Stability of Landfill Lining Systems: Report No. 2 Guidance

R&D Technical Report P1-385/TR2

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This report has been produced to accompany R&D Technical Report P1-385/TR1 and should be used in conjunction with that report. This report provides the design assessment framework for the underpinning science provided by the 1st report. Both these reports should be used by people who design, construct, operate and regulate landfill sites, however they should be used in conjunction with advice from a suitably experienced geotechnical engineer. Guidance will be produced as a result of this research. It is essential that any person carrying out an assessment of stability or integrity of a landfill lining system as part of a Pollution Prevention and Control Permit Application for a landfill should use the guidance as a foundation for that assessment. It is recommended that any persons assessing the ongoing stability of a landfill either as a review of a Waste Management Licence or as a result of a identified failure of the waste or liner, should consider the advice and guidance provided as a result these reports.

Keywords
Landfill, Landfill Liner, Stability, Integrity, Geotechnical Assessment, Liner Failure, Engineering, Material Strength, Waste, Landfill Directive.

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EXECUTIVE SUMMARY

Consideration of landfill lining system stability is a fundamental part of the design and the regulatory process by the application of the EC Landfill Directive (1999) requirements through the Pollution Prevention and Control (PPC) permitting process. The stability of the waste mass, lining system and sub-grade should be ensured. Incorrect or incomplete assessment of stability has led to a number of failures both in the United Kingdom (UK) and overseas. The occurrence of failures, introduction of new materials and construction practices, developments of new design methods and ongoing changes in waste materials, together with the legislative need to remove the risk to human health and the environment have all contributed to the need for this review.

Design of landfills must consider stability both within and between elements of the lining system, within the waste and involving the sub-grade. This is to ensure that uncontrolled slippage of any of the elements does not occur. However, the design must also consider the long-term integrity of the lining system. Stresses, and hence deformations, in both mineral and geosynthetic lining materials must be controlled to ensure preferential flow paths are not formed (e.g. shear zones in clay liners and tears in geomembranes). An assessment of integrity requires knowledge of the lining sub-grade behaviour (i.e. cut and fill slopes, cell base), consideration of interaction between elements of the lining system and an assessment of the influence of time dependent waste deformations (e.g. settlement). Use of traditional limit equilibrium stability methods cannot by themselves provide a full assessment of a lining system. Instability is taken to include failure by complete collapse and loss of integrity, therefore both are covered in this report

Report No. 1 provides information on case studies of failures and a review of international literature on landfill engineering practice, with particular reference to the stability and integrity of lining systems. It has been produced as part of the Environment Agency funded R&D project P1-385: '*Assessment of the stability of landfill lining systems*'. From the literature review a series of limitations in current knowledge and current practice have been identified. The information gained in this literature review has been assimilated to produce guidance on the stability of landfill lining systems, and this is presented in this Report.

CONTENTS

1. INTRODUCTION

This report gives recommendations on the assessment of landfill liner system stability and integrity. It provides guidance on design philosophy and assessment, and includes example calculations demonstrating the design process and covering a number of issues specific to landfill design. This is the second of two reports and it fully references Report 1: Literature Review, which is a detailed summary of the key issues controlling landfill stability assessment based on the international state-of-the-art.

Guidance on design philosophy is provided in Chapter 2 covering the selection of appropriate safety factors to ensure the stability and integrity of landfill lining systems. It includes a summary of the design process, a description of the key issues influencing the selection of safety factors, selection of characteristic values and specific guidance on selection of appropriate factors of safety.

Chapter 3 covers design assessment. It provides a summary of design issues, controlling factors and methods of analysis. The aim is to provide information on all aspects of landfill liner design with respect to stability and integrity in a format that is readily accessible. This information is a summary of and compliment to the detailed contents of Report 1. It is anticipated that this section will be used as an aid memoir to those involved in producing and checking design calculations. Information is presented in two formats: design flow charts and summary lists of key issues. Design flow charts and supporting information on controlling factors are given for each of the six main landfill elements.

- sub-grade;
- basal lining system;
- shallow side slope lining system;
- steep side slope lining system;
- waste slope; and
- capping lining system.

Four examples are presented in Chapter 4. These have been selected to demonstrate use of the design flow charts and selection of appropriate design cases. Each of the examples has been chosen to highlight specific landfill liner stability and integrity issues. Detailed calculations, including justification of parameters, analysis method and factors of safety, are provided.

2. DESIGN PHILOSOPHY

2.1 Introduction

The purpose of this section is to provide guidance on the selection of appropriate safety factors to ensure the stability and integrity of landfill lining systems. It includes a summary of the design process, a description of the key issues influencing the selection of safety factors, selection of characteristic values and specific guidance on selection of appropriate factors of safety.

Despite the relative simplicity of the concept of safety factors, there is considerable scope for their misuse and misapplication. Any guidance that is provided cannot be prescriptive. Suitable values of safety factor for a particular design case can only be obtained after a careful assessment of all relevant controlling factors and the exercise of sound engineering judgement. It cannot be stressed too strongly or too often that an experienced geotechnical specialist must be involved in all aspects of the design process and that all factors of safety considered acceptable must be justified fully.

2.2 Summary of Design Process

2.2.1 Design concept

The aim of correct design is to ensure that the product or structure being designed performs satisfactorily in its intended environment for the duration of its intended life. It should sustain any adverse effects or actions with an adequate degree of safety. An apposite quote from BS 8110 (BSI:1985a) refers to the design method:

> "account should be taken of accepted theory, experiment and experience and the need to design for durability. Calculations alone do not produce safe, serviceable and durable structures. Suitable materials, quality control and good supervision are equally important".

The design forms only part of the process to produce a stable and durable structure. If other aspects of the process are inadequate the design calculations could be misleading and the performance of the structure compromised. In the discussion of the design process in this chapter it is assumed that the approach (i.e. good practice) outlined below is followed (BSI: 1995b):

- data required for design are collected, recorded and interpreted;
- structures are designed by appropriately qualified and experienced personnel;
- adequate continuity and communication exist between personnel involved in data collection, design and construction;
- adequate supervision and quality control is provided in factories, in plants and on site;
- execution is carried out according to the relevant standards and specifications by personnel having the appropriate skill and experience; and
- construction materials and products are used as specified.

A *factor of safety* is a concept or tool used in the design process to assists engineers in the safe and efficient design, specification and construction of structures to an appropriate standard. This means that for a given application the requirements of safety and function are met, whilst avoiding unnecessary or excessive cost. The use of factors of safety allows engineers to overcome a range of uncertainties in analysis. Such uncertainties may arise from the inevitable simplification and approximation required in analysis methods, uncertainty with respect to the controlling material parameters, the possibility of missing a potential failure mechanism and changes that might occur locally and with time.

Current engineering design practice is to use the limit state approach. Failure can be defined in terms of two states:

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

In the context of landfill lining system design:

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

2.2.2 Limit equilibrium

Limit equilibrium analysis assesses the possible motion of a rigid body moving on defined planes. The starting point of any analysis is to propose a potential mechanism of failure (i.e. to define the extent of the body involved in the mechanism and the planes along which movement could occur). In many applications there are a number of potential failure mechanisms and each must be assessed in order to find the most likely. For example, assessment of a shallow side slope landfill lining system would require the possibility of failure along each of the interfaces between components and through each of the mineral layers to be checked individually. This does not necessarily mean that calculations are required for each possible mechanism, but that each component or interface is considered to assess the likelihood that it controls behaviour. Simple comparison of the shear strengths measured for each interface and mineral layer will often indicate which will control the design.

While limit equilibrium analysis can be used to design against the occurrence of ultimate limit states (e.g. slope instability) it is less useful in ensuring serviceability limit states are not exceeded. In many design cases, including landfill liner design, serviceability limit states are related to deformations in the system and stress levels within defined components. Deformations and stresses can be controlled in limit equilibrium analyses by increasing the size of the factor of safety, however, it is difficult to quantify strains related to a given factor of safety. It is often more appropriate to analyse the problem as a continuum in order to assess the stresses and strains in the system and hence to design for the serviceability limit state directly. This type of analysis requires the use of computer programs based on analytical techniques such as finite element and finite difference formulations (e.g. as used in Chapter 11, Report 1, to assess waste/barrier interaction). These programs are more complex to use, require users with specific skills and experience and they employ a larger number of material parameters, which often have to be obtained by carrying out sophisticated laboratory and field tests.

2.2.3 Definition of factors of safety

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. It is commonly expressed as the ratio of *the load or action, which would cause failure* against *the actual load or actions likely to be applied during service.* For example the factor of safety (F) can be written as:

$$F = \frac{Available\ restraining\,force}{Disturbing\ force}\ or\ \frac{Ultimate\ load}{Design\ load}\ or\ \frac{Shear\ strength}{Mobilised\ shear\ stress}$$

The above forms are generally applied to simple situations where the stress at failure exceeds the stress in service (e.g. slope instability).

In the case of soils, their strength is often described by more than one parameter, the effective cohesion c′ and effective angle of internal friction φ′. Rather than applying a single overall or global factor of safety it is sometimes more appropriate to design utilising *partial factors* applied to reflect the uncertainties of individual parameters e.g.:

Design $c' = c'/F_c$ and, design $\tan\phi' = \tan\phi'/F_\phi$

Where F_c and F_ϕ are partial factors for cohesion and friction respectively.

2.2.4 Design process

Two approaches are currently used in the UK for geotechnical design:

- traditional approach based on the use of a global factor of safety; and
- the Eurocode 7 (BSI: 1995b) approach using partial factors applied to both actions and material properties.

Traditional Approach

Calculations are carried out using *conservatively chosen mean values of the material parameters* (see Section 2.4) with the expectation of achieving a factor of safety greater than 1.0 against occurrence of the specific mechanism under consideration. The actual value of the factor of safety required depends upon many factors as discussed in Section 2.3. The factor of safety is considered a global value because it is the only factor explicitly applied in the analysis. However, the material parameters used in the analysis and the actions (e.g. slope angle, pore water pressures, unit weight of materials) are selected to represent unfavourable, and in some instances extreme, conditions and therefore this process represents the application of additional factors. These are essentially derived using engineering judgement. Using the traditional approach, a calculated factor of safety of unity would suggest the structure is only marginally stable and therefore inadequate.

Eurocode 7 Approach

Eurocode 7 (BSI: 1995b) formalises the use of partial factors and limit state design in geotechnical engineering. Calculations are carried out using *characteristic values* of the material parameters (see Section 2.4) with partial factors applied to obtain the *design values* as described in Section 2.2.3. The magnitude of the factors depends upon the design case considered. In addition, factors are applied to the actions (i.e. dead and live loads). As for the traditional approach the actions are selected to represent unfavourable, or in some cases extreme, conditions. Following the application of the partial factors, the calculations are carried out for the ultimate limit state in the same manor as for the traditional approach. The factor of safety obtained from the calculations is required to be greater than 1.0. Values significantly in excess of 1.0 represent overly conservative designs. Using the Eurocode 7 approach, a calculated factor of safety of unity would suggest the structure is stable and therefore adequate.

For slope stability cases the two approaches have been shown to produce similar designs. The partial factors for the ultimate limit state defined in Eurocode 7 for application to the material parameters, have an effect comparable to the typical global factors of safety applied in the traditional approach. In the remainder of this guidance, the traditional approach will be the focus of discussion.

2.3 Specification and Interpretation of Factors of Safety

2.3.1 Controlling factors

The choice of what is an acceptable value for a global factor of safety requires detailed consideration and the application of engineering judgement to a number of elements. These can be summarised as:

Issues related to confidence in the adequacy of the design

- representative nature of the parameters (i.e. characteristic values) chosen for use in design to the as-constructed conditions (i.e. related to the quality and extent of the geotechnical investigation and predictions of changes that occur with time);
- appropriateness of the analysis method employed;
- appropriateness of the failure mechanism analysed and coverage of all possible failure mechanisms;
- consideration of the deformations implied by the magnitude of the factor of safety obtained;
- control of stresses to pre-peak values in brittle materials (i.e. mobilisation of post-peak values in such materials can lead to large deformations, hence significant consequence of failure); and
- quality of construction (i.e. variability in design standards and specification of materials).

Issues related to the consequences of failure

- risks to persons and/or the environment; and
- ease and cost of remedial actions.

In cases where knowledge of ground conditions is poor or limited, or the consequences of failure are significant, higher factors of safety would be required than if the information on ground conditions is known to be accurate and precise, or where the risks associated with failure are negligible. In the majority of engineering applications experience plays a major part in the choice of what is an acceptable factor of safety. In more novel applications that have not been 'tried and tested' it is more sensible to adopt a cautionary approach and use a higher factor of safety. Landfill lining systems fall into this category. For most of the lining systems presently in use there is less than 10 years experience and a dearth of information on their long-term performance.

Choosing a low factor of safety results in obvious consequences (i.e. the design will fail to meet the needs of the application and result in increased risks), and any remedial actions will be costly in both monetary and materials terms. Conversely, specifying an excessively high value leads to a wasteful 'over specification' of material property requirements and in the case of landfill design it can result in the loss of valuable void space.

2.3.2 Specific issues related to landfill engineering

A major consideration in the geotechnical design for landfill is that unlike many civil engineering projects, a key material (i.e. waste) is very variable. Design cases that involve the waste body must take into consideration both the heterogeneous nature of waste and the limited amount of information currently available on its material engineering properties. Unlike many above ground structures, it is generally difficult to inspect or check the integrity of the structures after waste has been placed. Monitoring the lining system with geotechnical instruments would provide the required information but this is presently not incorporated in UK landfills. Without the information provided by such instrumentation it is not possible to assess the performance of current lining systems, and hence to review the design, including the appropriateness of currently used factors of safety. Although the consequences of failure may be significant, the risks associated with repair or remediation are often considered to be prohibitively dangerous or expensive.

The combination of the relatively short time period over which landfills have been either designed or "engineered" and the changing composition of waste means that it is difficult to make assumptions regarding characteristic properties of waste or failure mechanisms. Where structures are designed to meet particular and specific needs, materials are usually selected on the basis of their particular properties and the consistency and predictability of these properties. Unfortunately the properties of many waste materials are not beneficial to the function of lining systems. They have poor drainage properties that may result in high pore pressures, high compressibility generating large settlements, non-uniform stress distributions are exerted on structural elements and low stiffness results in poor support conditions. Uncertainty regarding waste material engineering properties should be considered in the selection of an appropriate factor of safety.

2.3.3 Consequences of failure

The value of factor of safety required by a specific design must also reflect the consequence of failure. It is obvious that the nature and volume of deposited materials in the majority of landfills means that failure of the liner is likely to result in increased environmental risks and/or extremely costly and problematic remedial measures. This should be reflected in the choice of factor of safety adopted.

2.3.4 Characteristic values and unfavourable actions

In the traditional approach, partial factors are not explicitly applied to material properties, the problem geometry or forces acting on the system. However, implied partial factors are used through selection of characteristic material values and the use of unfavourable actions (e.g. worst-case slope angle, maximum pore water pressures etc.). Although some formal procedures exist for obtaining characteristic values of material properties (see below), it is rare for sufficient site-specific information to be available to employ statistical techniques. Therefore, the problem definition, including material properties, geometry and actions, is often based on the interpretation of limited information. An experienced geotechnical engineer using past experience to develop engineering judgements must carry this out. The process by which judgements are made must be fully documented in the design calculations (i.e. reference to supporting data and explaining the decision process). Use of favourable or even mean values of parameters can lead to local failure under normal operating conditions and complete failure under exceptional or extreme conditions. There is considerable evidence to show that ignoring unfavourable actions leads to many of the failures observed in landfill engineering (see Chapter 4, Report 1).

Characteristic Values

Conservatively chosen mean values of the material parameters (traditional approach) and characteristic values can be considered to be comparable. The term *characteristic value* is used here. Selection of characteristic values of soil and geosynthetic properties must take account of:

- inherent variability of soil;
- inherent variability of manufactured geosynthetic materials;
- measurement errors; and
- extent of zone governing behaviour of limit state being considered.

Measurement errors are a significant factor and are caused by equipment, procedural, operator and random test effects. These have been discussed in Chapter 7, Report 1, where typical variability of measured strengths is also discussed.

In Eurocode 7 (BSI: 1997), the characteristic value of a soil property is defined as a *cautious estimate of the value affecting the occurrence of the limit state*. The characteristic value should be a cautious estimate of the mean value over the governing zone of soil (Orr & Farrell, 1999). Assessment of an interface between a geosynthetic and soil requires characteristic values of the shear strength parameters that produce a cautious calculated mean shear strength over the entire area of the interface involved in the potential failure. Eurocode 7 advises that: i*f statistical methods are used, the characteristic value should be derived such that the calculated probability of a worse value governing the occurrence of a limiting state is not greater than 5%.*

Schneider (1997) has proposed a statistical approach for determining the characteristic value (X_k) using the mean value of the test results (X_m) and the standard deviation of the test results (σ_m):

$$X_k = X_m - 0.5\sigma_m \qquad \text{(Equation 2.1)}$$

The approach aims to ensure in the order of 95% confidence that the real statistical mean of the interface strength is superior to the selected X_k. This equation has been in use in Switzerland for several years and has been proven to produce values that are in close agreement with values estimated by experienced geotechnical engineers (Schneider, 1997).

The process of obtaining design parameters is typically:

- selection of representative samples;
- measure material properties (e.g. results of laboratory direct shear tests at specific normal stress levels);
- calculate derived values based on theory, empirical relationship or correlations (e.g. obtaining α_m and δ_m values that describe the best fit straight line through the measured strengths); then
- calculate characteristic values α_k and δ_k (a cautious estimate of α_m and δ_m as discussed above).

These values are then used in the analysis with the aim of obtaining the required factor of safety. Further guidance on the selection of characteristic values in relation to interface shear strength and an example are included in Section 7.5.5, Report 1.

If there is insufficient data to carry out a statistical analysis of a material property then past experience and engineering judgement must be used to define a *cautious estimate* of the value. It should be noted that this does not always mean obtaining a lower value. For example, the unit weight of a material above a potential failure plane may produce a disturbing action. The characteristic value should be larger than the mean, thus leading to the worst case, while a value below the mean will result in an un-conservative and potentially unsafe design.

Unfavourable Actions

As discussed in Section 2.2 above, a key element of stability calculations is the selection of design values, and their possible ranges, for the controlling actions. This includes; slope geometry, material properties (e.g. unit weight of liner components and waste properties), water pressures, gas pressures, construction plant forces and actions related to the method of construction (e.g. stockpiles of material).

Slope geometry: Design must consider the maximum slope angle, slope height, location and size of berms and all possible combinations of these parameters. Failure to assess all combinations could result in local failures occurring. Tolerances involved in construction of the slopes should also be considered.

Material properties: Characteristic values should be obtained for all material properties used in the analysis. Where there is inadequate data to enable statistical determination, past experience and engineering judgement must be used in conjunction with the available data. As noted above, in the case of destabilising actions such as self-weight of materials, characteristic values may be larger than mean values. Where waste properties are used in analyses and limited information is available, it is appropriate to carry out sensitivity analyses using the range of possible values based on the description of the waste and information in the literature.

Water pressures: Water plays an important role in any analysis of stability. Analyses should be carried out using the expected worst case pressures for normal operation conditions. It might also be appropriate to assess the consequences of extreme pore pressure conditions (e.g. failure of drainage provision).

Gas pressures: Where gas pressures are considered to influence slope stability, the worst case pressures must be assessed using an approach such as described in Section 11.3.3, Report 1. Due to the approximate nature of predicted values, it is appropriate to carry out a sensitivity analysis. If the gas pressure is found to be important for design, a gas pressure relief system should be designed within the lining system to ensure critical gas pressures are not produced.

Construction plant forces: Types of construction plant required to form the slope and the likely mode of operation of such plant must be considered as part of the design. Equipment self weight and operational forces (e.g. braking) should be included. Where particular modes of operation are shown to cause instability (e.g. spreading material down slope), the design must be modified or restrictions placed, and enforced, on the site operations. The possibility of generating post-peak shear strengths on interfaces should also be considered (see section 2.4).

Method of construction: Consideration must be given to the method of construction in all designs in order to identify temporary cases that could produce instability. Such cases could include: locally steeper slopes, removal of toe support, additional loading (e.g. stockpiles of material), short-term stability of cohesive materials and higher pore pressure prior to drainage systems becoming fully operational.

2.4 Selection of Appropriate Factors of Safety

2.4.1 General guidance

This guidance relates specifically to slope stability, basal heave and stresses in components. As discussed above, there are many issues that must be considered when selecting an appropriate factor of safety. The main controls are site specific, material specific, dependent upon the experience of the designer and related to the consequences of failure. Therefore, it is impractical to specify absolute values for use in design as part of this guidance document.

However, if the good practice outlined in sections 2.2 and 2.3 is followed, it is possible to indicate appropriate magnitudes for factors of safety and to suggest how different factors can be deemed acceptable in specific circumstances.

Slope Stability

Slopes should be designed to obtain factors of safety in the region of 1.3 to 1.5. Experience has shown that if factors of this magnitude are obtained having followed accepted practice, then in the general case long-term stability will be assured (see below for cases where this might not be acceptable). This guidance has been in existence for many years (e.g. BS 6031: 1981 {BSI: 1981}) and is supported by general industry experience. Such analyses would be expected to represent unfavourable actions but not necessarily extreme conditions. If an extreme condition is possible, but it is considered unlikely, it is often appropriate to carry out an analysis for the extreme condition but to accept a lower factor of safety, but obviously still greater than 1.0. An example of where this approach might be used is in the assessment of an extreme groundwater condition.

The primary aim in many stability calculations is to ensure that post-peak shear strengths are not mobilised and hence to control deformations. The factor of safety applied in these cases is partly accounting for uncertainty in measured shear strengths. Where the design case being analysed is controlled by a pre-existing, or interface controlled, slip surface which is known to have residual shear strength, then it is often appropriate to accept a lower factor of safety (i.e. post-peak shear strengths are already mobilised). A factor of safety in the order of 1.2 can be used (e.g. BS 6031: 1981 {BSI: 1981}).

An additional consideration in the selection of an appropriate factor of safety is the size of the problem being assessed in relation to the magnitude of likely variations in actions. For example, a small slope will require a relatively minor increase in pore water pressure to reduce the slope to failure (e.g. Factor of safety < 1.0), although a similar magnitude increase in pore water pressure would have a limited affect on a larger slope. An appreciation of this issue can result in a more considered approach to the selection of appropriate factors for a given design case.

Basal Heave

Basal heave calculations are relatively simple and rely on knowledge of three main parameters; depth to permeable stratum from ground level, unit weight of layers above permeable stratum and pore water pressure in permeable stratum. Of these three parameters it is the pore water pressures which represent the biggest potential for uncertainty (i.e. in situ measurements are often made over a limited time and the values might not reflect worst case conditions). Each permeable layer that could cause basal heave should be analysed independently. Also, the variability of the parameters across the site should be assessed in order to ensure that unfavourable actions are analysed. A factor of safety in the order of 1.5 is generally considered to be appropriate. However, if a particularly detailed ground investigation has been conducted and the designer considers the controlling parameters to be known with a high degree of certainty then it is acceptable to justify the use of a lower factor of safety.

As for slope stability assessments, the size of possible variations in the parameters (actions) should be considered in relation to the size of the factor of safety. For example, a permeable layer located only 1 metre below excavation level would required an increase in pore water pressure of only 7 kPa to reduce the factor of safety from 1.5 to 1.0. For a permeable layer 5 metres below excavation level this same change in pore pressure of 7 kPa would decrease the factor of safety from 1.5 to 1.36.

Tensile Strength

Assessment of the design of geosynthetic components can include calculation of factors of safety on tensile strength (e.g. geotextile protection layers and reinforcement layers). If the primary function of the geosynthetic is reinforcement then a factor of safety in the order of 2.0 is typically required. However, where the control of strains is not a primary concern then a lower factor of safety may be appropriate. In cases where strains in the material control the design, the factor of safety is selected to limit the tensile stress and hence strain in the material. An example of this is the design of reinforcement layers to control strains in lining components (e.g. Chapter 10, Report 1).

2.4.2 Drained and undrained analyses

Cut slopes and compacted fill formed of cohesive soils can have a higher shear strength in the short-term undrained condition than in the long-term drained condition. The higher undrained shear strength is a function of the pore water suctions generated either during stress relief on slope formation (cut slope) or the compaction process (fill). If it can be shown that the suctions, and hence strength, will be acting during the period of time that the specific design case is valid, then undrained strengths can be used in the analysis (i.e. a total stress analysis). For example, if waste is placed in a cell quickly it might be considered that a mineral liner placed on a shallow side slope remains in an essentially undrained condition up until waste is placed against the slope. A factor of safety in the order of 1.3 to 1.5 would be required as discussed above.

However, if there is doubt that the suctions will remain, a drained analysis using effective stresses and shear strengths must be carried out to ensure that stability is guaranteed if the suctions dissipate. As the suctions dissipate the effective stresses will reduce causing the shear strength to reduce. This will result in the factor of safety decreasing with time. If material assessment and experience indicate that drained conditions are likely to exist and hence control the design, then a factor of safety in the order of 1.3 to 1.5 will be required for this case.

If there is confidence in the existence of undrained conditions, the design will be based on undrained strengths but the drained case should still be checked as the extreme condition (i.e. just in case the suctions dissipate). A factor of safety in the order of 1.3 to 1.5 would be achieved for the undrained condition and a factor of safety greater than 1.0 for the extreme drained case. Guidance on the choice of drained or undrained (i.e. short-term and long-term) analyses is given in Section 9.2.3, Report 1, and in standard soil mechanics and geotechnics textbooks.

2.4.3 Peak and residual conditions

Some materials used in lining systems, and the interfaces between them, can be described as strain-softening (i.e. their strength reduces as they are strained past the peak shear strength), see Chapter 7, Report 1. This strain-softening, or brittle behaviour, must be considered as part of the design process. Designing a lining system to ensure that shear stresses are kept below the peak shear strength (i.e. by the application of an appropriate factor of safety and using peak shear strengths) will limit strains in and between lining components and this can guarantee both stability and integrity. Such analyses must consider all actions that stress the lining system and that could lead to the generation of post peak strengths. These include issues of material strain incompatibility (e.g. deformation of the adjacent compressible waste body) and repeated construction plant loading. If the lining system cannot be isolated from the action stressing it, it may be appropriate to design the slope using residual shear strength and to accept that peak values can not be relied upon. As discussed in Section 2.4.1 above, if the shear strength controlling stability is known to be the residual value then a lower factor of safety might be justified.

The danger in this approach is that the strains required to mobilise the post-peak strength might result in loss of liner integrity. This must be checked as part of the design. A possible design approach is to allow post-peak stresses to develop, use residual shear strengths in the analyses and to design the lining system to accommodate the strains that will occur, and hence ensure both stability and integrity. For example, slippage could be allowed along a specific interface in order to isolate the key elements of the liner from waste settlement, and protection layers can be designed to accommodate the large movements without compromising the integrity of the lining system.

2.5 Guidance for Waste/Barrier Interaction

The key mechanism causing the generation of post-peak strengths discussed in Section 2.4.3 above is the settlement of waste adjacent to the lining system. This issue was discussed in detail in Section 11.4.4, Report 1, and a methodology was proposed based on numerical analysis to assess the likelihood of post-peak strengths being mobilised, and hence to quantify the strains at a given interface. It was shown that limit equilibrium analyses using standard factors of safety can significantly underestimate the possibility of large strains occurring along sections of an interface and that this can lead to loss of integrity. While the results presented and discussed in Section 11.4.4, Report 1, can be used as a guide to likely behaviour, they only cover one interface and a limited range of slope geometries. It is advised that comparable numerical analyses be carried out for site specific conditions in order to assess designs in terms of integrity. Limit equilibrium analyses can be used to assess overall waste/barrier stability but should be used with extreme care and the results assessed by an experienced geotechnical engineer.

2.6 Need for Appropriate Monitoring

Since the engineering solutions applied to landfill are often novel and do not have the benefit of many years of in-service experience, it is essential that appropriate geotechnical instrumentation and monitoring procedures are applied. The information obtained from such instruments is required to assess the structural performance of the lining system and hence to review the design. Without this feedback it is not possible to optimise the selection of suitable factors of safety. Monitoring is of fundamental importance to the continued development of efficient cost effective lining systems that protect the environment.

2.7 Evolution of Design Criteria

It may be evident from examination of the design and construction of many existing sites that appropriate factors of safety may not have been chosen and that some designs have been implemented which are either inherently unsafe or rely on factors which are hard to quantify. The continuing usage of such systems on operational sites may cause a dilemma for operators and regulators alike. The designer should be guided by the state of knowledge at the time of design taking into account the life of the landfill and its aftercare. If, for a particular site there is evidence that indicates the system is not performing as designed, then the design should be reassessed and revised to ensure a valid approach is used in subsequent phases and other similar landfills.

The opportunity to learn from failures should not be missed. Back analysis of failures provides a useful tool to identify mechanisms, and this further informs the design process and avoids repetition of poor design.

3. DESIGN ASSESSMENT

3.1 Introduction

This section provides a summary of design issues, controlling factors and analysis methods. The aim is to provide information on all aspects of landfill liner design with respect to stability and integrity in a format that is readily accessible. This information is a summary of and compliment to the detailed contents of Report 1. It is anticipated that this section will be used as an aid memoir to those involved in producing and checking design calculations. Information is presented in two formats: design flow charts and summary lists of key issues.

3.2 Design Flow Charts

Design flow charts are given for each of the six main landfill elements:

- sub-grade (Figure 3.1);
- basal lining system (Figure 3.2);
- shallow side slope lining system (Figure 3.3);
- steep side slope lining system (Figure 3.4);
- waste slope (Figure 3.5);
- capping lining system (Figure 3.6).

They include information on all main design cases. For each case lists of design issues and controlling factors are provided. It is intended that they be used to identify the design cases and key design issues for a particular site that should be assessed as part of the design process. In many instances it will be necessary to assess a number of design cases, as they are often not mutually exclusive.

3.3 Key Issues for Consideration

A second level of information is provided in support of the flow charts in the form of detailed lists of '*key issues for consideration*' for each possible design case. These are a summary of the key factors identified in Report 1. Information is included on the factors controlling each particular design condition, the input parameters required for design and the appropriate analysis methods. References are given to the appropriate supporting sections of Report 1.

It is not proposed that detailed calculations be required to assess each design case. In many instances a review of the site and liner system specific information will enable the likelihood of a number of possible failure conditions to be discounted. This may entail carrying out simple calculations or using engineering judgement, although the engineering argument must always be fully documented as part of the design assessment.

In the following sections each design case is considered separately. All cases highlighted in the design flow charts (Figures 3.1 to 3.6) are included individually. Where design cases are interrelated, reference to all relevant cases is provided. When design cases are governed by the same or similar sets of issues, a full list is provided under each design case to limit the amount of cross-referencing and hence to simplify access to the information.

3.3.1 Sub-grade

Stability and deformability of the sub-grade are key issues in the design of landfill lining systems. The stability of void side slopes must be ensured both during construction and in the long-term. The deformability of the sub-grade controls the strains in the lining system and hence its integrity. A full assessment is required prior to detailed liner design as information on the sub-grade is required for use in the design calculations. Design issues, controlling factors and analysis methods are given below. Comprehensive information on sub-grade stability is given in Chapter 9, Report 1 including key references.

Table 3.1 Base/Excessive Deformations/Compressible Sub-grade

	Design Issues: Adequate site investigation, information is used in design of basal lining system (see Section 3.3.2)

Table 3.2 Base/Excessive Deformations/Cavities

	Design Issues: Adequate site investigation, information is used in design of basal lining system (see Section 3.3.2)

Table 3.3 Base/Excessive Deformations/Basal Heave

	Design Issues: Adequate site investigation Prevent heave
	Controlling Factors: Groundwater pressure distribution permeability (aquifer and aquiclude) dewatering time dependency (e.g. climate) Stratification thickness of soil/rock layers and variation across site relationship between pore water pressures and layers permeability shear strength Unit weight Modes of deformation doming hydraulic fracture and piping softening Formation level
	Analysis: Calculate ratio between total stress and pore water pressure at the base of all aquicludes
	Stabilisation Techniques: Pore water pressure dissipation relief well system Increase elevation of formation increases total stress

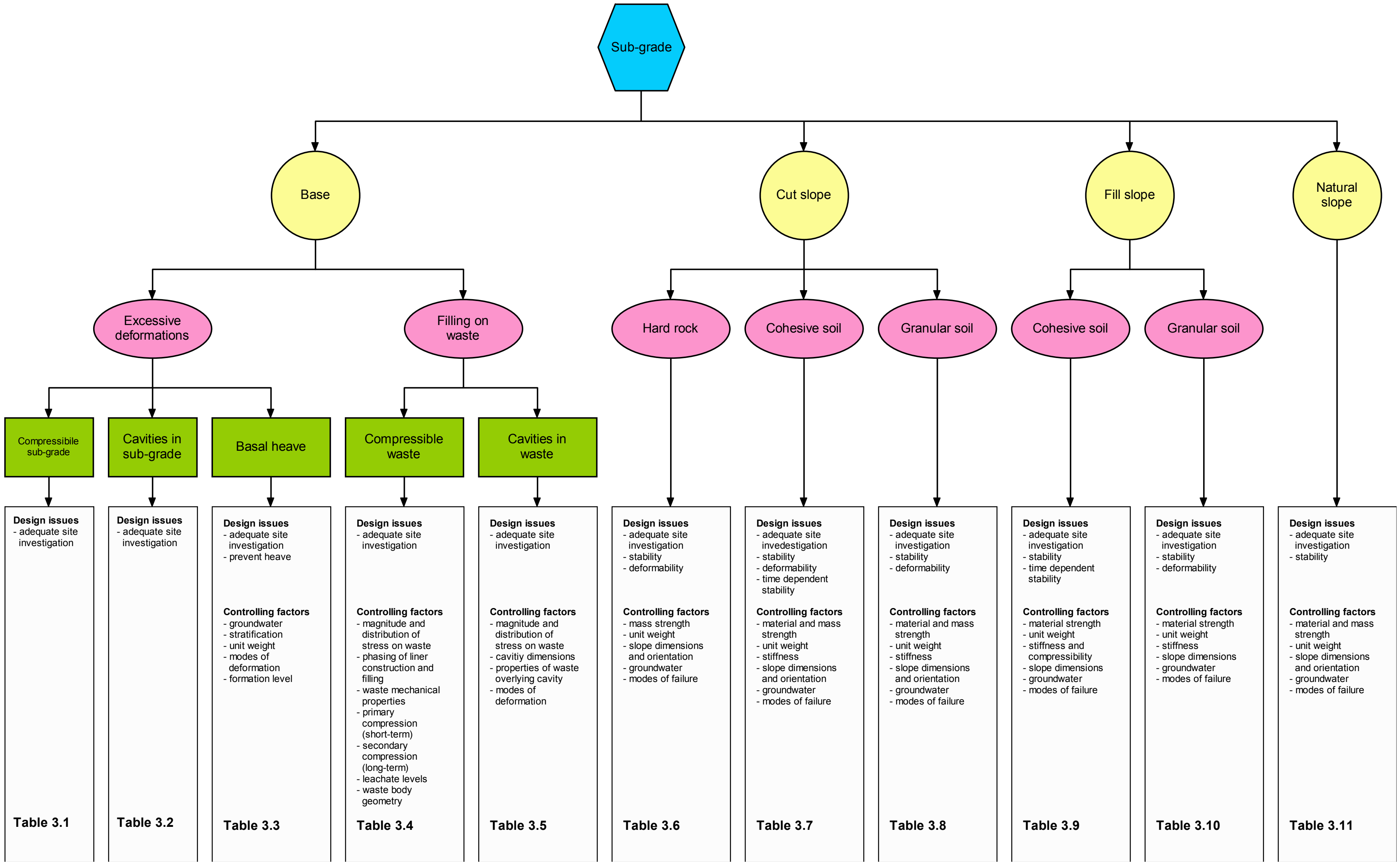


Figure 3.1 Design Flow Chart 1: Sub-grade

Table 3.4 Base/Filling on Waste/Compressible Waste

	Design Issues: Adequate site investigation
	Controlling Factors: Magnitude and distribution of stress on waste Phasing of liner construction and filling Waste mechanical properties material type age density moisture content Primary compression (short-term) elastic compression Secondary compression (long-term) creep degradation Leachate levels leachate pressure degree of saturation Waste body geometry thickness of deposit variation of thickness across site
	Analysis: Quantify magnitude and distribution of both short and long-term settlements for use in design of the lining system (see Section 3.3.2)
	Stabilisation Techniques: Pre-treatment compaction (densification) Raft foundation geosynthetic reinforced raft increases total stress

Table 3.5 Base/Filling on Waste/Cavities in Waste

	Design Issues: Adequate site investigation
	Controlling Factors: Magnitude and distribution of stress on waste Cavity dimensions estimated plan size depth below lining system rate of change of size rate of migration to underside of lining system Properties of waste overlying cavity mass strength Modes of deformation collapse of overlying material into cavity deformation of overlying material into cavity
	Analysis: Quantify magnitude and distribution of both short and long-term settlements for use in design of the lining system (see Section 3.3.2)
	Stabilisation Techniques: Pre-treatment compaction (densification) Spanning geosynthetic reinforced raft

Table 3.6 Cut Slope/Hard Rock

	Design Issues:
	    Adequate site investigation
	    Stability
	    Deformability

	Controlling Factors:
	    Mass strength
	        stratification
	        orientation of discontinuities
	        frequency
	        shear strength
	            planarity
	            surface roughness
	            infill
	            aperture
	        stress relief
	            strain softening
	        slope formation
	            blasting
	    Unit weight
	    Slope dimensions and orientation
	        height
	        angle
	    Groundwater
	        distribution of pressures
	        flow conditions
	        perched groundwater
	        drainage
	        dewatering
	    Modes of failure
	        falls
	        toppling
	        wedge
	        rotational

	Analysis:
	    Site observations
	    Stability calculations

	Stabilisation Techniques:
	    Drainage
	        surface
	        sub-surface
	    Cut and fill
	        re-profile slope
	    Support
	        retaining structure
	        rock bolting

Table 3.7 Cut Slope/Cohesive Soil

	Design Issues: Adequate site investigation Stability Deformability Time-dependent stability
	Controlling Factors: Material and mass strength stratification orientation of discontinuities (e.g. bedding planes) frequency shear strength drained undrained stress relief strain softening slope formation history Unit weight Stiffness drained undrained Slope dimensions and orientation height angle Groundwater distribution of pressures long-term steady seepage values permeability consolidation/swelling consolidation rate boundary conditions drainage dewatering Modes of failure translational rotational falls
	Analysis: Site observations Stability calculations translational circular non-circular undrained drained charts
	Stabilisation Techniques: Drainage surface sub-surface Cut and fill re-profile slope Support retaining structure soil nails

Table 3.8 Cut Slope/Granular Soil

	Design Issues: Adequate site investigation Stability Deformability
	Controlling Factors: Material and mass strength stratification structure cementation cohesive soils orientation of strata (e.g. cohesive soil layers) shear strength drained grading particle shape density slope formation history Unit weight Stiffness drained Slope dimensions and orientation height angle Groundwater distribution of pressures seepage piping drainage dewatering Modes of failure piping translational rotational
	Analysis: Site observations Stability calculations translational circular non-circular drained
	Stabilisation Techniques: Drainage surface sub-surface Cut and fill re-profile slope Support retaining structure soil nails

Table 3.9 Fill Slope/Cohesive Soil

	Design Issues: Adequate site investigation Stability Time dependent stability
	Controlling Factors: Material strength grading density moisture content suctions swelling/softening drained undrained time related changes slope formation history Unit weight Stiffness/compressibility density Slope dimensions Groundwater distribution of pressures long-term steady seepage values permeability consolidation/swelling consolidation rate boundary conditions drainage dewatering Modes of failure translational rotational
	Analysis: Site observations Stability calculations translational circular non-circular undrained drained charts
	Stabilisation Techniques: Drainage surface sub-surface Cut and fill re-profile slope Support retaining structure Compaction

Table 3.10 Fill Slope/Granular Soil

Design Issues:
- Adequate site investigation
- Stability
- Deformability

Controlling Factors:
- Material strength
  - shear strength
    - drained
    - grading
    - particle shape
    - density
  - slope formation history
- Unit weight
- Stiffness
  - drained
- Slope dimensions
  - height
  - angle
- Groundwater
  - distribution of pressures
  - seepage
  - piping
  - drainage
  - dewatering
- Modes of failure
  - piping
  - translational

Analysis:
- Site observations
- Stability calculations
  - translational
  - drained

Stabilisation Techniques:
- Drainage
  - surface
  - sub-surface
- Cut and fill
  - re-profile slope
- Support
  - retaining structure
- Compaction

Table 3.11 Natural Slope

	Design Issues: Adequate site investigation Stability
	Controlling Factors: Material and mass strength stratification orientation of discontinuities (e.g. bedding planes) frequency pre-existing shear surfaces shear strength drained residual Unit weight Slope dimensions and orientation height angle Groundwater distribution of pressures long-term steady seepage values climate drainage dewatering Modes of failure translational rotational falls toppling wedge block
	Analysis: Site observations Stability calculations translational circular non-circular wedge toppling block drained
	Stabilisation Techniques: Drainage surface sub-surface Cut and fill re-profile slope Support retaining structure soil nails, rock bolts, rock anchors

3.3.2 Basal lining systems

Basal lining system design is primarily concerned with assessing and hence controlling stresses in the liner. Excessive stresses can cause shearing of mineral liners and tearing and/or stress cracking in geomembranes. This will then lead to increased permeability of the liner. Design issues, controlling factors and analysis methods are given below. Comprehensive information on basal lining design is given in Chapter 10, Report 1 including key references.

Table 3.12 Mineral Only/Compressible Sub-grade

	Design Issues: Control stress in liner to prevent increased permeability
	Controlling Factors: Assessment requires information obtained in site investigation for Section 3.3.1 *Sub-grade/Base/Excessive deformation/Compressible sub-grade* Liner system details thickness of mineral layer type and dimensions of ancillary underlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Total settlement type and extent of compressible deposits area affected Differential settlement settlement profile Rate of settlement time dependency of settlement profile formation Modes of deformation tension cracks formation of shear zones Groundwater pore water pressure distribution in sub-grade drainage dewatering Engineering properties of mineral layer shear strength stiffness plasticity of material grading (% clay materials) clay mineralogy Support layer design stiffness tensile capacity (geosynthetics)
	Analysis: Radius of curvature of deformation profile see Report 1 10.3.2 Assessment of mineral layer plasticity Assessment of control provided by underlying lining system layers (i.e. after Report 1 10.3.3)

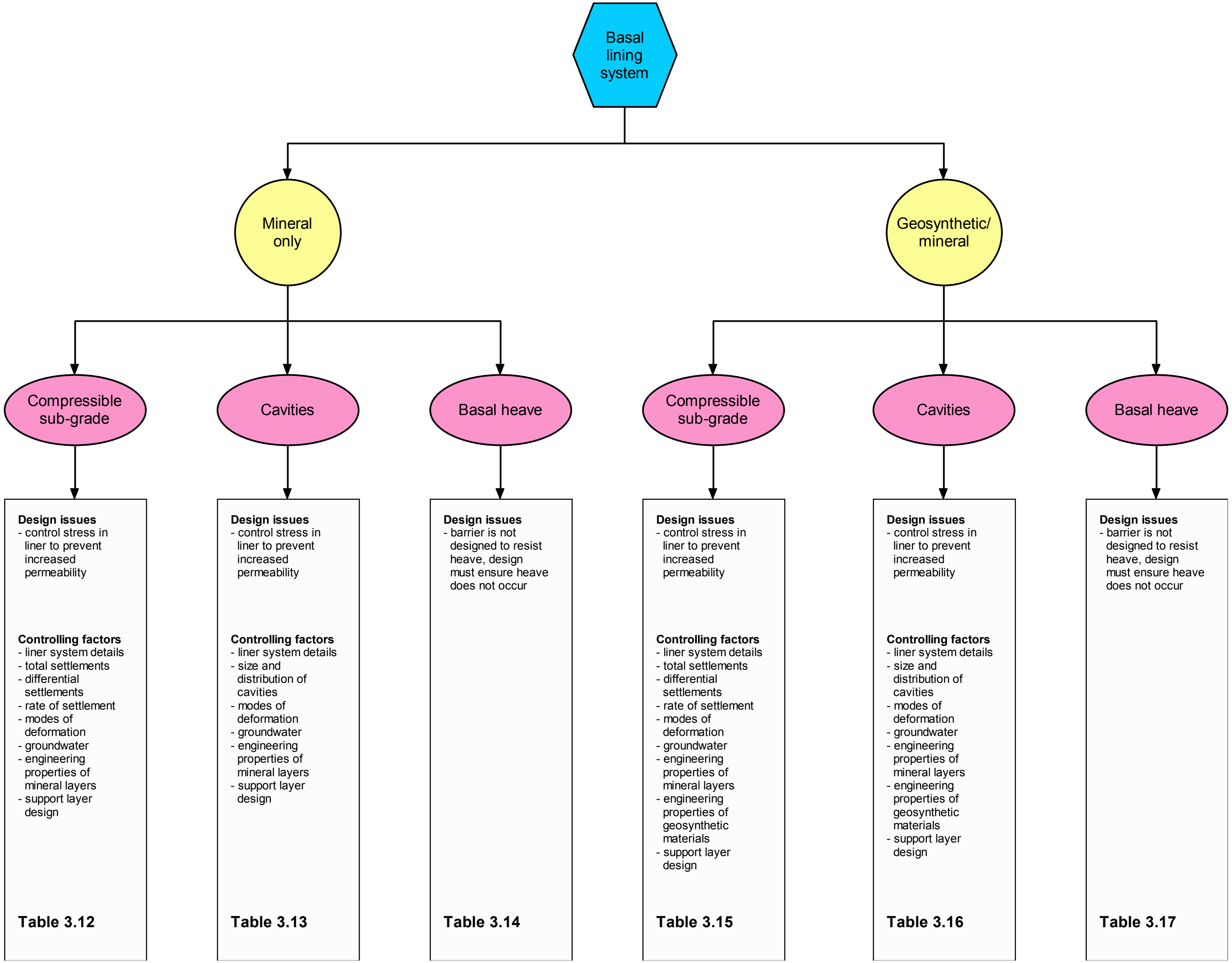


Figure 3.2 Design Flow Chart 2: Basal Lining System

Table 3.13 Mineral Only/Cavities

	Design Issues: Control stress in liner to prevent increased permeability
	Controlling Factors: Assessment requires information obtained in site investigation for Section 3.3.1 *Sub-grade/Base/Excessive deformation/Cavities* Liner system details thickness of mineral layer type and dimensions of ancillary underlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Size and distribution of cavities size of cavity depth below liner rate of migration to underside of liner maximum settlement area affected time dependency of settlement profile formation Modes of deformation tension cracks formation of shear zones Groundwater pore water pressure distribution in sub-grade drainage dewatering Engineering properties of mineral layer shear strength stiffness plasticity of material grading (% clay materials) clay mineralogy Support layer design stiffness tensile capacity (geosynthetics)
	Analysis: Radius of curvature of deformation profile see Report 1 10.3.2 Assessment of mineral layer plasticity Assessment of control provided by underlying lining system layers (i.e. after Report 1 10.3.3)

Table 3.14 Mineral Only/Basal Heave

	Design Issues: Barrier is not designed to resist basal heave, design must ensure heave does not occur. See also Section 8.3.1 *Sub-grade/Base/Excessive Deformations/Basal Heave.*

Table 3.15 Geosynthetic-Mineral/Compressible Sub-grade

	Design Issues: Control stress in liner to prevent increased permeability
	Controlling Factors: Assessment requires information obtained in site investigation for Section 3.3.1 Sub-grade/Base/Excessive Deformation/Compressible Sub-grade Liner system details thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) type, thickness and unit weight of overlying layers Total settlement type and extent of compressible deposits area affected Differential settlement settlement profile Rate of settlement time dependency of settlement profile formation Modes of deformation tension cracks in mineral liner formation of shear zones in mineral liner tensile failure (tearing) pf geosynthetic liner excessive strains in geosynthetic liner Groundwater pore water pressure distribution in sub-grade drainage dewatering Engineering properties of mineral layer shear strength stiffness plasticity of material grading (% clay materials) clay mineralogy Engineering properties of geosynthetic materials tensile strength limiting strains for stress cracking Support layer design Stiffness tensile capacity (geosynthetics)
	Analysis: Radius of curvature of deformation profile Assessment of stresses in ancillary support layers (e.g. geosynthetic reinforcement) (see Report 1 10.3.3) Assessment of mineral liner plasticity Assessment of strains in geosynthetic barrier

Table 3.16 Geosynthetic-Mineral/Cavities

	Design Issues: Control stress in liner to prevent increased permeability
	Controlling Factors: Assessment requires information obtained in site investigation for Section 3.3.1 *Sub-grade/Base/Excessive Deformation/Cavities* Liner system details thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Type, thickness and unit weight of overlying layers Size and distribution of cavities size of cavity depth below liner rate of migration to underside of liner maximum settlement area affected time dependency of settlement profile formation Modes of deformation tension cracks in mineral liner formation of shear zones in mineral liner tensile failure (tearing) of geosynthetic liner excessive strains in geosynthetic liner Groundwater pore water pressure distribution in sub-grade drainage dewatering Engineering properties of mineral layer shear strength stiffness plasticity of material grading (% clay materials) clay mineralogy Engineering properties of geosynthetic materials tensile strength limiting strains for stress cracking Support layer design stiffness tensile capacity (geosynthetics)
	Analysis: Radius of curvature of deformation profile Assessment of stresses in ancillary support layers (e.g. geosynthetic reinforcement) (see Report 1 10.3.3) Assessment of mineral liner plasticity Assessment of strains in geosynthetic barrier

Table 3.17 Geosynthetic-Mineral/Basal Heave

	Design Issues: Barrier is not designed to resist basal heave, design must ensure heave does not occur. See also Section 3.3.1 *Sub-grade/Base/Excessive Deformations/Basal Heave.*

3.3.3 Shallow side slope lining systems

Shallow side slope lining system design must consider stability and integrity failure modes both during construction (unconfined) and in the long-term following waste placement (confined). Excessive stresses can cause shearing of mineral liners and tearing and/or stress cracking in geomembranes. This will then lead to increased permeability of the liner. In addition, in a number of the design cases the stability of the drainage system and continuity of protection layers also require consideration. Design issues, controlling factors and analysis methods are given below. Comprehensive information on shallow slope lining system design is given in Chapter 11, Report 1 including key references.

