN/m | = 0.11 | kN/m | = 0.09 | kN/m | |
| Tensile strength at yield | = 120 | kN/m | = 120 | kN/m | = 120 | kN/m | Data sheet |
| Factor of Safety | = 120 / 0.14 | | = 120 / 0.11 | | = 120 / 0.09 | | |
| | = **843.61** | | = **1054.52** | | = **1406.02** | | |

## D.6. Mariannhill Landfill Cell 4 – Phase 3 – Consultant Letter

# DRENNAN, MAUD & PARTNERS

Consulting Civil Engineers and Engineering Geologists
Registered Member : S.A. Association of Consulting Engineers
Registered Member : Consulting Engineers of South Africa

PARTNERS:
R.D. COLLYER, Pr.Eng.,B.Sc.(Eng.),M.Sc.(Eng.),MSAICE.
M.J.F. BÉNET, Pr.Sci.Nat.,B.Sc.(Hons.),M.Sc.,FSAIEG.
M.J. HADLOW, Pr.Sci.Nat.,B.Sc.(Hons.),MSAIEG.

CONSULTANTS:
R.R. MAUD, Pr.Sci.Nat.,B.Sc.,Ph.D.,FGS.,FGSSA., FSAIEG.,FSAII

68 RIDGE ROAD
TOLLGATE
DURBAN 4001

P.O. BOX 30464
MAYVILLE 4058

TELEPHONE (031) 201-8992
TELEFAX (031) 201-7920

E-MAIL dmp@iafrica.com

OUR REF.: 21504

YOUR REF.

15 June 2011

P D Naidoo & Associates
P O Box 37659
OVERPORT
4067

**Attention: Mr Nash Dookhi**

**MARIANHILL LANDFILL - CELL 4 - 3**

Hi Nash,

As a follow-up to this mornings meeting on site, herewith a summary of issues discussed and a few additional guidelines/points noted:

- The fill to be placed in the undercut areas shown on site this morning is anticipated to be stable provided:
  - The base is horizontally benched with bench widths limited to a minimum of 3m.
  - The fill material is granular (relatively free drainage as found on site) and is well compacted.
  - Extensive drainage (subsoils) are inserted to prevent any build up of the water table and poor water pressures in the fill.
  - The outer fill slope angles are of the order of 1 in 2,4 as indicated on site.

- For definite answers regarding the fill stability a recommended way forward would be to run some stability analysis in the fill areas and see what factors of safety are obtained. This will however require time, a few cross-sections of the undercut profile, and some shearbox tests on a re-compacted sample of the fill.

- It is recommended that the earthworks be performed as rapidly as possible or in limited length segments because:
  - Stormwater erosion will cause extensive damage to the exposed sandy fill slope prior to lining/sealing.
  - The steep face portions below the upper cut off drain are susceptible to localised failures. If practically possible, temporary support soil berms can be placed in steeper under cut areas to provide temporary support until such time as a particular area is worked.

- As mentioned on site this morning, a brief review of the proposed liner detail raises the following concerns:
  - There are some areas where the stabilised sand liner approaches 27 - 30° which may have stability (limited safety factor built in) and practical (compaction) implications. A test section on the steeper areas will shed light on whether it is possible to use stabilised sand on the steeper areas (>26°) or whether it would be better to use a thick protection geotextile instead.
  - Interface shearbox testing of the proposed liner will reveal the weakest layer with the lowest shear strength. This layer should be above the HDPE geomembrane.
  - Our preliminary stability analysis reveals that a Residual Friction angle >9° for this weakest layer should result in a stable landfill. However due to limitations of our stability analysis relative to the complexity of Marianhill, as outlined in our letter (27 October 2010), a second opinion is still recommended in this regard.

Yours faithfully
**DRENNAN, MAUD AND PARTNERS**

**KARL RIBBINK Pr.Sci.Nat**