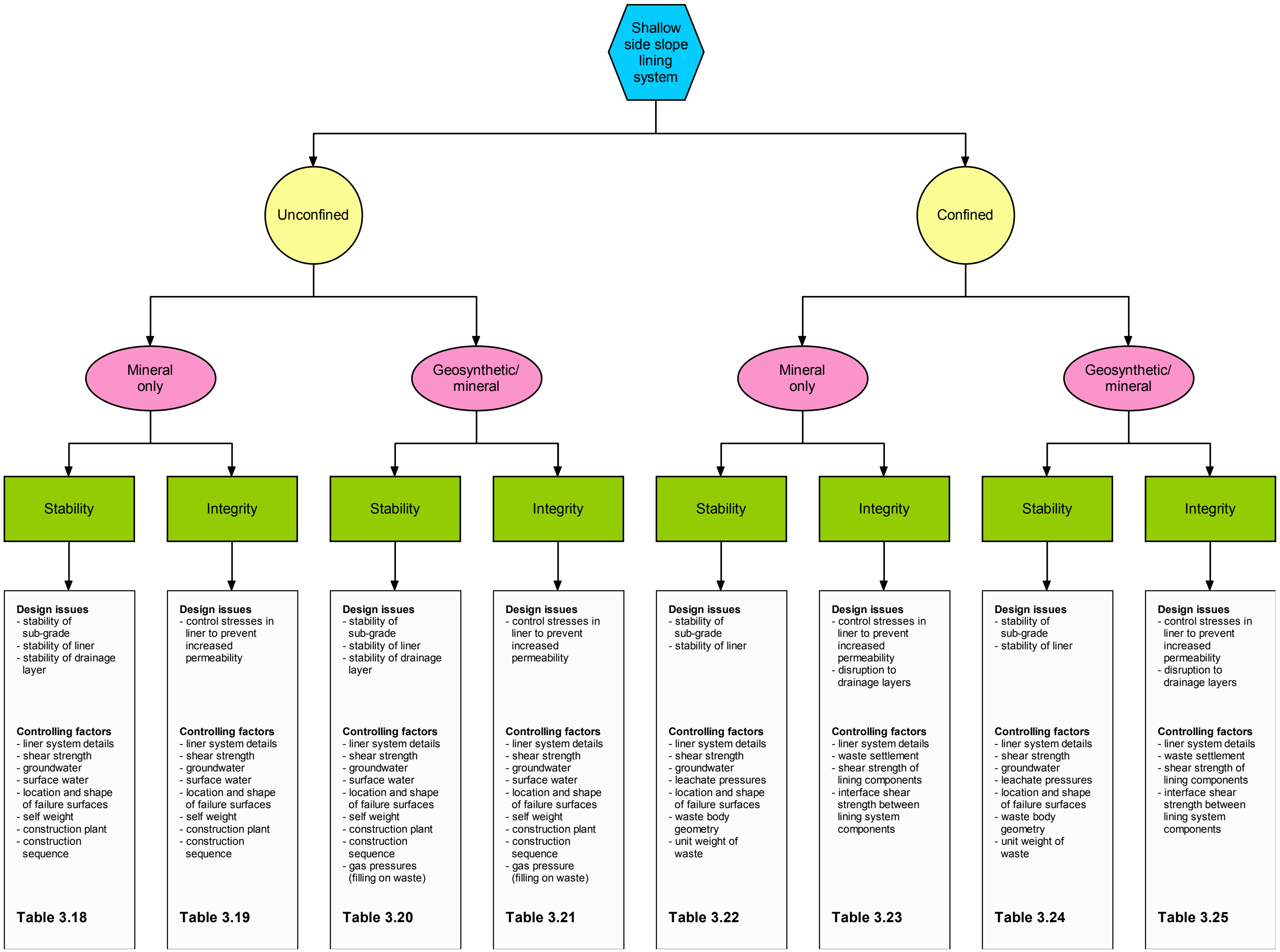


Figure 3.3 Design Flow Chart 3: Shallow Side Slope Lining System

Table 3.18 Unconfined/Mineral Only/Stability

Design Issues:

- Stability of sub-grade
- Stability of liner
- Stability of drainage layer

Controlling Factors:

- Liner system details
  - thickness of mineral layer
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - mineral layers of lining system
  - sub-grade
  - drained/undrained conditions
  - Strain softening
- Groundwater
  - pore water pressure
    - sub-grade
    - lining system
  - influence of dewatering
  - modification to groundwater regime from construction of barrier
  - climate controlled time dependency
- Surface water
  - discharges on slope
  - precipitation
  - changes in unit weight of mineral layers
  - changes in pore water pressures (recharge)
  - seepage
- Location and shape of potential failure surfaces
  - weak layers
  - interfaces between components of lining system
  - interfaces between phases of compaction in mineral layer
- Self weight
  - unit weight of materials
  - influence of moisture content changes
- Construction plant
  - dead weight
  - braking/acceleration forces
  - mode of operation
    - uphill/downhill
- Construction sequence
  - method of placement
  - stockpiling of material

Analysis:

- Limit equilibrium stability analysis
  - infinite slope method (Report 1, 11.3.3)
  - method of slices (Report 1, 11.4.2)
- Construction plant loading (Report 1, 11.3.3)

Table 3.19 Unconfined/Mineral Only/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability
	Controlling Factors: Assessment is also required of the Section 3.3.2 design cases of *Basal Lining System/Mineral Only/Compressible Sub-grade* and *Cavities*. Liner system details thickness of mineral layer type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite Shear strength mineral layers of lining system sub-grade drained/undrained conditions strain softening Groundwater pore water pressure sub-grade lining system influence of dewatering modification to groundwater regime from construction of barrier climate controlled time dependency Surface water discharges on slope precipitation changes in unit weight of mineral layers changes in pore water pressures (recharge) seepage Location and shape of potential failure surfaces weak layers interfaces between components of lining system interfaces between phases of compaction in mineral layer Self weight unit weight of materials influence of moisture content changes Construction plant dead weight braking/acceleration forces mode of operation uphill/downhill Construction sequence method of placement stockpiling of material
	Analysis: Limit equilibrium stability analysis infinite slope method (Report 1, 11.3.3) method of slices (Report 1, 11.4.2) Construction plant loading (Report 1, 11.3.3) Assessment of factor of safety to control strains in system Assessment of basal lining system modes (mineral only)

Table 3.20 Unconfined/Geosynthetic-Mineral/Stability

Design Issues:

- Stability of sub-grade
- Stability of liner
- Stability of drainage layer

Controlling Factors:

- Liner system details
    - thickness of mineral layer
    - type of geosynthetic liner
    - type and dimensions of ancillary underlying and overlying layers
        - reinforcement (geogrid)
        - drainage layers (mineral, geocomposite)
- Shear strength
    - mineral layers of lining system
    - sub-grade
    - interfaces
        - geosynthetic/geosynthetic
        - geosynthetic/soil
    - Strain softening
- Groundwater
    - pore water pressure
        - sub-grade
        - lining system
    - influence of dewatering
    - modification to groundwater regime from construction of barrier
    - climate controlled time dependency
- Surface water
    - discharges on slope
    - precipitation
    - changes in unit weight of mineral layers
    - changes in pore water pressures (recharge)
    - seepage
- Location and shape of potential failure surfaces
    - weak layers (mineral)
    - interfaces
- Self weight
    - unit weight of materials
    - influence of moisture content changes on mineral layers
- Construction plant
    - dead weight
    - braking/acceleration forces
    - mode of operation
        - uphill/downhill
- Construction sequence
    - method of placement
    - stockpiling of material
- Gas pressure (filling on waste)
    - important where existing waste slopes are lined
    - gas pressure related to
    - age and type of waste
    - gas control and extraction system

Analysis:

- Limit equilibrium stability analysis
    - infinite slope method (Report 1, 11.3.3)
    - finite slope method (Report 1, 11.3.3)
    - method of slices (Report 1, 11.4.2)
- Gas pressure (Report 1, 11.3.3)
- Construction plant loading (Report 1, 11.3.3)
- Assessment of geosynthetic stress (Report 1, 11.3.3)

Table 3.21 Unconfined/Geosynthetic-Mineral /Integrity

Design Issues:

- Control stresses in liner to prevent increased permeability

Controlling Factors:

- Assessment is also required of the Section 3.3.2 design cases of *Basal Lining System/Geosynthetic-Mineral/Compressible Sub-grade* and *Cavities*.
- Liner system details
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite
- Shear strength
  - mineral layers of lining system
  - sub-grade
  - interfaces
    - geosynthetic/geosynthetic
    - geosynthetic/soil
  - mineral layers – drained/undrained
  - strain softening interfaces
  - tensile strength of geosynthetics
- Groundwater
  - pore water pressure
    - sub-grade
    - lining system
  - influence of dewatering
  - modification to groundwater regime from construction of barrier
  - climate controlled time dependency
- Surface water
  - discharges on slope
  - precipitation
  - changes in unit weight of mineral layers
  - changes in pore water pressures (recharge)
  - seepage
- Location and shape of potential failure surfaces
  - weak layers (mineral)
  - interfaces
- Self weight
  - unit weight of materials
  - influence of moisture content changes
- Construction plant
  - dead weight
  - braking/acceleration forces
  - mode of operation
    - uphill/downhill
- Construction sequence
  - method of placement
  - stockpiling of material
- Gas pressure (filling on waste)
  - important where existing waste slopes are lined
  - gas pressure related to
    - age and type of waste
    - gas control and extraction system

Table 3.21 Unconfined/Geosynthetic-Mineral /Integrity (continued)

	Analysis: Limit equilibrium stability analysis infinite slope method (Report 1, 11.3.3) finite slope method (Report 1, 11.3.3) method of slices (Report 1, 11.4.2) Assessment of factor of safety to control strains in system Gas pressure (Report 1, 11.3.3) Construction plant loading (Report 1, 11.3.3) Assessment of geosynthetic stress (Report 1, 11.3.3) Assessment of tensile force in geosynthetic (Report 1, 11.3.3) Assessment of basal lining system modes (mineral only)

Table 3.22 Confined/Mineral Only/Stability

Design Issues:

- Stability of sub-grade
- Stability of liner

Controlling Factors:

- Liner system details
  - thickness of mineral layer
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - waste
  - sub-grade
  - mineral lining components
  - strain softening behaviour
  - drained/undrained conditions (cohesive soils)
  - characteristic values
- Groundwater
  - in sub-grade
  - in lining system
  - pore water pressures generated by construction (undrained loading)
  - modification to pressures in sub-grade caused by barrier construction
- Leachate pressures
  - Pressure distribution (see Report 1, 11.4.1)
    - on liner
    - on cover soil layers
    - influence of re-circulation of leachate
- Location and shape of potential failure surfaces
  - non-circular surfaces are common
  - controlling factors → weak layers
    - sub-grade, soft cohesive layers/ discontinuities
    - lining components, cohesive
    - daily cover soil layers
    - through waste body
- Waste body geometry
  - side lining system slope angle
  - waste external slope angle
  - waste height
  - basal length of waste mass
  - consider temporary geometries
- Unit weight of waste (see Report 1, 8.2)
  - depth (vertical stress level) dependent
  - modified by cover soil
  - waste type
  - placement practices
  - moisture content
  - time dependent

Analysis:

- Limit equilibrium stability analysis
  - method of slices (Report 1, 11.4.2)

Table 3.23 Confined/Mineral Only/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability Disruption to drainage layers
	Controlling Factors: Assessment is also required of the Section 3.3.2 design cases of *Basal Lining System/Mineral/Compressible Sub-grade* and *Cavities*. Liner system details thickness of mineral layer type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Waste settlement (see Report 1, 8.3) short-term compression (see Report 1, 8.3.3) long-term creep and degradation (see Report 1, 8.3.4) magnitude and distribution (laterally and with depth) Shear strength of lining components drained conditions/undrained conditions cohesive soil Interface shear strength between lining components strain softening shear behaviour mobilisation of post-peak values
	Analysis: Numerical modelling techniques (see Report 1, 11.4.4) waste/barrier interaction non-linear material behaviour

Table 3.24 Confined/Geosynthetic-Mineral/Stability

Design Issues:

- Stability of sub-grade
- Stability of liner

Controlling Factors:

- Liner system details
  - thickness of mineral layer
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - waste
  - sub-grade
  - mineral lining components
  - strain softening behaviour
  - drained/undrained conditions (cohesive soils)
  - characteristic values
  - geosynthetic/geosynthetic and geosynthetic/soil interfaces
  - characteristic interface shear strength values (Report 1, 7.5)
- Groundwater
  - in sub-grade
  - in lining system
  - pore water pressures generated by construction (undrained loading)
  - modification to pressures in sub-grade caused by barrier construction
- Leachate pressures
  - Pressure distribution (see Report 1, 11.4.1)
    - on liner
    - on cover soil layers
    - influence of re-circulation of leachate
- Location and shape of potential failure surfaces
  - non-circular surfaces are common
  - controlling factors → weak layers
    - sub-grade, soft cohesive layers/ discontinuities
    - lining components, cohesive
    - interfaces between lining components
    - daily cover soil layers
    - through waste body
- Waste body geometry
  - side lining system slope angle
  - waste external slope angle
  - waste height
  - basal length of waste mass
  - consider temporary geometries
- Unit weight of waste (see Report 1, 8.2)
  - depth (vertical stress level) dependent
  - modified by cover soil
  - waste type
  - placement practices
  - moisture content
  - time dependent

Analysis:

- Limit equilibrium stability analysis
  - method of slices (Report 1, 11.4.2)

Table 3.25 Confined/Geosynthetic-Mineral/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability Disruption to drainage layers
	Controlling Factors: Assessment is also required of the Section 3.3.2 design cases of *Basal Lining System/Geosynthetic/Mineral/Compressible Sub-grade* and *Cavities*. Liner system details thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Waste settlement (see Report 1, 8.3) short-term compression (see Report 1, 8.3.3) long-term creep and degradation (see Report 1, 8.3.4) magnitude and distribution (laterally and with depth) Shear strength of lining components drained conditions/undrained conditions cohesive soil Interface shear strength between lining components strain softening shear behaviour mobilisation of post-peak values particularly geosynthetic/geosynthetic and geosynthetic/soil interfaces
	Analysis: Numerical modelling techniques (see Report 1, 11.4.4) waste/barrier interaction non-linear material behaviour

3.3.4 Steep slope lining systems

Steep side slope lining system design must consider stability and integrity failure modes both during construction (unconfined) and in the long-term following waste placement (confined). Excessive stresses can cause shearing of mineral liners and tearing and/or stress cracking in geomembranes. This will then lead to increased permeability of the liner. In addition, in a number of the design cases the stability of the drainage system and continuity of protection layers also require consideration. Design issues, controlling factors and analysis methods are given below for the two classes of lining system considered: self-supporting and waste supported. Mineral, geosynthetic and composite lining systems are covered in each design case. Comprehensive information on steep slope lining system design is given in Chapter 12, Report 1 including key references.

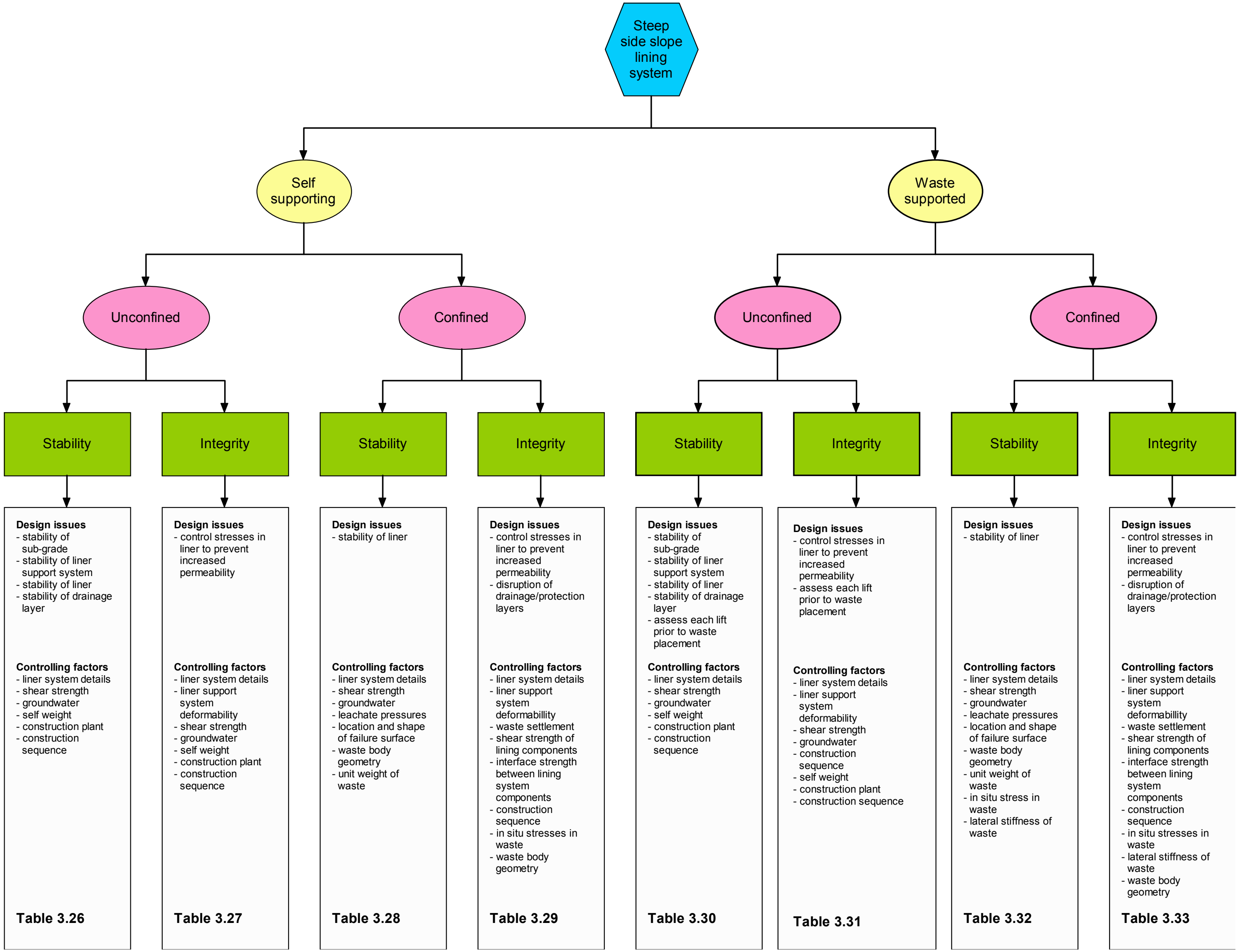


Figure 3.4 Design Flow Chart 4: Steep Side Slope Lining System

Table 3.26 Self Supporting/Unconfined/Stability

Design Issues:

- Stability of sub-grade
- Stability of liner support system
- Stability of liner
- Stability of drainage layer

Controlling Factors:

- Assessment is required of design cases in Section 3.3.1 on *Sub-grade/Cut Slope, Fill Slope* and *Natural Slope*
- Liner system details
  - type and dimensions of liner support system
  - geometry of lining system
    - slope angle, including variability
    - slope height
    - variability of slope along length of slope
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - strength of structural components (frame, geosynthetic reinforcement, no fines concrete)
  - mineral layers of lining system
    - Drained/undrained conditions
  - interfaces between components
  - connections between barrier and sub-grade (e.g. rock bolts)
  - strain softening behaviour
- Groundwater
  - pore water pressures
    - sub-grade
    - lining system
  - influence of de-watering
  - modification to groundwater regime from construction of barrier
- Self weight
  - structural components (frames, concrete)
  - unit weight of mineral components (granular backfill, clay liner)
  - influence of moisture content changes
- Construction plant
  - dead weight
  - braking/acceleration forces
- Construction sequence
  - phasing of construction
  - stockpiling of material

Analysis:

- Shear failure of mineral liners => Limit equilibrium analysis – Method of slices (Report 1, 11.4.2)
- Tensile failure of geomembrane under self-weight and loads from adjacent liner components (Compare tensile stresses with wide width tensile strength)
- Structural stability of support systems
  - reinforced soil design (BS8006:1995)
  - structural assessment of frame systems (including rock bolt design)
  - structural assessment of no fines concrete

Table 3.27 Self Supporting/Unconfined/Integrity

Design Issues:

- Control stresses in liner to prevent increased permeability

Controlling Factors:

- Assessment is required of design cases in Section 3.3.1 on *Sub-grade/Cut Slope, Fill Slope* and *Natural Slope* with regard to deformability of sub-grade
- Liner system details
  - type and dimensions of liner support system
  - geometry of lining system
    - slope angle, including variability
    - slope height
    - variability of slope along length of slope
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Liner support system deformability
  - stiffness of support system (composite behaviour)
- Shear strength
  - strength of structural components (frame, geosynthetic reinforcement, no fines concrete)
  - mineral layers of lining system
    - drained/undrained conditions
  - interfaces between components
  - connections between barrier and sub-grade (e.g. rock bolts)
  - strain softening behaviour
- Groundwater
  - pore water pressures
    - sub-grade
    - lining system
  - influence of de-watering
  - modification to groundwater regime from construction of barrier
- Self weight
  - structural components (frames, concrete)
  - unit weight of mineral components (granular backfill, clay liner)
  - influence of moisture content changes
- Construction plant
  - dead weight
  - braking/acceleration forces
- Construction sequence
  - phasing of construction
  - stockpiling of material

Analysis:

- Shear failure of mineral liners => Limit equilibrium analysis – Method of slices (Report 1, 11.4.2)
- Assessment of factors of safety to control the strains in the liner components
- Tensile stresses in geomembrane under self-weight and loads from adjacent liner components (Compare tensile stresses with wide width tensile strength to ensure strains are acceptable)
- Use numerical modelling techniques (see Report 1, 12.6 for general methodology)
  - assess barrier/support system/sub-grade interaction
  - include non-linear material behaviour

Table 3.28 Self Supporting/Confined/Stability

	Design Issues: Stability of liner
	Controlling Factors: Liner system details type and dimensions of liner support system geometry of lining system slope angle, including variability slope height variability of slope along length of slope thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Shear strength waste sub-grade mineral lining components strain softening behaviour drained/undrained conditions (cohesive soils) characteristic values geosynthetic/geosynthetic and geosynthetic/soil interfaces characteristic interface shear strength values (Report 1, 7.5) Groundwater in sub-grade in lining system pore water pressures generated by construction (undrained loading) modification to pressures in sub-grade caused by barrier construction Leachate pressures Pressure distribution (see Report 1, 11.4.1) on liner on cover soil layers influence of re-circulation of leachate Location and shape of potential failure surfaces non-circular surfaces are common controlling factors → weak layers Sub-grade, soft cohesive layers/ discontinuities lining components, cohesive interfaces between lining components daily cover soil layers through waste body Waste body geometry side lining system slope angle waste external slope angle waste height basal length of waste mass consider temporary geometries Unit weight of waste (see Report 1, 8.2) depth (vertical stress level) dependent modified by cover soil waste type placement practices moisture content time
	Analysis: Limit equilibrium stability analysis Method of slices (Report 1, 11.4.2)

Table 3.29 Self Supporting/Confined/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability Disruption of drainage and protection layers
	Controlling Factors: Assessment is required of design cases in Section 3.3.1 on *Sub-grade/Cut Slope, Fill Slope* and *Natural Slope* with regard to deformability of sub-grade Liner system details type and dimensions of liner support system geometry of lining system slope angle, including variability slope height variability of slope along length of slope thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Liner support system deformability stiffness of support system (composite behaviour) Waste settlement short-term compression (see Report 1, 8.3.3) long-term creep and degradation (see Report 1, 8.3.4) magnitude and distribution (laterally and with depth) Shear strength of lining components cohesive soil (drained/undrained conditions) tensile strength of geosynthetic components Interface strength between lining components strain softening behaviour of interfaces mobilisation of post peak shear strengths Construction sequence phasing of barrier construction and waste placement In situ stresses in waste (see Report 1, 8.6) influence of waste degradation Waste body geometry slope angle and variability slope height variability of slope along length of slope
	Analysis: Use numerical modelling techniques (see Report 1, 12.6 for general methodology) consider waste/barrier/support system interaction non- linear material behaviour

Table 3.30 Waste Supported/Unconfined/Stability

Design Issues:

- Stability of sub-grade
- Stability of liner support system
- Stability of liner
- Stability of drainage layer
- Assess each lift prior to waste placement

Controlling Factors:

- Assessment is required of design cases in Section 3.3.1 on *Sub-grade/Cut Slope, Fill Slope* and *Natural Slope*
- Liner system details
  - type and dimensions of liner support system
  - geometry of lining system
    - slope angle, including variability
    - slope height
    - variability of slope along length of slope
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - strength of structural components (frame, geosynthetic reinforcement, no fines concrete)
  - mineral layers of lining system
    - drained/undrained conditions
  - interfaces between components
  - connections between barrier and sub-grade (e.g. rock bolts)
  - strain softening behaviour
- Groundwater
  - pore water pressures
    - sub-grade
    - lining system
  - influence of de-watering
  - modification to groundwater regime from construction of barrier
- Self weight
  - structural components (frames, concrete)
  - unit weight of mineral components (granular backfill, clay liner)
  - influence of moisture content changes
- Construction plant
  - dead weight
  - braking/acceleration forces
- Construction sequence
  - phasing of construction
  - stockpiling of material

Analysis:

- Shear failure of mineral liners => Limit equilibrium analysis – Method of slices (Report 1, 11.4.2)
- Tensile failure of geomembrane under self-weight and loads from adjacent liner components (Compare tensile stresses with wide width tensile strength)
- Structural stability of support systems
  - reinforced earth design (BS8066:1995)
  - structural assessment of frame systems (including rock bolt design)
  - structural assessment of no fines concrete

Table 3.31 Waste Supported/Unconfined/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability Assess each lift prior to waste placement
	Controlling Factors: Assessment is required of design cases in Section 3.3.1 on *Sub-grade/Cut Slope, Fill Slope* and *Natural Slope* with regard to deformability of sub-grade Liner system details type and dimensions of liner support system geometry of lining system slope angle, including variability slope height variability of slope along length of slope thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Liner support system deformability stiffness of support system (composite behaviour) Shear strength strength of structural components (frame, geosynthetic reinforcement, no fines concrete) mineral layers of lining system drained/undrained conditions interfaces between components connections between barrier and sub-grade (e.g. rock bolts) strain softening behaviour Groundwater pore water pressures sub-grade lining system influence of de-watering Assess each lift prior to waste placement Modification to groundwater regime from construction of barrier Self weight structural components (frames, concrete) unit weight of mineral components (granular backfill, clay liner) influence of moisture content changes Construction plant dead weight braking/acceleration forces Construction sequence phasing of construction stockpiling of material
	Analysis: Shear failure of mineral liners => Limit equilibrium analysis – Method of slices (Report 1, 11.4.2) Assessment of factors of safety to control the strains in the liner components Tensile stresses in geomembrane under self-weight and loads from adjacent liner components (Compare tensile stresses with wide width tensile strength to ensure strains are acceptable) Use numerical modelling techniques (see report 1, 12.6 for general methodology) assess barrier/support system/sub-grade interaction include non-linear material behaviour

Table 3.32 Waste Supported/Confined/Stability

Design Issues:

- Stability of liner

Controlling Factors:

- Liner system details
  - type and dimensions of liner support system
  - geometry of lining system
    - slope angle, including variability
    - slope height
    - variability of slope along length of slope
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - waste
  - sub-grade
  - mineral lining components
  - strain softening behaviour
  - drained/undrained conditions (cohesive soils)
  - characteristic values
  - geosynthetic/geosynthetic and geosynthetic/soil interfaces
  - characteristic interface shear strength values (Report 1, 7.5)
- Groundwater
  - in sub-grade
  - in lining system
  - pore water pressures generated by construction (undrained loading)
  - modification to pressures in sub-grade caused by barrier construction
- Leachate pressures
  - pressure distribution (see Report 1, 11.4.1)
    - on liner
    - on cover soil layers
    - influence of re-circulation of leachate
- Location and shape of potential failure surfaces
  - Non-circular surfaces are common
  - Controlling factors → weak layers
    - Sub-grade, soft cohesive layers/discontinuities
    - lining components, cohesive
    - interfaces between lining components
    - daily cover soil layers
    - through waste body
- Waste body geometry
  - side lining system slope angle
  - waste external slope angle
  - waste height
  - basal length of waste mass
  - consider temporary geometries
- Unit weight of waste (see Report 1, 8.2)
  - depth (vertical stress level) dependent
  - modified by cover soil
  - waste type
  - placement practices
  - moisture content
  - time dependent
- In situ stresses in waste (see Report 1, 8.6)
  - influence of waste degradation
- Lateral stiffness of waste (see Report 1, 8.5)
  - influence of waste degradation

Table 3.32 Waste Supported/Confined/Stability (Continued)

	Analysis: Limit equilibrium stability analysis Method of slices (Report 1, 11.4.2)

Table 3.33 Waste Supported/Confined/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability Disruption of drainage and protection layers
	Controlling Factors: Assessment is required of design cases in Section 3.3.1 on *Sub-grade/Cut Slope, Fill Slope* and *Natural Slope* with regard to deformability of sub-grade Liner system details type and dimensions of liner support system geometry of lining system slope angle, including variability slope height variability of slope along length of slope thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Liner support system deformability stiffness of support system (composite behaviour) Waste settlement short-term compression (see Report 1, 8.3.3) long-term creep and degradation (see Report 1, 8.3.4) magnitude and distribution (laterally and with depth) Shear strength of lining components cohesive soil (drained/undrained conditions) tensile strength of geosynthetic components Interface strength between lining components strain softening behaviour of interfaces mobilisation of post peak shear strengths Construction sequence phasing of barrier construction and waste placement In situ stresses in waste (see Report 1, 8.6) influence of waste degradation Lateral stiffness of waste (see Report 1, 8.5) Influence of waste degradation Waste body geometry slope angle and variability slope height variability of slope along length of slope
	Analysis: Use numerical modelling techniques (see Report 1, 12.6 for general methodology) consider waste/barrier/support system interaction non- linear material behaviour

3.3.5 Waste slope

Waste stability must be assessed as part of the design process for both the final slope profile condition and temporary waste slope configurations. Stability assessment is required for failure modes wholly within the waste body and failure incorporating elements of the lining system. Failure involving the lining system is essentially the same mode as *Shallow Side slope/Confined/Stability*. Design issues, controlling factors and analysis methods are given below for the two modes of waste slope failure considered. Comprehensive information on waste slope stability assessment is given in Chapters 11 and 13, Report 1 including key references.

Table 3.34 Failure Wholly in Waste

	Design Issues: Stability of waste slope
	Controlling Factors: Slope geometry angle height Waste shear strength shear strength of waste and likely variation with depth and laterally shear strength of waste/cover soil interfaces and likely variation shear strength of cover soil material Unit weight of waste (see Report 1, 8.2) depth (vertical stress level) dependent modified by cover soil waste type placement practices moisture content time dependent Leachate pressures Pore pressure distribution (see Report 1, 11.4.1) in waste body perched on cover soil layers influence of leachate re-circulation Location and shape of failure surface Controlling factors daily cover soil layers anisotropic shear strength of waste Non-circular surfaces are common
	Analysis: Limit equilibrium analysis – Method of slices (see Report 1, 11.4.2)

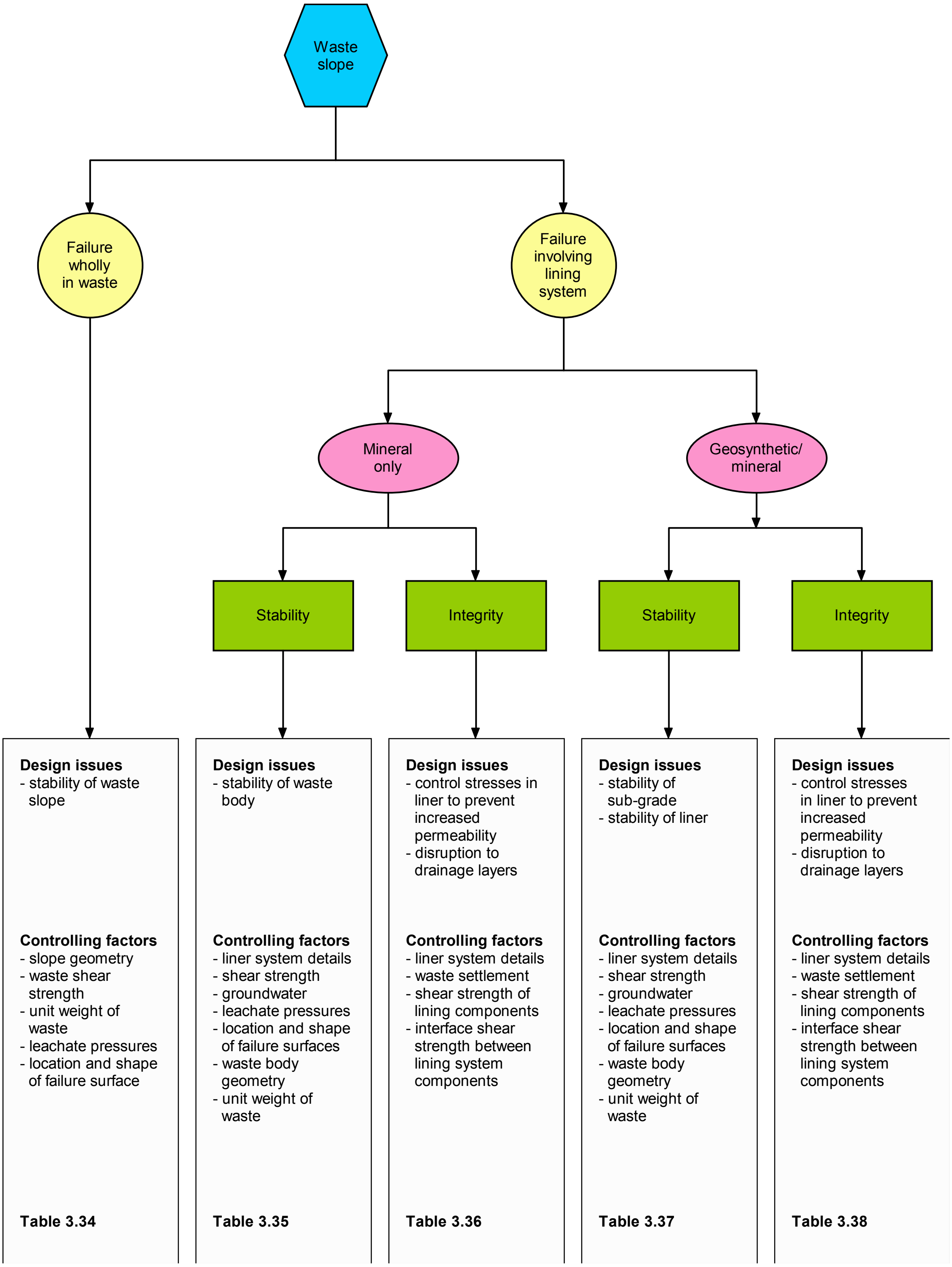


Figure 3.5 Design Flow Chart 5: Waste Slope

Table 3.35 Failure Involving Lining System/Mineral Only/Stability

Design Issues:

- Stability of waste body

Controlling Factors:

- Liner system details
  - thickness of mineral layer
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - waste
  - sub-grade
  - mineral lining components
  - strain softening behaviour
  - drained/undrained conditions (cohesive soils)
  - characteristic values
- Groundwater
  - in sub-grade
  - in lining system
  - pore water pressures generated by construction (undrained loading)
  - modification to pressures in sub-grade caused by barrier construction
- Leachate pressures
  - Pressure distribution (see Report 1, 11.4.1)
    - on liner
    - on cover soil layers
    - influence of re-circulation of leachate
- Location and shape of potential failure surfaces
  - non-circular surfaces are common
  - controlling factors → weak layers
    - sub-grade, soft cohesive layers/ discontinuities
    - lining components, cohesive
    - daily cover soil layers
    - through waste body
- Waste body geometry
  - side lining system slope angle
  - waste external slope angle
  - waste height
  - basal length of waste mass
  - consider temporary geometries
- Unit weight of waste (see Report 1, 8.2)
  - depth (vertical stress level) dependent
  - modified by cover soil
  - waste type
  - placement practices
  - moisture content
  - time dependent

Analysis:

- Limit equilibrium stability analysis
  - method of slices (Report 1, 11.4.2)

Table 3.36 Failure Involving Lining System/Mineral Only/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability Disruption to drainage layers
	Controlling Factors: Liner system details thickness of mineral layer type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Waste settlement (see Report 1, 8.3) short-term compression (see Report 1, 8.3.3) long-term creep and degradation (see Report 1, 8.3.4) magnitude and distribution (laterally and with depth) Shear strength of lining components drained conditions/undrained conditions cohesive soil Interface shear strength between lining components strain softening shear behaviour mobilisation of post-peak values
	Analysis: Numerical modelling techniques (see Report 1, 11.4.4) waste/barrier interaction non-linear material behaviour

Table 3.37 Failure Involving Lining System/Geosynthetic-Mineral/Stability

Design Issues:

- Stability of sub-grade
- Stability of liner

Controlling Factors:

- Liner system details
  - thickness of mineral layer
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
- Shear strength
  - waste
  - sub-grade
  - mineral lining components
  - strain softening behaviour
  - drained/undrained conditions (cohesive soils)
  - characteristic values
  - geosynthetic/geosynthetic and geosynthetic/soil interfaces
  - characteristic interface shear strength values (Report 1, 7.5)
- Groundwater
  - in sub-grade
  - in lining system
  - pore water pressures generated by construction (undrained loading)
  - modification to pressures in sub-grade caused by barrier construction
- Leachate pressures
  - Pressure distribution (see Report 1, 11.4.1)
    - on liner
    - on cover soil layers
    - influence of re-circulation of leachate
- Location and shape of potential failure surfaces
  - non-circular surfaces are common
  - controlling factors → weak layers
    - sub-grade, soft cohesive layers/ discontinuities
    - lining components, cohesive
    - interfaces between lining components
    - daily cover soil layers
    - through waste body
- Waste body geometry
  - side lining system slope angle
  - waste external slope angle
  - waste height
  - basal length of waste mass
  - consider temporary geometries
- Unit weight of waste (see Report 1, 8.2)
  - depth (vertical stress level) dependent
  - modified by cover soil
  - waste type
  - placement practices
  - moisture content
  - time dependent

Analysis:

- Limit equilibrium stability analysis
  - method of slices (Report 1, 11.4.2)

Table 3.38 Failure Involving Lining System/Geosynthetic-Mineral/Integrity

	Design Issues: Control stresses in liner to prevent increased permeability Disruption to drainage layers
	Controlling Factors: Assessment is also required of the Section 3.3.2 design cases of *Basal Lining System/Geosynthetic-Mineral/Compressible Sub-grade* and *Cavities*. Liner system details thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) Waste settlement (see Report 1, 8.3) short-term compression (see Report 1, 8.3.3) long-term creep and degradation (see Report 1, 8.3.4) magnitude and distribution (laterally and with depth) Shear strength of lining components drained conditions/undrained conditions cohesive soil Interface shear strength between lining components strain softening shear behaviour mobilisation of post-peak values particularly geosynthetic/geosynthetic and geosynthetic/soil interfaces
	Analysis: Numerical modelling techniques (see Report 1, 11.4) waste/barrier interaction non-linear material behaviour

3.3.6 Capping Systems

Capping system design must consider side slope stability and integrity failure modes. Excessive stresses can cause shearing of mineral liners and tearing and/or stress cracking in geomembranes. This will then lead to increased permeability of the liner. Instability of the capping system can result in disruption of the drainage system and protection layers. Design issues, controlling factors and analysis methods are given below. Stability design cases are essentially the same as *Shallow side slope/Unconfined/Stability*. In addition, integrity of the capping system can be compromised by excessive deformations in the waste sub-grade (*Sub-grade/Base/Filling on waste*) and by slope deformations. Comprehensive information on shallow slope lining system design is given in Chapter 11, Report 1 and base deformations in Chapter 9. These include key references.

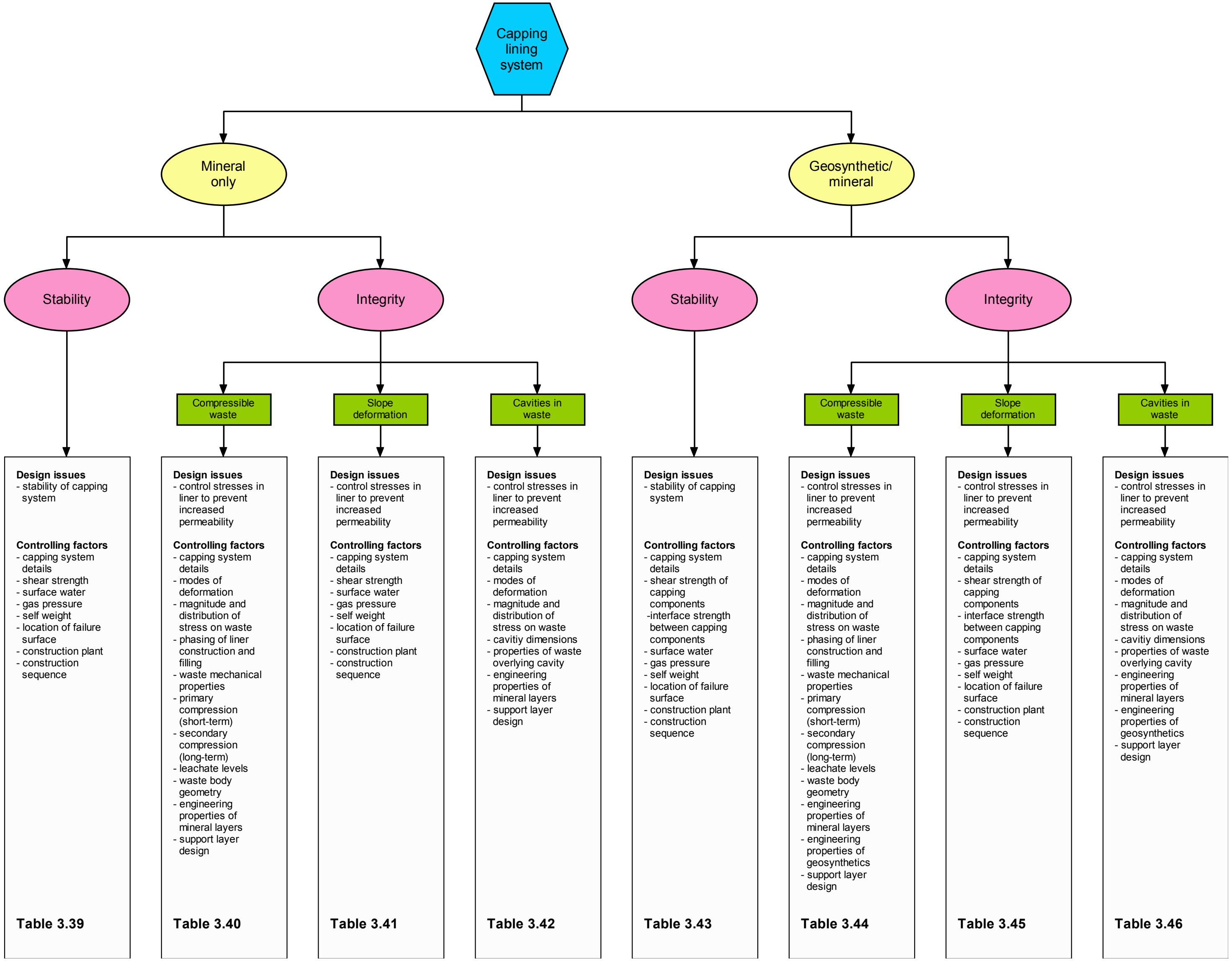


Figure 3.6 Design Flow Chart 6: Capping Lining System

Table 3.39 Mineral Only/Stability

	Design Issues: Stability of capping system
	Controlling Factors: Capping system details thickness of mineral layer type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) cover soil Shear strength mineral layers of lining system sub-grade drained/undrained conditions strain softening Surface water discharges on slope precipitation changes in unit weight of mineral layers changes in pore water pressures (recharge) seepage Gas pressure (filling on waste) important where existing waste slopes are lined gas pressure related to age and type of waste gas control and extraction system Self weight unit weight of materials influence of moisture content changes Location and shape of potential failure surfaces weak layers interfaces between components of lining system interfaces between phases of compaction in mineral layer Construction plant dead weight braking/acceleration forces mode of operation uphill/downhill Construction sequence method of placement stockpiling of material
	Analysis: Limit equilibrium stability analysis infinite slope method (Report 1, 11.3.3) method of slices (Report 1, 11.4.2) Gas pressure (Report 1, 11.3.3) Construction plant loading (Report 1, 11.3.3)

Table 3.40 Mineral Only/Integrity/Compressible Waste

	Design Issues: Control stresses in liner to prevent increased permeability
	Controlling Factors: Capping system details thickness of mineral layer type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) cover soil Modes of deformation tension cracks formation of shear zones Magnitude and distribution of stress on waste Phasing of capping construction and filling Waste mechanical properties material type age density moisture content Primary compression (short-term) elastic compression Secondary compression (long-term) creep degradation Leachate levels leachate pressure degree of saturation Waste body geometry thickness of deposit variation of thickness across site surface slope angle Engineering properties of mineral layer shear strength stiffness plasticity of material grading (% clay materials) clay mineralogy Support layer design stiffness tensile capacity (geosynthetics)
	Analysis: Radius of curvature of deformation profile see Report 1 10.3.2 Assessment of mineral layer plasticity Assessment of control provided by underlying lining system layers (i.e. after Report 1 10.3.3)

Table 3.41 Mineral Only/Integrity/Slope Deformation

	Design Issues: Control stresses in liner to prevent increased permeability
	Controlling Factors: Capping system details thickness of mineral layer type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) cover soil Shear strength of capping components mineral layers of lining system drained/undrained conditions tensile strength of geosynthetics strain softening Surface water discharges on slope precipitation changes in unit weight of mineral layers changes in pore water pressures (recharge) seepage Gas pressure (filling on waste) important where existing waste slopes are lined gas pressure related to age and type of waste gas control and extraction system Self weight unit weight of materials influence of moisture content changes Location and shape of potential failure surfaces weak layers interfaces between components of lining system interfaces between phases of compaction in mineral layer Construction plant dead weight braking/acceleration forces mode of operation uphill/downhill Construction sequence method of placement stockpiling of material
	Analysis: Limit equilibrium stability analysis infinite slope method (Report 1, 11.3.3) method of slices (Report 1, 11.4.2) Gas pressure (Report 1, 11.3.3) Construction plant loading (Report 1, 11.3.3) Assessment of factor of safety to control strains in system

Table 3.42 Mineral Only/Integrity/Cavities in Waste

	Design Issues: Control stresses in liner to prevent increased permeability
	Controlling Factors: Capping system details thickness of mineral layer type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) cover soil Modes of deformation tension cracks formation of shear zones Magnitude and distribution of stress on waste Cavity dimensions estimated plan size depth below lining system rate of change of size rate of migration to underside of lining system Properties of waste overlying cavity mass strength Engineering properties of mineral layer shear strength stiffness plasticity of material grading (% clay materials) clay mineralogy Support layer design stiffness tensile capacity (geosynthetics)
	Analysis: Radius of curvature of deformation profile see Report 1 10.3.2 Assessment of mineral layer plasticity Assessment of control provided by underlying lining system layers (i.e. after Report 1 10.3.3)

Table 3.43 Geosynthetic-Mineral/Stability

Design Issues:

- Stability of capping system

Controlling Factors:

- Capping system details
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
    - cover soil
- Shear strength of capping components
  - mineral layers of lining system
  - mineral layers - drained/undrained
  - tensile strength of geosynthetics
- Interface strength between capping components
  - geosynthetic/geosynthetic
  - geosynthetic/soil
  - strain softening
- Surface water
  - discharges on slope
  - precipitation
  - changes in unit weight of mineral layers
  - changes in pore water pressures (recharge)
  - seepage
- Gas pressure
  - important where existing waste slopes are lined
  - gas pressure related to
    - age and type of waste
    - gas control and extraction system
- Self weight
  - unit weight of materials
  - influence of moisture content changes on mineral layers
- Location and shape of potential failure surfaces
  - weak layers (mineral)
  - interfaces
- Construction plant
  - dead weight
  - braking/acceleration forces
  - mode of operation
    - Uphill/downhill
- Construction sequence
  - method of placement
  - stockpiling of material

Analysis:

- Limit equilibrium stability analysis
  - infinite slope method (Report 1, 11.3.3)
  - finite slope method (Report 1, 11.3.3)
  - method of slices (Report 1, 11.4.2)
- Gas pressure (Report 1, 11.3.3)
- Construction plant loading (Report 1, 11.3.3)
- Assessment of geosynthetic stress (Report 1, 11.3.3)

Table 3.44 Geosynthetic-Mineral/Integrity/Compressible Waste

Design Issues:

- Control stresses in liner to prevent increased permeability

Controlling Factors:

- Capping system details
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
    - cover soil
- Modes of deformation
  - tension cracks in mineral layer
  - formation of shear zones in mineral layer
  - tensile failure (tearing) of geosynthetic liner
  - excessive strains in geosynthetic liner
- Magnitude and distribution of stress on waste
- Phasing of capping construction and filling
- Waste mechanical properties
  - material type
  - age
  - density
  - moisture content
- Primary compression (short-term)
  - elastic compression
- Secondary compression (long-term)
  - creep
  - degradation
- Leachate levels
  - leachate pressure
  - degree of saturation
- Waste body geometry
  - thickness of deposit
  - variation of thickness across site
  - surface slope angle
- Engineering properties of mineral layer
  - shear strength
  - stiffness
  - plasticity of material
    - grading (% clay materials)
    - clay mineralogy
- Engineering properties of geosynthetic materials
  - tensile strength
  - limiting strains for stress cracking
- Support layer design
  - stiffness
  - tensile capacity (geosynthetics)

Analysis:

- Radius of curvature of deformation profile
- Assessment of stresses in ancillary support layers (e.g. geosynthetic reinforcement) (see Report 1 10.3.3)
- Assessment of mineral liner plasticity
- Assessment of strains in geosynthetic barrier

Table 3.45 Geosynthetic-Mineral/Integrity/Slope Deformation

	Design Issues: Control stresses in liner to prevent increased permeability
	Controlling Factors: Capping system details thickness of mineral layer type of geosynthetic liner type and dimensions of ancillary underlying and overlying layers reinforcement (geogrid) drainage layers (mineral, geocomposite) cover soil Shear strength of capping components mineral layers of lining system drained/undrained conditions tensile strength of geosynthetic layers Interface strength between capping components geosynthetic/geosynthetic geosynthetic/soil strain softening Surface water discharges on slope precipitation changes in unit weight of mineral layers changes in pore water pressures (recharge) seepage Gas pressure (filling on waste) important where existing waste slopes are lined gas pressure related to age and type of waste gas control and extraction system Self weight unit weight of materials influence of moisture content changes Location and shape of potential failure surfaces weak layers interfaces between components of lining system interfaces between phases of compaction in mineral layer Construction plant dead weight braking/acceleration forces mode of operation uphill/downhill Construction sequence method of placement stockpiling of material
	Analysis: Limit equilibrium stability analysis infinite slope method (Report 1, 11.3.3) method of slices (Report 1, 11.4.2) Gas pressure (Report 1, 11.3.3) Construction plant loading (Report 1, 11.3.3) Assessment of factor of safety to control strains in system

Table 3.46 Geosynthetic-Mineral/Integrity/Cavities in Waste

Design Issues:

- Control stresses in liner to prevent increased permeability

Controlling Factors:

- Capping system details
  - thickness of mineral layer
  - type of geosynthetic liner
  - type and dimensions of ancillary underlying and overlying layers
    - reinforcement (geogrid)
    - drainage layers (mineral, geocomposite)
    - cover soil
- Modes of deformation
  - tension cracks in mineral layer
  - formation of shear zones in mineral layer
  - tensile failure (tearing) of geosynthetic liner
  - excessive strains in geosynthetic liner
- Magnitude and distribution of stress on waste
- Cavity dimensions
  - estimated plan size
  - depth below lining system
  - rate of change of size
  - rate of migration to underside of lining system
- Properties of waste overlying cavity
  - mass strength
- Engineering properties of mineral layer
  - shear strength
  - stiffness
  - plasticity of material
    - grading (% clay materials)
    - clay mineralogy
- Engineering properties of geosynthetic materials
  - tensile strength
  - limiting strains for stress cracking
- Support layer design
  - stiffness
  - tensile capacity (geosynthetics)

Analysis:

- Radius of curvature of deformation profile
- Assessment of stresses in ancillary support layers (e.g. geosynthetic reinforcement) - see Report 1 10.3.3
- Assessment of mineral liner plasticity
- Assessment of strains in geosynthetic barrier

4. EXAMPLE CALCULATIONS

This Chapter provides details of four example calculations. These have been selected to demonstrate the use of the design flow charts and selection of appropriate design cases. Each of the examples has been chosen to highlight specific landfill liner stability and integrity issues. The examples are:

- Example 1: Single clay liner in an old clay pit, includes assessment of basal heave;
- Example 2: Composite BES/geomembrane liner in an old sand and gravel quarry, includes design solution to the presence of cavities;
- Example 3: Geomembrane capping, includes design solution for construction on compressible waste and the presence of cavities; and
- Example 4: Self-supporting steep slope lining system, includes issues of integrity related to waste settlement.

Design flow charts are included for each design case considered (e.g. sub-grade, basal lining system, shallow side slope lining system etc.) and the issues specific to that example are highlighted. For each case history a summary of the controlling factors is provided along with explanation and justification of the approach taken.

4.1 Example 1: Single Clay Liner in Old Clay Pit

4.1.1 Description

The site is a disused clay pit where the existing slopes are to be cut back to 1 (vertical) in 2 (horizontal) to form the proposed landfill perimeter. The site investigation has shown that the in situ clay is homogeneous. Groundwater was encountered in a sandstone band beneath the site and its piezometric level has been monitored for a representative period. The proposed lining system is a single clay liner, 1m thick, on base and side slopes. A 500 mm thick gravel drainage blanket will cover the base and the side slopes, and a separator geotextile will be placed above and below the gravel. The landfill will be developed as one cell. Design flow charts and calculations for this example are presented in Section 4.1.6 below.

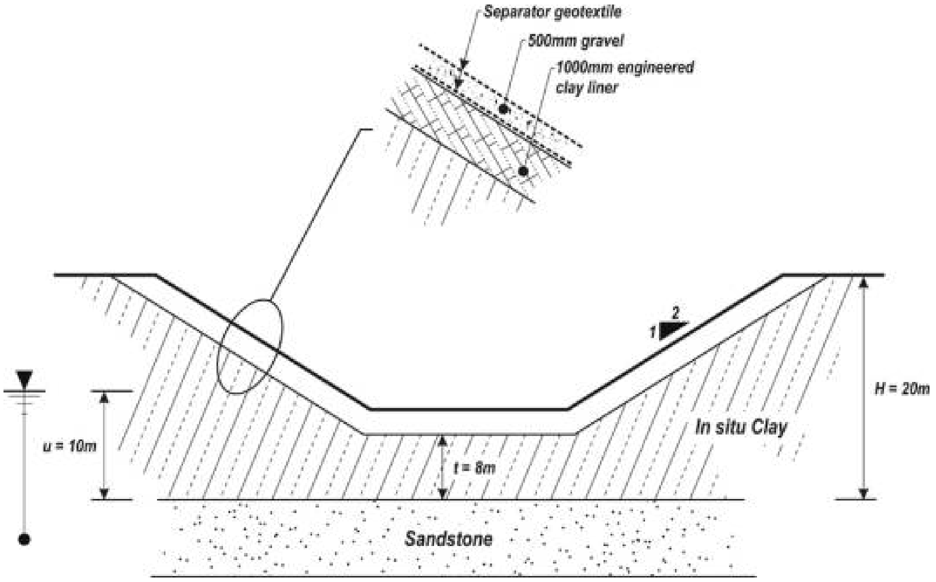


Figure 4.1 Schematic Cross Section of Example 1

4.1.2 Sub-grade

The sub-grade design cases to be considered are highlighted in Figure 4.2.

Base Stability

The site investigation showed that there was no compressible material or cavities beneath the site.

Excessive Deformations - Basal Heave

Design issues:

- adequate site investigation.

Based on the results of the site investigation and the groundwater monitoring, the geology and hydrogeology have been well defined. A suitable factor of safety for this calculation would be 1.5.

4.1.3 Cut slope stability

Cohesive Soil

Design issues:

- adequate site investigation;
- stability;
- deformability;
- time dependent stability.

The stability of the cohesive cut slopes need to be assessed for both the short-term and the long-term; this can be carried out by an undrained and drained analysis respectively. A suitable factor of safety for the slope would be 1.5. In the assessment of the long-term stability, consideration needs to be given to the time taken for the build-up of pore pressures within the clay and also the time for which the slope will be exposed (i.e. before the waste is placed). In this example, it is considered that the slope will not be exposed long enough for positive pore pressures to develop and suitable factor of safety would be 1.1.

4.1.4 Basal lining system

The basal lining system design cases to be considered are highlighted in Figure 4.3.

Mineral Only Liner

The site investigation showed that there was no compressible material or cavities beneath the site.

Basal Heave

Design issues:

- barrier is not designed to resist heave, design must ensure that heave does not occur.

These calculations have been carried out for the sub-grade and therefore do not have to be repeated since the placement of the lining system will increased the factor of safety against basal heave.

4.1.5 Shallow side slope liner

The shallow side slope liner design cases to be considered are highlighted in Figure 4.4.

Unconfined Slope

Mineral Only Liner – Stability

Design issues:

- stability of sub-grade;

- stability of liner;
- stability of drainage layer.

The stability of the unconfined slope needs to be assessed with the liner in place. When the clay liner is placed it will have an undrained shear strength in excess of 70 kPa as this is a specified requirement. As the liner is left exposed, the negative pore pressures (suctions) within the clay will slowly dissipate and the clay will soften, and this can be modelled by considering a reduction in undrained shear strength. A suitable factor of safety would be 1.5.

For the long-term analysis, an effective stress approach is used. As for the cut slope, consideration needs to be given to the time taken for the build-up of pore pressures within the clay and also the time for which the slope will be exposed. In this example, it is considered that the slope will not be exposed long enough for positive pore pressures to develop and suitable factor of safety would be 1.1.

Mineral Only Liner – Integrity

Design issues:

- control stresses in liner to prevent increased permeability.

In this instance, the mode of integrity failure is the same as stability failure and therefore no additional calculations are required.

Confined Slope

Mineral Only Liner – Stability

Design issues:

- stability of sub-grade;
- stability of liner.

If the unconfined slope is demonstrated to be stable then the placement of waste will increase the stability and no further calculations are required.

Mineral Only Liner – Integrity

Design issues:

- control stresses in liner to prevent increased permeability;
- disruption to drainage layers.

The integrity of the shallow side slope lining system once waste has been placed can be assessed by carrying out an analysis of the slope with waste placed in front. The contribution of the waste to the stability of the slope can be modelled by applying a load to the slope based on the vertical and horizontal stresses within the waste. The horizontal support is based on a value of the earth pressure coefficient K_0.

It is considered that there will be no disruption to the gravel drainage layer due to geotextile separator between drainage layer and waste.

4.1.6 Waste slope

The waste slope design cases to be considered are highlighted in Figure 4.5.

Failure Wholly in Waste

Design issue:

- stability of waste slope.

Since the cell will be filled in one operation and the waste will be placed in horizontal layers for the full width, there will be no temporary waste slope.

Failure involving Lining System

Mineral Only Liner – Stability

Design issues:

- stability of sub-grade;
- stability of liner.

Since the cell will be filled in one operation and the waste will be placed in horizontal layers for the full width, there will be no temporary waste slope.

Mineral Only Liner – Integrity

Design issues:

- control stresses in liner to prevent increased permeability;
- disruption to drainage layers.

This failure mode has been assessed for confined shallow side slope liner in Section 4.1.4.

4.1.7 Design flow charts and calculations

See Figures 4.2 to 4.6

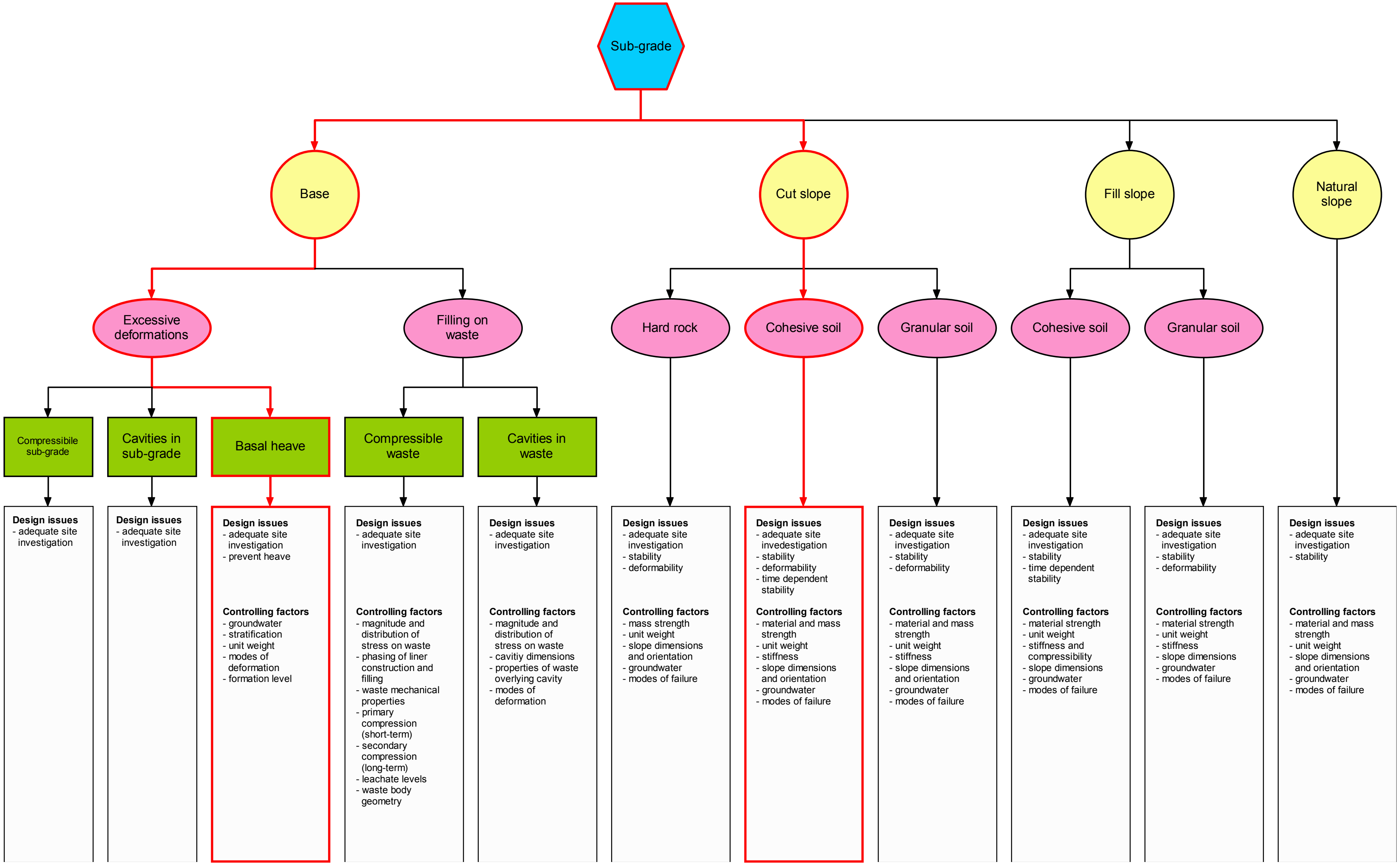


Figure 4.2 Design Flow Chart for Example 1: Sub-grade

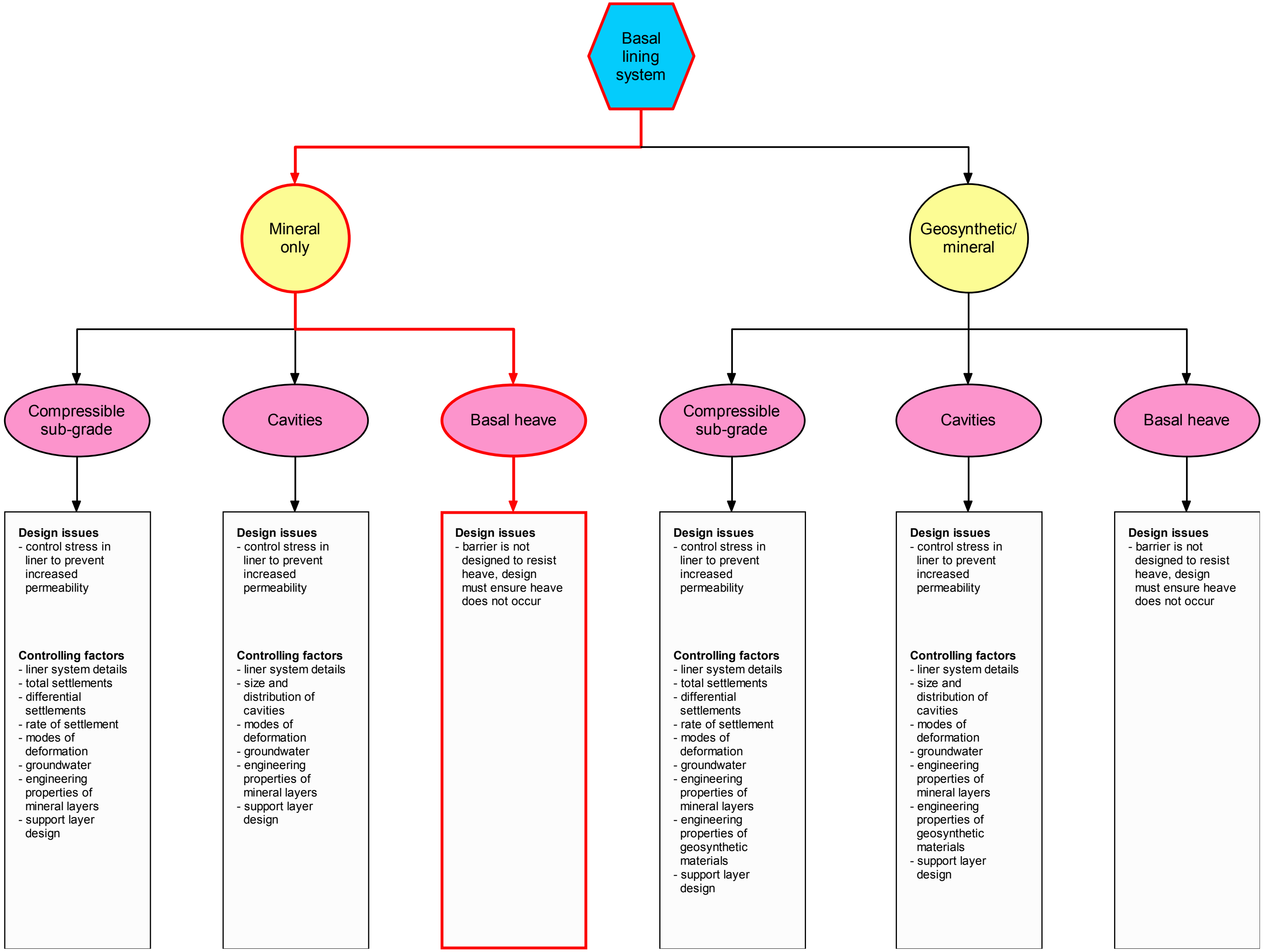


Figure 4.3 Design Flow Chart for Example 1: Basal Lining System

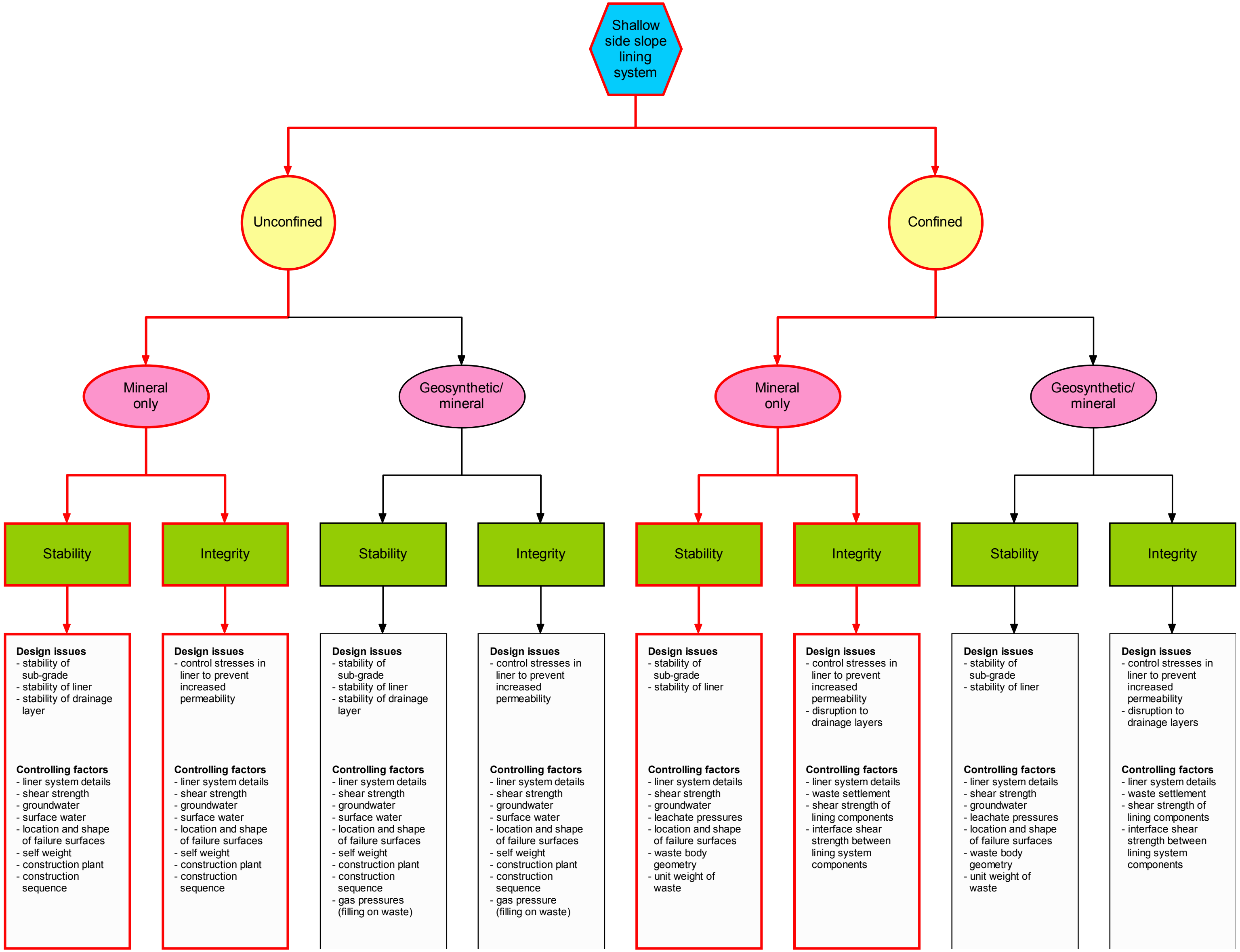


Figure 4.4 Design Flow Chart for Example 1: Shallow Side Slope Lining System

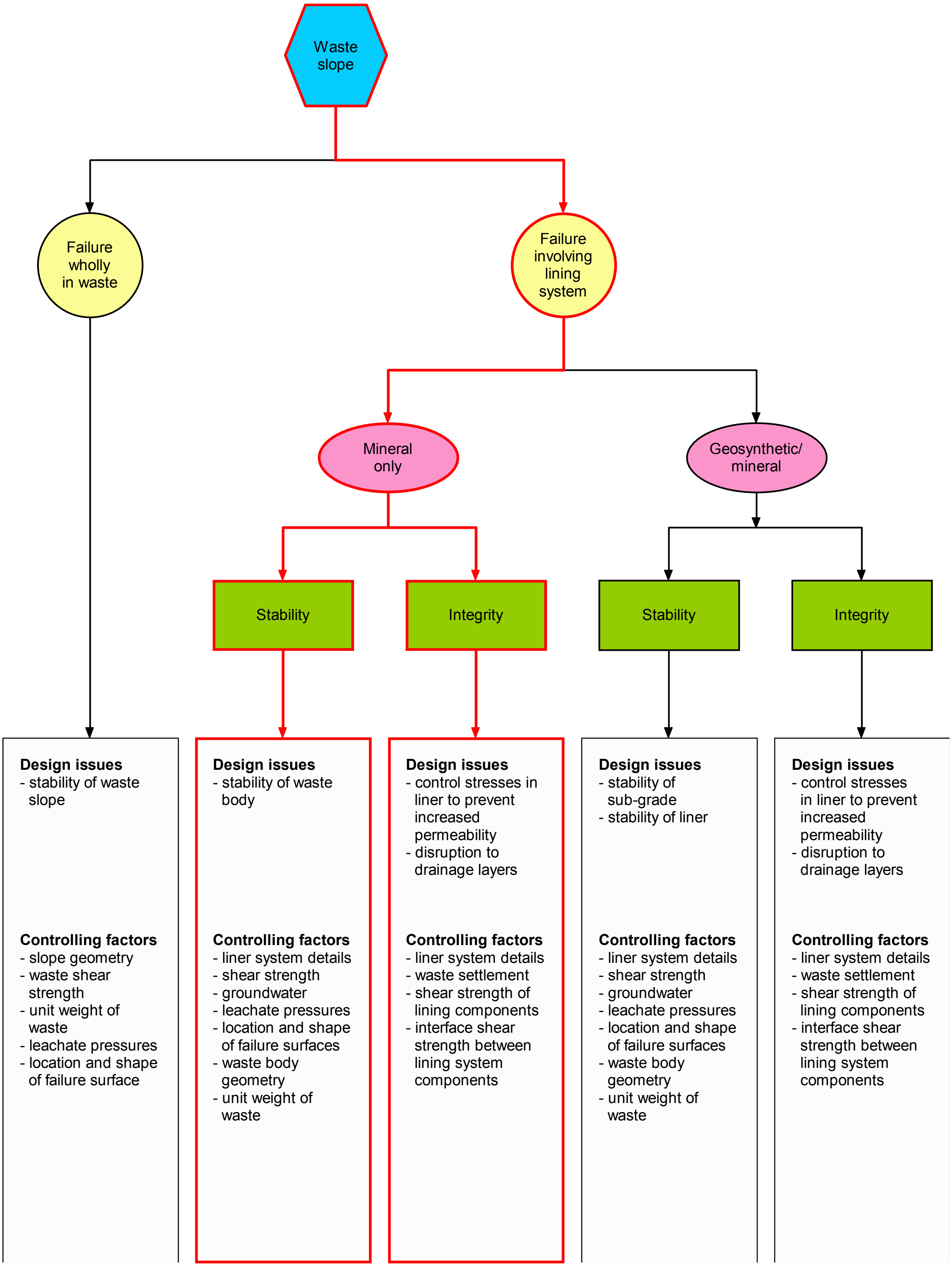


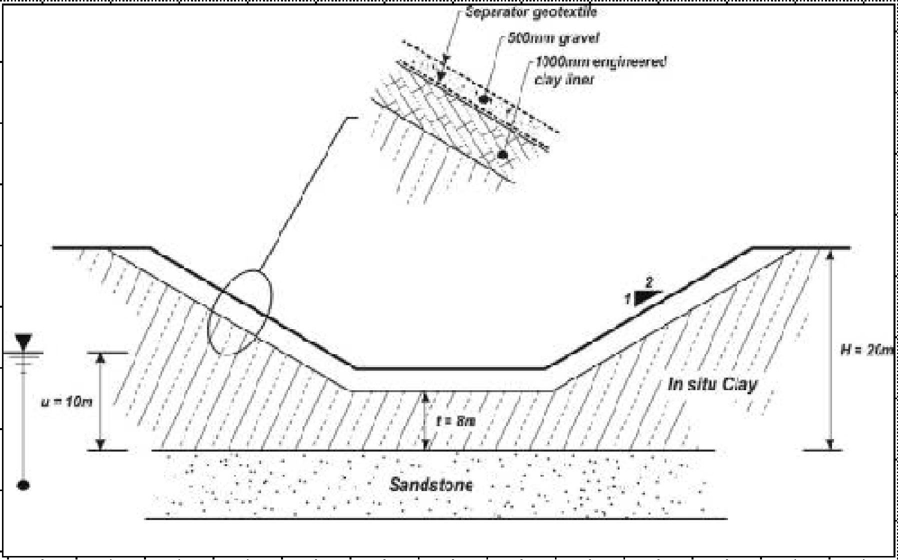
Figure 4.5 Design Flow Chart for Example 1: Waste Slope

]

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 1	Checked:		Sheet:	1
			Reviewed:		of:	14

DESCRIPTION: Single clay lined landfill situated on a confined sandstone band

GEOMETRY:



1. SUBGRADE

1.1 Base Stability

Excessive deformations: basal heave

From the site investigation, the geology and hydrogeology beneath the site is known
The factor of safety against basal heave is:

$$\text{F of S} = \frac{\gamma_{soil}\, t}{\gamma_{water}\, u} = \frac{19 * 8}{9.8 * 10} = 1.55 \qquad \mathbf{1.55}$$

This is > than 1.5, and is therefore considered satisfactory. **OK**

1.2 Cut slope stability

a) Short-term stability: undrained analysis

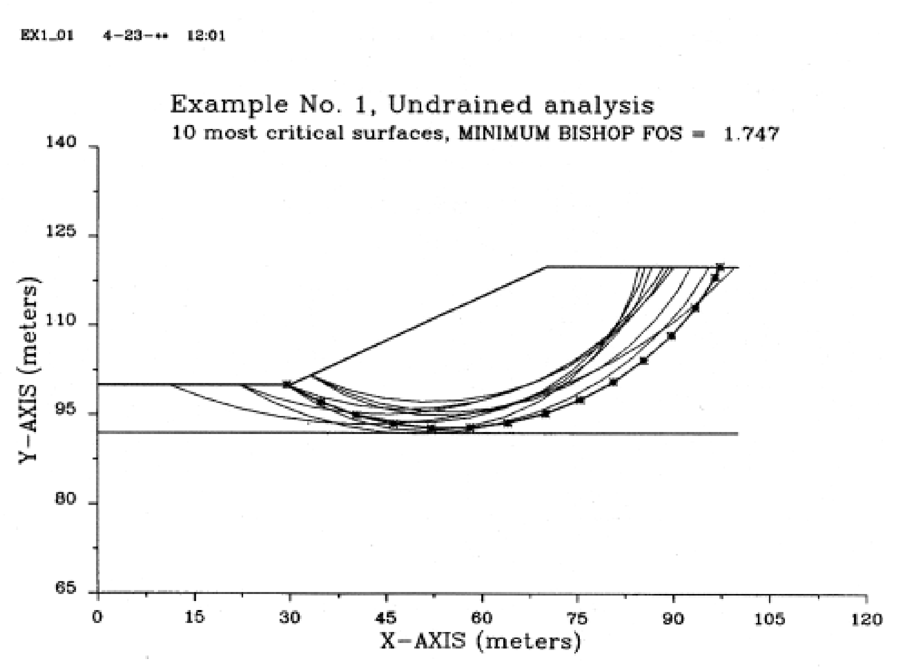
Aim: Assess the stability of the cut slope in the short term

Approach: Use the computer code XSTABL to calculate the factor of safety for a range of circular failures. Use undrained shear strength and vary to model reduction with time.

Figure 4. 6 Calculations for Example 1

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 1	Checked:		Sheet:	2
			Reviewed:		of:	14

Calculations:



Results:

Run	File Name	c_u (kPa)	F of S	Comments	
1	Ex1_01	100	1.75	Large circular failure	**1.75**

The undrained shear strength of the in situ material has been measured as greater than 100 kPa

Conclusions:

The calculated factor of safety is > 1.5 and is therefore considered satisfactory **OK**

b) Long-term stability: drained analysis

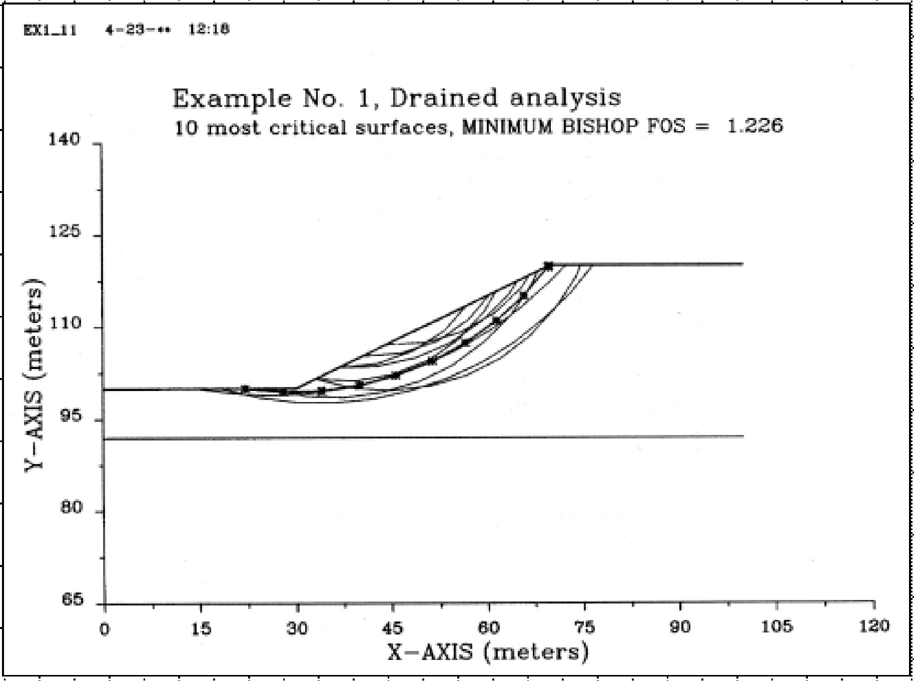
Aim: Assess the stability of the cut slope in the long-term

Approach: Use the computer code XSTABL to calculate the factor of safety for a range of circular failures. Use effective shear strength parameters and use r_u to model pore pressures in clay.

Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 1	Checked:		Sheet:	3
			Reviewed:		of:	14

Calculations:



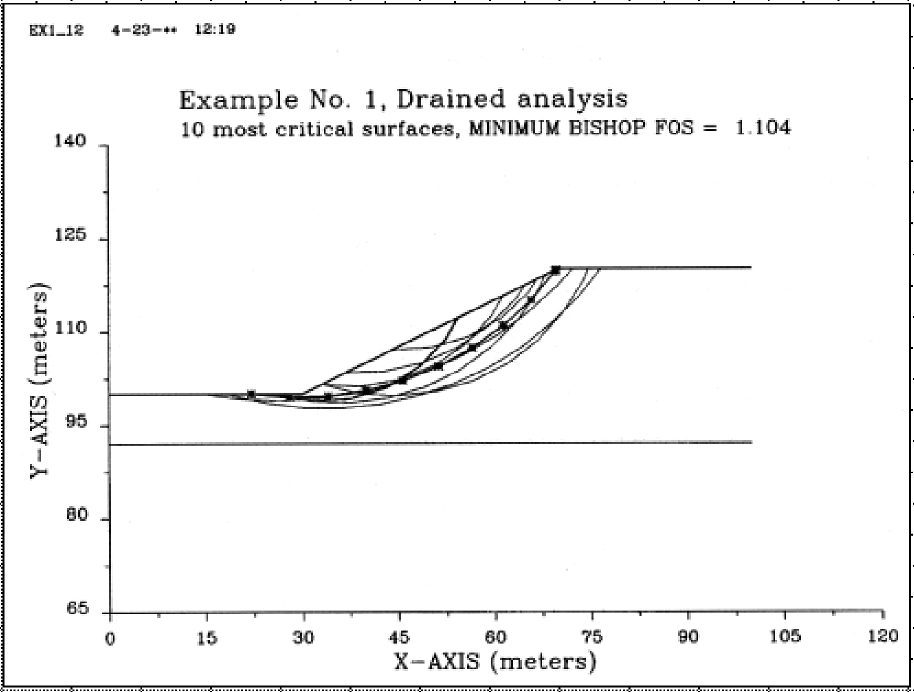


Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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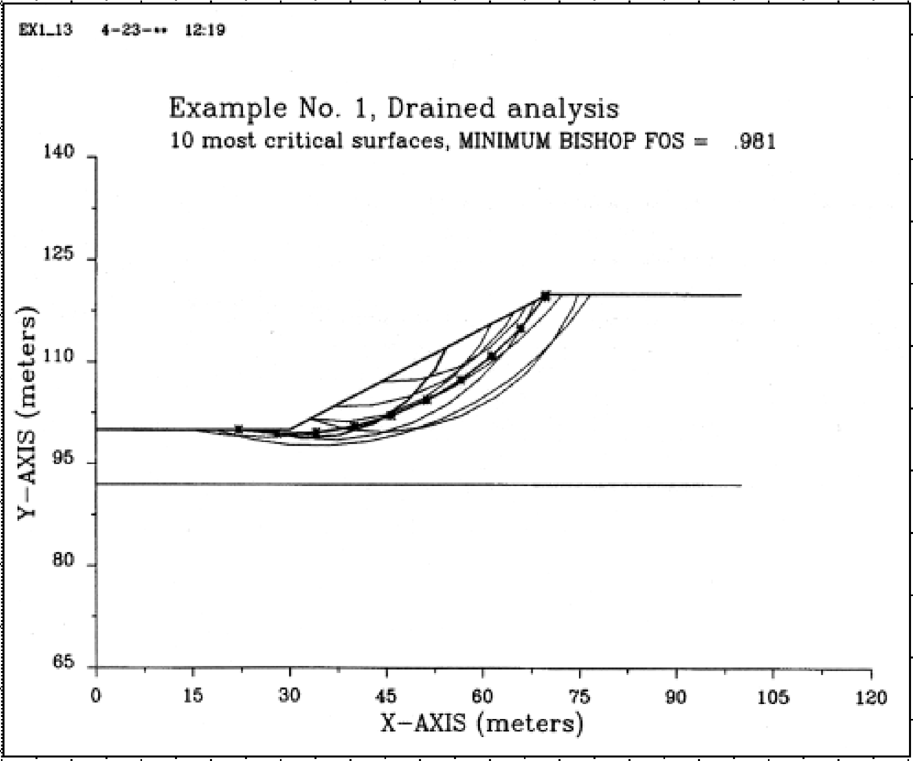


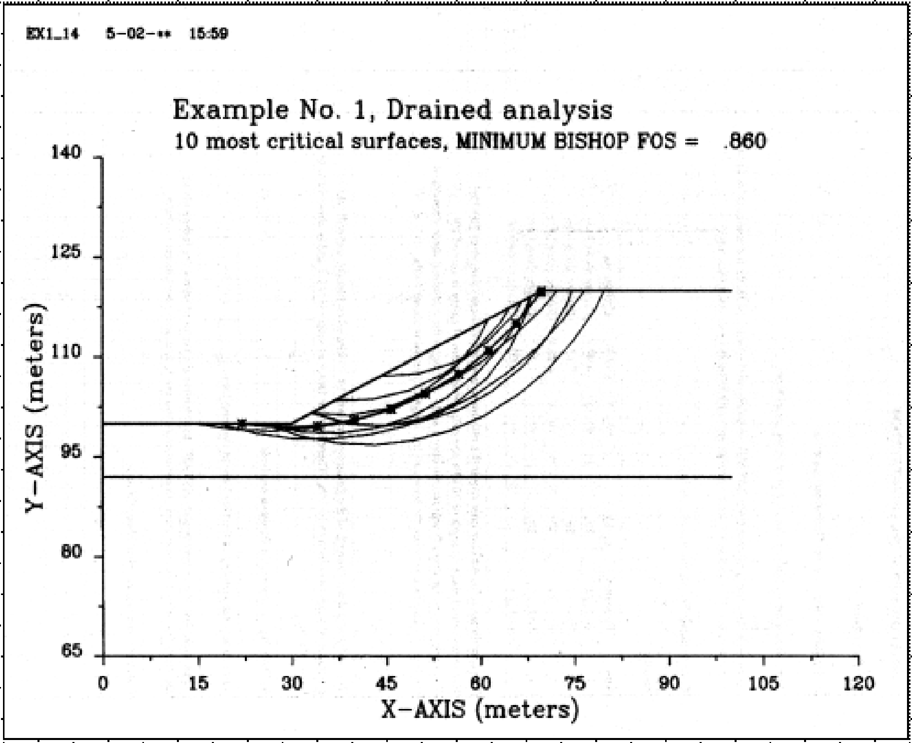
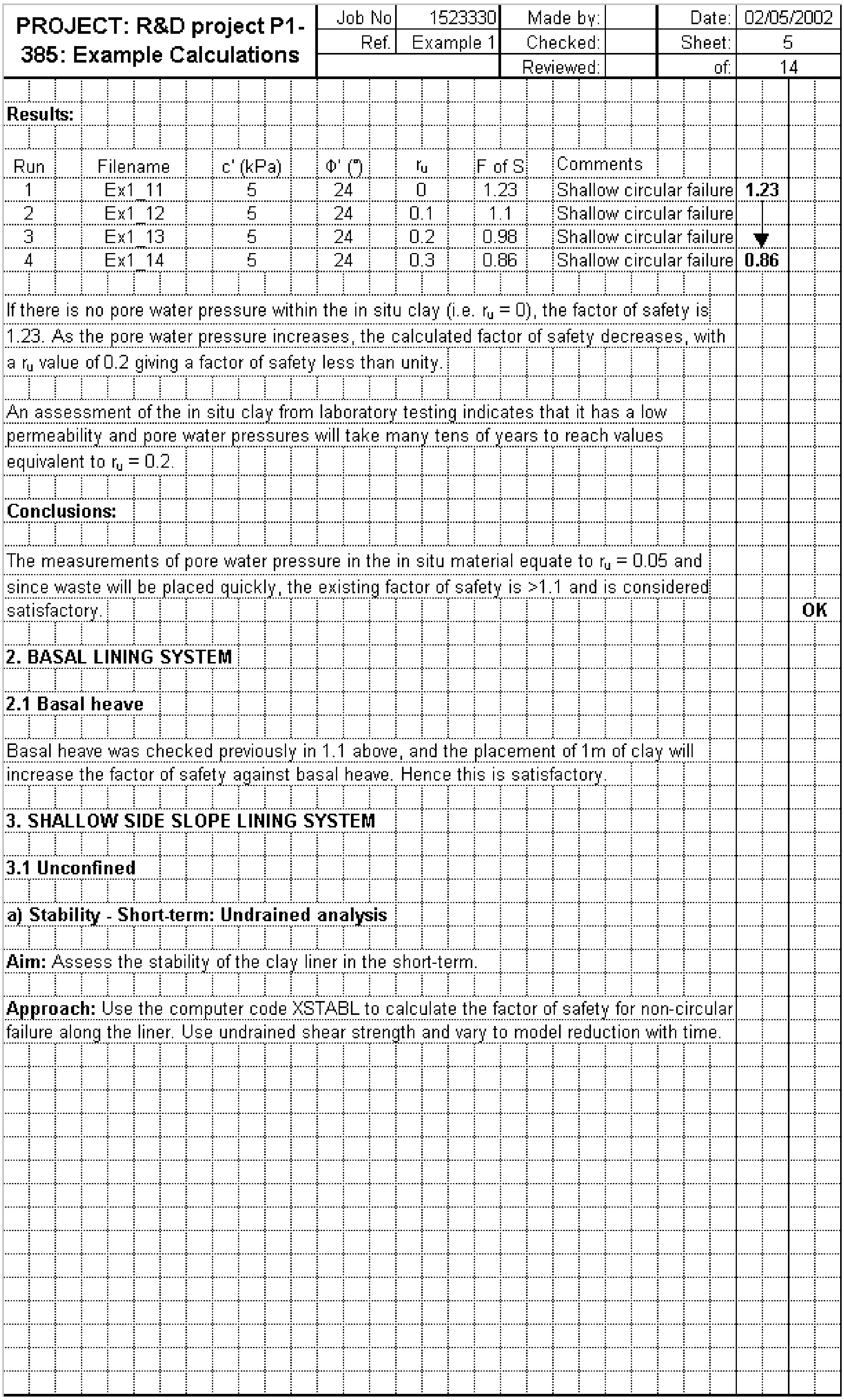


Figure 4.6 **Calculations for Example 1 continued**



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 1	Checked:		Sheet:	5
			Reviewed:		of:	14

Results:

Run	Filename	c' (kPa)	Φ' (°)	r_u	F of S	Comments	
1	Ex1_11	5	24	0	1.23	Shallow circular failure	**1.23**
2	Ex1_12	5	24	0.1	1.1	Shallow circular failure	
3	Ex1_13	5	24	0.2	0.98	Shallow circular failure	↓
4	Ex1_14	5	24	0.3	0.86	Shallow circular failure	**0.86**

If there is no pore water pressure within the in situ clay (i.e. $r_u = 0$), the factor of safety is 1.23. As the pore water pressure increases, the calculated factor of safety decreases, with a r_u value of 0.2 giving a factor of safety less than unity.

An assessment of the in situ clay from laboratory testing indicates that it has a low permeability and pore water pressures will take many tens of years to reach values equivalent to $r_u = 0.2$.

Conclusions:

The measurements of pore water pressure in the in situ material equate to $r_u = 0.05$ and since waste will be placed quickly, the existing factor of safety is >1.1 and is considered satisfactory.

OK

2. BASAL LINING SYSTEM

2.1 Basal heave

Basal heave was checked previously in 1.1 above, and the placement of 1m of clay will increase the factor of safety against basal heave. Hence this is satisfactory.

3. SHALLOW SIDE SLOPE LINING SYSTEM

3.1 Unconfined

a) Stability - Short-term: Undrained analysis

Aim: Assess the stability of the clay liner in the short-term.

Approach: Use the computer code XSTABL to calculate the factor of safety for non-circular failure along the liner. Use undrained shear strength and vary to model reduction with time.

Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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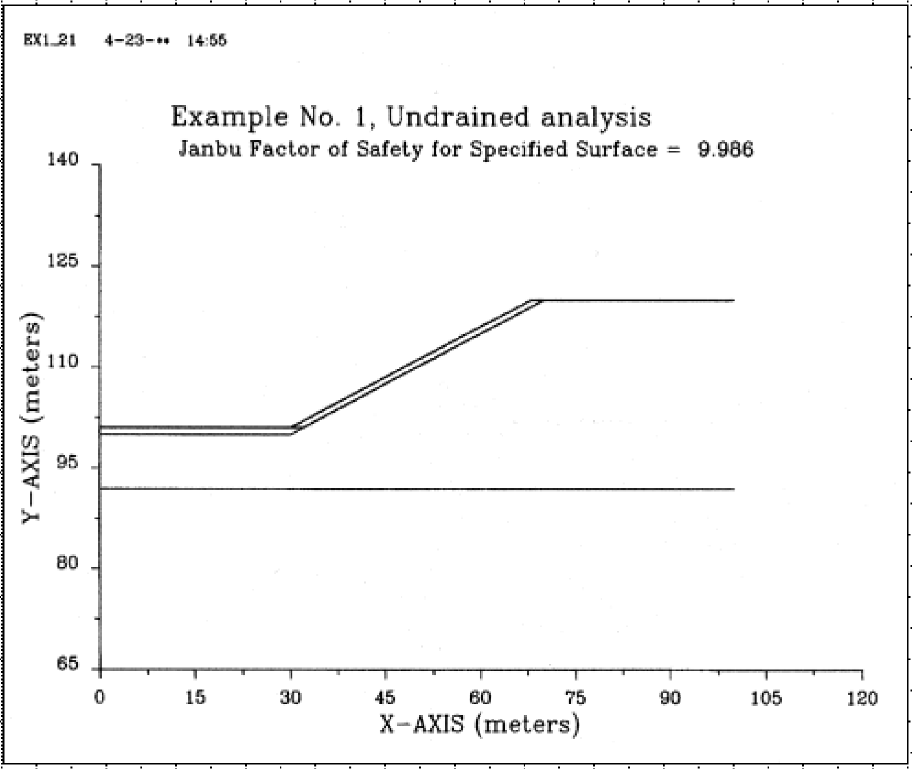
Calculations:



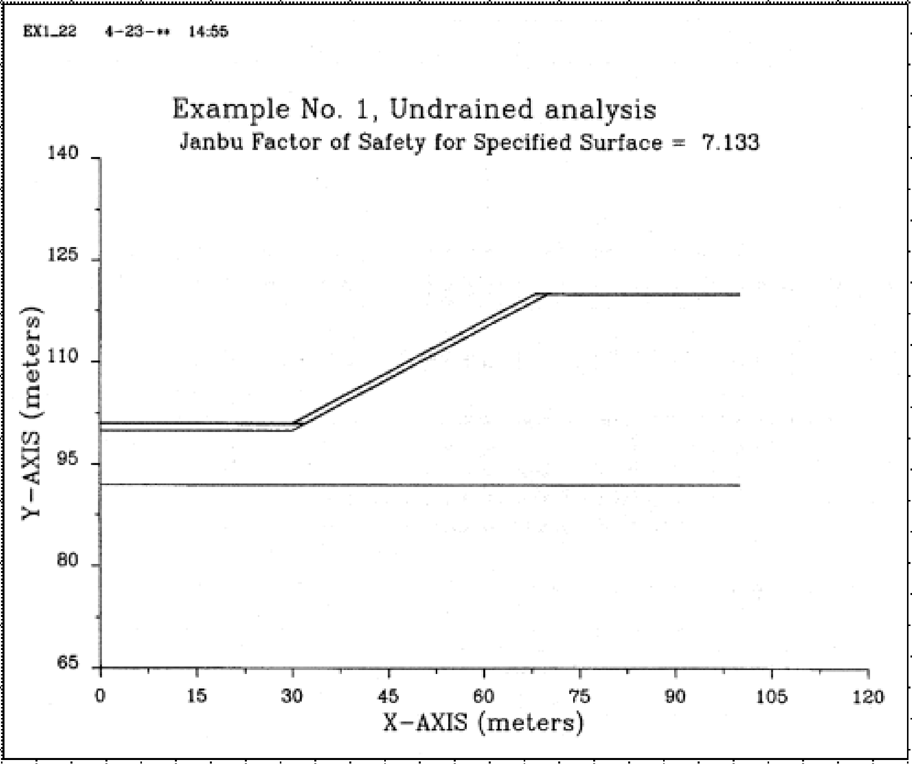


Figure 4.6 Calculations for Example 1 continued

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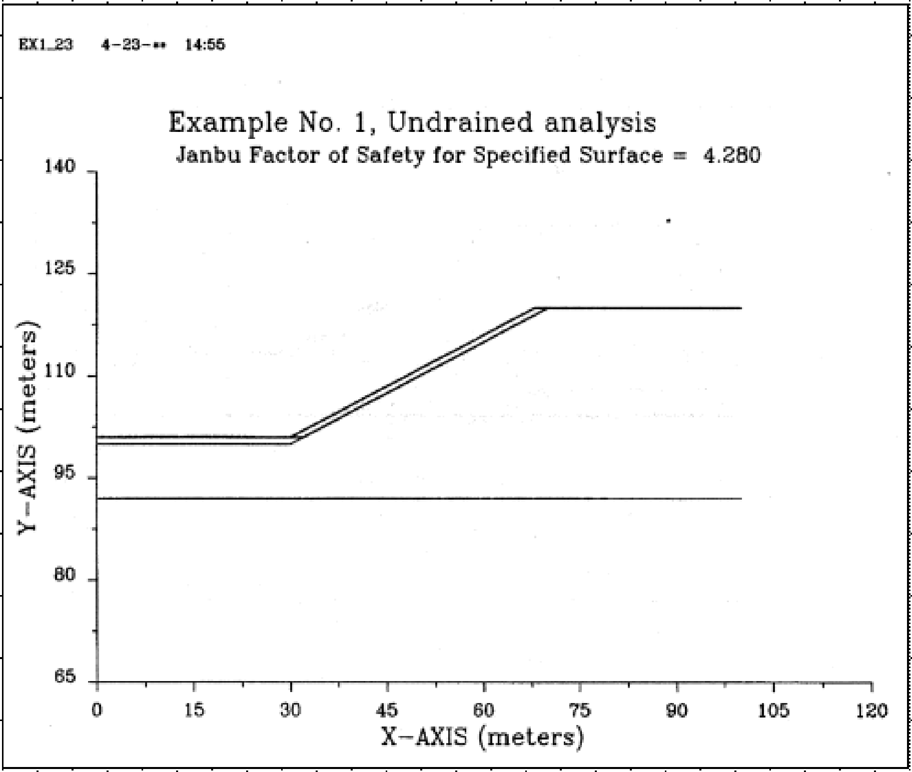

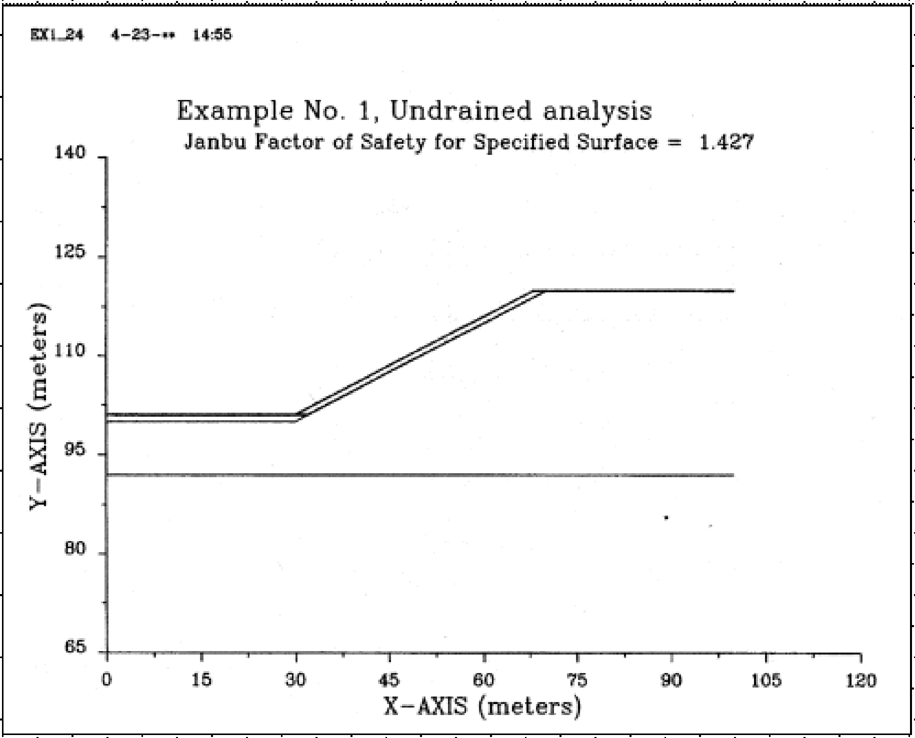

Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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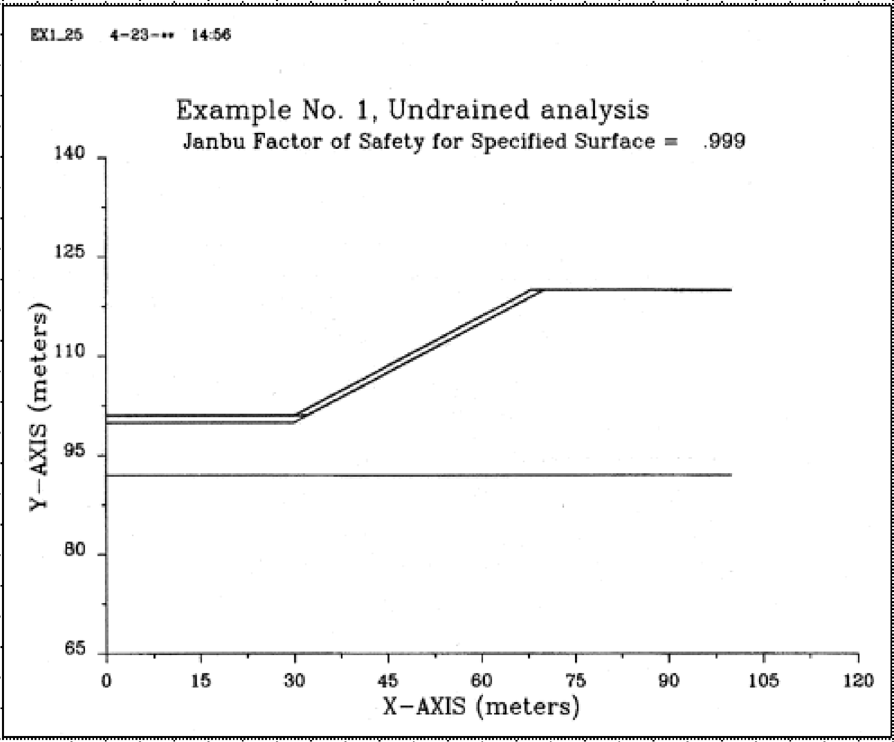
			Reviewed:		of:	14



Results:

Run	Filename	c_u (kPa)	F of S	Comments	
1	Ex1_21	70	9.99	Failure along liner	9.99
2	Ex1_22	50	7.13	Failure along liner	↓
3	Ex1_23	30	4.28	Failure along liner	
4	Ex1_24	10	1.43	Failure along liner	
5	Ex1_25	7	1.00	Failure along liner	1.00

The specification for the clay liner requires a minimum undrained shear strength of 70 kPa. For an undrained shear strength of 70 kPa, the calculated factor of safety is around 10. The undrained strength will remain above unity as long as the undrained shear strength of the liner (or the interface between the liner and the subgrade) remains above 7 kPa.

Conclusions:

The undrained shear strength of the lining system will be 70 kPa when place, and will take a number of years to reduce to 10 kPa. Therefore the factor of safety is >1.5 and is considered to be satisfactory. **OK**

b) Stability - Long-term: Drained analysis

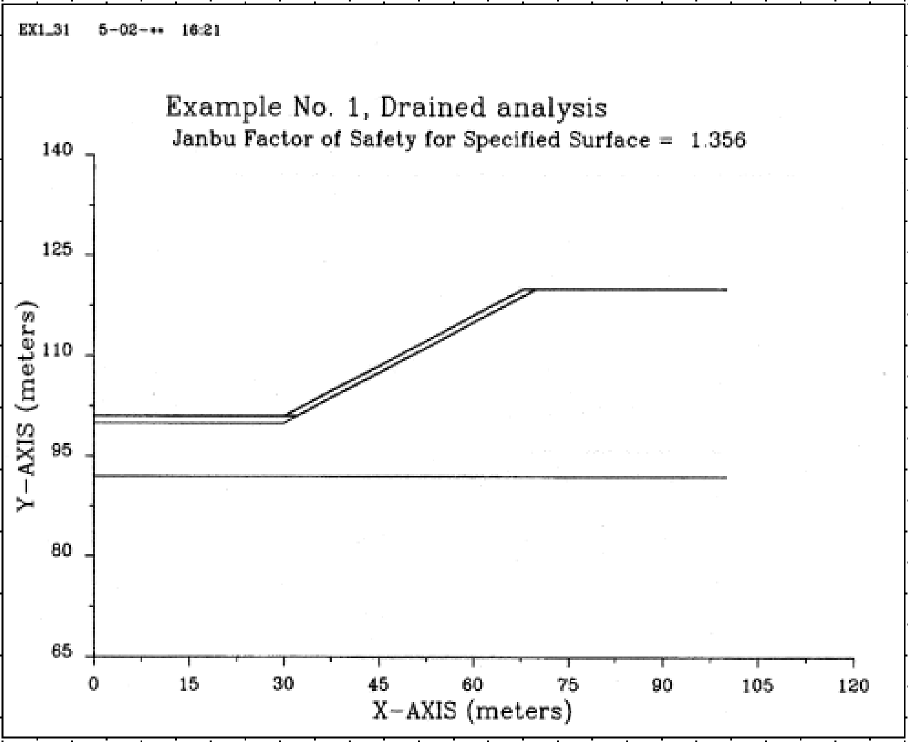
Aim: Assess the stability of the clay liner in the long-term.

Approach: Use the computer code XSTABL to calculate the factor of safety for failure along the liner. Use effective shear strength parameters and use r_u to model pore pressures in clay.

Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 1	Checked:		Sheet:	9
			Reviewed:		of:	14

Calculations:



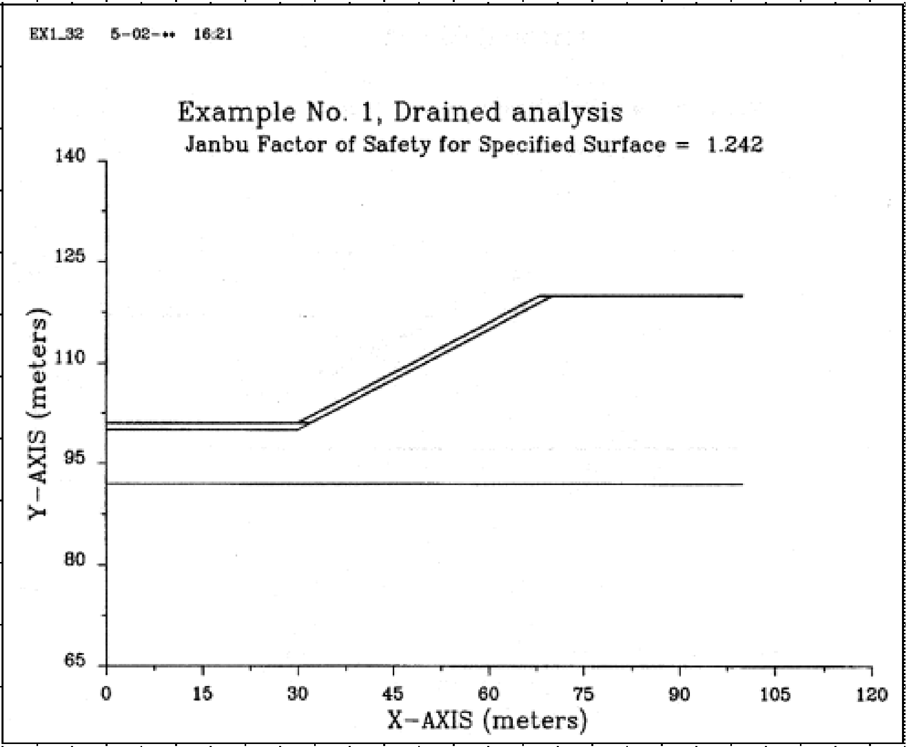


Figure 4.6 Calculations for Example 1 continued

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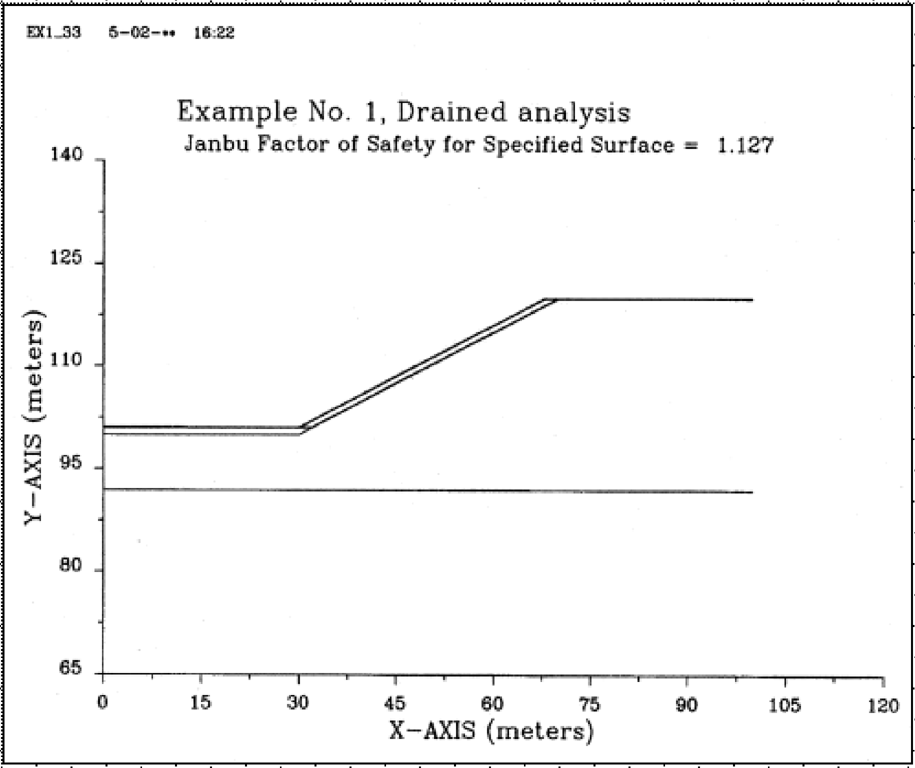

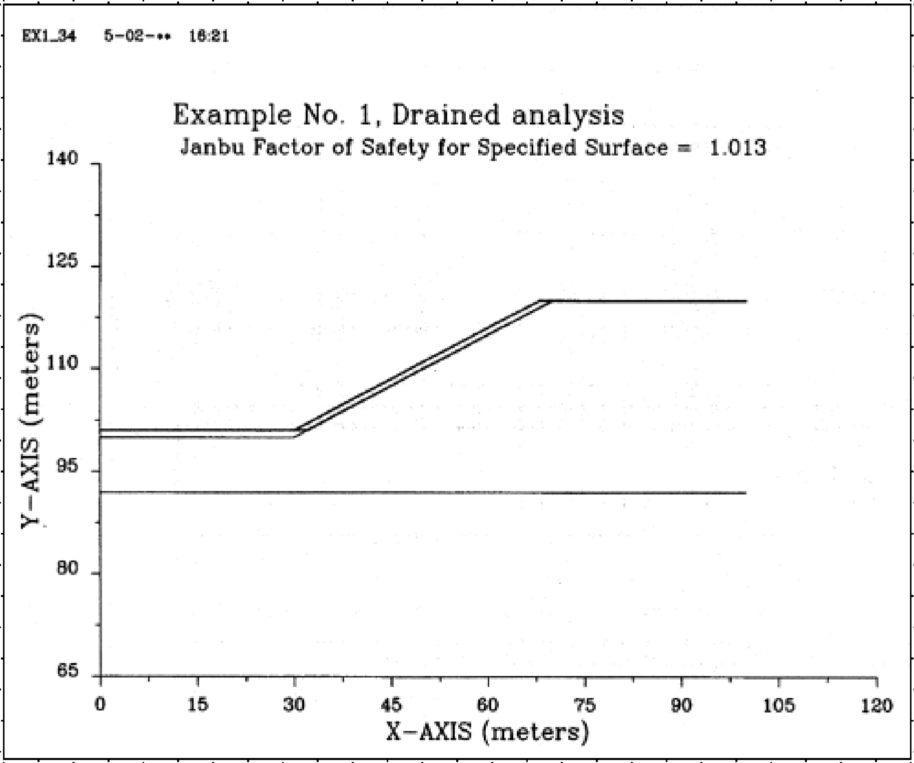

Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 1	Checked:		Sheet:	11
			Reviewed:		of:	14

Results:

Run	Filename	c' (kPa)	Φ' (°)	r_u	F of S	Comments	
1	Ex1_31	3	24	0.0	1.36	Failure along liner	**1.36**
2	Ex1_32	3	24	0.1	1.24	Failure along liner	↓
3	Ex1_33	3	24	0.2	1.13	Failure along liner	
4	Ex1_34	3	24	0.3	1.01	Failure along liner	**1.01**

Conclusions:

When the clay liner is first placed it will have suctions and therefore the factor of safety will be greater than 1.36. It will take a number of years for the pore pressures to equilibrate and even if the pore pressures reach a value equal to a ru value of 0.2, the factor of safety is >1.1 and is therefore considered satisfactory. **OK**

c) Integrity

The mode of integrity failure is the same as stability failure (long term) and therefore no additional calculations are required. **OK**

3.2 Confined

a) Stability

By inspection, if the unconfined slope is stable then the confined slope will be stable. **OK**

b) Integrity

Since the subgrade stability was marginal (I.e. it depended on the pore pressures), an assessment of the integrity of the liner post-waste placement can be carried out by assessing the stability of the confined subgrade and liner system.

Aim: Calculate the stability of the confined slope

Approach: Use the computer code XSTABL to calculate the factor of safety for a range of circular failures. Apply waste loading to the slope based on the vertical load and a horizontal load calculated from the K_o of the waste. Use effective shear strength parameters and use r_u to model pore pressures in clay.

Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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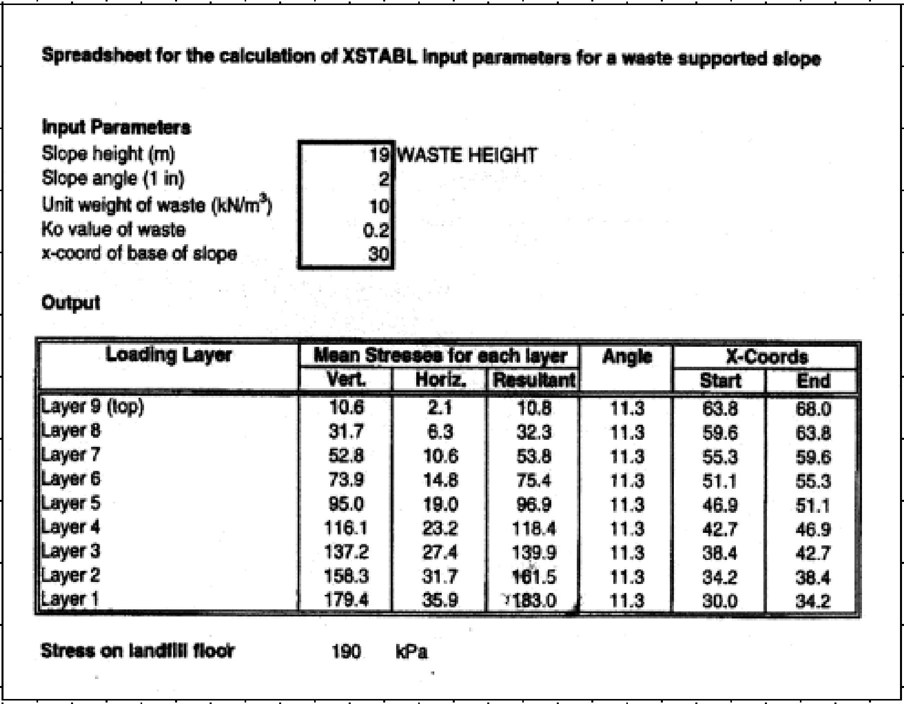
			Reviewed:		of:	14

Calculations:



Spreadsheet for the calculation of XSTABL input parameters for a waste supported slope

Input Parameters

Slope height (m)	19	WASTE HEIGHT
Slope angle (1 in)	2	
Unit weight of waste (kN/m^3)	10	
Ko value of waste	0.2	
x-coord of base of slope	30	

Output

Loading Layer	Mean Stresses for each layer			Angle	X-Coords	
	Vert.	Horiz.	Resultant		Start	End
Layer 9 (top)	10.6	2.1	10.8	11.3	63.8	68.0
Layer 8	31.7	6.3	32.3	11.3	59.6	63.8
Layer 7	52.8	10.6	53.8	11.3	55.3	59.6
Layer 6	73.9	14.8	75.4	11.3	51.1	55.3
Layer 5	95.0	19.0	96.9	11.3	46.9	51.1
Layer 4	116.1	23.2	118.4	11.3	42.7	46.9
Layer 3	137.2	27.4	139.9	11.3	38.4	42.7
Layer 2	158.3	31.7	161.5	11.3	34.2	38.4
Layer 1	179.4	35.9	183.0	11.3	30.0	34.2

Stress on landfill floor 190 kPa

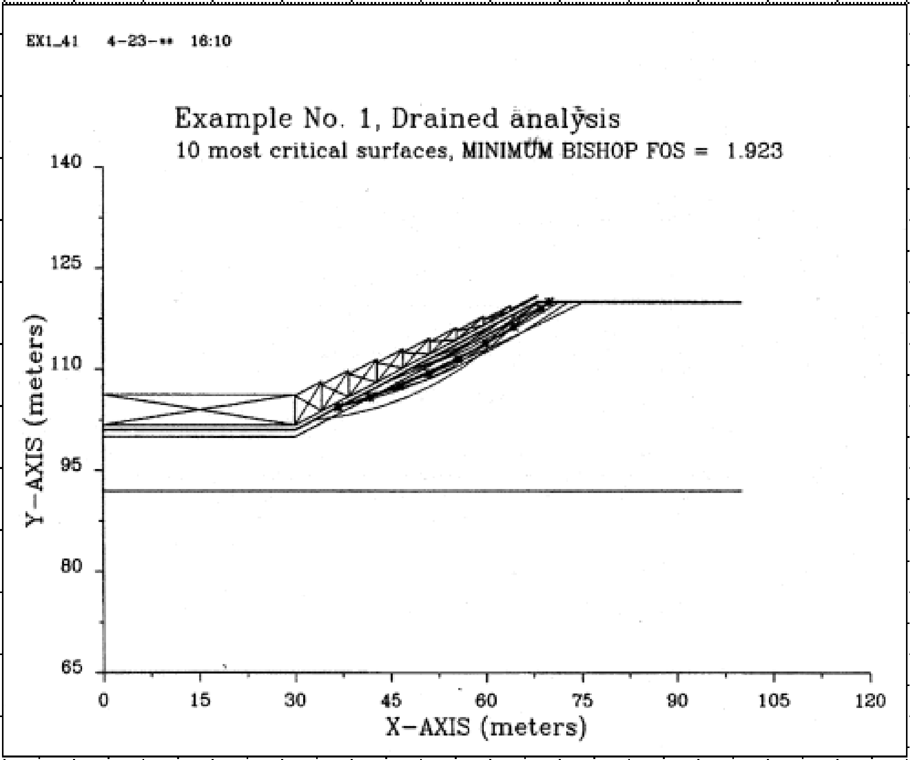


Figure 4.6 Calculations for Example 1 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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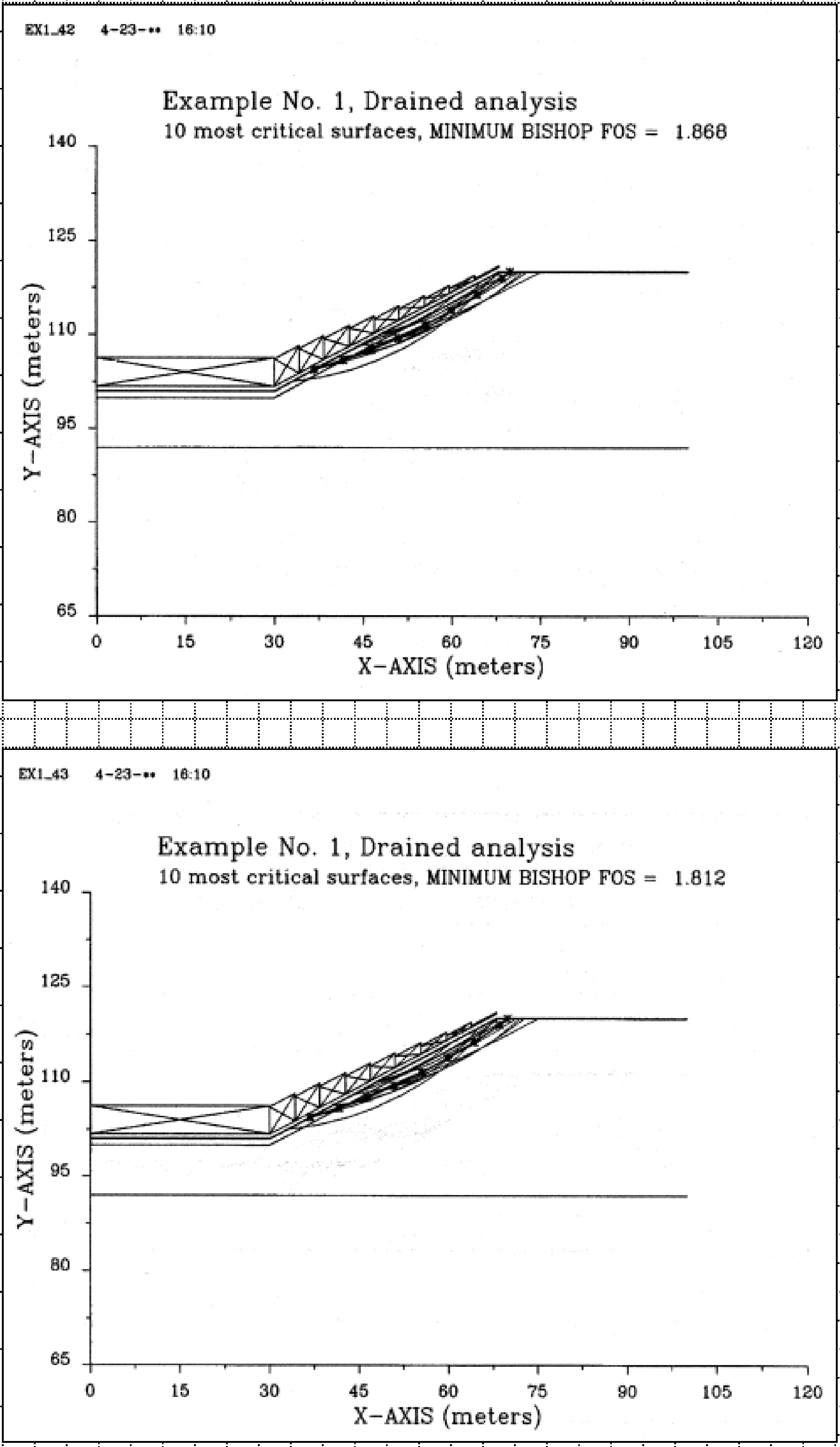

Figure 4.6 Calculations for Example 1 continued

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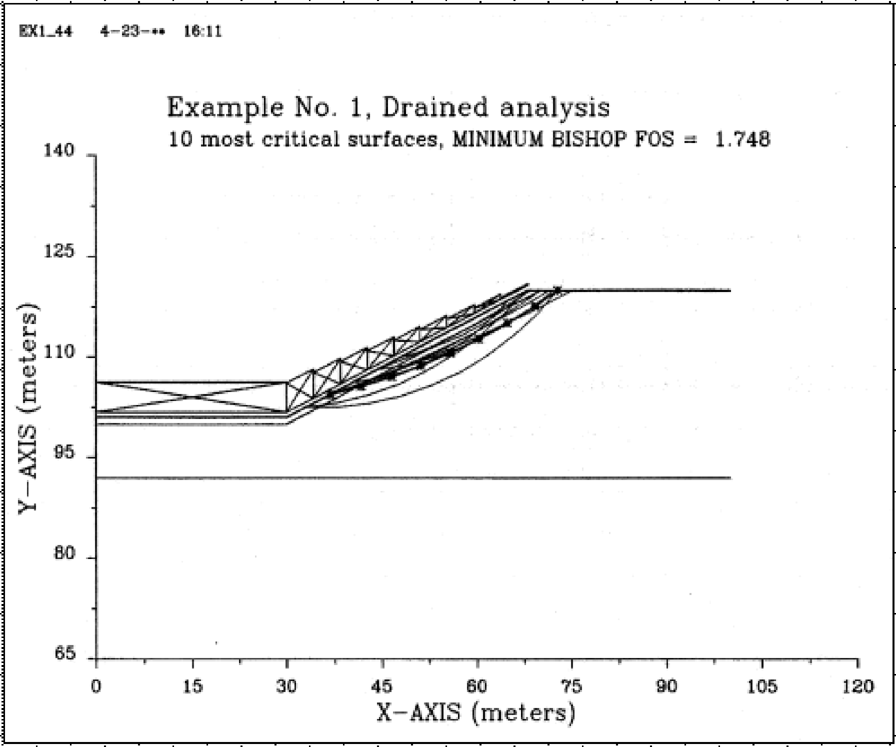

Results:

Run	Filename	c' (kPa)	Φ' (°)	r_u	F of S	Comments	
1	Ex1_41	5	24	0.0	1.92	Shallow circular failure	1.92
2	Ex1_42	5	24	0.1	1.87	Shallow circular failure	↓
3	Ex1_43	5	24	0.2	1.81	Shallow circular failure	
4	Ex1_44	5	24	0.3	1.75	Shallow circular failure	1.75

Conclusions: Since the factors of safety are greater than 1.7, the integrity of the lining system is considered to be adequate. **OK**

4. WASTE SLOPE

4.1 Failure wholly in waste

The cell will be filled as one cell and waste will be placed in horizontal layers for the full width. Hence there will be no temporary waste slope. **OK**

4.2 Failure involving lining system

a) Stability

As described in 4.1 above, the waste slope is stable due to the cell geometry. **OK**

b) Integrity

The integrity of the lining system post-waste placement has been assessed in 3.2b above. **OK**

Figure 4.6 Calculations for Example 1 continued

4.2 Example 2: Composite BES/Geomembrane Liner in Old Sand and Gravel Quarry

4.2.1 Description

The site is a disused sand and gravel quarry and the existing slopes will be lined to form proposed landfill. In situ sand excavated from the site will be used to produce a BES lining material. The site investigation encountered groundwater in the sand and gravel perched on a clay layer; monitoring has shown this to have a 2m head. A composite BES/HDPE geomembrane lining system will be constructed on the base and side slopes. A 500mm thick gravel drainage layer will be placed on the base and sides with protection geotextile between the gravel and the geomembrane. The landfill will be developed in several cells. Design flow charts and calculations are given in Section 4.2.6 below.

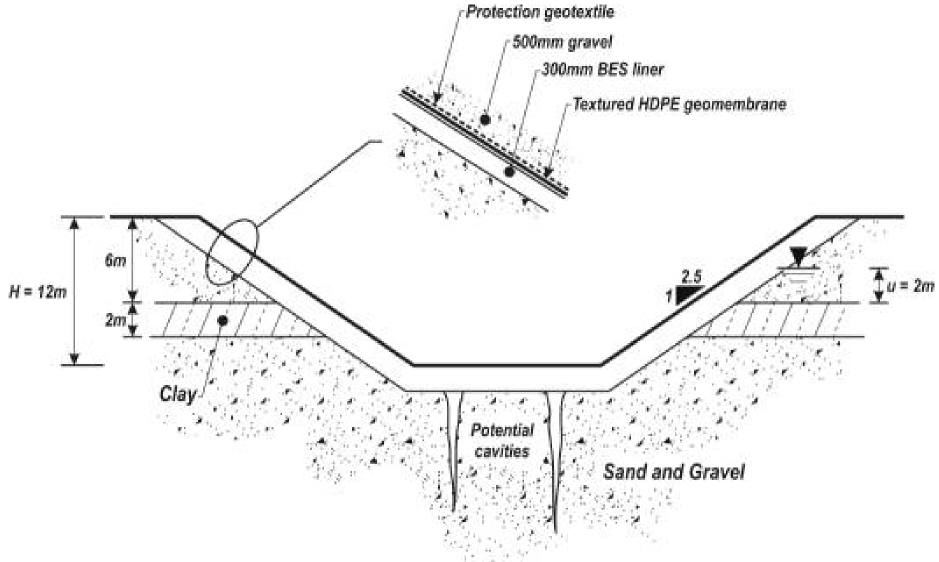

Figure 4.7 Schematic Cross Section of Example 2

4.2.2 Sub-grade

The sub-grade design cases to be considered are highlighted in Figure 4.8.

Base Stability

The site investigation showed that there was no compressible material beneath the site and no potential for basal heave.

Excessive Deformations – Cavities in Sub-Grade

Design issues:

- adequate site investigation.

Based on the site investigation results, it has been established that there is a possibility of a 700mm diameter cavity appearing at the surface of the quarry. No design calculations are required for the sub-grade but are needed for the basal liner, see Section 4.2.3 below.

Cut Slope Stability

Granular Soil

Design issues:

- adequate site investigation;
- stability; and
- deformability.

Based on the site inspection, the existing slopes are observed to be stable and no seepage erosion was observed. Circular and non-circular analysis can be carried out to confirm the stability, and no long-term reduction in stability is expected.

4.2.3 Basal lining system

The basal lining system design cases to be considered are highlighted in Figure 4.9.

Geosynthetic/Mineral Liner

Cavities

Design issues:

- control stress in liner to prevent increased permeability.

Calculate the effect of the likely cavities on both the BES and geomembrane components of the lining system. There is little information available in the technical literature for the performance of BES in such an application. However, the available information links the Plasticity Index of the mineral liner to its performance and work has shown that the application of a confining stress reduces the likelihood of cracking.

Calculations can be carried out to assess the likely strain in the geomembrane and a suitable reinforcing layout can be designed. The strain in the geogrid (and hence the geomembrane) should be limited to 3%.

4.2.4 Shallow side slope lining system

The shallow side slope lining system design cases to be considered are highlighted in Figure 4.10.

Unconfined Slope

Geosynthetic/Mineral Liner – Stability

Design issues:

- stability of sub-grade;
- stability of liner; and

- stability of drainage layer.

The installation of the 300mm thick BES liner will have very little effect on the overall stability. It will, however, prevent the escape of the perched groundwater and so a suitable back drainage system should be installed. The stability of the sub-grade and liner can be assessed using the same calculations are described for the cut slope stability in Section 4.2.2 above.

The veneer stability of the drainage blanket on top of the lining system can be assessed by carrying out a finite slope analysis (Jones & Dixon, 1998). The factor of safety against cover soil slippage is calculated for different parallel submergence ratios (PSR's) to model seepage forces above the liner. Since the gravel will be placed by a hydraulic excavator and no plant will traffic on the slope, it is considered that peak interface shear strengths are relevant. A suitable factor of safety for these calculations would be 1.3.

Geosynthetic/Mineral Liner – Integrity

Design issues:

- control stresses in liner to prevent increased permeability.

The veneer stability analysis described above can also be used to assess the integrity of the geosynthetic by considering the transfer of stresses through the lining system. A suitable factor of safety would be 1.5.

Confined Slope

Geosynthetic/Mineral Liner – Stability

Design issues:

- stability of sub-grade;
- stability of liner.

Due to the development of the site in cells, placement of waste will not necessarily increase the stability. Non-circular stability analysis of the lining system (including the waste mass) using peak shear strengths on the base and residual strengths on the side slopes can be used to assess the overall stability. A suitable factor of safety would be 1.5.

Geosynthetic/Mineral Liner – Integrity

Design issues:

- control stresses in liner to prevent increased permeability;
- disruption to drainage layers.

The integrity of the mineral liner can be assessed by carrying out an analysis of the slope with waste placed in front. The contribution of the waste to the stability of the slope can be modelled by applying a load to the slope based on the vertical and horizontal stresses within the waste. The horizontal support is based on a value of the earth pressure coefficient K_0. Since the integrity of the system is being assessed, a higher factor of safety (1.7) would be appropriate.

The integrity of the geosynthetic components once waste has been placed can only be assessed by finite element or finite difference numerical modelling. The results given in Report No. 1 (Chapter 11, tables 11.6 and 11.8) can be used to assess the performance of the present system.

4.2.5 Waste slope

The waste slope design cases to be considered are highlighted in Figure 4.11.

Failure Wholly in Waste

Design issue:

- stability of waste slope.

Since sand will be used as daily cover there are no potential weak planes within the waste and so circular slip analysis is appropriate, a suitable factor of safety would be 1.5. The impact of the Landfill Directive on the shear strength of the waste stream should be investigated and this can be done by reducing the cohesion intercept.

Failure involving Lining System

Geosynthetic/Mineral Liner – Stability

Design issues:

- stability of sub-grade;
- stability of liner.

This has been assessed previously for the confined slope stability in Section 4.2.4 above.

Geosynthetic/Mineral Liner – Integrity

Design issues:

- control stresses in liner to prevent increased permeability;
- disruption to drainage layers.

This has been assessed previously for the confined slope integrity in Section 4.2.4 above.

4.2.6 Design flow chart and calculations

See Figures 4.8 to 4.12.

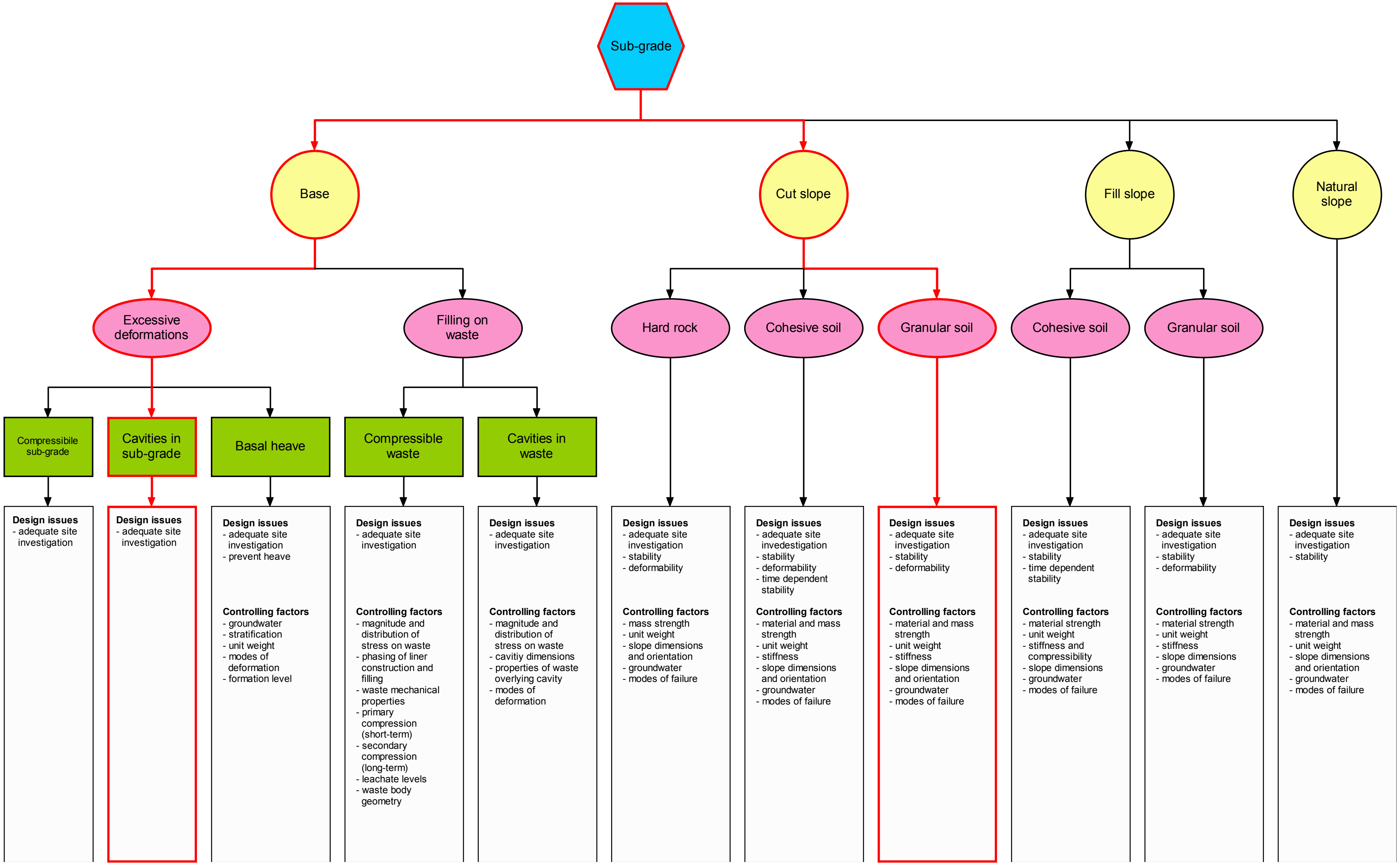

Figure 4.8 Design Flow Chart for Example 2: Sub-grade

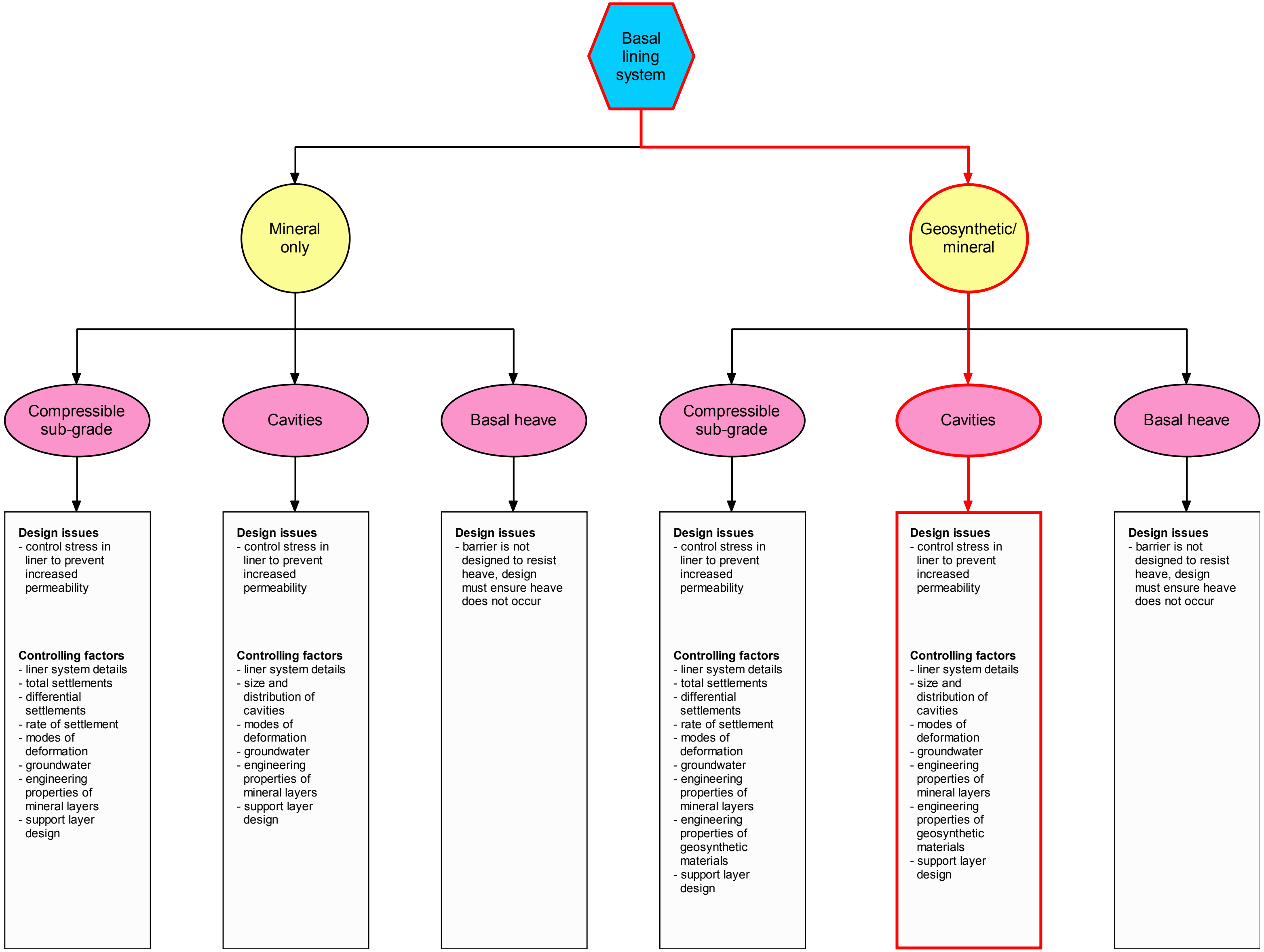

Figure 4.9 Design Flow Chart for Example 2: Basal Lining System

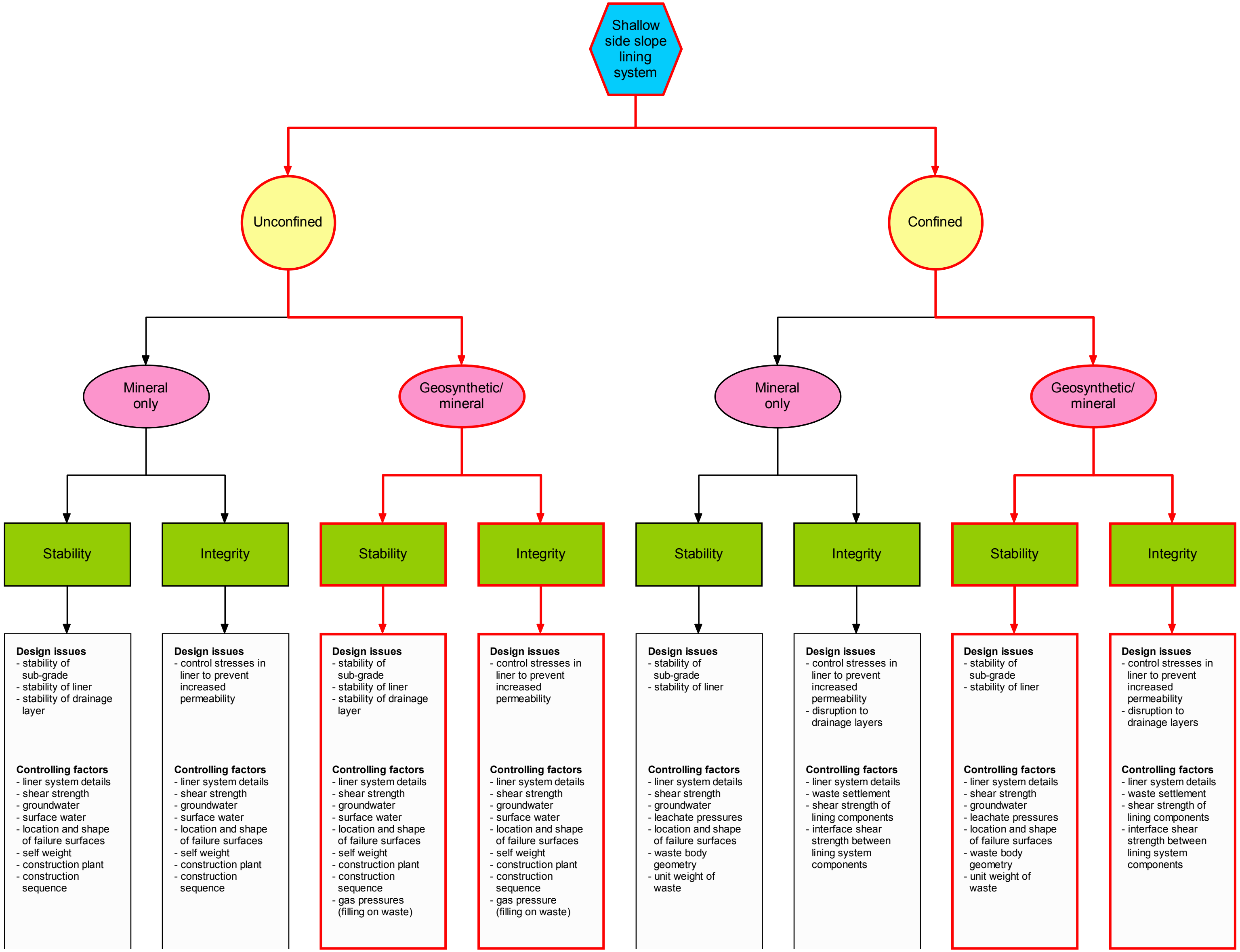

Figure 4.10 Design Flow Chart for Example 2: Shallow Side Slope Lining System

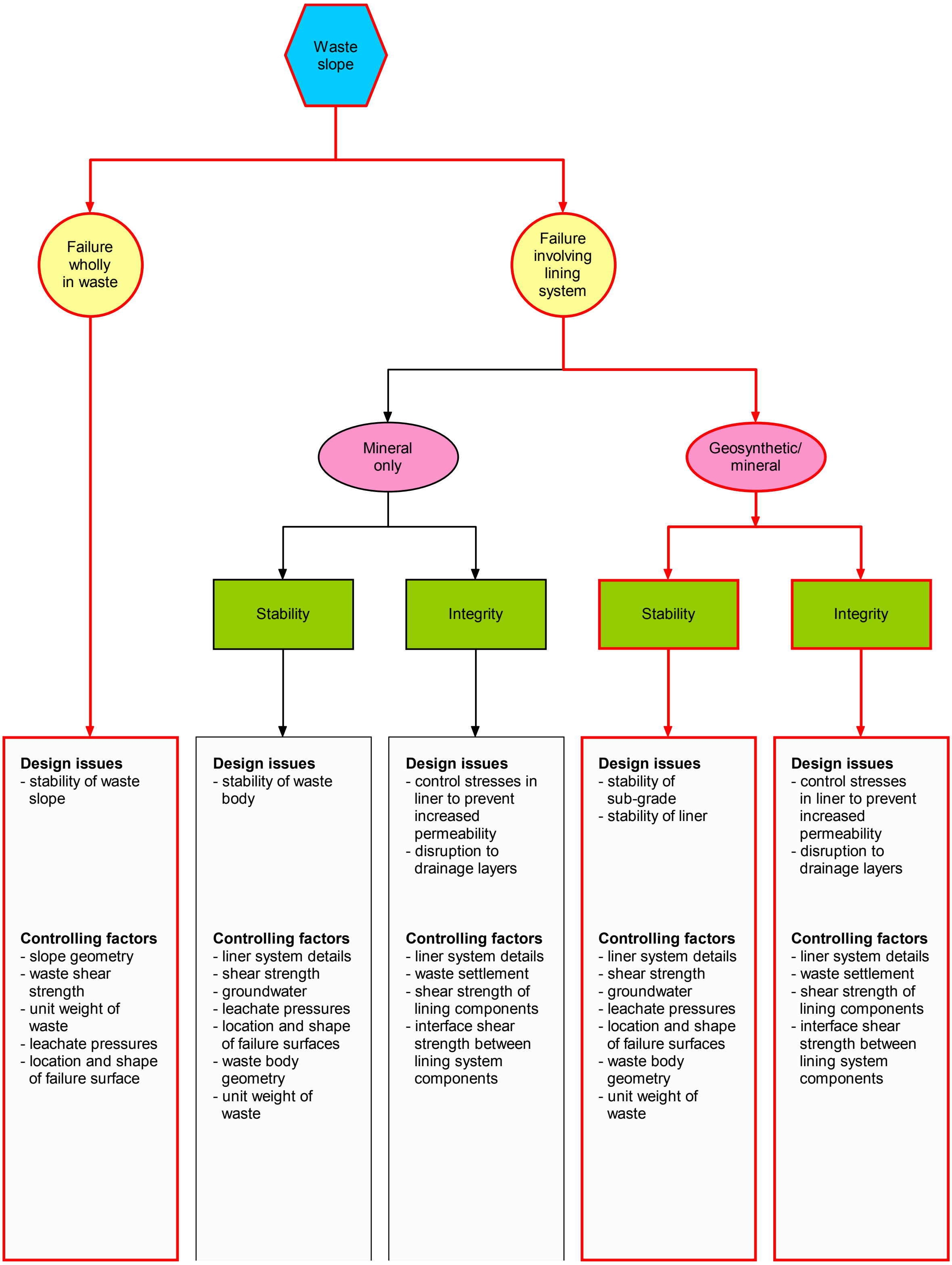

Figure 4.11 Design Flow Chart for Example 2: Waste Slope

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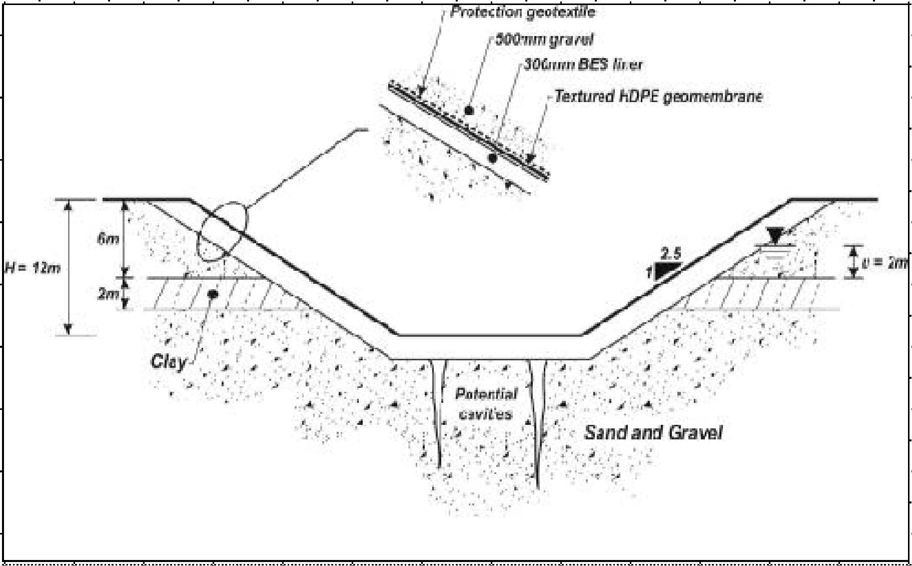
DESCRIPTION: BES/HDPE geomembrane lined landfill overlying potential voids

GEOMETRY:



1. SUB-GRADE

1.1 Base stability

Excessive deformations: cavities in sub-grade

From the site investigation, it has been established that there is a possibility of a 700 mm diameter cavity appearing at the surface of the quarry.

Calculations are carried out for the basal lining system in 2. Below.

1.2 Cut slope stability

Aim: Assess the stability of the cut slope

Approach: Use the computer code XSTABL to calculate the factor of safety for a range of circular failures. Look at effect of groundwater above clay layer.

From the site investigation, sand/gravel $\Phi' = 34°$, and clay $c' = 5kPa$ and $\Phi' = 24°$

Figure 4.12 Calculations for Example 2

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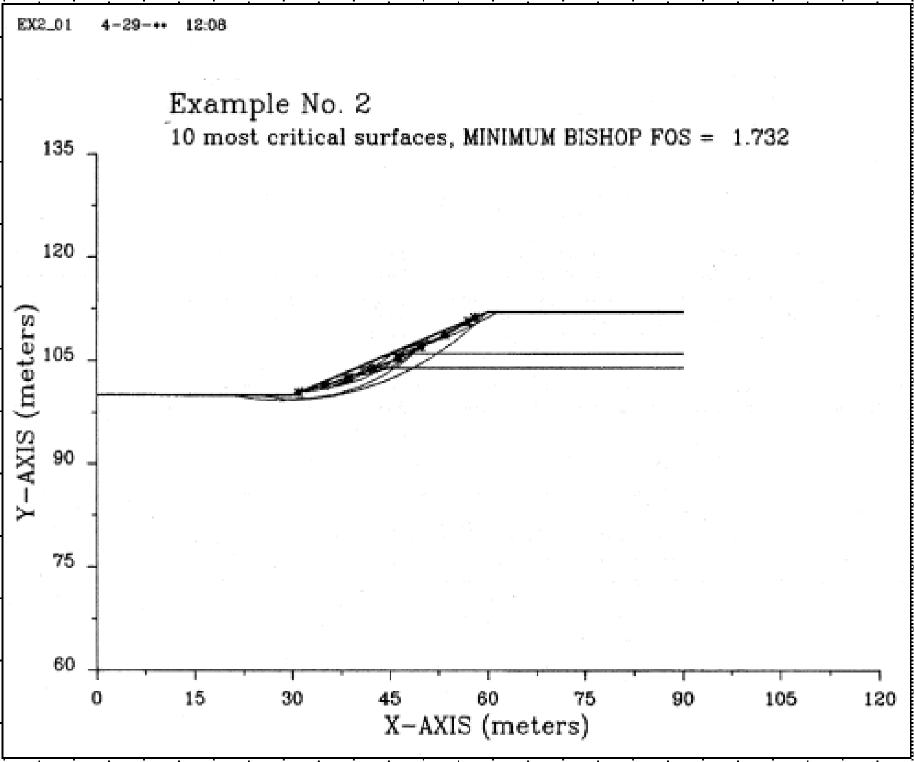
Calculations:



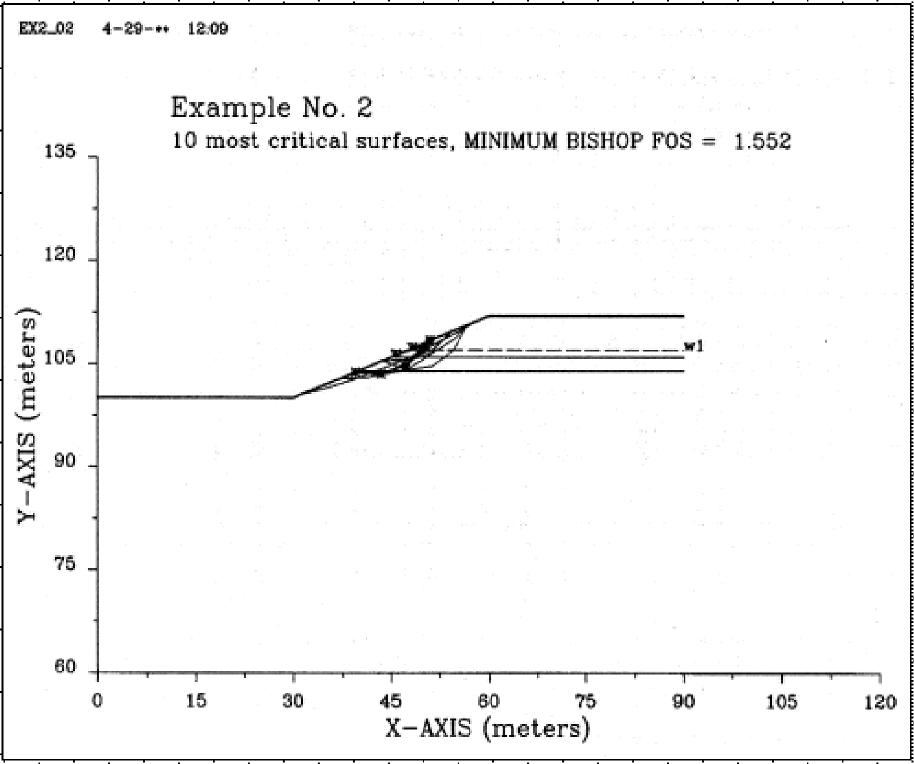


Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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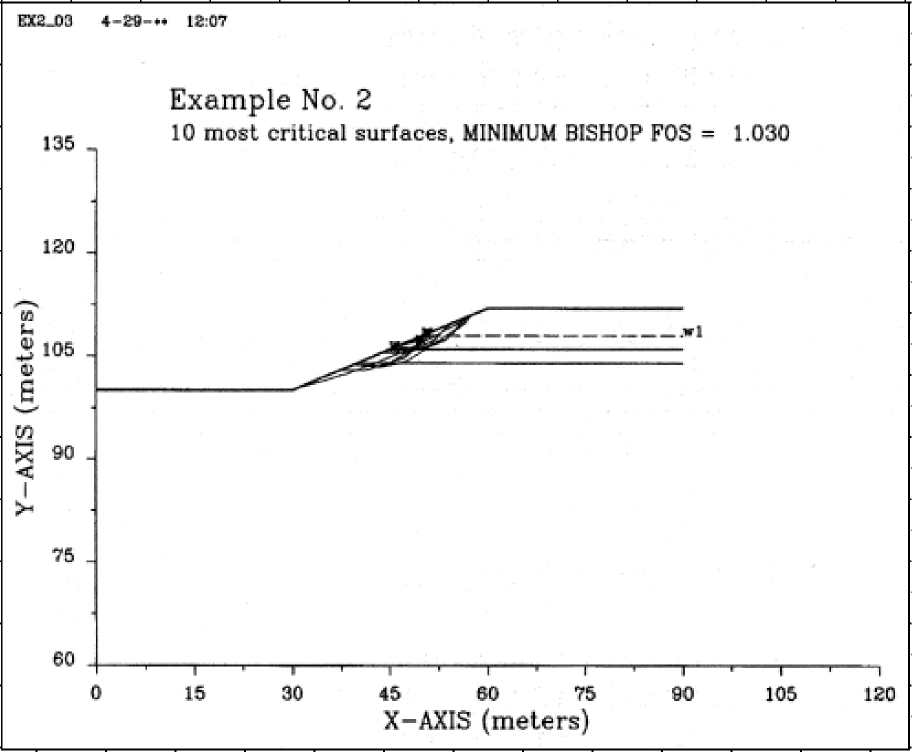

Results:

Run	Filename	Water	F of S	Comments	
1	Ex1_01	Dry	1.73	Shallow circular failure	1.73
2	Ex1_02	1m	1.55	Small failure through clay	▼
3	Ex1_03	2m	1.03	Small failure in saturated sand	1.03

Conclusions:

From the site investigation, the water level is 2m above the clay and this is the maximum over a prolonged period. There is no evidence of seepage erosion or slumping on site. Therefore the stability of the slope is considered to be satisfactory. **OK**

2. BASAL LINING SYSTEM

2.1 Cavities

The development of a cavity directly beneath the lining system should not cause excessive strain in HDPE geomembrane. The design of a reinforced soil layer to span over the potential void can be carried out based on the method proposed by Jones & Pine (2001).

For a waste height of 12m and a unit weight of 10kN.m^{-3}, the applied load on the reinforcement layer is 120 kN.m^{-1}

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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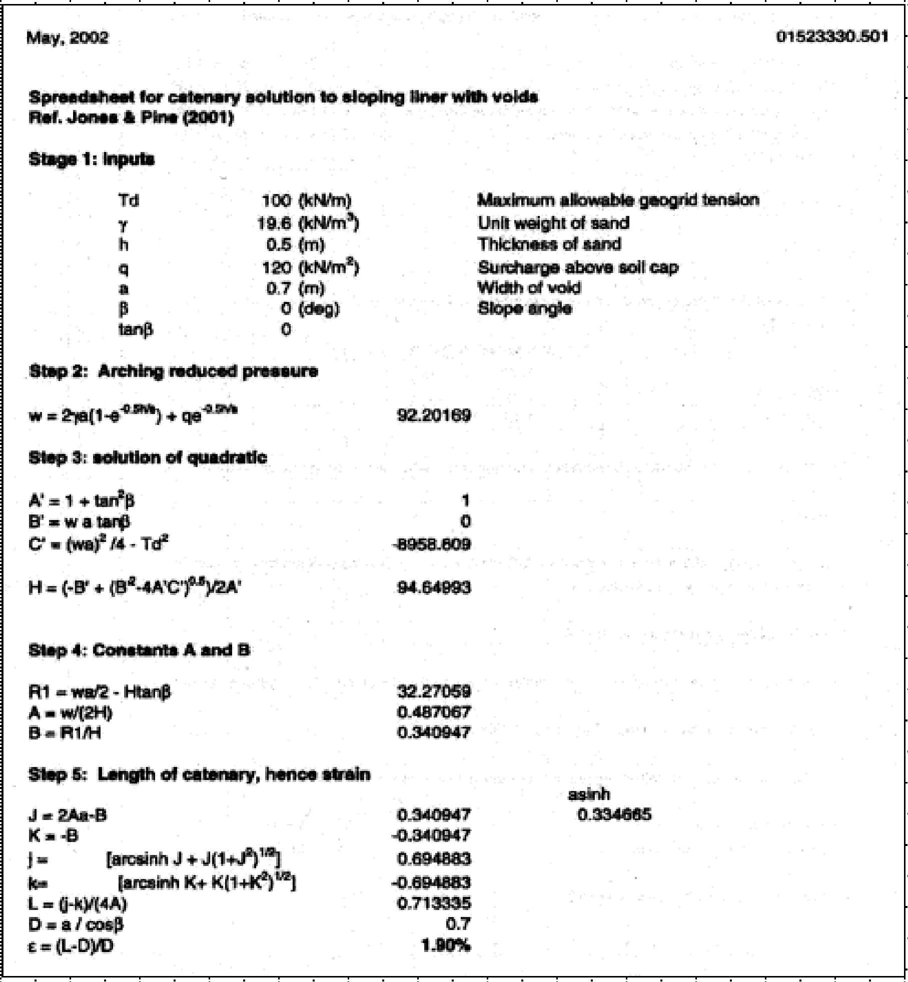


May, 2002 01523330.501

Spreadsheet for catenary solution to sloping liner with voids
Ref. Jones & Pine (2001)

Stage 1: Inputs

Td	100	(kN/m)	**Maximum allowable geogrid tension**
γ	19.6	(kN/m^3)	**Unit weight of sand**
h	0.5	(m)	**Thickness of sand**
q	120	(kN/m^2)	**Surcharge above soil cap**
a	0.7	(m)	**Width of void**
β	0	(deg)	**Slope angle**
tanβ	0		

Step 2: Arching reduced pressure

$w = 2\gamma a(1-e^{-0.5h/a}) + qe^{-0.5h/a}$	92.20169

Step 3: solution of quadratic

$A' = 1 + \tan^2\beta$	1
$B' = w\, a \tan\beta$	0
$C' = (wa)^2 /4 - Td^2$	-8958.609
$H = (-B' + (B'^2-4A'C')^{0.5})/2A'$	94.64993

Step 4: Constants A and B

$R1 = wa/2 - H\tan\beta$	32.27059
$A = w/(2H)$	0.487067
$B = R1/H$	0.340947

Step 5: Length of catenary, hence strain

		asinh
$J = 2Aa-B$	0.340947	0.334665
$K = -B$	-0.340947	
$j =$ $[\text{arcsinh } J + J(1+J^2)^{1/2}]$	0.694883	
$k =$ $[\text{arcsinh } K + K(1+K^2)^{1/2}]$	-0.694883	
$L = (j-k)/(4A)$	0.713335	
$D = a / \cos\beta$	0.7	
$\varepsilon = (L-D)/D$	**1.90%**	

From the above calculation, using a 0.5m thick sand layer and reinforcement with a maximum tensile strength of 100 kN.m^{-1}, the maximum strain in the reinforcement (and therefore the HDPE geomembrane) is 1.9%. **OK**

A suitable reinforcing layer (or layers) can be chosen based on the guidelines given in BS 8006 for partial factors etc.

Based on current knowledge, the performance of the BES liner under these conditions is considered to be satisfactory. **OK**

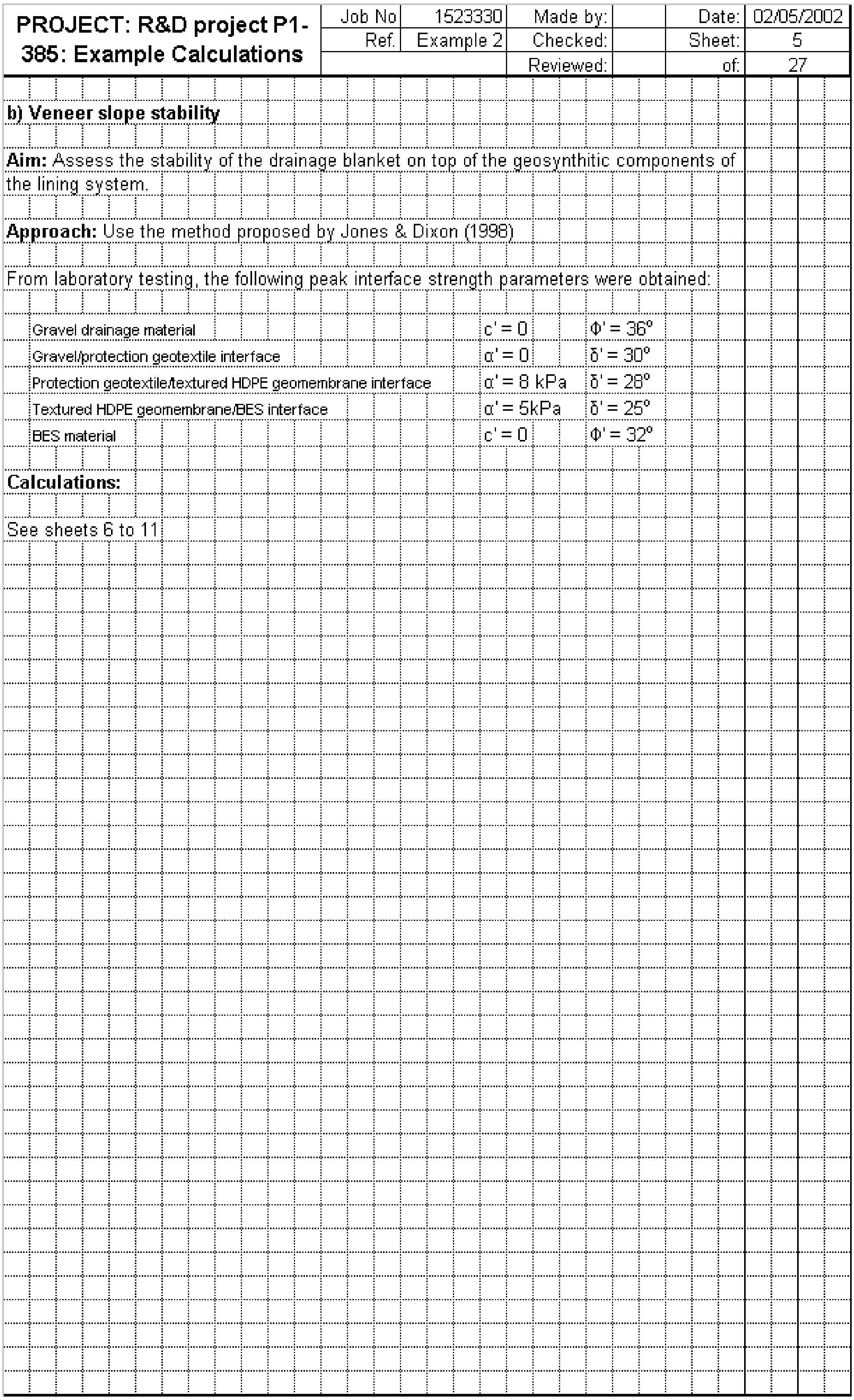
3. SHALLOW SIDE SLOPE LINING SYSTEM

3.1 Unconfined

a) Overall slope stability

The installation of the 300mm thick BES liner will have very little effect on the overall stability. It will however, prevent the escape of groundwater perched on the clay layer. From the calculations in 1.2 above, it is clear that groundwater needs to be limited to a maximum of 2m above the clay. Therefore a suitable back-drainage system (e.g. drainage pipe) should be installed behind the liner to ensure overall stability. **OK**

Figure 4.12 Calculations for Example 2 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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b) Veneer slope stability

Aim: Assess the stability of the drainage blanket on top of the geosynthitic components of the lining system.

Approach: Use the method proposed by Jones & Dixon (1998)

From laboratory testing, the following peak interface strength parameters were obtained:

Gravel drainage material	c' = 0	Φ' = 36°
Gravel/protection geotextile interface	α' = 0	δ' = 30°
Protection geotextile/textured HDPE geomembrane interface	α' = 8 kPa	δ' = 28°
Textured HDPE geomembrane/BES interface	α' = 5kPa	δ' = 25°
BES material	c' = 0	Φ' = 32°

Calculations:

See sheets 6 to 11

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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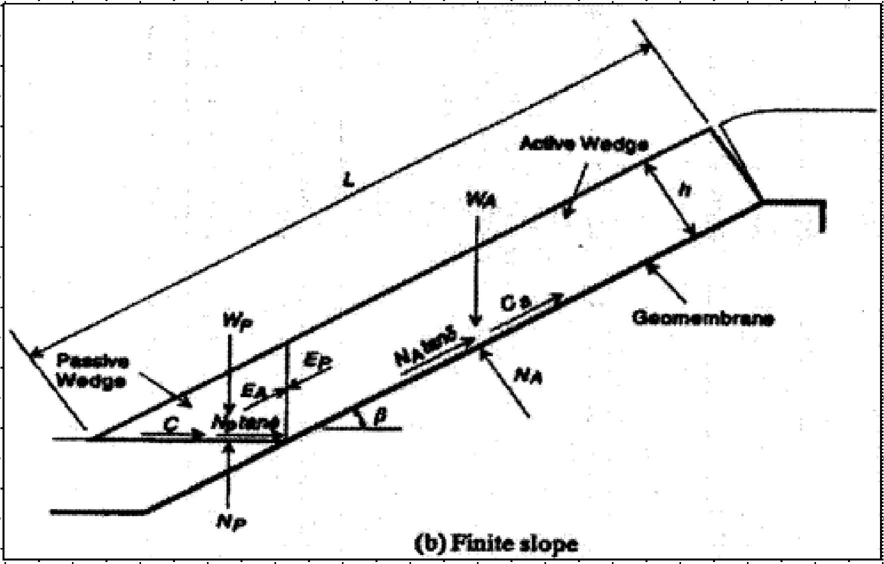
Stability of geosynthetic lining system

Aim: To assess the stability of the geosynthitic lining system (PSR = 0)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

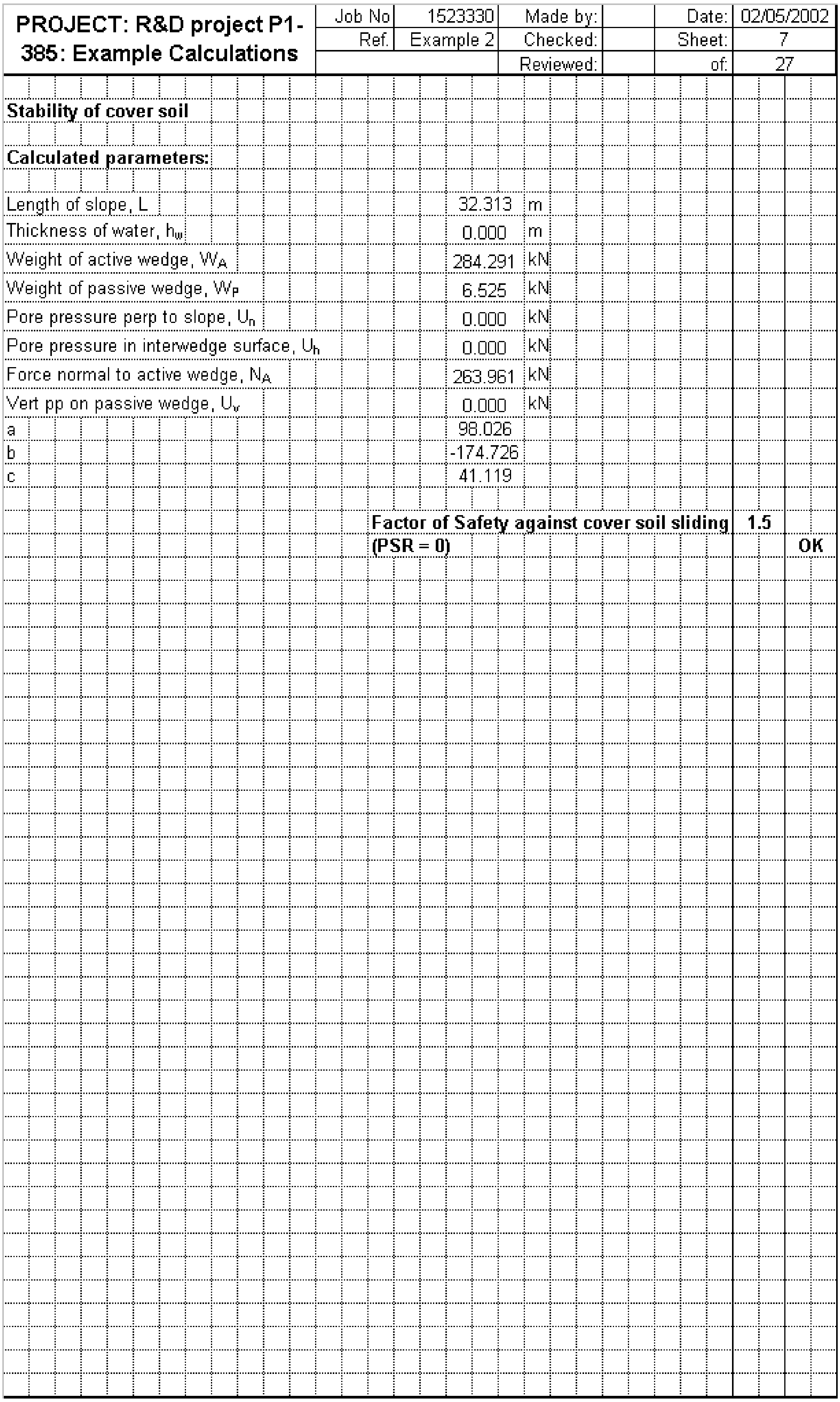


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	36	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	0.50	m
Height of slope, H	12	m
Slope angle, β	21.8	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geotextile friction angle, δ_1	30	
Cover soil/geotextile cohesion intercept, α_1	0	
Geotextile/geomembrane friction angle, δ_2	28	
Geotextile/geomembrane cohesion intercept, α_2	8	
Geomembrane/BES friction angle, δ_3	25	
Geomembrane/BES cohesion intercept, α_3	5	
Parallel submergence ratio, PSR	0	

Figure 4.12 Calculations for Example 2 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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Stability of cover soil

Calculated parameters:

Length of slope, L	32.313	m
Thickness of water, h_w	0.000	m
Weight of active wedge, W_A	284.291	kN
Weight of passive wedge, W_P	6.525	kN
Pore pressure perp to slope, U_n	0.000	kN
Pore pressure in interwedge surface, U_h	0.000	kN
Force normal to active wedge, N_A	263.961	kN
Vert pp on passive wedge, U_v	0.000	kN
a	98.026	
b	-174.726	
c	41.119	

Factor of Safety against cover soil sliding **1.5**
(PSR = 0) **OK**

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	8
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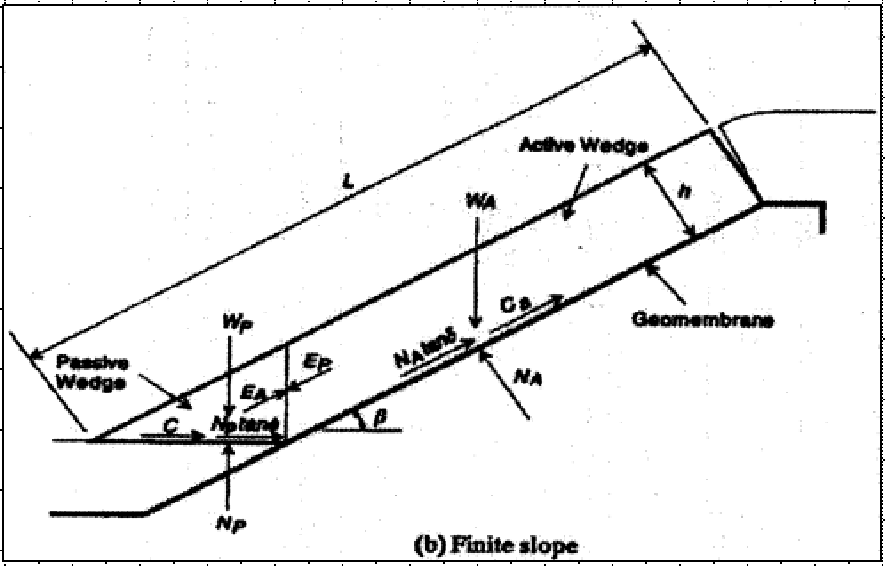
Stability of geosynthetic lining system

Aim: To assess the stability of the geosynthitic lining system (PSR = 0.25)

Approach: Use the approach proposed by Jones & Dixon (1998).

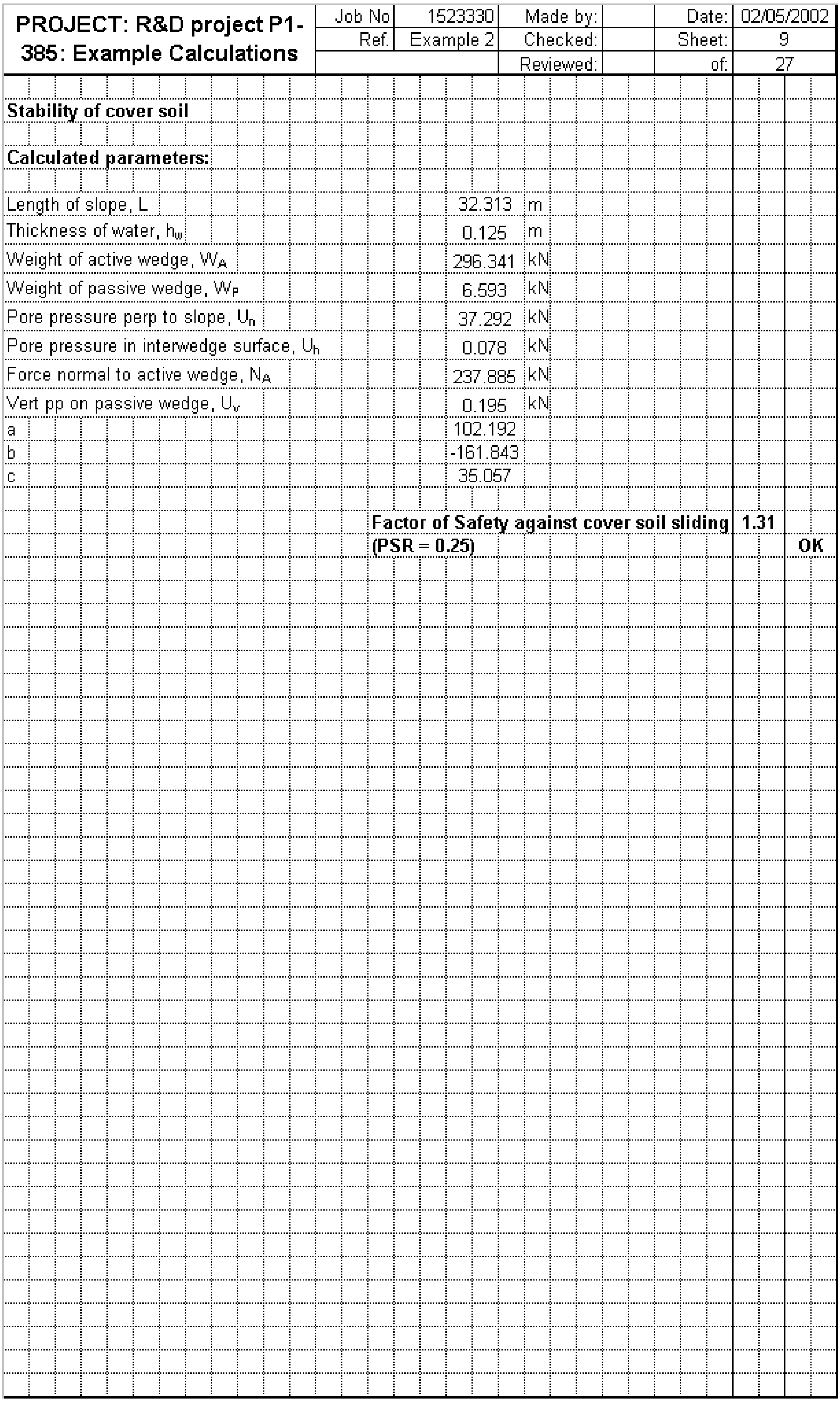
Geometry:



Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	36	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	0.50	m
Height of slope, H	12	m
Slope angle, β	21.8	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geotextile friction angle, δ_1	30	
Cover soil/geotextile cohesion intercept, α_1	0	
Geotextile/geomembrane friction angle, δ_2	28	
Geotextile/geomembrane cohesion intercept, α_2	8	
Geomembrane/BES friction angle, δ_3	25	
Geomembrane/BES cohesion intercept, α_3	5	
Parallel submergence ratio, PSR	0.25	

Figure 4.12 Calculations for Example 2 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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Stability of cover soil

Calculated parameters:

Length of slope, L	32.313	m
Thickness of water, h_w	0.125	m
Weight of active wedge, W_A	296.341	kN
Weight of passive wedge, W_P	6.593	kN
Pore pressure perp to slope, U_n	37.292	kN
Pore pressure in interwedge surface, U_h	0.078	kN
Force normal to active wedge, N_A	237.885	kN
Vert pp on passive wedge, U_v	0.195	kN
a	102.192	
b	-161.843	
c	35.057	

Factor of Safety against cover soil sliding **1.31**
(PSR = 0.25) **OK**

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	10
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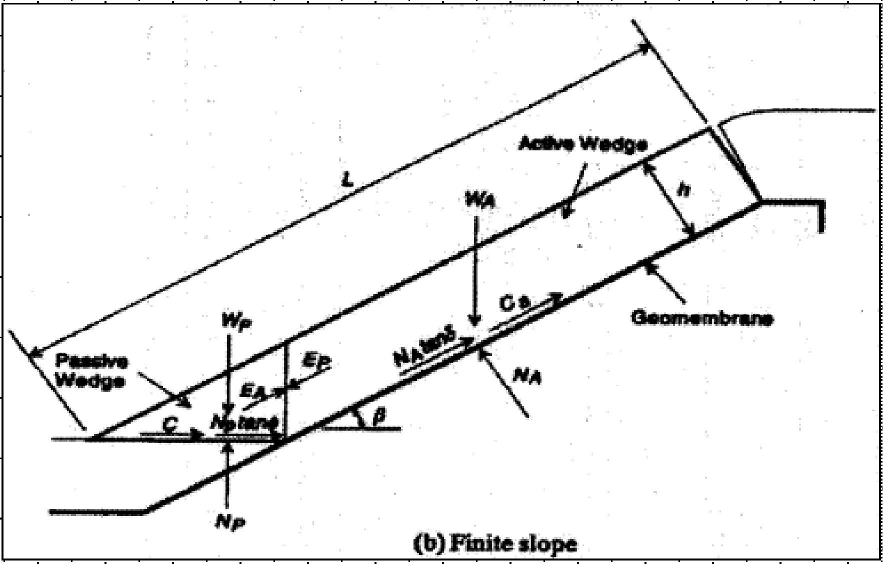
Stability of geosynthetic lining system

Aim: To assess the stability of the geosynthitic lining system (PSR = 0.5)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

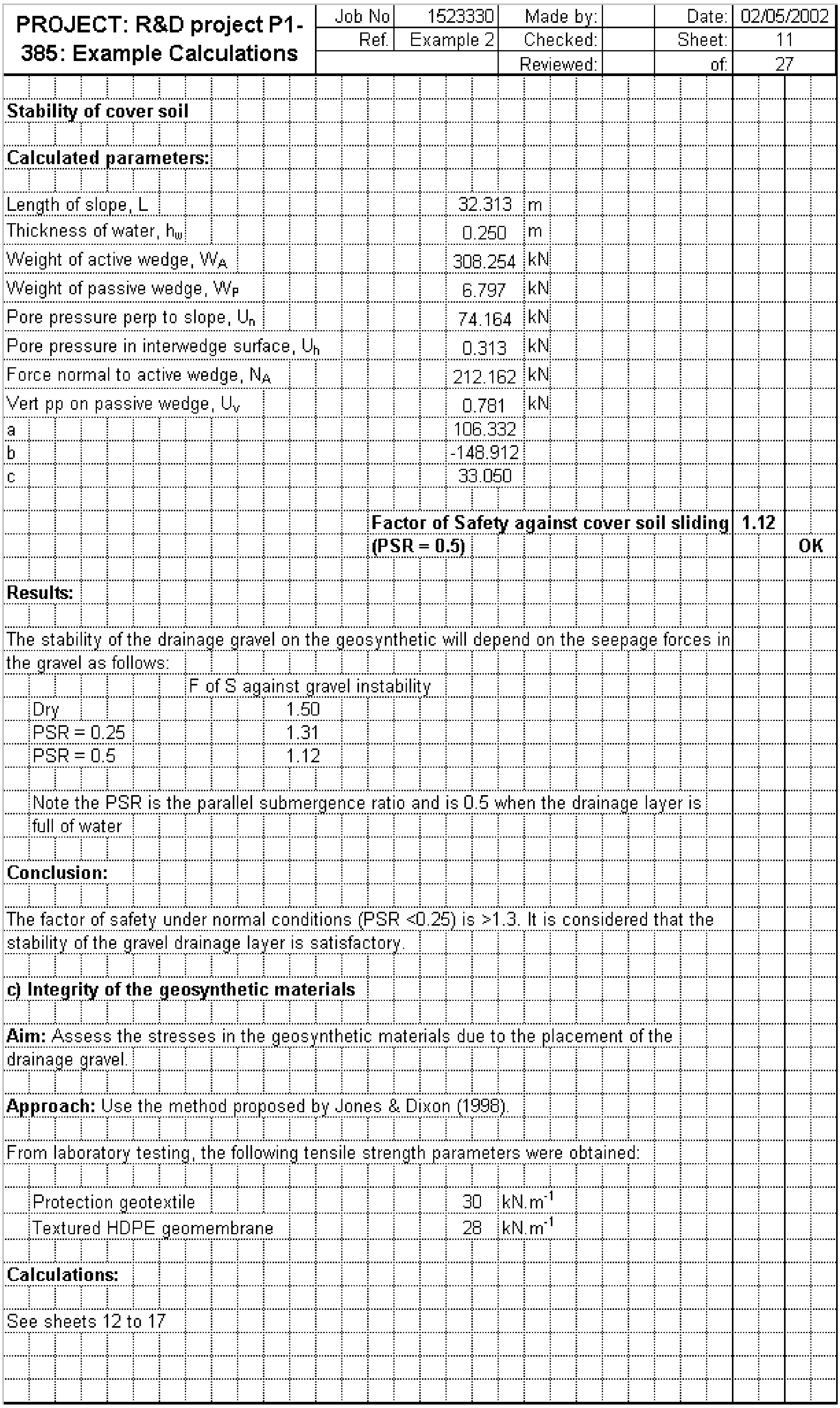


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	36	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	0.50	m
Height of slope, H	12	m
Slope angle, β	21.8	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geotextile friction angle, δ_1	30	
Cover soil/geotextile cohesion intercept, α_1	0	
Geotextile/geomembrane friction angle, δ_2	28	
Geotextile/geomembrane cohesion intercept, α_2	8	
Geomembrane/BES friction angle, δ_3	25	
Geomembrane/BES cohesion intercept, α_3	5	
Parallel submergence ratio, PSR	0.5	

Figure 4.12 Calculations for Example 2 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	11
			Reviewed:		of:	27

Stability of cover soil

Calculated parameters:

Length of slope, L	32.313	m
Thickness of water, h_w	0.250	m
Weight of active wedge, W_A	308.254	kN
Weight of passive wedge, W_P	6.797	kN
Pore pressure perp to slope, U_n	74.164	kN
Pore pressure in interwedge surface, U_h	0.313	kN
Force normal to active wedge, N_A	212.162	kN
Vert pp on passive wedge, U_v	0.781	kN
a	106.332	
b	-148.912	
c	33.050	

Factor of Safety against cover soil sliding (PSR = 0.5) **1.12** **OK**

Results:

The stability of the drainage gravel on the geosynthetic will depend on the seepage forces in the gravel as follows:

	F of S against gravel instability
Dry	1.50
PSR = 0.25	1.31
PSR = 0.5	1.12

Note the PSR is the parallel submergence ratio and is 0.5 when the drainage layer is full of water

Conclusion:

The factor of safety under normal conditions (PSR <0.25) is >1.3. It is considered that the stability of the gravel drainage layer is satisfactory.

c) Integrity of the geosynthetic materials

Aim: Assess the stresses in the geosynthetic materials due to the placement of the drainage gravel.

Approach: Use the method proposed by Jones & Dixon (1998).

From laboratory testing, the following tensile strength parameters were obtained:

Protection geotextile	30	$kN.m^{-1}$
Textured HDPE geomembrane	28	$kN.m^{-1}$

Calculations:

See sheets 12 to 17

Figure 4.12 Calculations for Example 2 continued

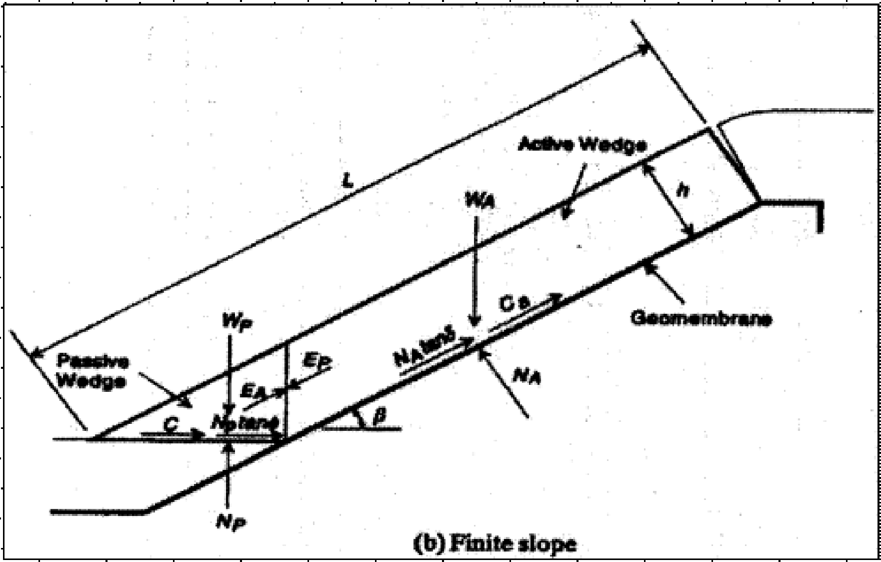
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	12
			Reviewed:		of:	27

Integrity of geosynthetic lining system

Aim: To assess the integrity of the geosynthitic lining system (PSR = 0)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

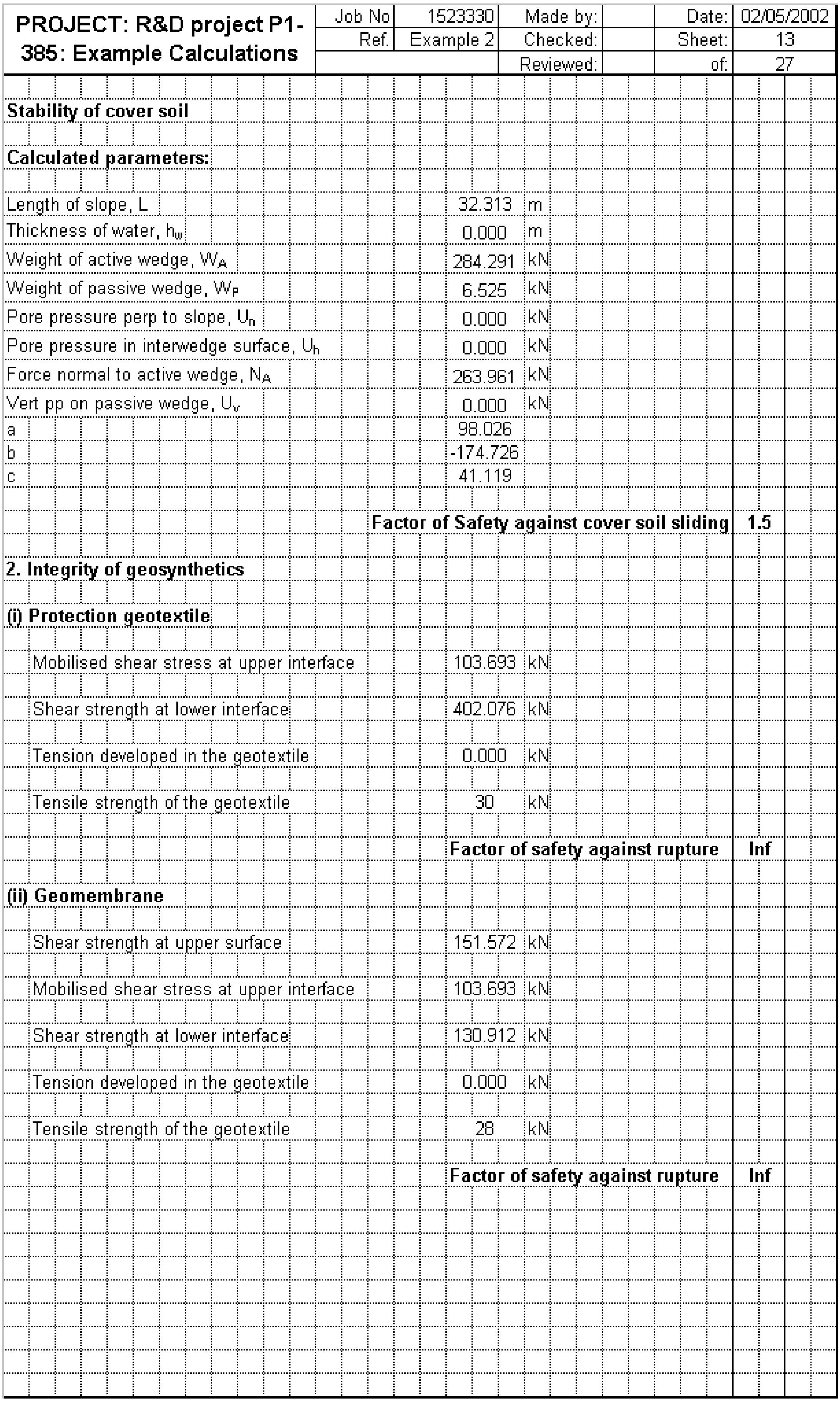


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	kN.m^{-3}
Cover soil unit weight (saturated). γ_{sat}	21	kN.m^{-3}
Cover soil internal shear strength, Φ	36	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	0.50	m
Height of slope, H	12	m
Slope angle, β	21.8	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geotextile friction angle, δ_1	30	
Cover soil/geotextile cohesion intercept, α_1	0	
Geotextile/geomembrane friction angle, δ_2	28	
Geotextile/geomembrane cohesion intercept, α_2	8	
Geomembrane/BES friction angle, δ_3	25	
Geomembrane/BES cohesion intercept, α_3	5	
Parallel submergence ratio, PSR	0	
Geosynthetic tensile strengths:		
Geotextile	30	kN.m^{-1}
Geomembrane	28	kN.m^{-1}

Figure 4.12 Calculations for Example 2 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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Stability of cover soil

Calculated parameters:

Length of slope, L	32.313	m
Thickness of water, h_w	0.000	m
Weight of active wedge, W_A	284.291	kN
Weight of passive wedge, W_P	6.525	kN
Pore pressure perp to slope, U_n	0.000	kN
Pore pressure in interwedge surface, U_h	0.000	kN
Force normal to active wedge, N_A	263.961	kN
Vert pp on passive wedge, U_v	0.000	kN
a	98.026	
b	-174.726	
c	41.119	

Factor of Safety against cover soil sliding **1.5**

2. Integrity of geosynthetics

(i) Protection geotextile

Mobilised shear stress at upper interface	103.693	kN
Shear strength at lower interface	402.076	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	30	kN

Factor of safety against rupture **Inf**

(ii) Geomembrane

Shear strength at upper surface	151.572	kN
Mobilised shear stress at upper interface	103.693	kN
Shear strength at lower interface	130.912	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	28	kN

Factor of safety against rupture **Inf**

Figure 4.12 Calculations for Example 2 continued

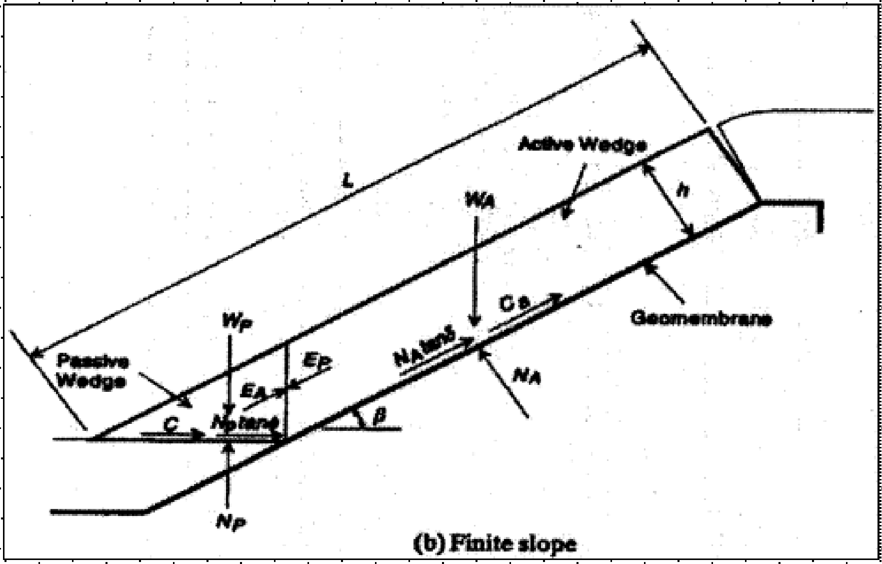
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	14
			Reviewed:		of:	27

Integrity of geosynthetic lining system

Aim: To assess the integrity of the geosynthitic lining system (PSR = 0.25)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

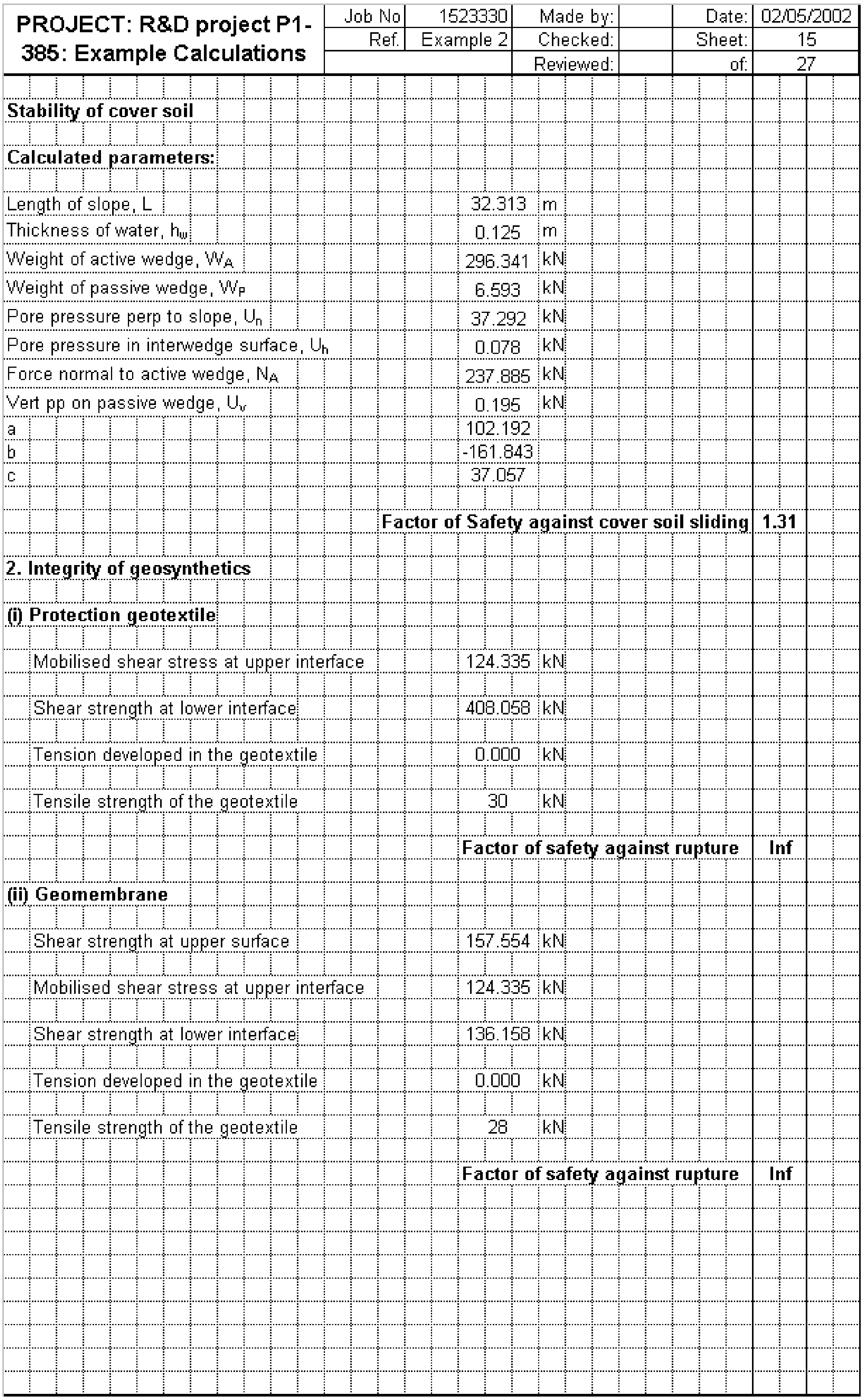


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	kN.m^{-3}
Cover soil unit weight (saturated). γ_{sat}	21	kN.m^{-3}
Cover soil internal shear strength, Φ	36	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	0.50	m
Height of slope, H	12	m
Slope angle, β	21.8	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geotextile friction angle, δ_1	30	
Cover soil/geotextile cohesion intercept, α_1	0	
Geotextile/geomembrane friction angle, δ_2	28	
Geotextile/geomembrane cohesion intercept, α_2	8	
Geomembrane/BES friction angle, δ_3	25	
Geomembrane/BES cohesion intercept, α_3	5	
Parallel submergence ratio, PSR	0.25	
Geosynthetic tensile strengths:		
Geotextile	30	kN.m^{-1}
Geomembrane	28	kN.m^{-1}

Figure 4.12 Calculations for Example 2 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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Stability of cover soil

Calculated parameters:

Length of slope, L	32.313	m
Thickness of water, h_w	0.125	m
Weight of active wedge, W_A	296.341	kN
Weight of passive wedge, W_P	6.593	kN
Pore pressure perp to slope, U_n	37.292	kN
Pore pressure in interwedge surface, U_h	0.078	kN
Force normal to active wedge, N_A	237.885	kN
Vert pp on passive wedge, U_v	0.195	kN
a	102.192	
b	-161.843	
c	37.057	

Factor of Safety against cover soil sliding **1.31**

2. Integrity of geosynthetics

(i) Protection geotextile

Mobilised shear stress at upper interface	124.335	kN
Shear strength at lower interface	408.058	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	30	kN

Factor of safety against rupture **Inf**

(ii) Geomembrane

Shear strength at upper surface	157.554	kN
Mobilised shear stress at upper interface	124.335	kN
Shear strength at lower interface	136.158	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	28	kN

Factor of safety against rupture **Inf**

Figure 4.12 Calculations for Example 2 continued

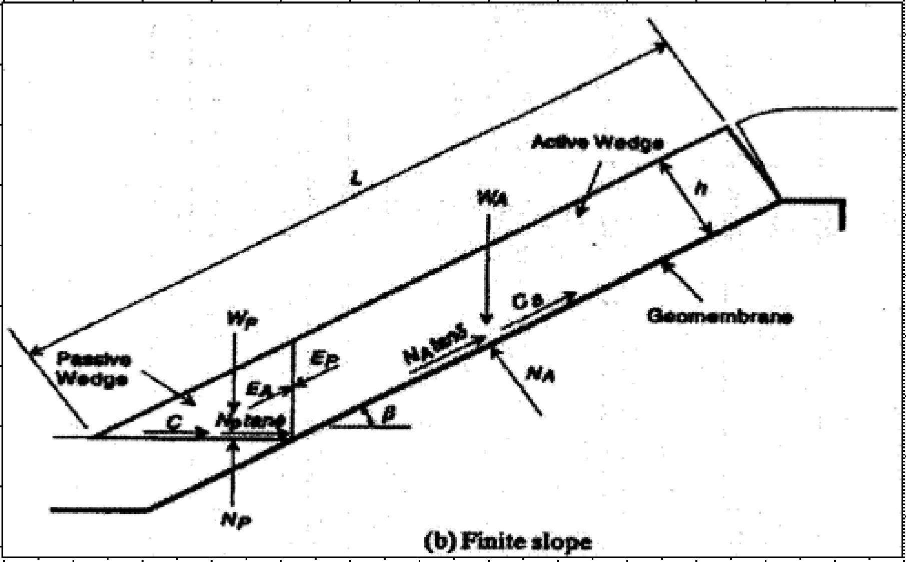
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	16
			Reviewed:		of:	27

Integrity of geosynthetic lining system

Aim: To assess the integrity of the geosynthitic lining system (PSR = 0.5)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:



(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	36	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	0.50	m
Height of slope, H	12	m
Slope angle, β	21.8	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geotextile friction angle, δ_1	30	
Cover soil/geotextile cohesion intercept, α_1	0	
Geotextile/geomembrane friction angle, δ_2	28	
Geotextile/geomembrane cohesion intercept, α_2	8	
Geomembrane/BES friction angle, δ_3	25	
Geomembrane/BES cohesion intercept, α_3	5	
Parallel submergence ratio, PSR	0.5	
Geosynthetic tensile strengths:		
Geotextile	30	$kN.m^{-1}$
Geomembrane	28	$kN.m^{-1}$

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	17
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Stability of cover soil

Calculated parameters:

Length of slope, L	32.313	m
Thickness of water, h_w	0.250	m
Weight of active wedge, W_A	308.254	kN
Weight of passive wedge, W_P	6.797	kN
Pore pressure perp to slope, U_n	74.164	kN
Pore pressure in interwedge surface, U_h	0.313	kN
Force normal to active wedge, N_A	212.162	kN
Vert pp on passive wedge, U_v	0.781	kN
a	106.332	
b	-148.912	
c	33.050	

Factor of Safety against cover soil sliding 1.12

2. Integrity of geosynthetics

(i) Protection geotextile

Mobilised shear stress at upper interface	150.272	kN
Shear strength at lower interface	414.040	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	30	kN

Factor of safety against rupture Inf

(ii) Geomembrane

Shear strength at upper surface	163.536	kN
Mobilised shear stress at upper interface	150.272	kN
Shear strength at lower interface	141.405	kN
Tension developed in the geotextile	8.867	kN
Tensile strength of the geotextile	28	kN

Factor of safety against rupture 3.16

Figure 4.12 Calculations for Example 2 continued

Results:

	F of S against geotextile rupture	F of S against geomembrane rupture
Dry	Infinite	Infinite
PSR = 0.25	Infinite	Infinite
PSR = 0.5	Infinite	3.16

Conclusion:

Since the factor of safety is in excess of 3 for all conditions, the integrity of the geosynthetics are considered to be satisfactory. **OK**

3.2 Confined

a) Overall slope stability

Aim: Assess the stability of the confined slope.

Approach: Use the computer code XSTABL to calculate the factor of safety for a non-circular failure through the lining system. Assume peak strengths on the base and residual on the side slopes. Assess the effect of build up of pore pressures in the lining system.

An assessment of the interface shear strengths indicates that the lowest peak strength is δ' = 30° and the lowest residual is δ' = 12°.

Calculations:

Note the base length is 30m and the waste face is 45°.

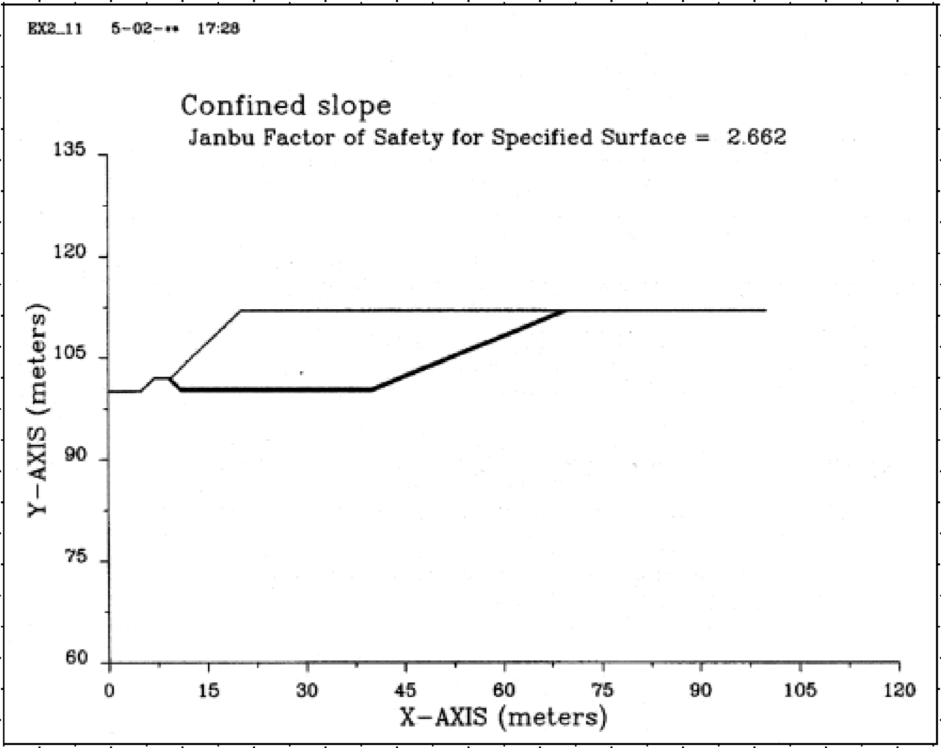

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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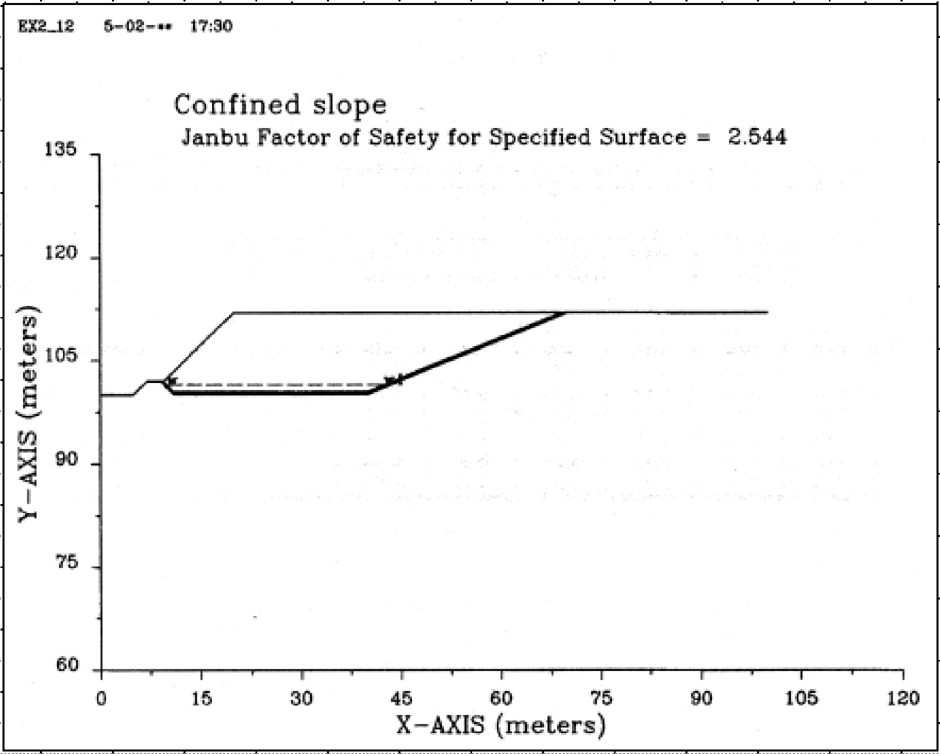


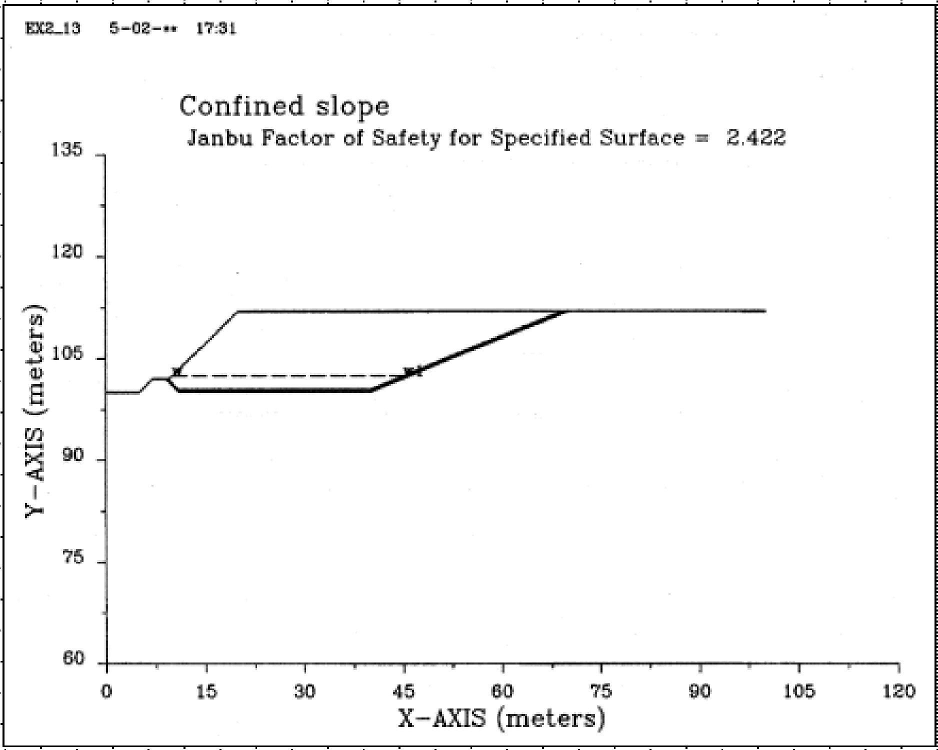
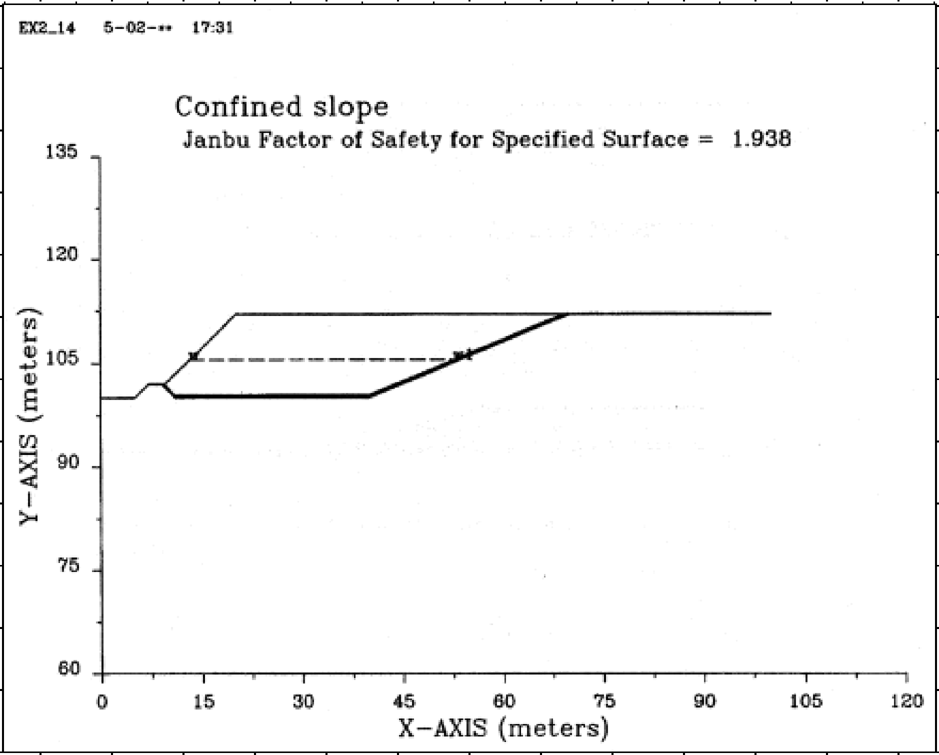


Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	20
			Reviewed:		of:	27



Results:

Run	Filename:	Leachate	F of S	Comments	
1	Ex2_11	Dry	2.66	Failure along lining system	2.66
2	Ex2_12	1m	2.54	Failure along lining system	↓
3	Ex2_13	2m	2.42	Failure along lining system	↓
4	Ex2_14	5m	1.94	Failure along lining system	1.94

Conclusion

Even the worst credible leachate level gives a factor of safety > 1.5, hence it is considered that the stability of the confined slope is satisfactory. **OK**

b) Integrity of the mineral liner

The integrity of the mineral liner can be assessed by establishing the effect of the waste support on the stability of the insitu slope.

Aim: Assess the integrity of the mineral liner by calculating the stability of the confined slope.

Approach: Use the computer code XSTABL to calculate the factor of safety for a range of circular failures. Apply waste loading to the slope based on the vertical load and a horizontal load calculated from the K_o of the waste.

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	21
			Reviewed:		of:	27

Calculations:

May, 2002

Spreadsheet for the calculation of XSTABL input parameters for a waste supported slope

Input Parameters

Slope height (m)	12	WASTE HEIGHT
Slope angle (1 in)	2.5	
Unit weight of waste (kN/m^3)	10	
Ko value of waste	0.2	
x-coord of base of slope	30	

Output

Loading Layer	Mean Stresses for each layer			Angle	X-Coords	
	Vert.	Horiz.	Resultant		Start	End
Layer 9 (top)	6.7	1.3	6.8	11.3	56.7	60.0
Layer 8	20.0	4.0	20.4	11.3	53.3	56.7
Layer 7	33.3	6.7	34.0	11.3	50.0	53.3
Layer 6	46.7	9.3	47.6	11.3	46.7	50.0
Layer 5	60.0	12.0	61.2	11.3	43.3	46.7
Layer 4	73.3	14.7	74.8	11.3	40.0	43.3
Layer 3	86.7	17.3	88.4	11.3	36.7	40.0
Layer 2	100.0	20.0	102.0	11.3	33.3	36.7
Layer 1	113.3	22.7	115.6	11.3	30.0	33.3

Stress on landfill floor 120 kPa

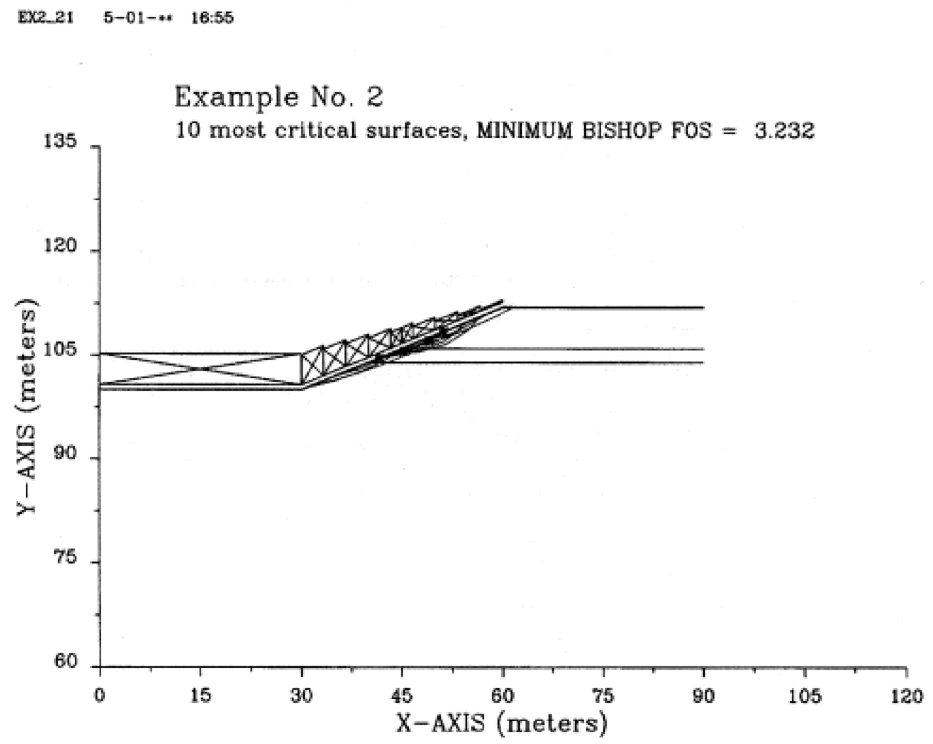


Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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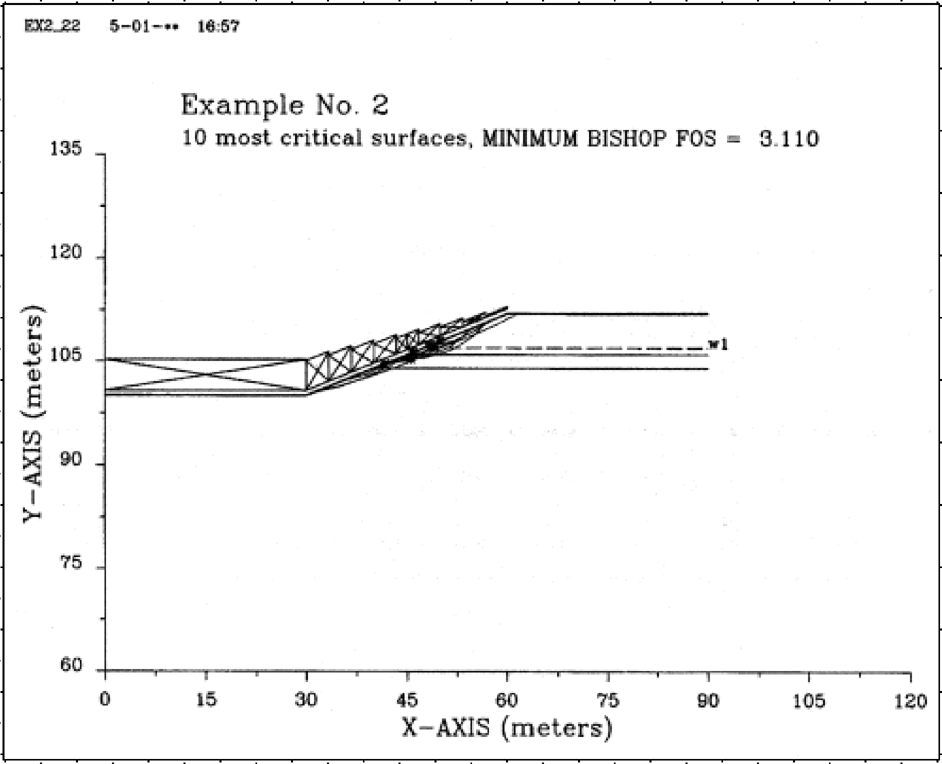

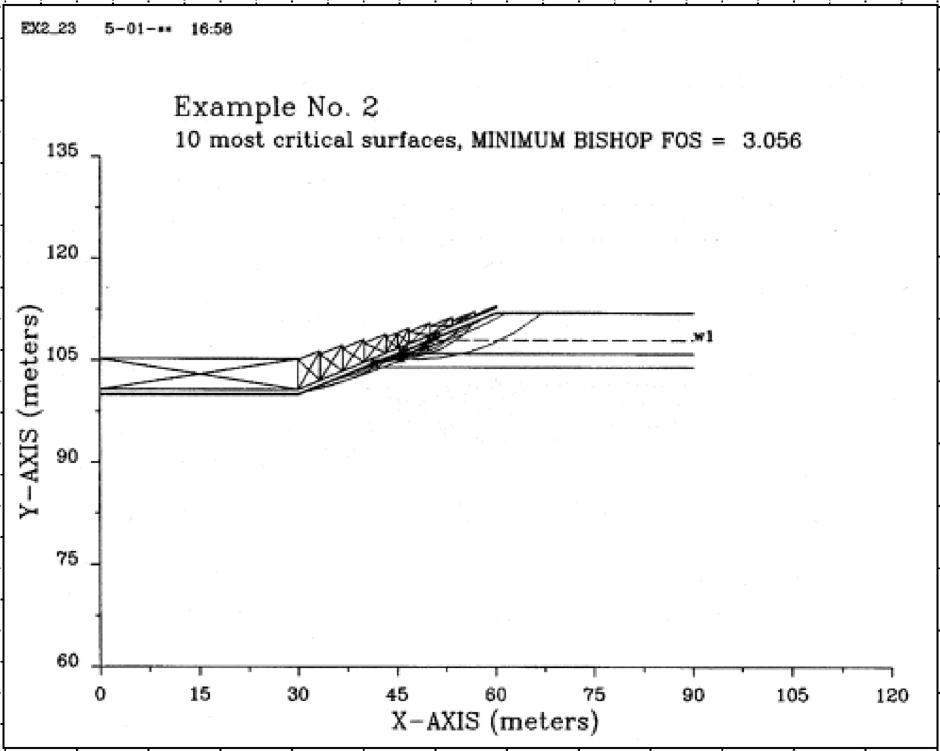

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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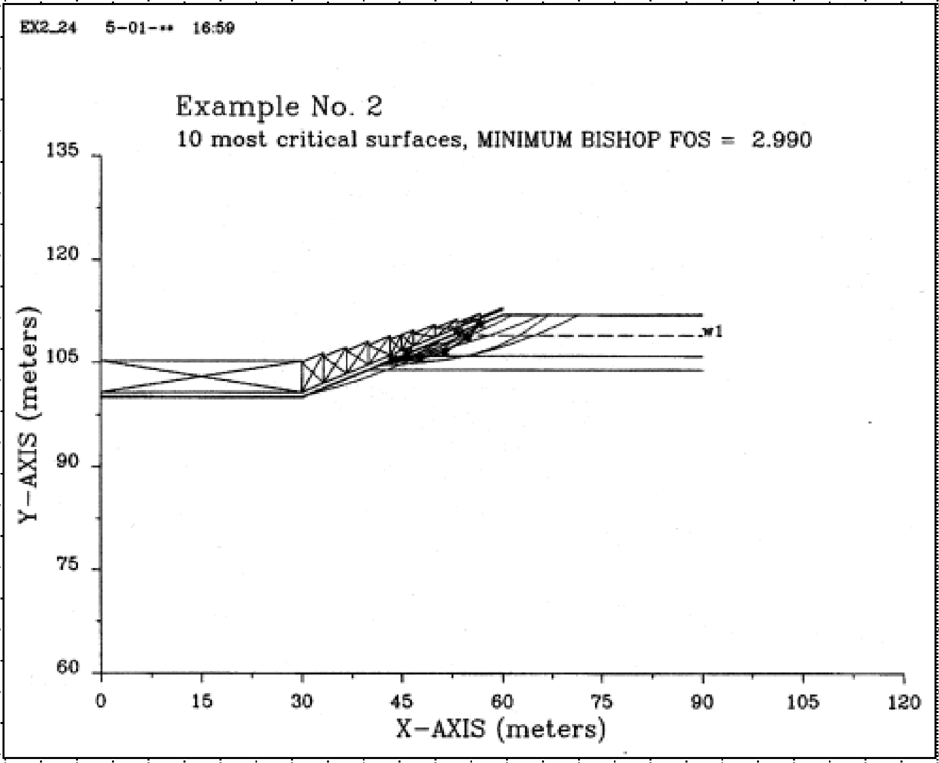

Results:

Run	Filename	Water	F of S	Comments	
1	Ex2_21	Dry	3.23	Failure into waste	3.23
2	Ex2_22	1m	3.11	Failure into waste	↓
3	Ex2_23	2m	3.06	Failure into waste	
4	Ex2_24	3m	2.99	Failure into waste	2.99

Conclusions:

All calculated factors of safety against failure into the waste are >1.5, hence it is considered that the integrity of the mineral liner is satisfactory.

c) Integrity of the geosynthetic materials

Numerical modelling results shown in Report No 1 (Chapter 11, tables 11.6 and 11.8), demonstrate that for a 1 in 2.5 slope 10m high, containing a geotextile/textured geomembrane interface, local failure (i.e. slippage) is unlikely to occur. Therefore the geomembrane protection and hence its integrity is considered to be satisfactory. **OK**

4. WASTE SLOPE STABILITY

4.1 Failure wholly in waste

Since sand will be used for daily cover, there are no potential weak planes in the waste. Therefore consider only circular failure through the waste body.

Aim: Assess the stability of the waste face.

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	24
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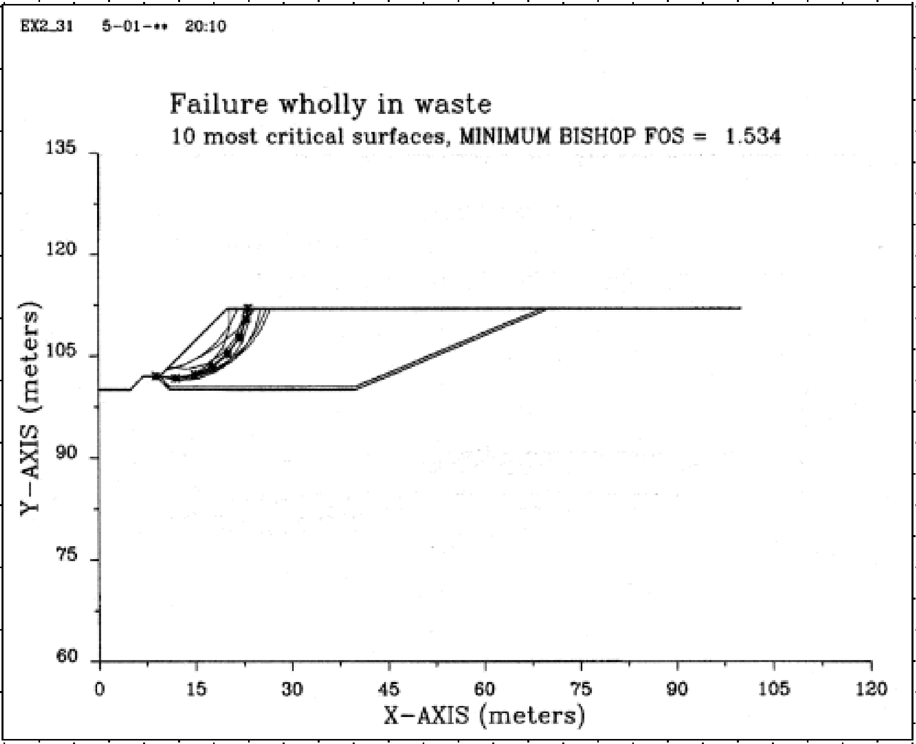
Approach: Use the computer code XSTABL to calculate the factor of safety against failure through the waste body. Assess the importance of different leachate levels within the waste.

Calculations:



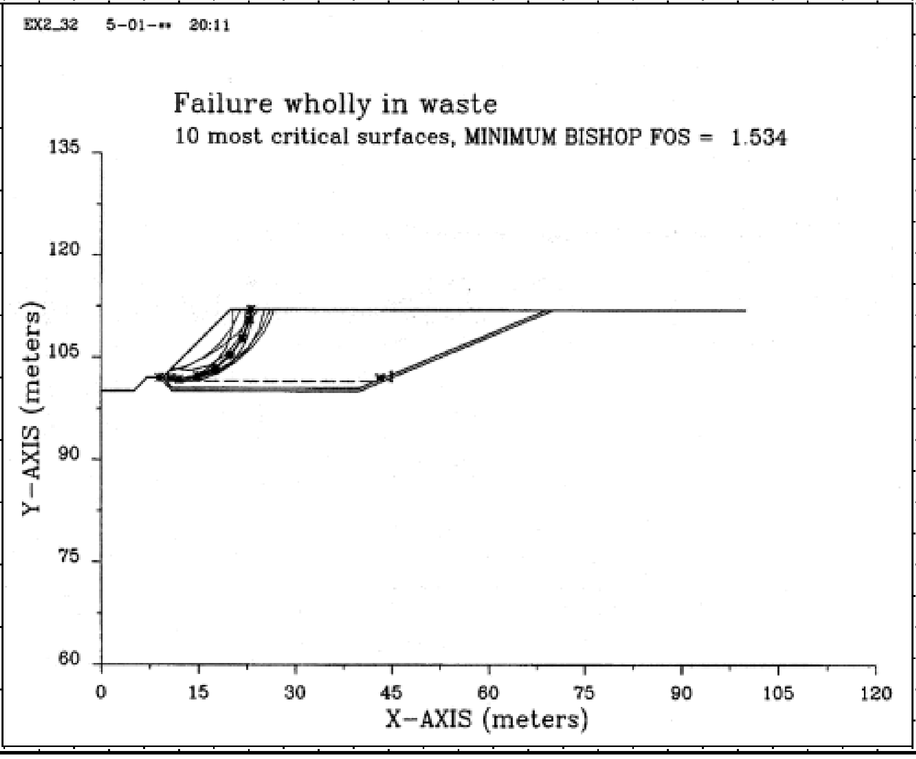


Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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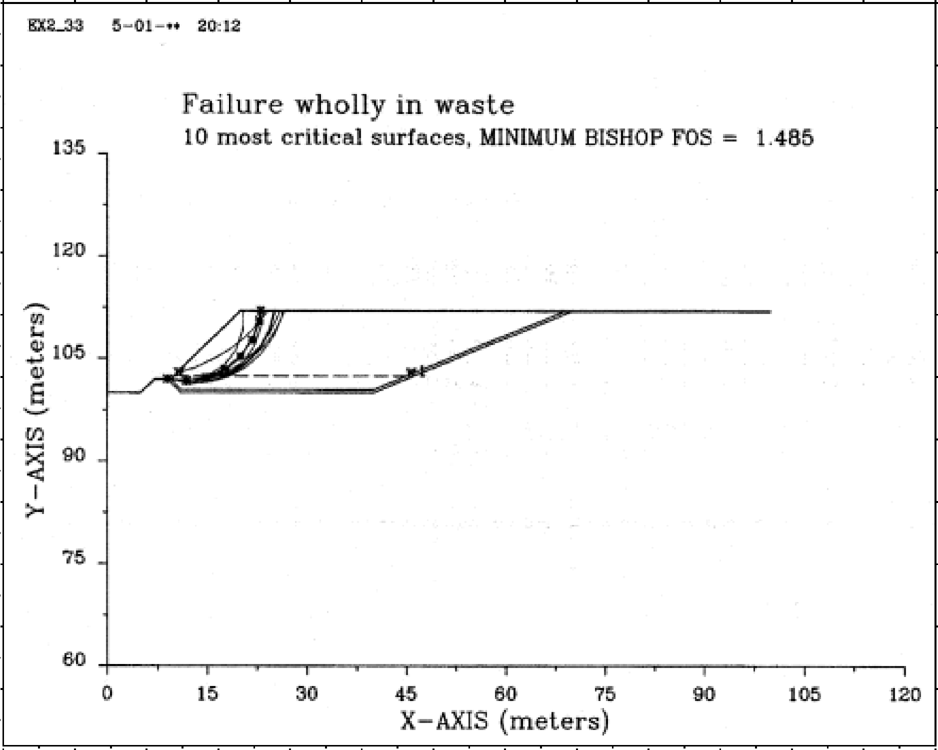

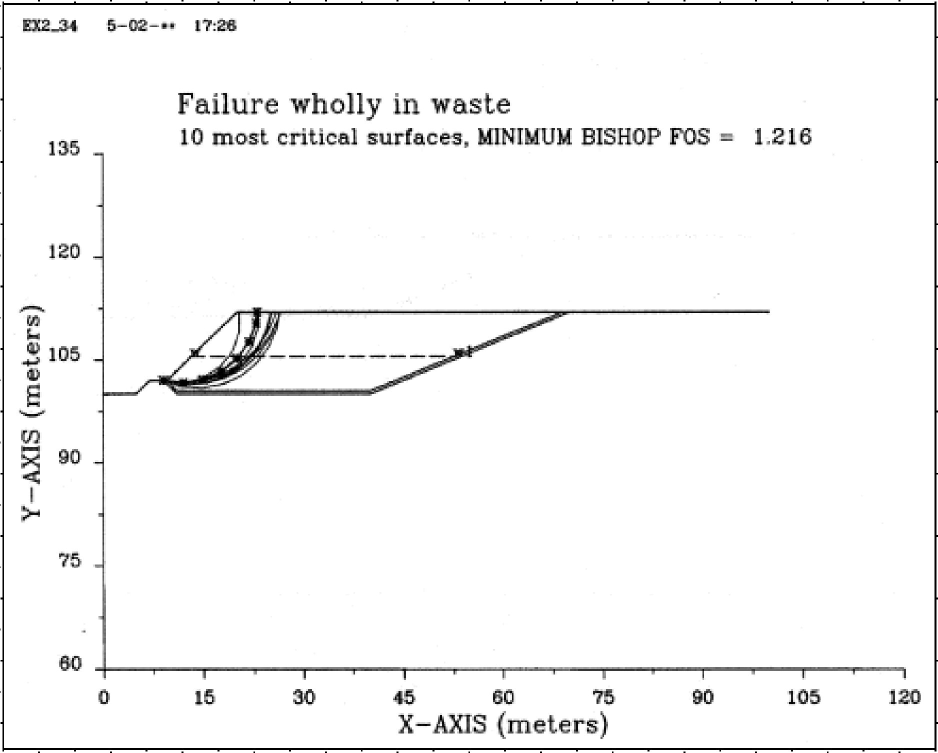

Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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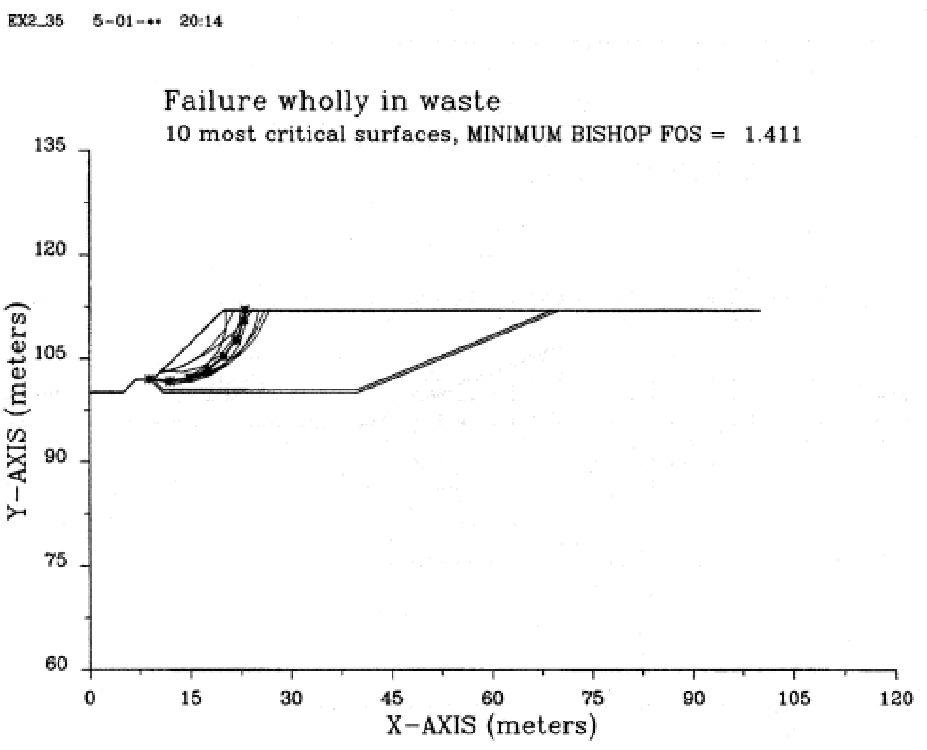


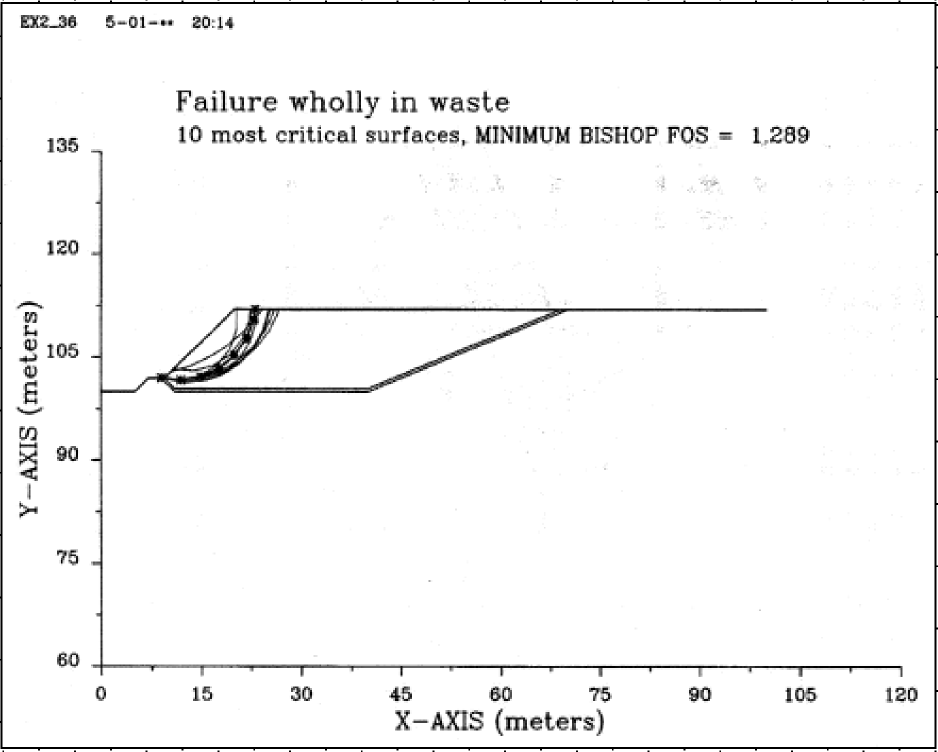
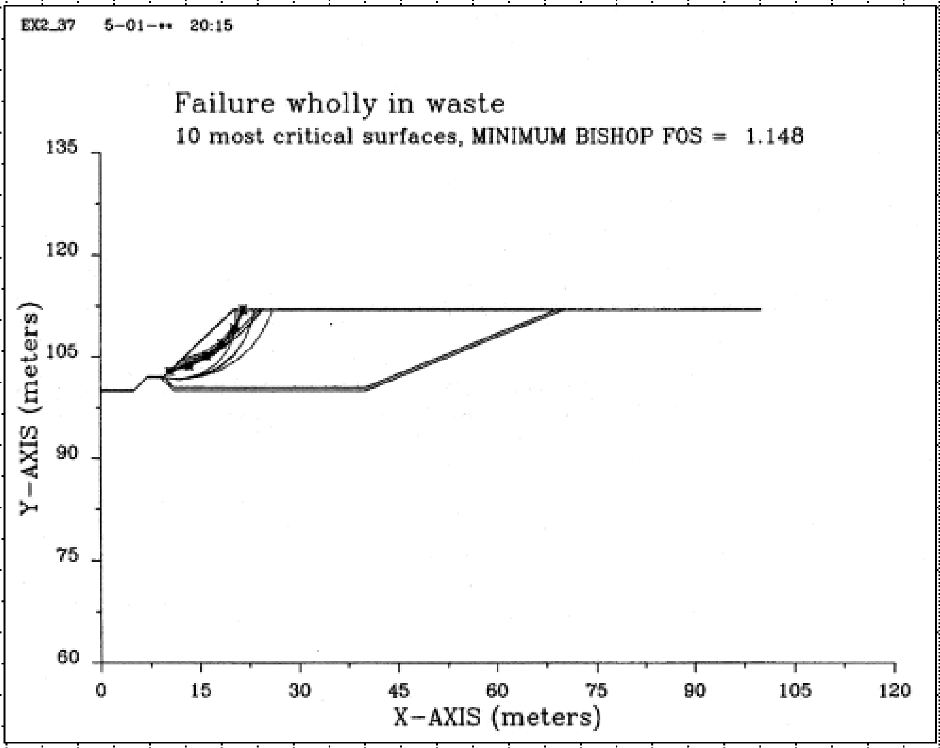


Figure 4.12 Calculations for Example 2 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 2	Checked:		Sheet:	27
			Reviewed:		of:	27



Results:

Run	Filename	Waste Strength	Leachate	F of S	Comments	
1	Ex2_31	c' = 10 kPa; ' =25°	Dry	1.53	Failure through waste	**1.53**
2	Ex2_32	c' = 10 kPa; ' =25°	1m	1.53	Failure through waste	
3	Ex2_33	c' = 10 kPa; ' =25°	2m	1.49	Failure through waste	
4	Ex2_34	c' = 10 kPa; ' =25°	5m	1.22	Failure through waste	
5	Ex2_35	c' = 10 kPa; ' =25°	r_u = 0.1	1.41	Leachate pressure in waste	
6	Ex2_36	c' = 10 kPa; ' =25°	r_u = 0.2	1.29	Leachate pressure in waste	
7	Ex2_37	c' = 5 kPa; ' =25°	Dry	1.15	Reduced c' in waste	**1.15**

Conclusions:

The waste slope has a factor of safety >1.5 for the anticipated case and in excess of 1.2 for all cases. Waste slope is stable for the range of leachate levels/pore pressures expected. However, if the waste stream changes and a c' of 10kPa cannot be relied on, then the waste slope should be reduced. **OK**

4.2 Failure involving the lining system

Both the stability and integrity of the lining system due to failure through the waste was assessed in 3.2 above. **OK**

Figure 4.12 Calculations for Example 2 continued

4.3 Example 3: Geomembrane Capping Liner

4.3.1 Description

This example is a capping system which comprises (from the top down) topsoil/subsoil, geocomposite drain, textured LLDPE geomembrane, blinding layer, waste. The height of slope is 10 m and the gradient is 1 (vert.) to 4 (horiz.). It is known that drums of waste were placed near the surface of the waste and it is possible that these will degrade and potentially give a 600mm diameter void at the surface. The design flow chart and calculations are given in Section 4.3.3 below.

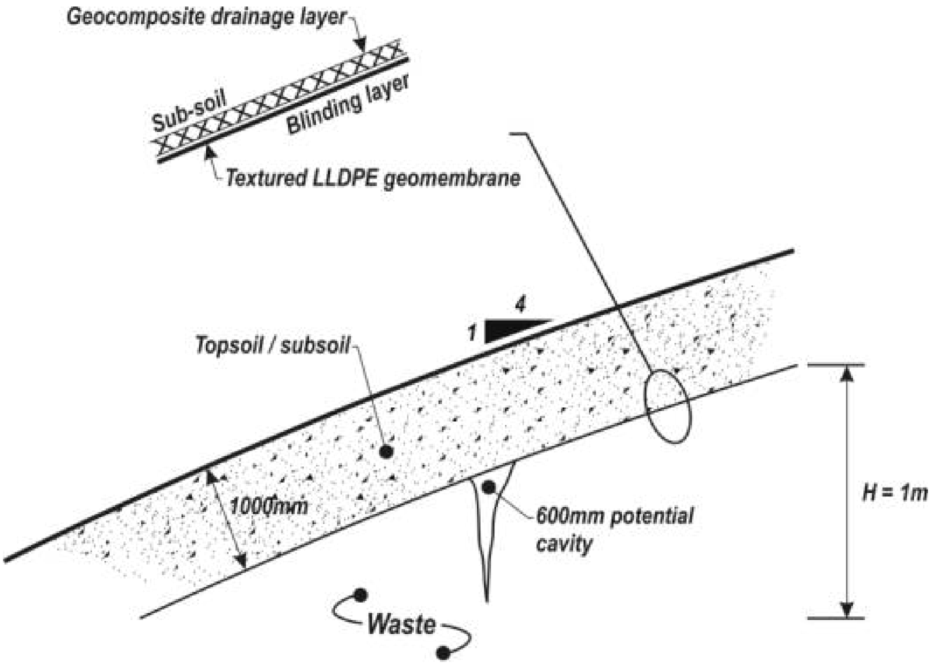


Figure 4.13 Schematic Cross Section of Example 3

4.3.2 Capping lining system

The capping lining system design cases to be considered are highlighted in Figure 4.14.

Geosynthetic/Mineral Liner

Stability

Design issues:

- stability of capping system.

In the assessment of the stability of the cover soil both peak and residual interface shear strengths should be considered. This is due to the possibility of the construction plant loading inducing post-peak shear strengths at the interfaces. Laboratory testing is required to establish characteristic interface shear strength values. Suitable factors of safety would be 1.5

for the peak strengths and 1.0 for the residual strengths (assuming the worst credible conditions). The analysis should consider the effect of seepage forces in the cover soil.

The effect of uplift pressures from landfill gas should be assessed for the interface underneath the geomembrane. A suitable factor of safety would be 1.3 for peak strengths and 1.0 for residual strengths.

It is also necessary to consider the possibility of internal shearing through the geocomposite; this can be addressed by ensuring that the internal strength is greater than the interface strength –should be confirmed by conformance testing.

Integrity – Compressible Waste

Design issues:

- control stresses in liner to prevent increased permeability.

The multi-axial performance of the LLDPE geomembrane is better than HDPE geomembrane, and is considered to be suitable for the proposed capping system.

Integrity – Slope Deformation

Design issues:

- control stresses in liner to prevent increased permeability.

The veneer stability analysis described above can also be used to assess the integrity of the geosynthetic by considering the transfer of stresses through the lining system. A suitable factor of safety would be 1.5.

Integrity – Cavities in Waste

Design issues:

- control stresses in liner to prevent increased permeability.

Assess the strain in the geomembrane due to the development of cavities in the waste. If strain is considered excessive then use a geosynthetic reinforcing layer.

4.3.3 Design flow charts and calculations

See Figures 4.14 and 4.15.

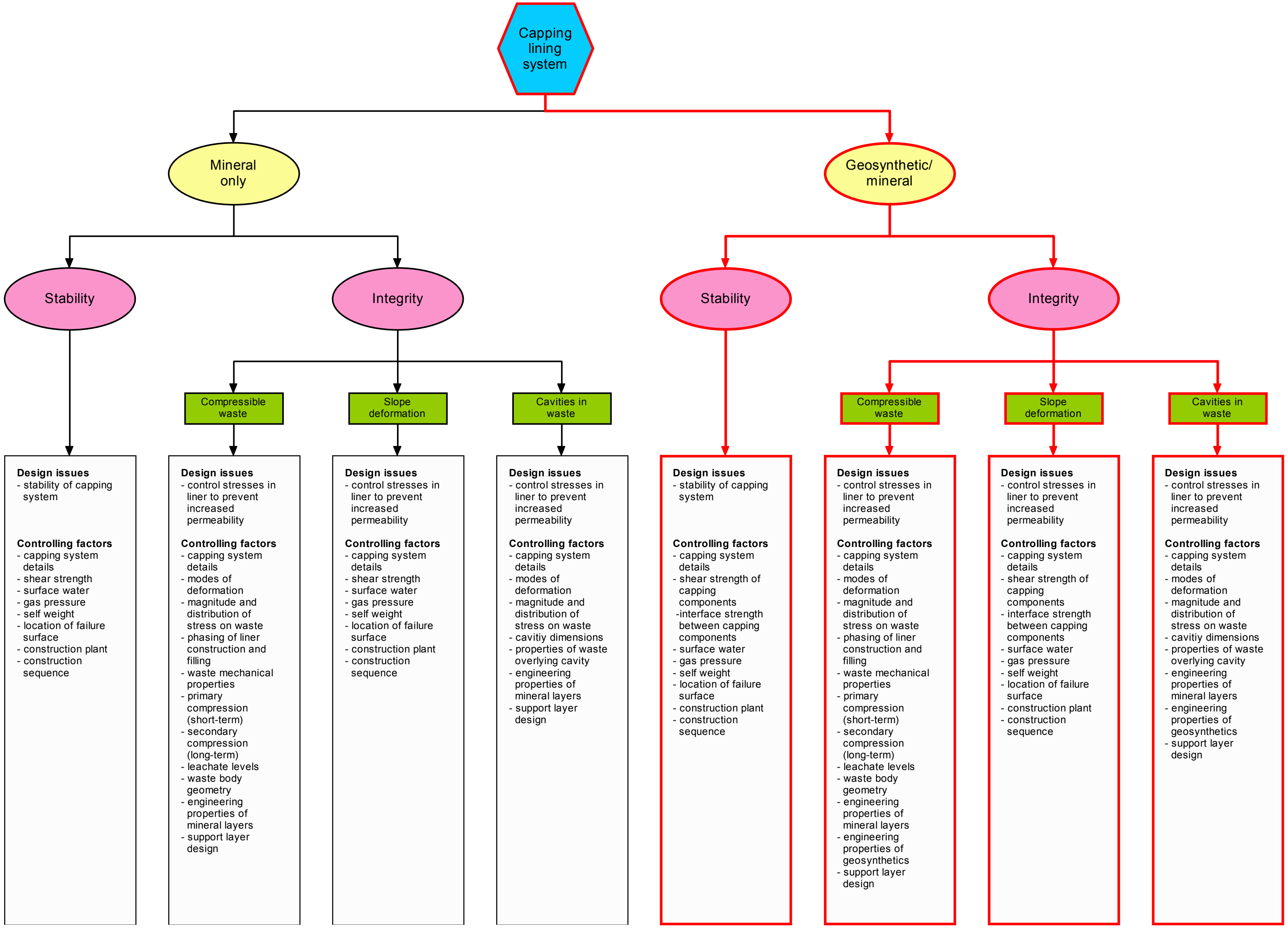
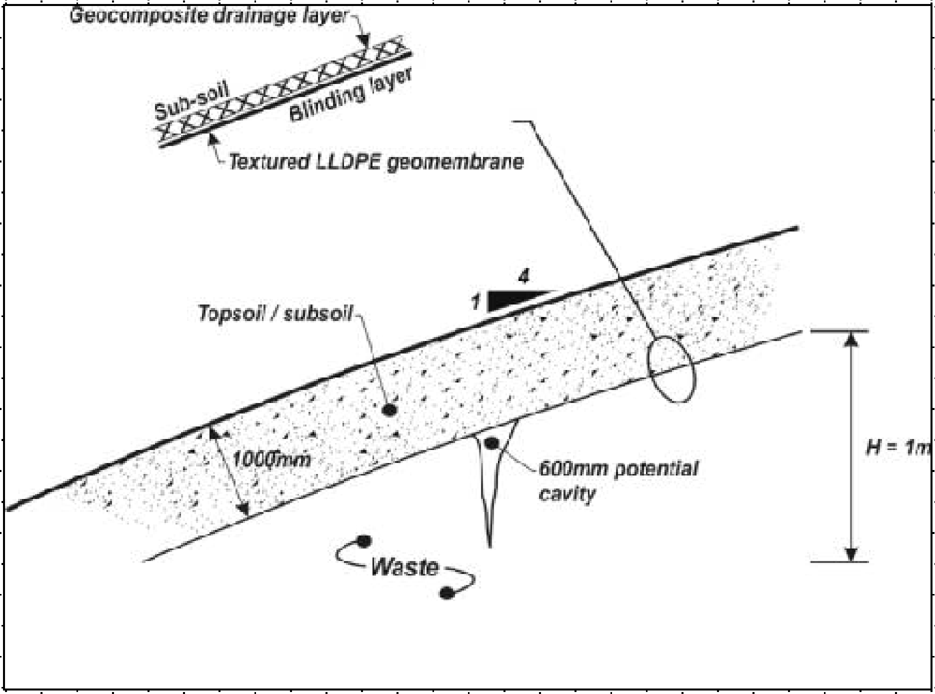


Figure 4.14 Design Flow Chart for Example 3: Capping Lining System

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	1
			Reviewed:		of:	29

DESCRIPTION: LLDPE geomembrane capping liner

GEOMETRY:



1. CAPPING LINER SYSTEM

1.1 Capping liner stability

a) Peak shear strengths

Aim: Assess the stability of the cover soil on top of the geocomposite drainage layer.

Approach: Use the method proposed by Jones & Dixon (1998).

From laboratory testing, the following peak interface strength parameters were obtained:

Granular sub-soil material	$c' = 0$	$\Phi' = 32°$
Sub-soil/drainage geocomposite interface	$\alpha' = 0$	$\delta' = 24°$
Geocomposite/textured LLDPE geomembrane interface	$\alpha' = 2$	$\delta' = 22°$
Textured LLDPE geomembrane/blinding layer interface	$\alpha' = 0$	$\delta' = 25°$

Calculations:

See sheets 2 to 7

Figure 4.15 Calculations for Example 3

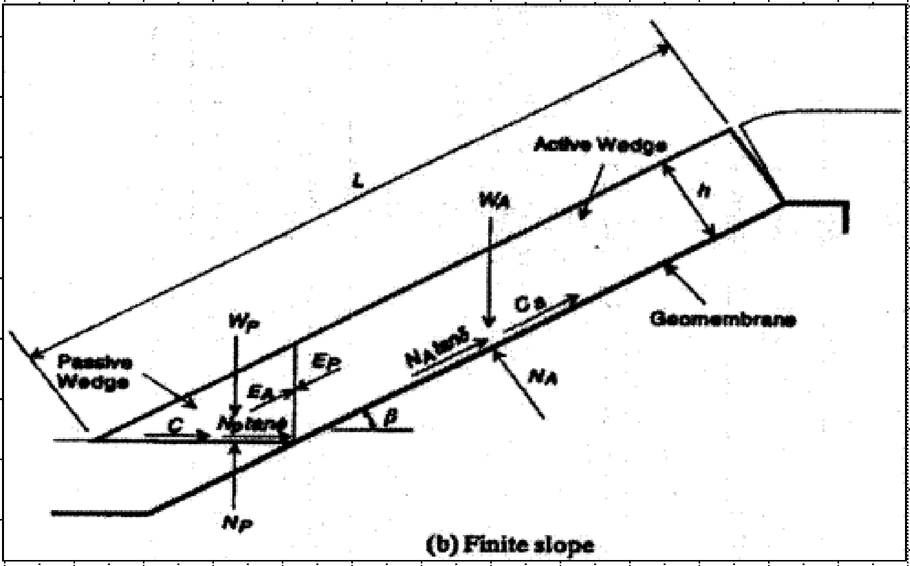
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	2
			Reviewed:		of:	29

Stability of the geosynthetic capping system

Aim: To assess the stability of the geosynthetic capping system (PSR = 0, peak strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

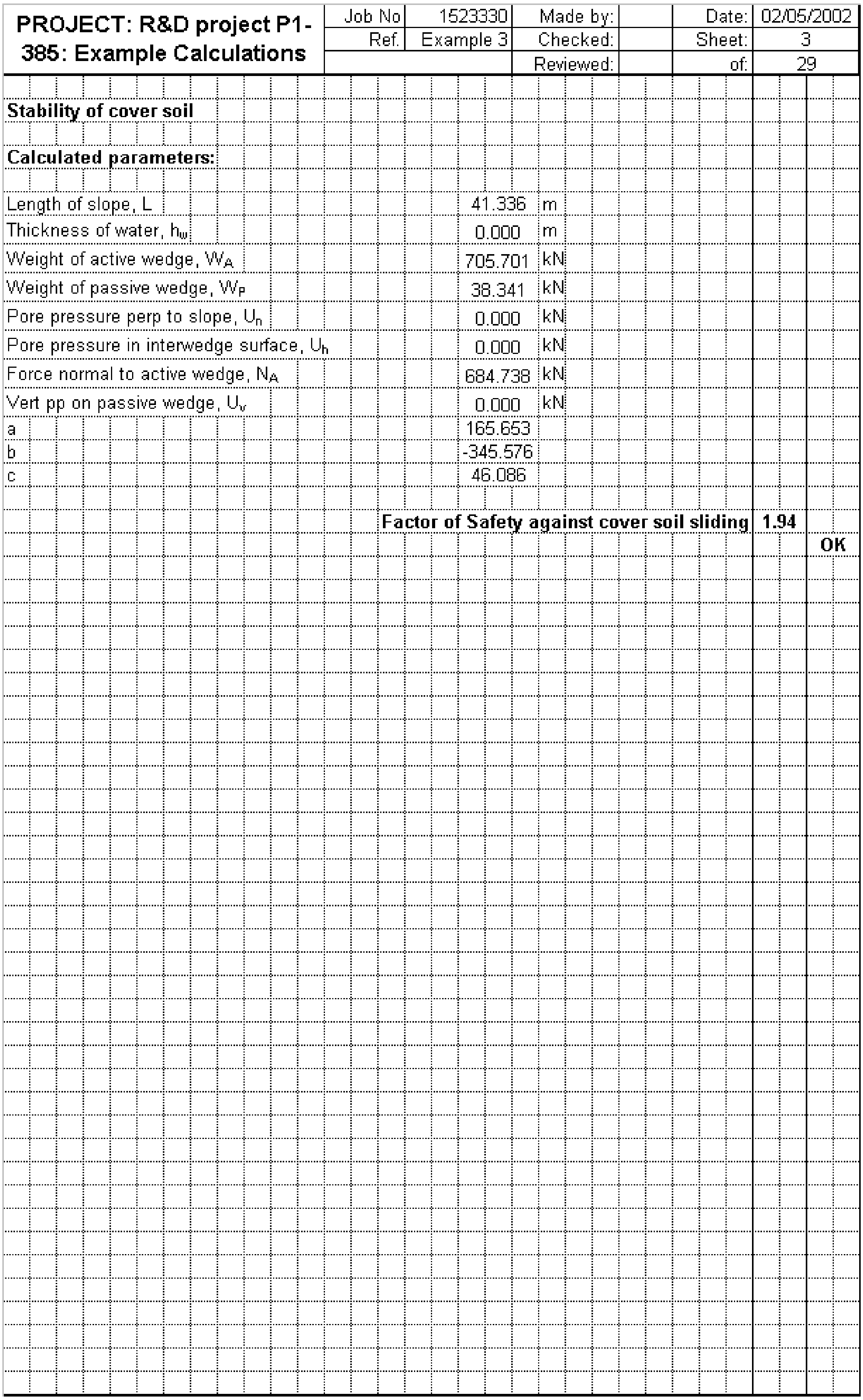
Geometry:



Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	kN.m^{-3}
Cover soil unit weight (saturated). γ_{sat}	21	kN.m^{-3}
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	24	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	22	
Geocomposite/geomembrane cohesion intercept, α_2	2	
Geomembrane/blinding layer friction angle, δ_3	25	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0	

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	3
			Reviewed:		of:	29

Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.000	m
Weight of active wedge, W_A	705.701	kN
Weight of passive wedge, W_P	38.341	kN
Pore pressure perp to slope, U_n	0.000	kN
Pore pressure in interwedge surface, U_h	0.000	kN
Force normal to active wedge, N_A	684.738	kN
Vert pp on passive wedge, U_v	0.000	kN
a	165.653	
b	-345.576	
c	46.086	

Factor of Safety against cover soil sliding **1.94**

OK

Figure 4.15 Calculations for Example 3 continued

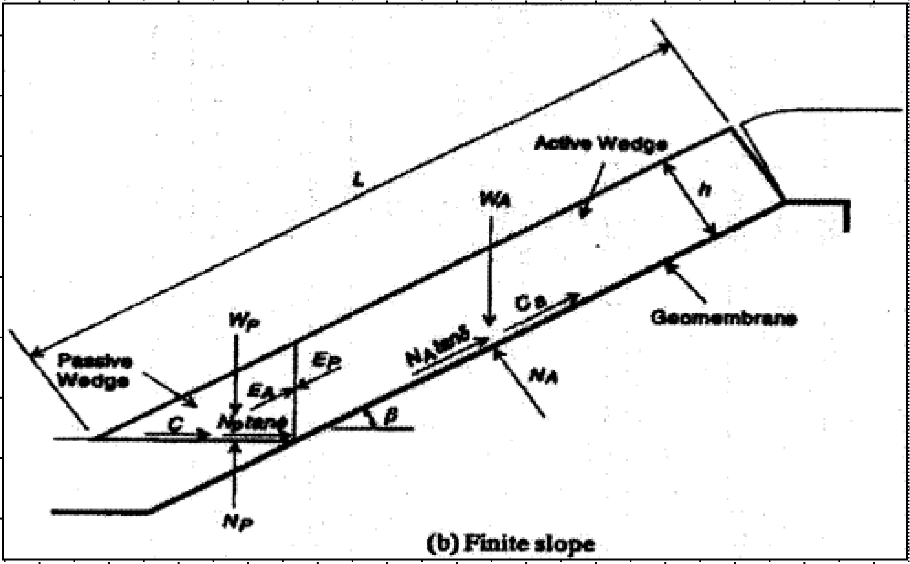
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	4
			Reviewed:		of:	29

Stability of the geosynthetic capping system

Aim: To assess the stability of the geosynthetic capping system (PSR = 0.25, peak strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

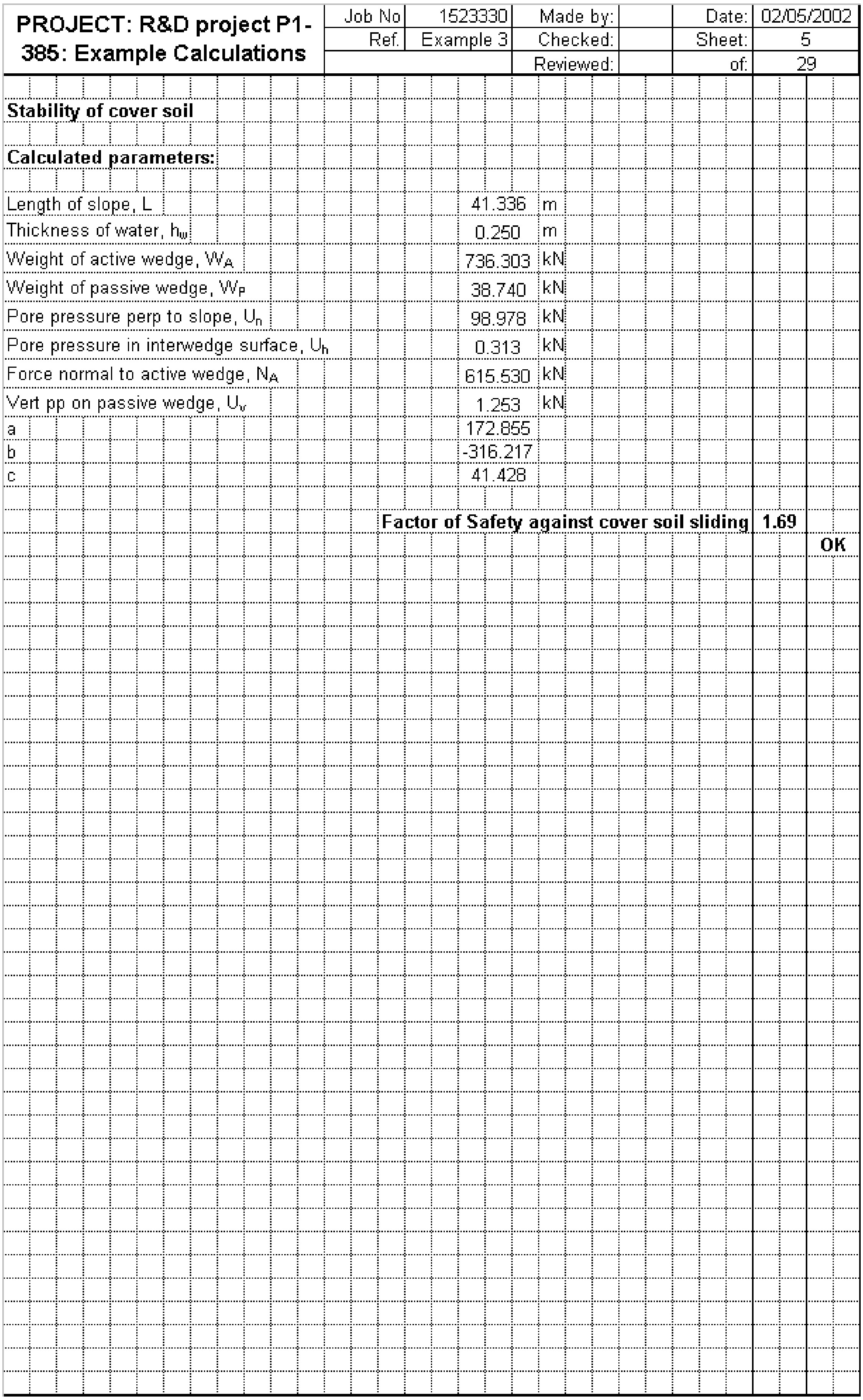
Geometry:



Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	kN.m^{-3}
Cover soil unit weight (saturated). γ_{sat}	21	kN.m^{-3}
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	24	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	22	
Geocomposite/geomembrane cohesion intercept, α_2	2	
Geomembrane/blinding layer friction angle, δ_3	25	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.25	

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	5
			Reviewed:		of:	29

Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.250	m
Weight of active wedge, W_A	736.303	kN
Weight of passive wedge, W_P	38.740	kN
Pore pressure perp to slope, U_n	98.978	kN
Pore pressure in interwedge surface, U_h	0.313	kN
Force normal to active wedge, N_A	615.530	kN
Vert pp on passive wedge, U_v	1.253	kN
a	172.855	
b	-316.217	
c	41.428	

Factor of Safety against cover soil sliding **1.69**

OK

Figure 4.15 Calculations for Example 3 continued

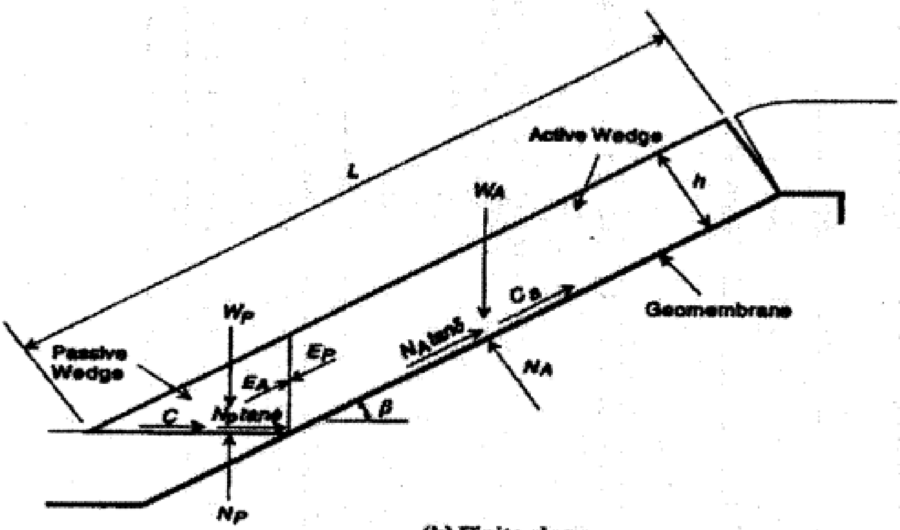
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	6
			Reviewed:		of:	29

Stability of the geosynthetic capping system

Aim: To assess the stability of the geosynthetic capping system (PSR = 0.5, peak strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

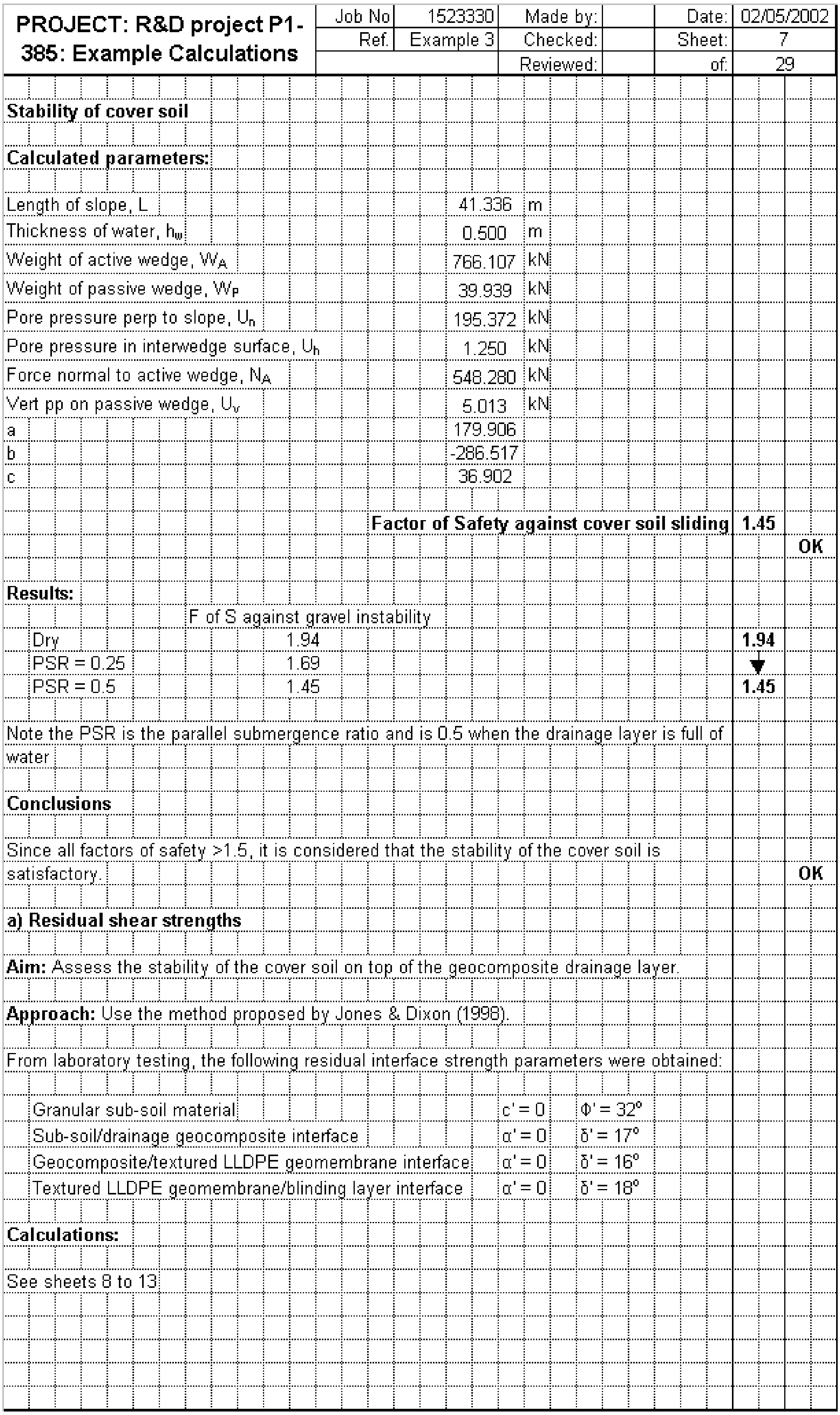


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	24	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	22	
Geocomposite/geomembrane cohesion intercept, α_2	2	
Geomembrane/blinding layer friction angle, δ_3	25	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.5	

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	7
			Reviewed:		of:	29

Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.500	m
Weight of active wedge, W_A	766.107	kN
Weight of passive wedge, W_P	39.939	kN
Pore pressure perp to slope, U_n	195.372	kN
Pore pressure in interwedge surface, U_h	1.250	kN
Force normal to active wedge, N_A	548.280	kN
Vert pp on passive wedge, U_v	5.013	kN
a	179.906	
b	-286.517	
c	36.902	

Factor of Safety against cover soil sliding **1.45**

OK

Results:

	F of S against gravel instability	
Dry	1.94	**1.94**
PSR = 0.25	1.69	↓
PSR = 0.5	1.45	**1.45**

Note the PSR is the parallel submergence ratio and is 0.5 when the drainage layer is full of water

Conclusions

Since all factors of safety >1.5, it is considered that the stability of the cover soil is satisfactory. **OK**

a) Residual shear strengths

Aim: Assess the stability of the cover soil on top of the geocomposite drainage layer.

Approach: Use the method proposed by Jones & Dixon (1998).

From laboratory testing, the following residual interface strength parameters were obtained:

Granular sub-soil material	$c' = 0$	$\Phi' = 32^\circ$
Sub-soil/drainage geocomposite interface	$\alpha' = 0$	$\delta' = 17^\circ$
Geocomposite/textured LLDPE geomembrane interface	$\alpha' = 0$	$\delta' = 16^\circ$
Textured LLDPE geomembrane/blinding layer interface	$\alpha' = 0$	$\delta' = 18^\circ$

Calculations:

See sheets 8 to 13

Figure 4.15 Calculations for Example 3 continued

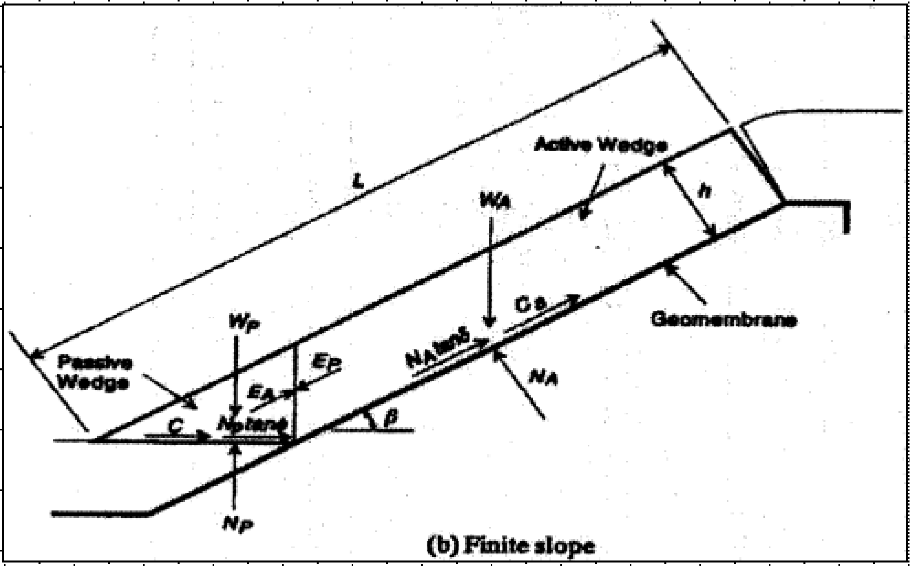
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	8
			Reviewed:		of:	29

Stability of the geosynthetic capping system

Aim: To assess the stability of the geosynthetic capping system (PSR = 0, residual strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

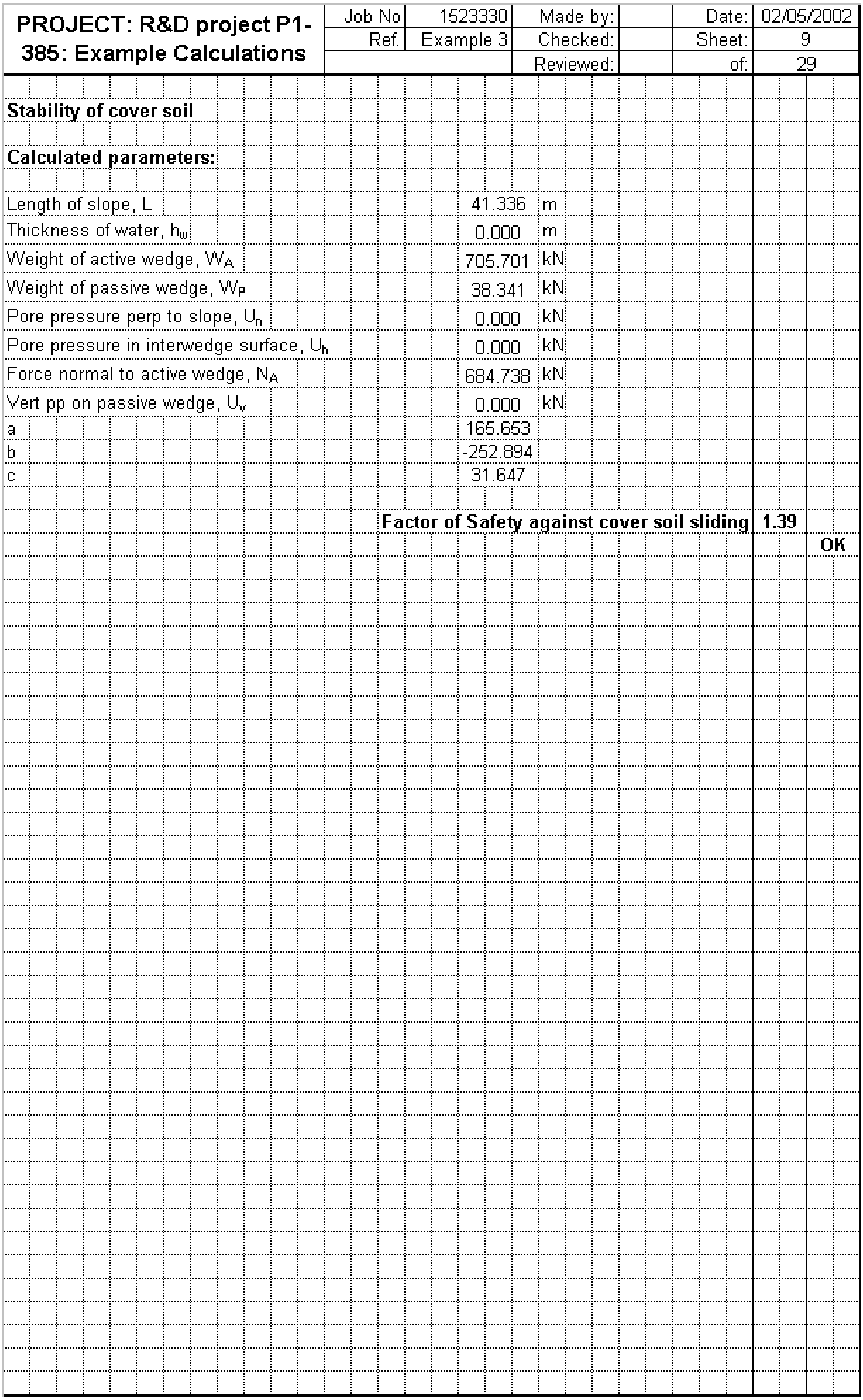


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	17	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	16	
Geocomposite/geomembrane cohesion intercept, α_2	0	
Geomembrane/blinding layer friction angle, δ_3	18	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0	

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	9
			Reviewed:		of:	29

Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.000	m
Weight of active wedge, W_A	705.701	kN
Weight of passive wedge, W_P	38.341	kN
Pore pressure perp to slope, U_n	0.000	kN
Pore pressure in interwedge surface, U_h	0.000	kN
Force normal to active wedge, N_A	684.738	kN
Vert pp on passive wedge, U_v	0.000	kN
a	165.653	
b	-252.894	
c	31.647	

Factor of Safety against cover soil sliding **1.39**

OK

Figure 4.15 Calculations for Example 3 continued

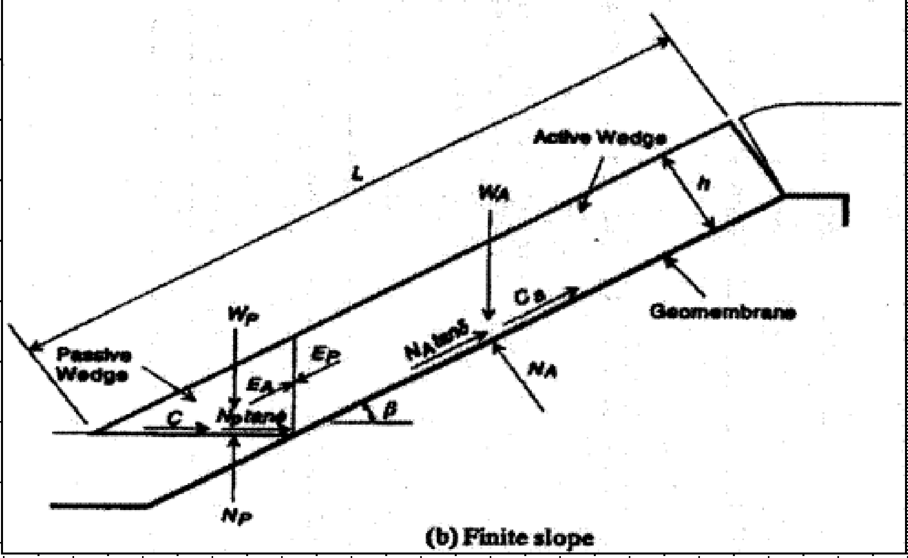
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	10
			Reviewed:		of:	29

Stability of the geosynthetic capping system

Aim: To assess the stability of the geosynthetic capping system (PSR = 0.25, residual strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

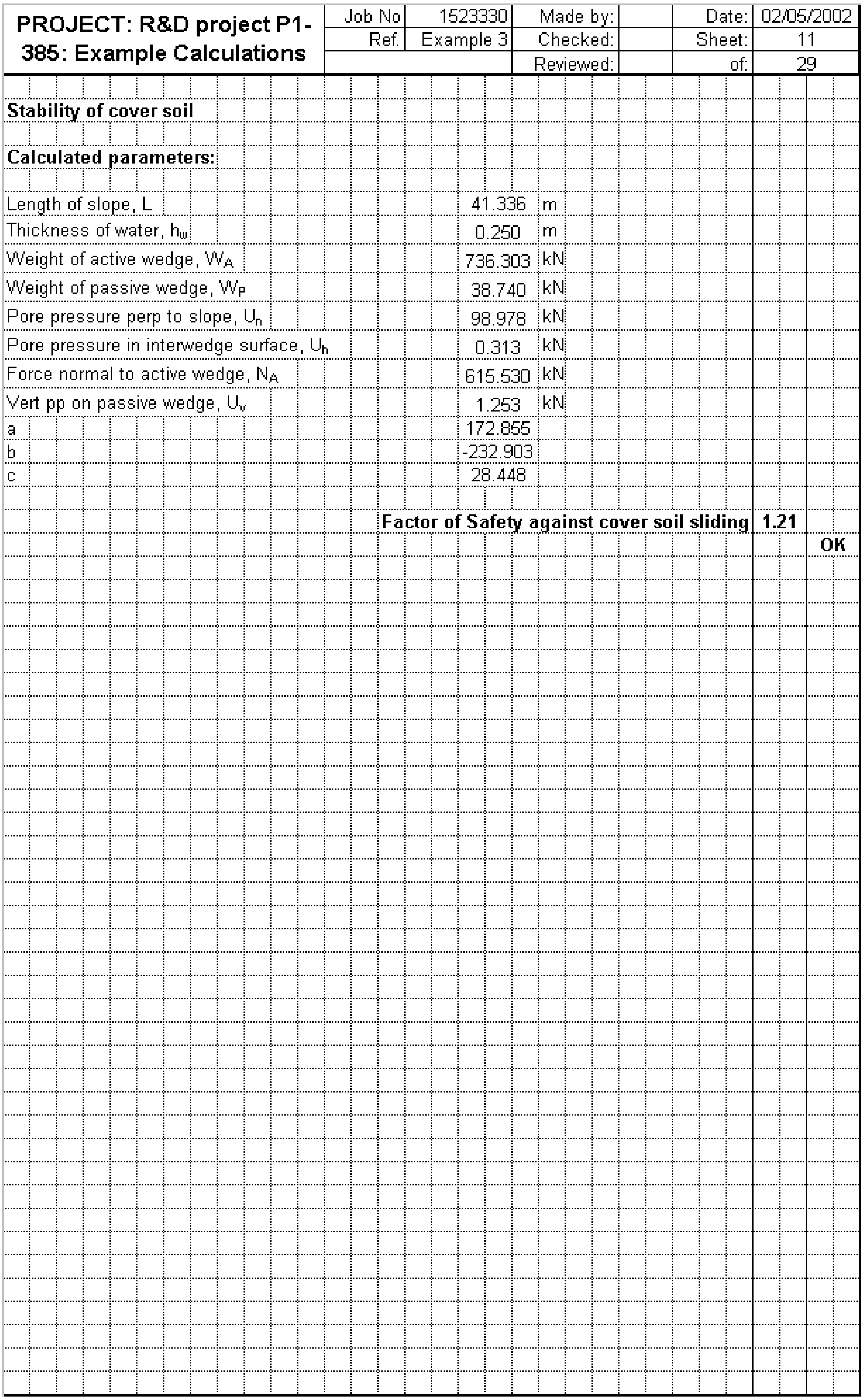


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	kN.m^{-3}
Cover soil unit weight (saturated). γ_{sat}	21	kN.m^{-3}
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	17	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	16	
Geocomposite/geomembrane cohesion intercept, α_2	0	
Geomembrane/blinding layer friction angle, δ_3	18	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.25	

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	11
			Reviewed:		of:	29

Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.250	m
Weight of active wedge, W_A	736.303	kN
Weight of passive wedge, W_P	38.740	kN
Pore pressure perp to slope, U_n	98.978	kN
Pore pressure in interwedge surface, U_h	0.313	kN
Force normal to active wedge, N_A	615.530	kN
Vert pp on passive wedge, U_v	1.253	kN
a	172.855	
b	-232.903	
c	28.448	

Factor of Safety against cover soil sliding **1.21**

OK

Figure 4.15 Calculations for Example 3 continued

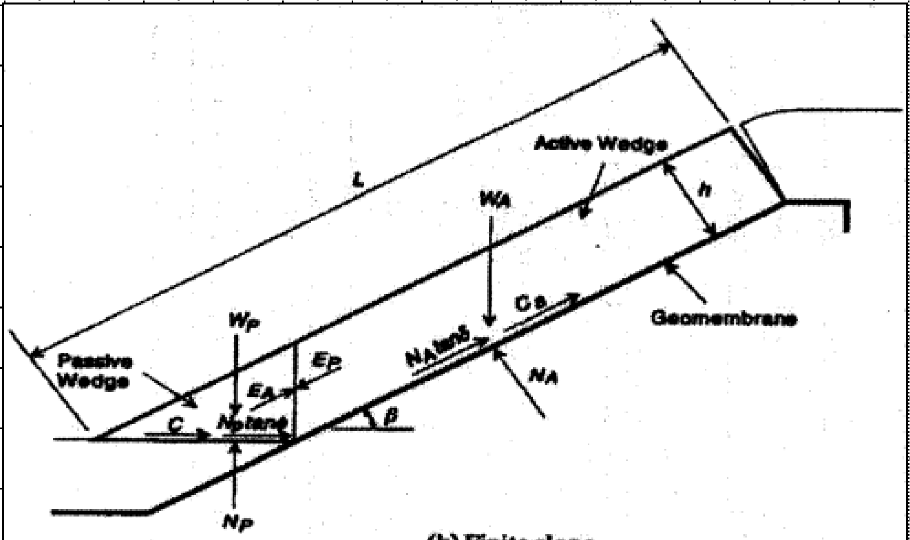
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	12
			Reviewed:		of:	29

Stability of the geosynthetic capping system

Aim: To assess the stability of the geosynthetic capping system (PSR = 0.5, residual strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:



(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	kN.m^{-3}
Cover soil unit weight (saturated). γ_{sat}	21	kN.m^{-3}
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	17	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	16	
Geocomposite/geomembrane cohesion intercept, α_2	0	
Geomembrane/blinding layer friction angle, δ_3	18	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.5	

Figure 4.15 Calculations for Example 3 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	13
			Reviewed:		of:	29

Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.500	m
Weight of active wedge, W_A	766.107	kN
Weight of passive wedge, W_P	39.939	kN
Pore pressure perp to slope, U_n	195.372	kN
Pore pressure in interwedge surface, U_h	1.250	kN
Force normal to active wedge, N_A	548.280	kN
Vert pp on passive wedge, U_v	5.013	kN
a	179.906	
b	-212.305	
c	25.340	

Factor of Safety against cover soil sliding **1.05**

OK

Results:

	F of S against gravel instability		
Dry	1.39	**1.39**	
PSR = 0.25	1.21	↓	
PSR = 0.5	1.05	**1.05**	

Conclusions:

Even if all the interfaces were at residual strength, the factor of safety > 1.0. This is considered to be adequate. **OK**

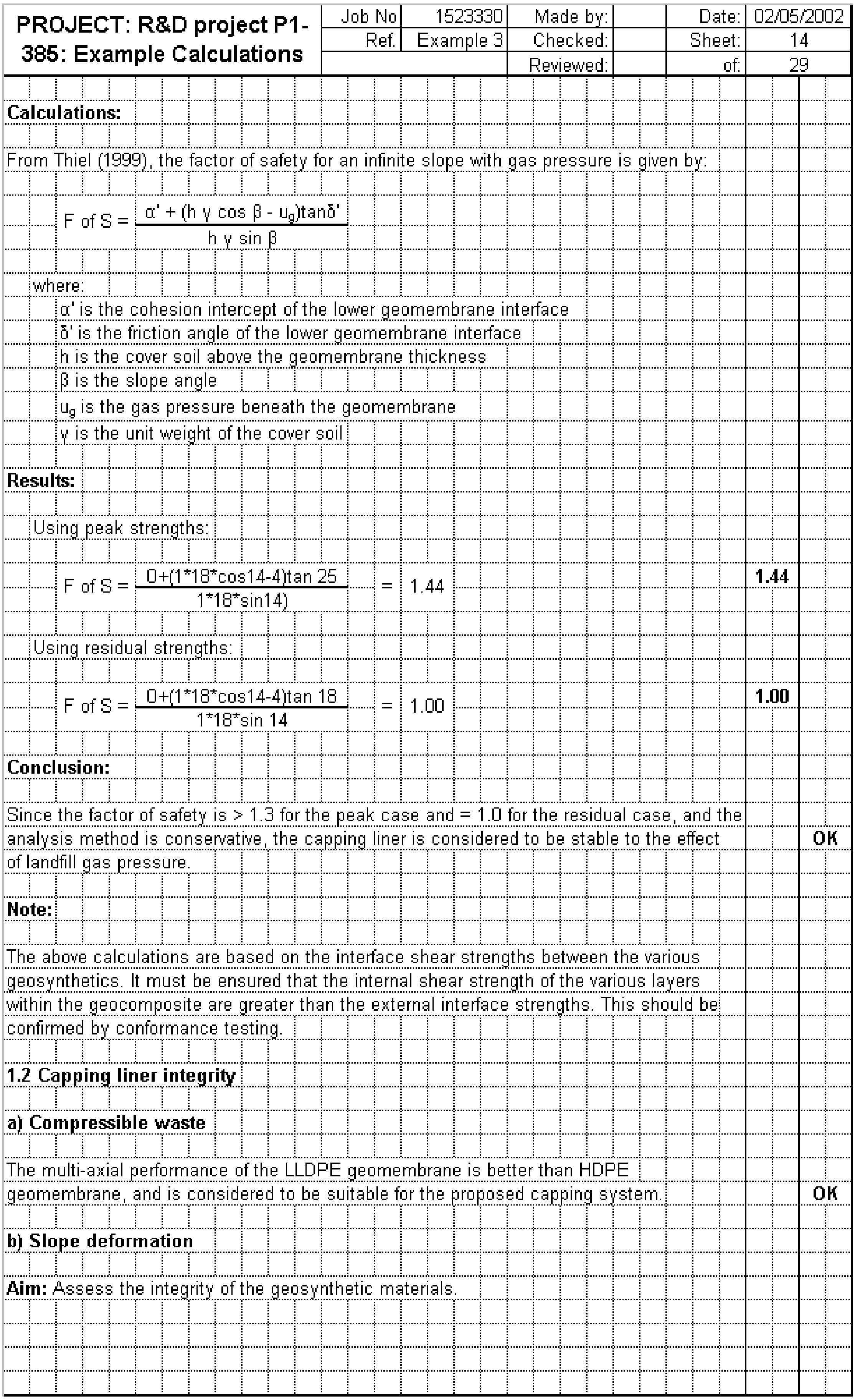
c) Consider the effect of landfill gas pressures

The active landfill gas extraction system should ensure that there is no build up of gas pressure beneath the geomembrane cap. However, in the event of a failure of the system, it has been calculated that there is a possibility of 4kPa of landfill gas acting beneath the cap.

Aim: Assess the stability of the cover soil with gas pressure from beneath.

Approach: Use the infinite slope method and substitute gas pressure for pore water pressure.

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	14
			Reviewed:		of:	29

Calculations:

From Thiel (1999), the factor of safety for an infinite slope with gas pressure is given by:

$$\text{F of S} = \frac{\alpha' + (h\ \gamma \cos\beta - u_g)\tan\delta'}{h\ \gamma \sin\beta}$$

where:

α' is the cohesion intercept of the lower geomembrane interface
δ' is the friction angle of the lower geomembrane interface
h is the cover soil above the geomembrane thickness
β is the slope angle
u_g is the gas pressure beneath the geomembrane
γ is the unit weight of the cover soil

Results:

Using peak strengths:

$$\text{F of S} = \frac{0+(1*18*\cos 14-4)\tan 25}{1*18*\sin 14)} = 1.44 \qquad \mathbf{1.44}$$

Using residual strengths:

$$\text{F of S} = \frac{0+(1*18*\cos 14-4)\tan 18}{1*18*\sin 14} = 1.00 \qquad \mathbf{1.00}$$

Conclusion:

Since the factor of safety is > 1.3 for the peak case and = 1.0 for the residual case, and the analysis method is conservative, the capping liner is considered to be stable to the effect of landfill gas pressure. **OK**

Note:

The above calculations are based on the interface shear strengths between the various geosynthetics. It must be ensured that the internal shear strength of the various layers within the geocomposite are greater than the external interface strengths. This should be confirmed by conformance testing.

1.2 Capping liner integrity

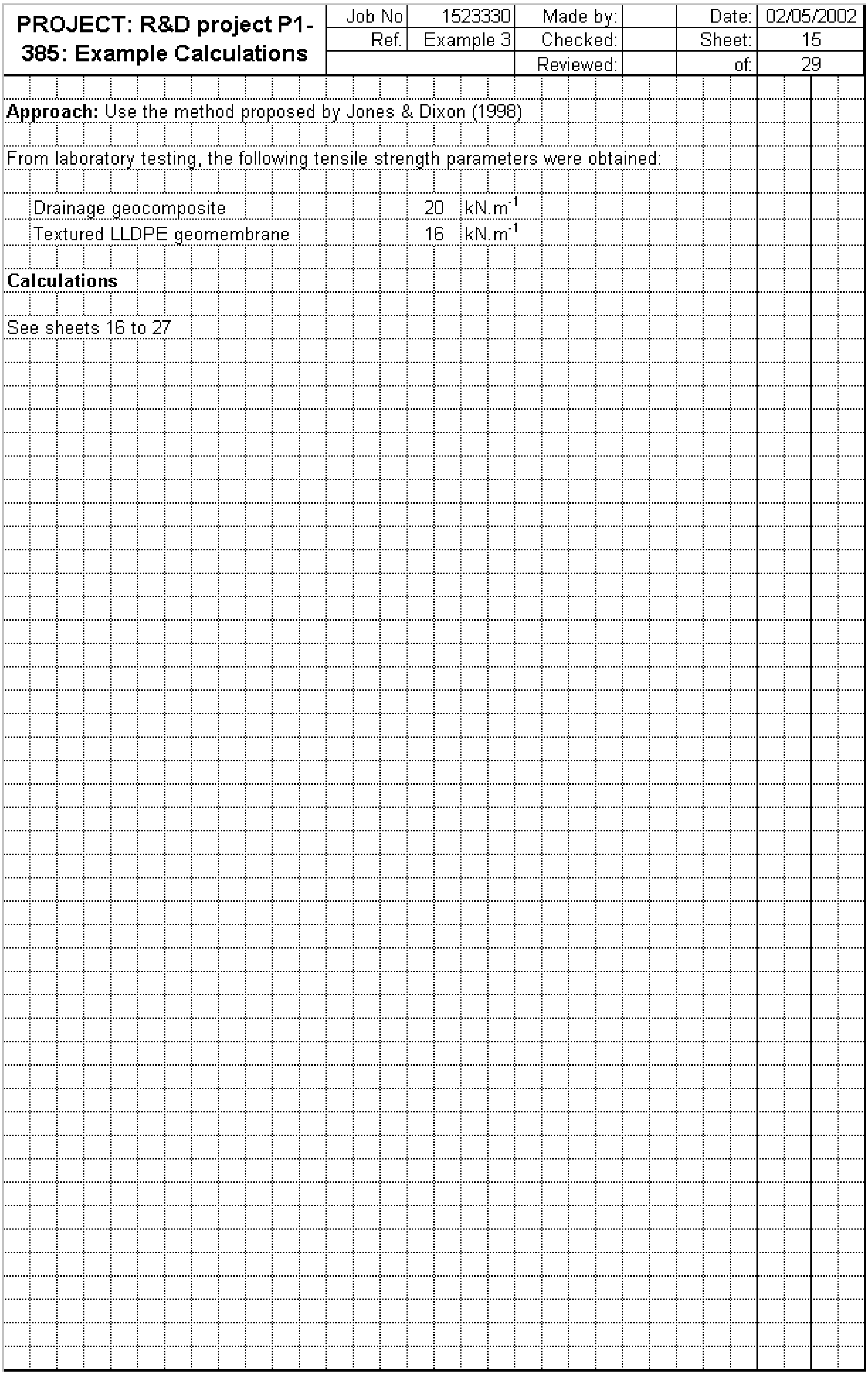
a) Compressible waste

The multi-axial performance of the LLDPE geomembrane is better than HDPE geomembrane, and is considered to be suitable for the proposed capping system. **OK**

b) Slope deformation

Aim: Assess the integrity of the geosynthetic materials.

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	15
			Reviewed:		of:	29

Approach: Use the method proposed by Jones & Dixon (1998)

From laboratory testing, the following tensile strength parameters were obtained:

Drainage geocomposite	20	kN.m^{-1}
Textured LLDPE geomembrane	16	kN.m^{-1}

Calculations

See sheets 16 to 27

Figure 4.15 Calculations for Example 3 continued

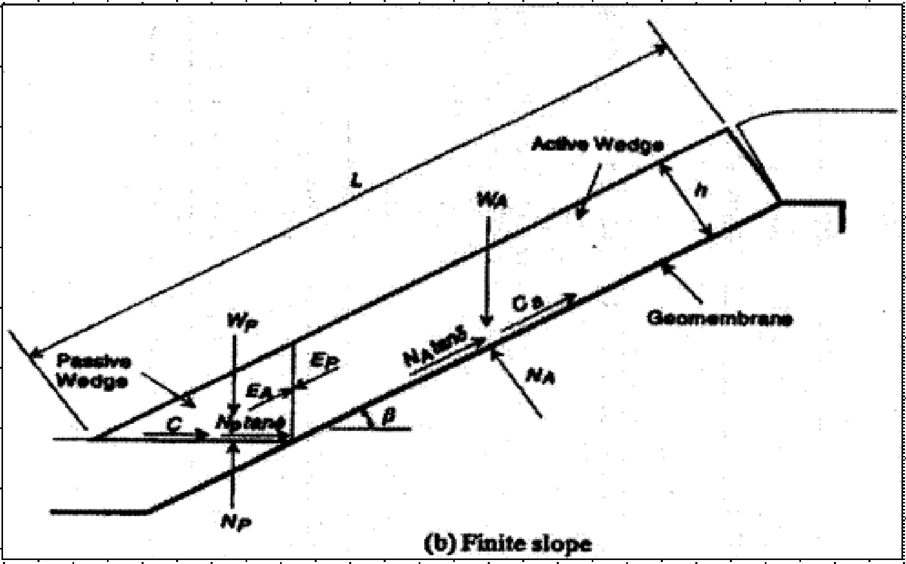
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	16
			Reviewed:		of:	29

Integrity of geosynthetic capping system

Aim: To assess the integrity of the geosynthetic capping system (PSR = 0, peak strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

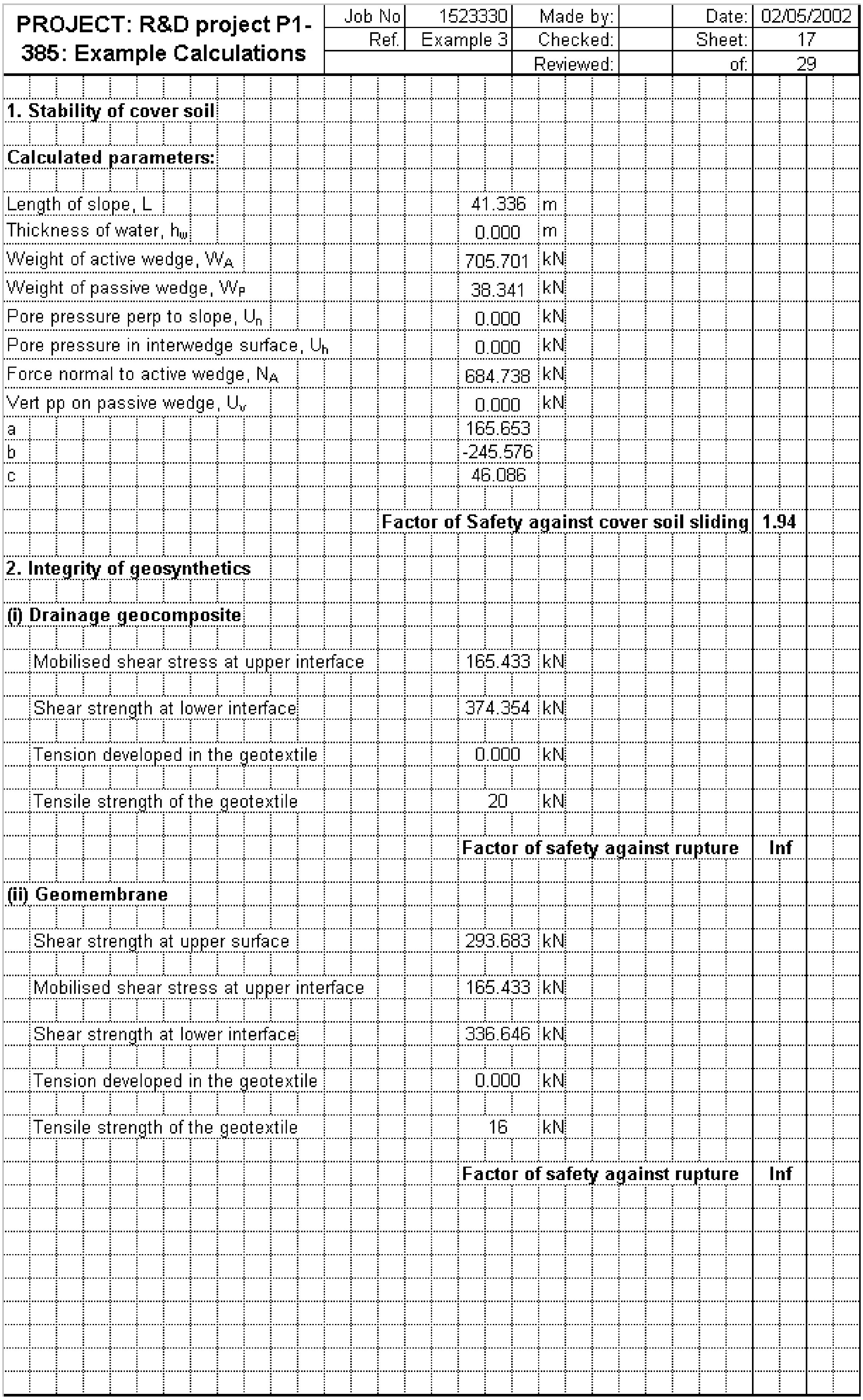


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	24	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	22	
Geocomposite/geomembrane cohesion intercept, α_2	2	
Geomembrane/blinding layer friction angle, δ_3	25	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0	
Geosynthetic tensile strengths:		
Geocomposite	20	$kN.m^{-1}$
Geomembrane	16	$kN.m^{-1}$

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	17
			Reviewed:		of:	29

1. Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.000	m
Weight of active wedge, W_A	705.701	kN
Weight of passive wedge, W_P	38.341	kN
Pore pressure perp to slope, U_n	0.000	kN
Pore pressure in interwedge surface, U_h	0.000	kN
Force normal to active wedge, N_A	684.738	kN
Vert pp on passive wedge, U_v	0.000	kN
a	165.653	
b	-245.576	
c	46.086	

Factor of Safety against cover soil sliding **1.94**

2. Integrity of geosynthetics

(i) Drainage geocomposite

Mobilised shear stress at upper interface	165.433	kN
Shear strength at lower interface	374.354	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	20	kN

Factor of safety against rupture **Inf**

(ii) Geomembrane

Shear strength at upper surface	293.683	kN
Mobilised shear stress at upper interface	165.433	kN
Shear strength at lower interface	336.646	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	16	kN

Factor of safety against rupture **Inf**

Figure 4.15 Calculations for Example 3 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	18
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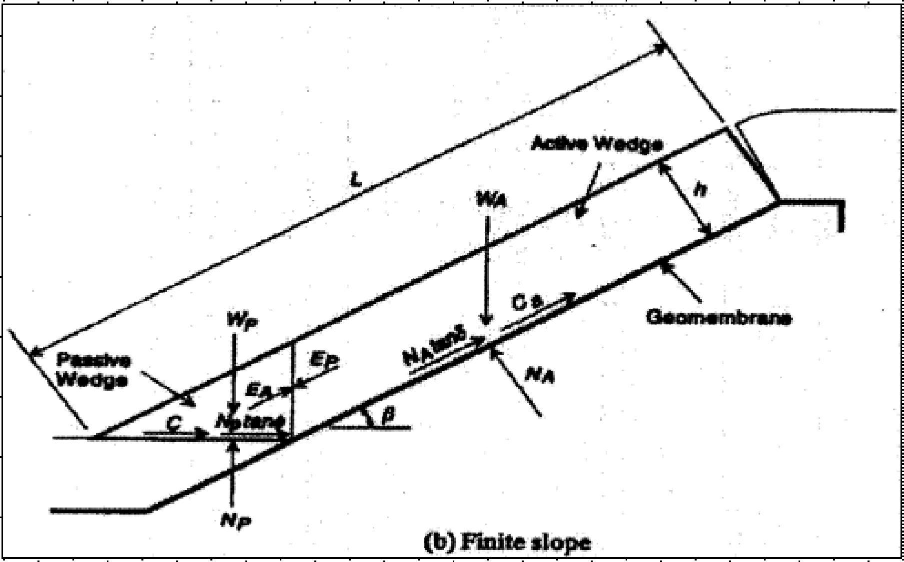
Integrity of geosynthetic capping system

Aim: To assess the integrity of the geosynthetic capping system (PSR = 0.25, peak strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

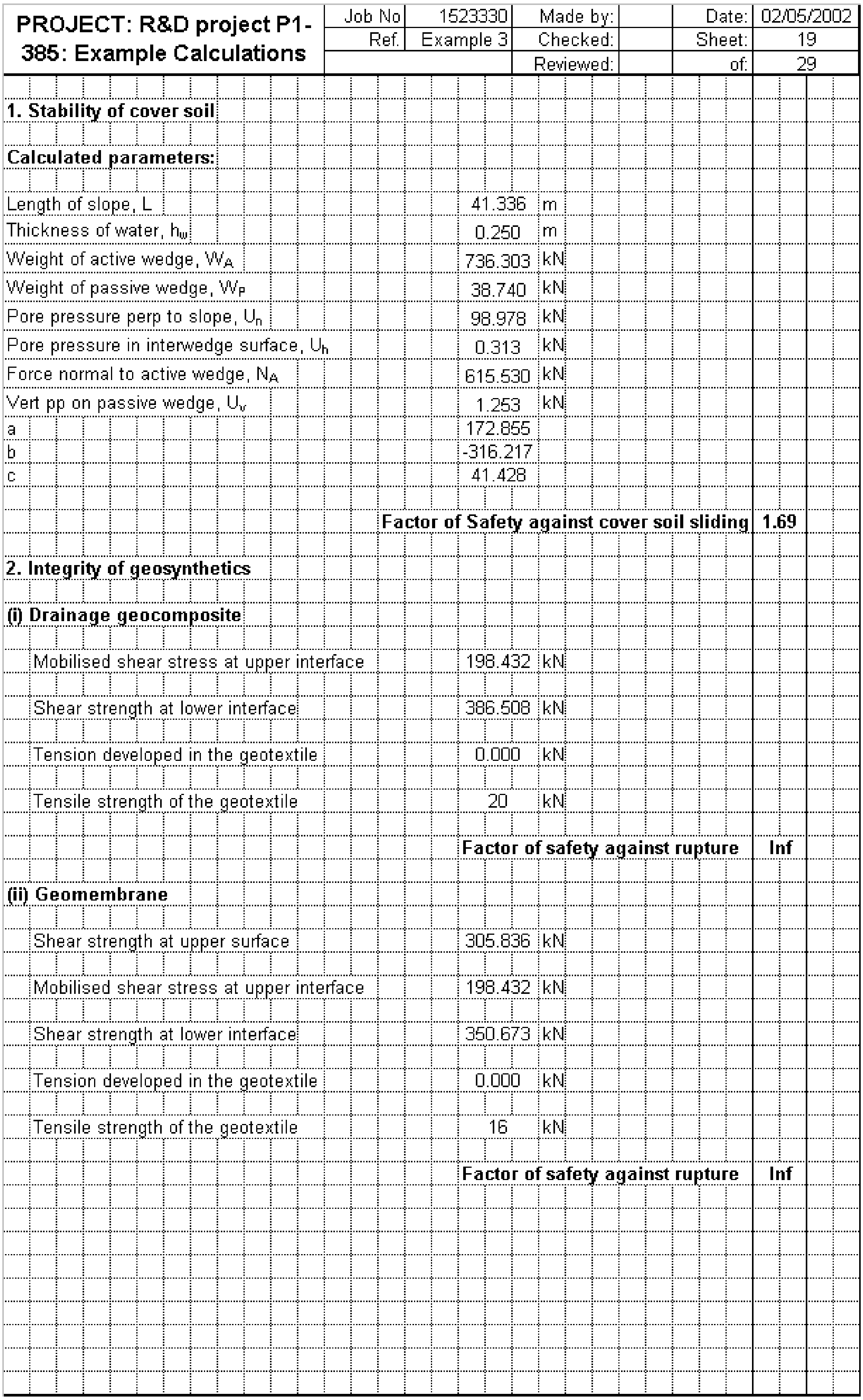


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	24	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	22	
Geocomposite/geomembrane cohesion intercept, α_2	2	
Geomembrane/blinding layer friction angle, δ_3	25	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.25	
Geosynthetic tensile strengths:		
Geocomposite	20	$kN.m^{-1}$
Geomembrane	16	$kN.m^{-1}$

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	19
			Reviewed:		of:	29

1. Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.250	m
Weight of active wedge, W_A	736.303	kN
Weight of passive wedge, W_P	38.740	kN
Pore pressure perp to slope, U_n	98.978	kN
Pore pressure in interwedge surface, U_h	0.313	kN
Force normal to active wedge, N_A	615.530	kN
Vert pp on passive wedge, U_v	1.253	kN
a	172.855	
b	-316.217	
c	41.428	

Factor of Safety against cover soil sliding **1.69**

2. Integrity of geosynthetics

(i) Drainage geocomposite

Mobilised shear stress at upper interface	198.432	kN
Shear strength at lower interface	386.508	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	20	kN

Factor of safety against rupture **Inf**

(ii) Geomembrane

Shear strength at upper surface	305.836	kN
Mobilised shear stress at upper interface	198.432	kN
Shear strength at lower interface	350.673	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	16	kN

Factor of safety against rupture **Inf**

Figure 4.15 Calculations for Example 3 continued

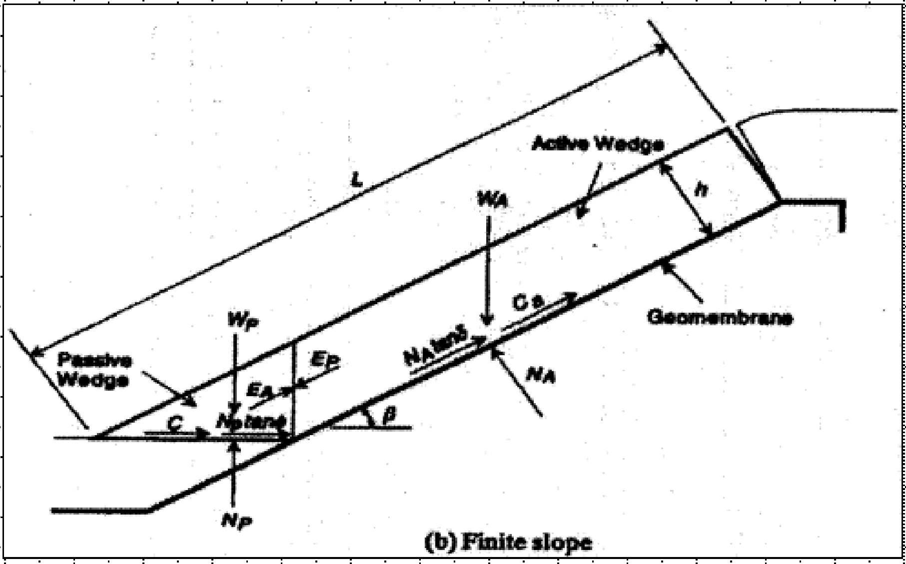
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	20
			Reviewed:		of:	29

Integrity of geosynthetic capping system

Aim: To assess the integrity of the geosynthetic capping system (PSR = 0.5, peak strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

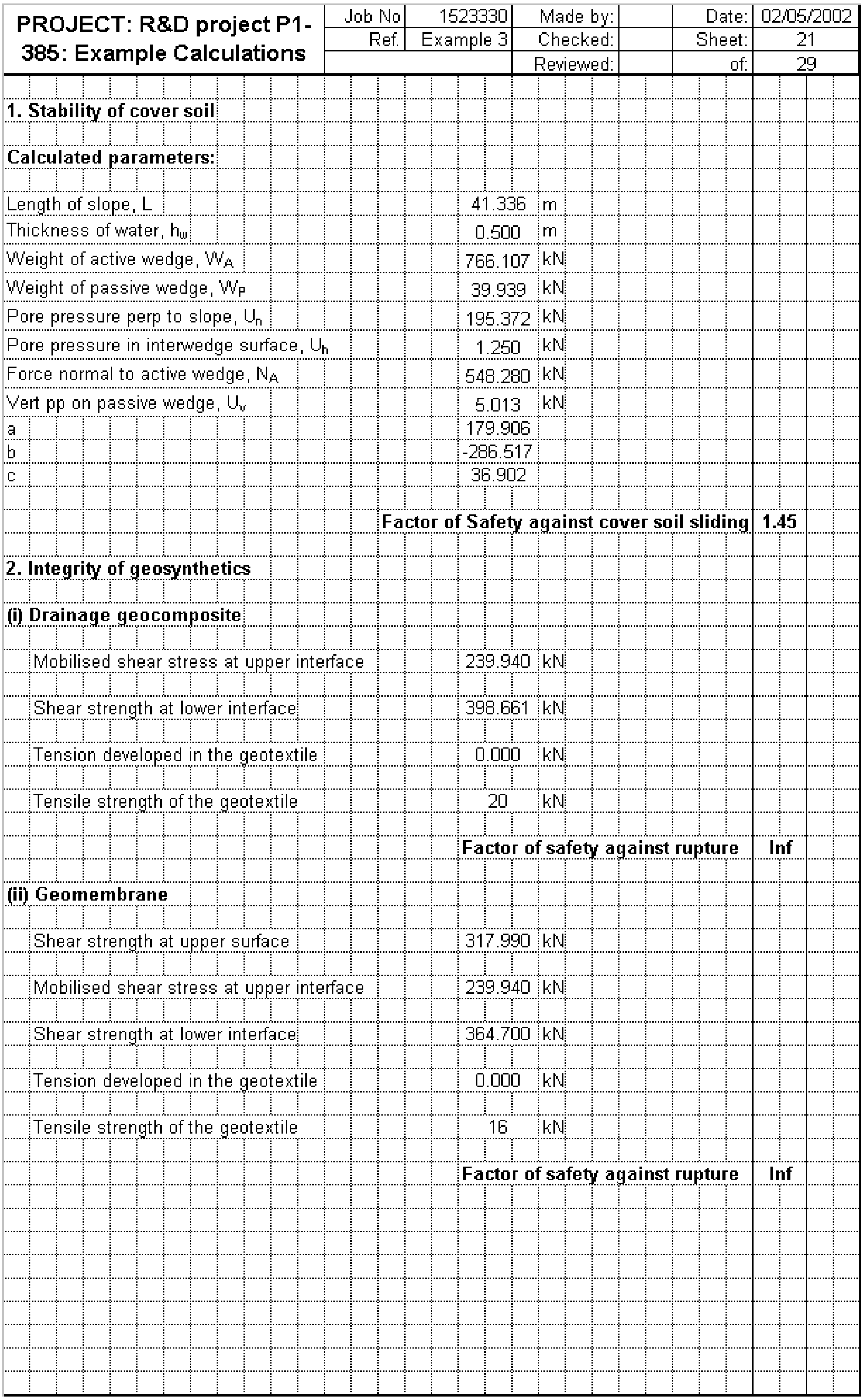
Geometry:



Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	24	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	22	
Geocomposite/geomembrane cohesion intercept, α_2	2	
Geomembrane/blinding layer friction angle, δ_3	25	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.5	
Geosynthetic tensile strengths:		
Geocomposite	20	$kN.m^{-1}$
Geomembrane	16	$kN.m^{-1}$

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	21
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1. Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.500	m
Weight of active wedge, W_A	766.107	kN
Weight of passive wedge, W_P	39.939	kN
Pore pressure perp to slope, U_n	195.372	kN
Pore pressure in interwedge surface, U_h	1.250	kN
Force normal to active wedge, N_A	548.280	kN
Vert pp on passive wedge, U_v	5.013	kN
a	179.906	
b	-286.517	
c	36.902	

Factor of Safety against cover soil sliding **1.45**

2. Integrity of geosynthetics

(i) Drainage geocomposite

Mobilised shear stress at upper interface	239.940	kN
Shear strength at lower interface	398.661	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	20	kN

Factor of safety against rupture **Inf**

(ii) Geomembrane

Shear strength at upper surface	317.990	kN
Mobilised shear stress at upper interface	239.940	kN
Shear strength at lower interface	364.700	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	16	kN

Factor of safety against rupture **Inf**

Figure 4.15 Calculations for Example 3 continued

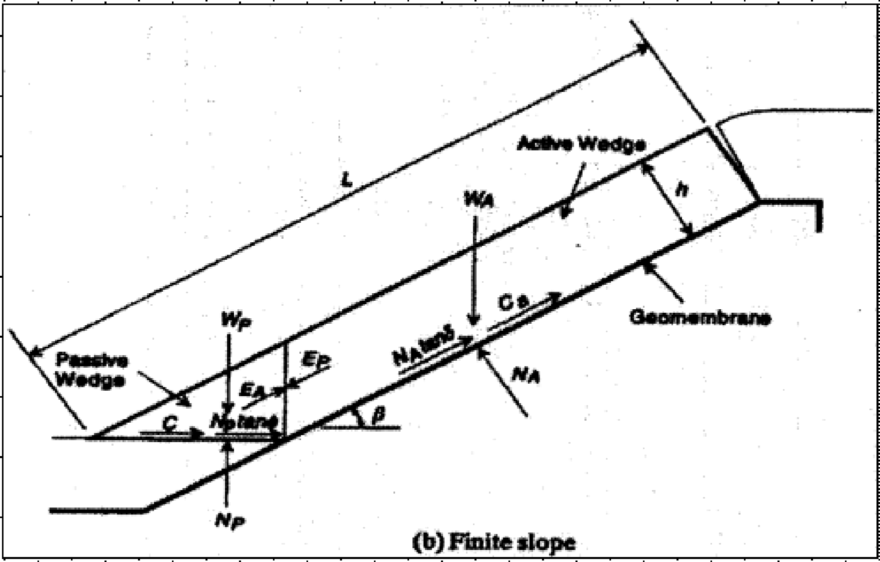
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	22
			Reviewed:		of:	29

Integrity of geosynthetic capping system

Aim: To assess the integrity of the geosynthetic capping system (PSR = 0, residual strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

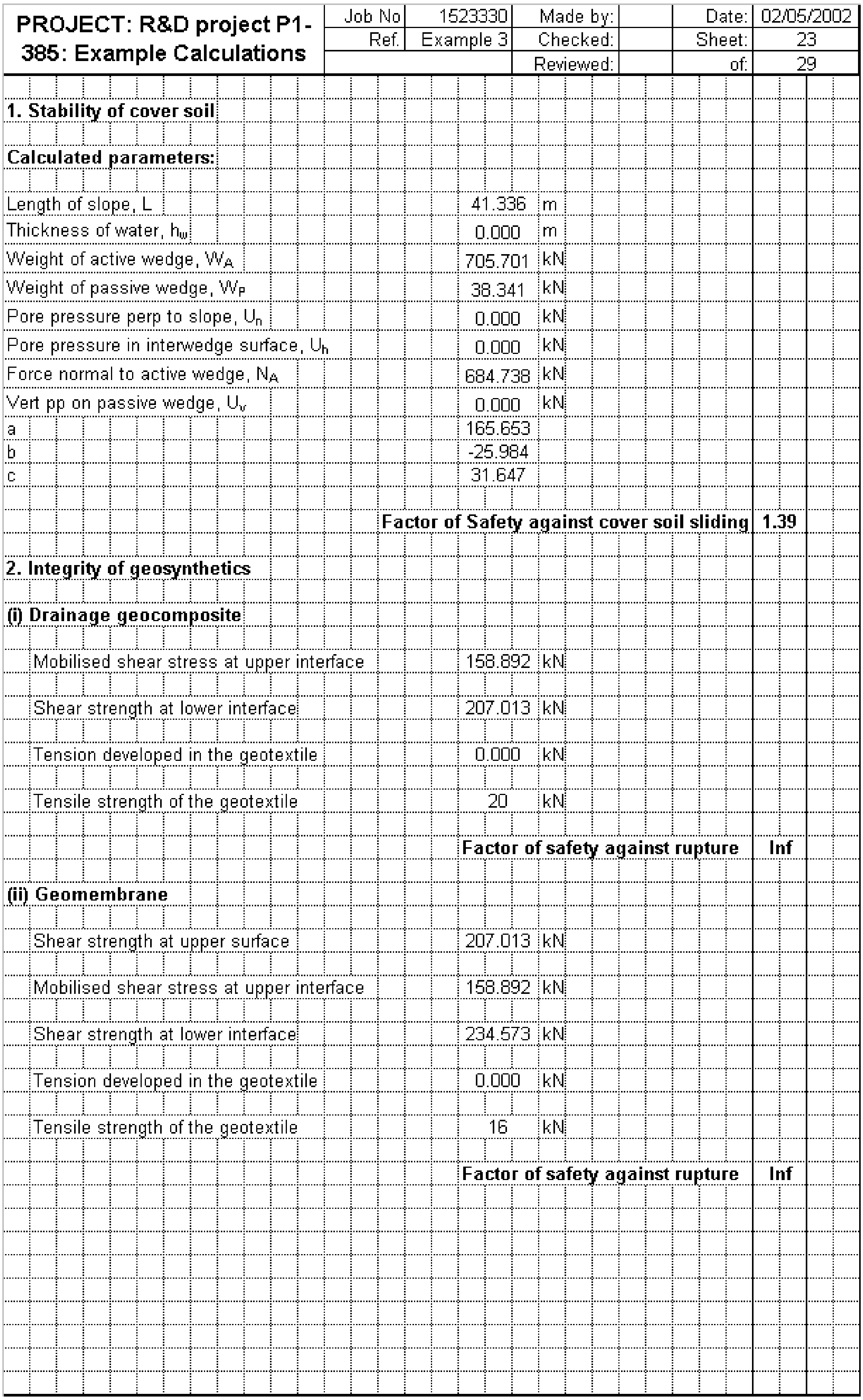
Geometry:



Input Parameters:

Cover soil unit weight (dry), γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated), γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	17	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	16	
Geocomposite/geomembrane cohesion intercept, α_2	0	
Geomembrane/blinding layer friction angle, δ_3	18	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0	
Geosynthetic tensile strengths:		
Geocomposite	20	$kN.m^{-1}$
Geomembrane	16	$kN.m^{-1}$

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	23
			Reviewed:		of:	29

1. Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.000	m
Weight of active wedge, W_A	705.701	kN
Weight of passive wedge, W_P	38.341	kN
Pore pressure perp to slope, U_n	0.000	kN
Pore pressure in interwedge surface, U_h	0.000	kN
Force normal to active wedge, N_A	684.738	kN
Vert pp on passive wedge, U_v	0.000	kN
a	165.653	
b	-25.984	
c	31.647	

Factor of Safety against cover soil sliding **1.39**

2. Integrity of geosynthetics

(i) Drainage geocomposite

Mobilised shear stress at upper interface	158.892	kN
Shear strength at lower interface	207.013	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	20	kN

Factor of safety against rupture **Inf**

(ii) Geomembrane

Shear strength at upper surface	207.013	kN
Mobilised shear stress at upper interface	158.892	kN
Shear strength at lower interface	234.573	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	16	kN

Factor of safety against rupture **Inf**

Figure 4.15 Calculations for Example 3 continued

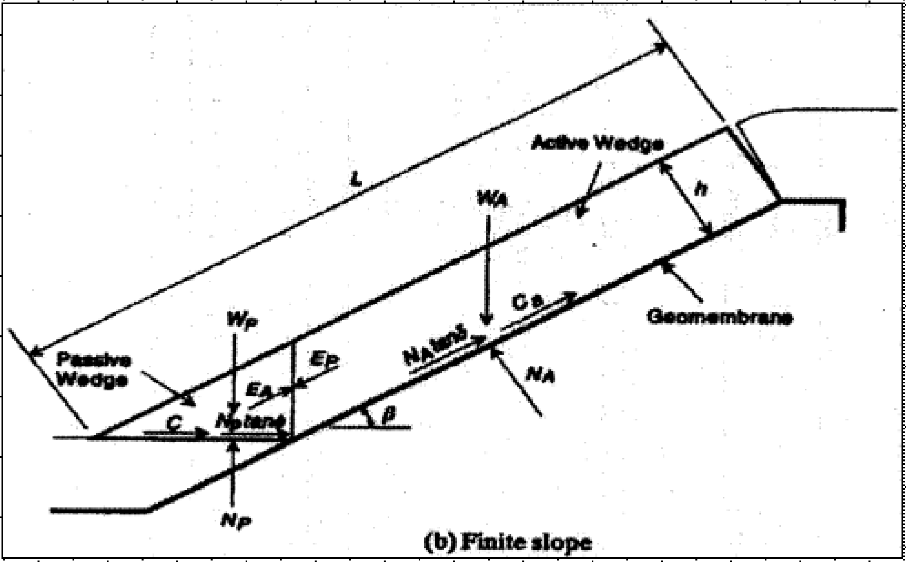
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	24
			Reviewed:		of:	29

Integrity of geosynthetic capping system

Aim: To assess the integrity of the geosynthetic capping system (PSR = 0.25, residual strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

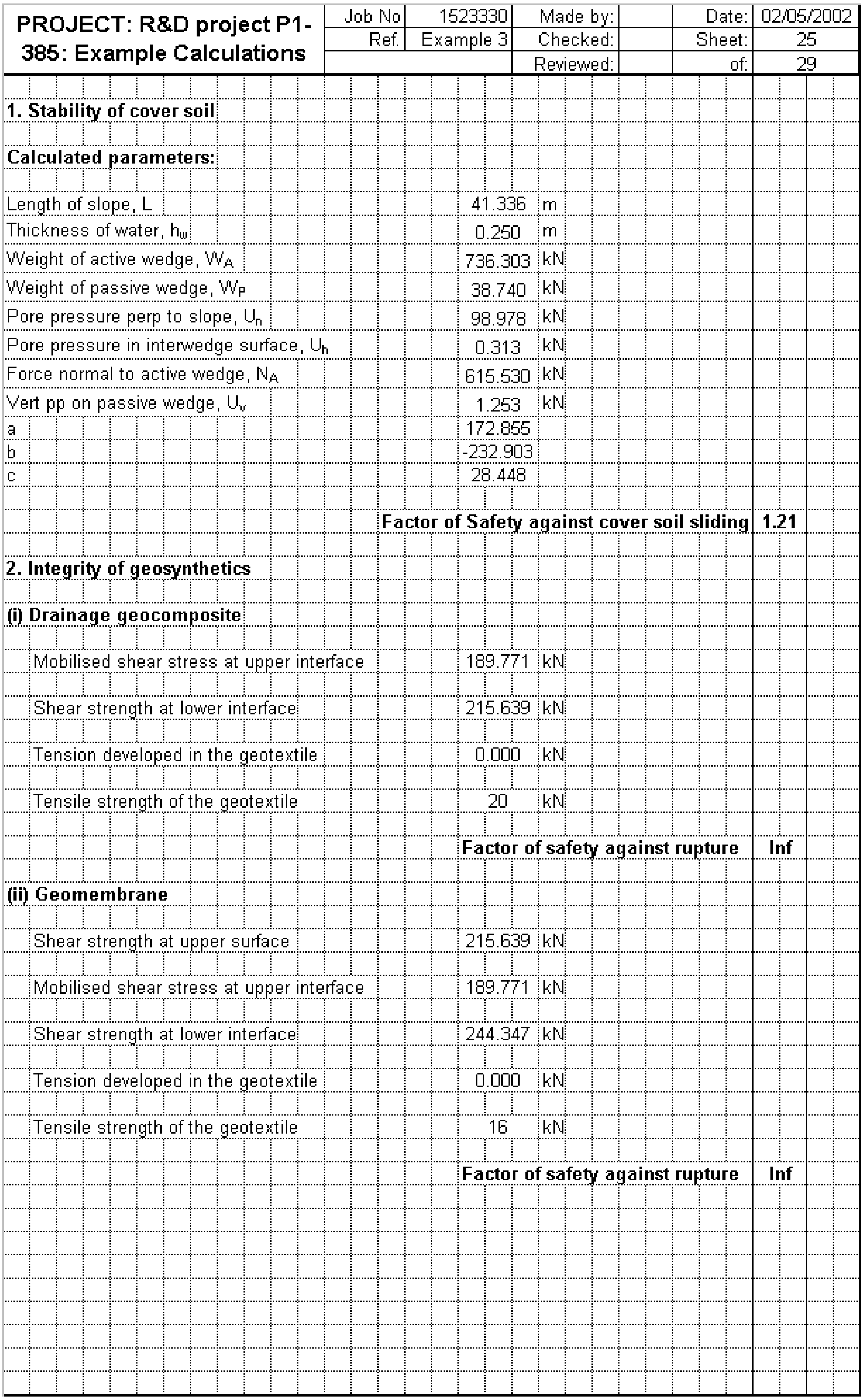


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	17	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	16	
Geocomposite/geomembrane cohesion intercept, α_2	0	
Geomembrane/blinding layer friction angle, δ_3	18	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.25	
Geosynthetic tensile strengths:		
Geocomposite	20	$kN.m^{-1}$
Geomembrane	16	$kN.m^{-1}$

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	25
			Reviewed:		of:	29

1. Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.250	m
Weight of active wedge, W_A	736.303	kN
Weight of passive wedge, W_P	38.740	kN
Pore pressure perp to slope, U_n	98.978	kN
Pore pressure in interwedge surface, U_h	0.313	kN
Force normal to active wedge, N_A	615.530	kN
Vert pp on passive wedge, U_v	1.253	kN
a	172.855	
b	-232.903	
c	28.448	

Factor of Safety against cover soil sliding **1.21**

2. Integrity of geosynthetics

(i) Drainage geocomposite

Mobilised shear stress at upper interface	189.771	kN
Shear strength at lower interface	215.639	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	20	kN

Factor of safety against rupture **Inf**

(ii) Geomembrane

Shear strength at upper surface	215.639	kN
Mobilised shear stress at upper interface	189.771	kN
Shear strength at lower interface	244.347	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	16	kN

Factor of safety against rupture **Inf**

Figure 4.15 Calculations for Example 3 continued

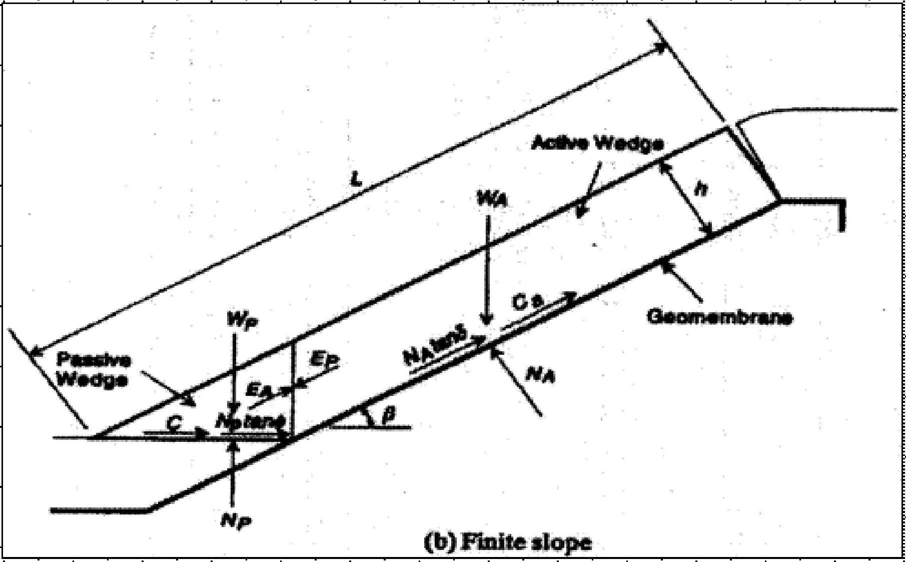
PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	26
			Reviewed:		of:	29

Integrity of geosynthetic capping system

Aim: To assess the integrity of the geosynthetic capping system (PSR = 0.5, residual strengths)

Approach: Use the approach proposed by Jones & Dixon (1998).

Geometry:

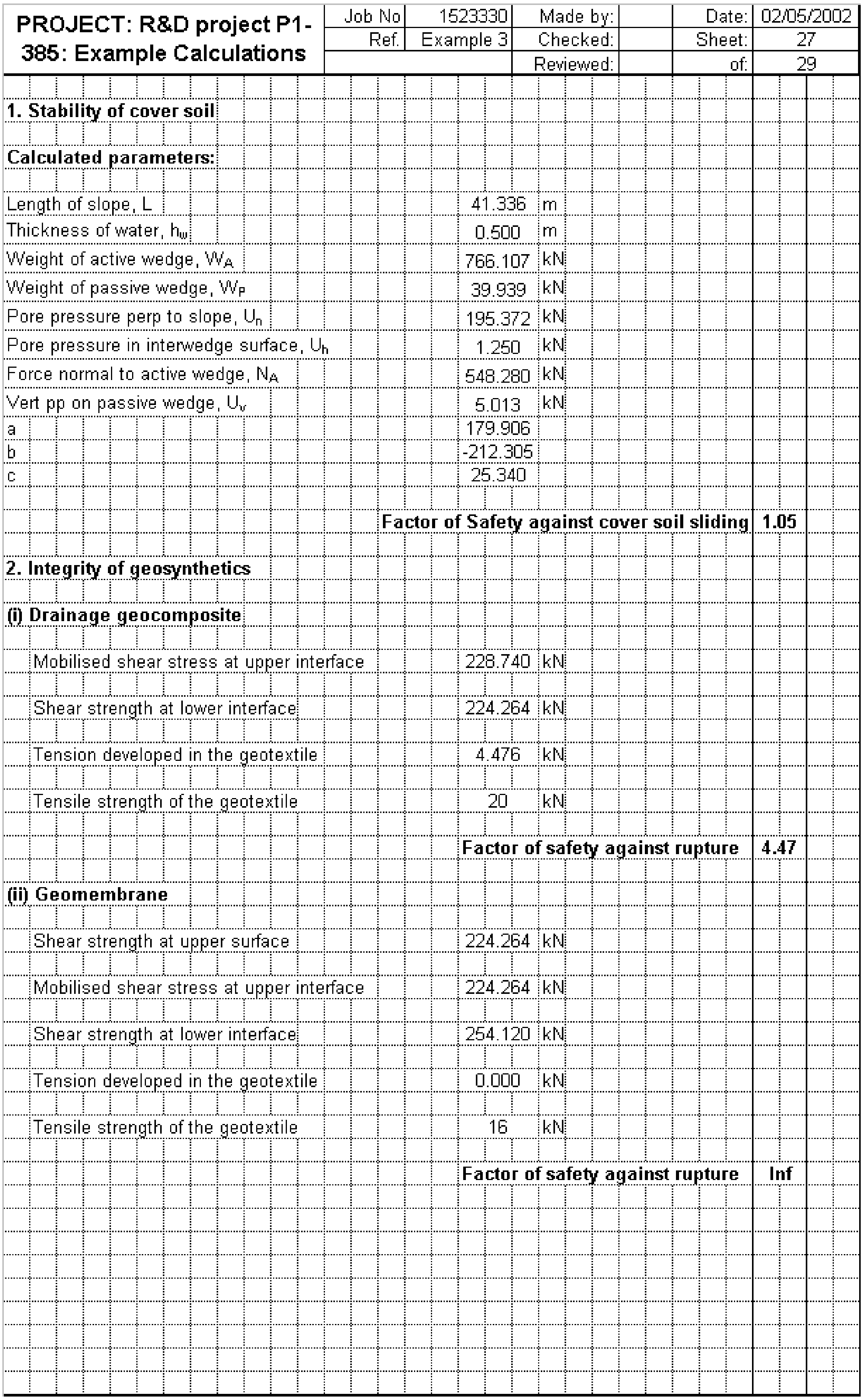


(b) Finite slope

Input Parameters:

Cover soil unit weight (dry). γ_{dry}	18	$kN.m^{-3}$
Cover soil unit weight (saturated). γ_{sat}	21	$kN.m^{-3}$
Cover soil internal shear strength, Φ	32	Deg.
Cover soil cohesion, c	0	kPa
Thickness of cover soil, h	1.00	m
Height of slope, H	10	m
Slope angle, β	14.0	Deg.
Geosynthetic interface shear strengths:		
Cover soil/geocomposite friction angle, δ_1	17	
Cover soil/geocomposite cohesion intercept, α_1	0	
Geocomposite/geomembrane friction angle, δ_2	16	
Geocomposite/geomembrane cohesion intercept, α_2	0	
Geomembrane/blinding layer friction angle, δ_3	18	
Geomembrane/blinding layer cohesion intercept, α_3	0	
Parallel submergence ratio, PSR	0.5	
Geosynthetic tensile strengths:		
Geocomposite	20	$kN.m^{-1}$
Geomembrane	16	$kN.m^{-1}$

Figure 4.15 Calculations for Example 3 continued



PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
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1. Stability of cover soil

Calculated parameters:

Length of slope, L	41.336	m
Thickness of water, h_w	0.500	m
Weight of active wedge, W_A	766.107	kN
Weight of passive wedge, W_P	39.939	kN
Pore pressure perp to slope, U_n	195.372	kN
Pore pressure in interwedge surface, U_h	1.250	kN
Force normal to active wedge, N_A	548.280	kN
Vert pp on passive wedge, U_v	5.013	kN
a	179.906	
b	-212.305	
c	25.340	

Factor of Safety against cover soil sliding **1.05**

2. Integrity of geosynthetics

(i) Drainage geocomposite

Mobilised shear stress at upper interface	228.740	kN
Shear strength at lower interface	224.264	kN
Tension developed in the geotextile	4.476	kN
Tensile strength of the geotextile	20	kN

Factor of safety against rupture **4.47**

(ii) Geomembrane

Shear strength at upper surface	224.264	kN
Mobilised shear stress at upper interface	224.264	kN
Shear strength at lower interface	254.120	kN
Tension developed in the geotextile	0.000	kN
Tensile strength of the geotextile	16	kN

Factor of safety against rupture **Inf**

Figure 4.15 Calculations for Example 3 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:	Date:	02/05/2002
	Ref.	Example 3	Checked:	Sheet:	28
			Reviewed:	of:	29

Results:

Using peak strengths

	F of S against geocomposite rupture	F of S against geomembrane rupture
Dry	Infinite	Infinite
PSR = 0.25	Infinite	Infinite
PSR = 0.5	Infinite	Infinite

Using residual strengths

	F of S against geocomposite rupture	F of S against geomembrane rupture
Dry	Infinite	Infinite
PSR = 0.25	Infinite	Infinite
PSR = 0.5	4.47	Infinite

Conclusions:

Since all the factors of safety > 1.5, it is considered that the integrity of the geosynthetic materials is considered satisfactory. **OK**

c) Cavities in waste

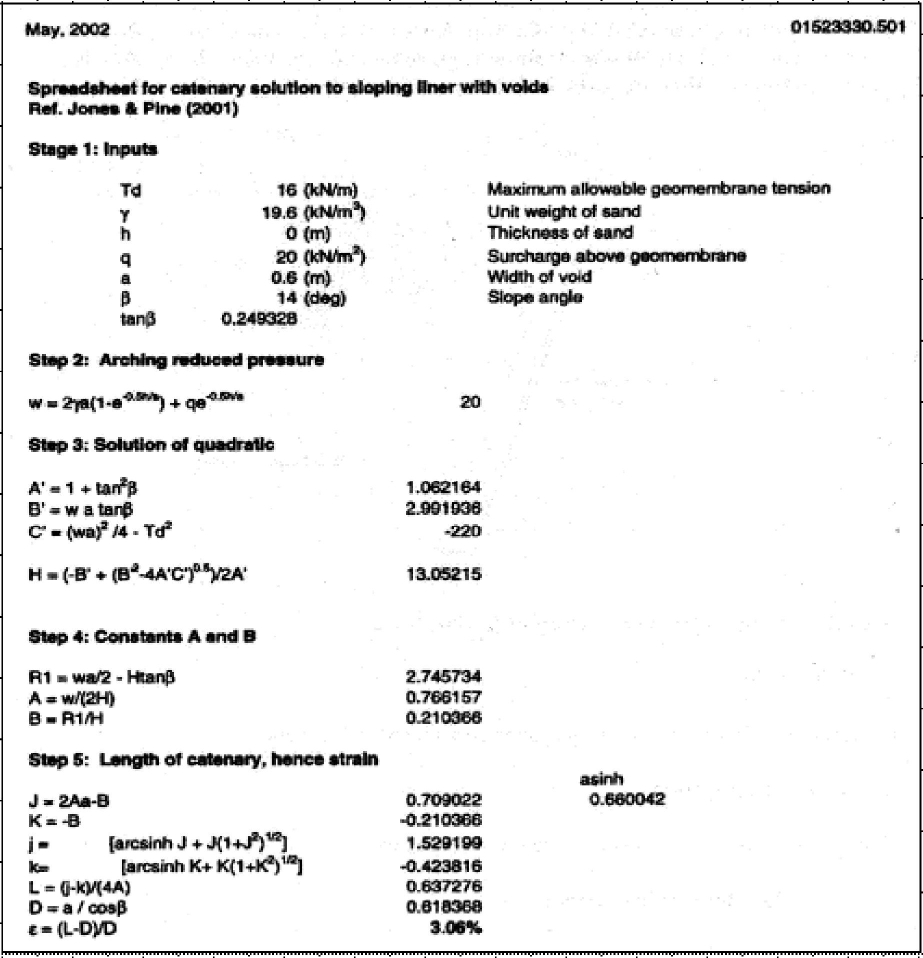
The development of a cavity directly beneath the lining system must not cause excessive strain in the LLDPE geomembrane. The design of a reinforced soil layer to span over the potential void can be carried out based on the method proposed by Jones & Pine (2001).

For a 1m layer of topsoil and sub-soils the applied load on the geomembrane is 20 kN.m^{-1}.

Figure 4.15 Calculations for Example 3 continued

PROJECT: R&D project P1-385: Example Calculations	Job No	1523330	Made by:		Date:	02/05/2002
	Ref.	Example 3	Checked:		Sheet:	29
			Reviewed:		of:	29

Calculations:



May, 2002

01523330.501

Spreadsheet for catenary solution to sloping liner with voids
Ref. Jones & Pine (2001)

Stage 1: Inputs

Td	16 (kN/m)	Maximum allowable geomembrane tension
γ	19.6 (kN/m^3)	Unit weight of sand
h	0 (m)	Thickness of sand
q	20 (kN/m^2)	Surcharge above geomembrane
a	0.6 (m)	Width of void
β	14 (deg)	Slope angle
$\tan\beta$	0.249328	

Step 2: Arching reduced pressure

$w = 2\gamma a(1-e^{-0.5h/a}) + qe^{-0.5h/a}$ 20

Step 3: Solution of quadratic

$A' = 1 + \tan^2\beta$ 1.062164
$B' = w\ a \tan\beta$ 2.991936
$C' = (wa)^2/4 - Td^2$ -220

$H = (-B' + (B'^2-4A'C')^{0.5})/2A'$ 13.05215

Step 4: Constants A and B

$R1 = wa/2 - H\tan\beta$ 2.745734
$A = w/(2H)$ 0.766157
$B = R1/H$ 0.210366

Step 5: Length of catenary, hence strain

		asinh
$J = 2Aa-B$	0.709022	0.660042
$K = -B$	-0.210366	
$j =$ [arcsinh $J + J(1+J^2)^{1/2}$]	1.529199	
$k =$ [arcsinh $K + K(1+K^2)^{1/2}$]	-0.423816	
$L = (j-k)/(4A)$	0.637276	
$D = a/\cos\beta$	0.618368	
$\varepsilon = (L-D)/D$	**3.06%**	

Results:

From the above calculations, using a tensile strength of 16 kN.m^{-1} for the LLDPE geomembrane, the maximum strain in the geomembrane is 3.06%.

This is considered satisfactory. **OK**

Figure 4.15 Calculations for Example 3 continued

4.4 Example 4: Self-Supporting Steep Slope Lining System

4.4.1 Description

The site is a former hard rock quarry with steep (65°) side slopes. A steep side slope lining system has been designed such that the liner is self-supporting and its subgrade is unyielding. The landfill will be 30 m high and the lining system will be constructed in a series of 5m lifts. The lining system comprises (from the top down) 500 mm thick sand protection layer, drainage geocomposite, HDPE geomembrane, geosynthetic clay liner, sub-grade. The design flow chart and calculations are given in Section 4.4.5 below.

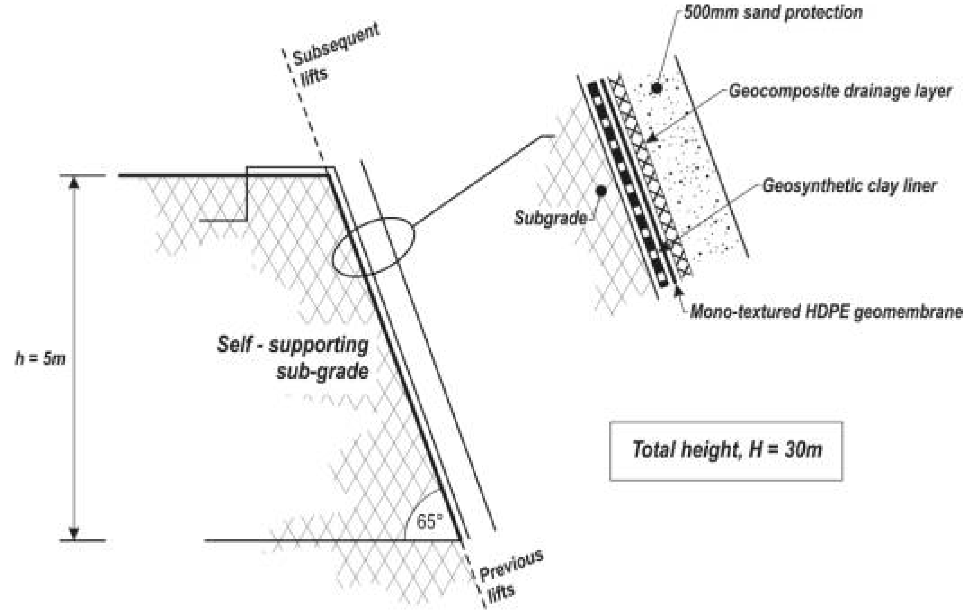


Figure 4.16 Schematic Cross Section of Example 4

4.4.2 Sub-grade

From the site investigation, the sub-grade is considered to be stable.

4.4.3 Basal lining system

The basal lining system is not considered in this example.

4.4.4 Steep side slope lining system

The steep side slope lining system design cases to be considered are highlighted in Figure 4.17.

Self-Supporting

Unconfined – Stability

Design issues:

- stability of sub-grade;
- stability of liner support system;
- stability of liner;
- stability of drainage layer.

Both the sub-grade and the liner support system are stable. The geosynthetic elements (geocomposite, geomembrane and GCL) are anchored at each bench level and are therefore stable. Note that the geocomposite is only fixed during the filling of each 5 m lift, and will then be un-anchored prior to the construction of the subsequent 5 m lift since it is designed to move as the waste settles.

The sand protection layer will need to be placed ahead of waste placement since it will not stand unsupported on the 65° slope.

Unconfined – Integrity

Design issues:

- control of stresses in liner to prevent increased permeability.

Prior to waste placement the only stresses acting on the lining system components will be self weight; this should be compared with the tensile strength of each geosynthetic.

Confined – Stability

Design issues:

- stability of liner.

Since the waste will be placed in horizontal layers for the full width of the cell, the lining system will be stable. Sufficient sand should be placed to prevent a reduction in protection layer thickness due to sand slumping into the waste.

Confined – Integrity

Design issues:

- control of stresses in liner to prevent increased permeability;
- disruption of drainage/protection layers.

The geocomposite material will be placed on top of the smooth face of the geomembrane and is designed to slide past the geomembrane as the waste settles. The amount of slippage at this interface depends on the shear strength at the interface, the geometry of the slope and the engineering properties of the waste. An assessment of the slippage can be carried out using the finite difference code FLAC.

A mono-textured geomembrane with the smooth surface upwards can be used to minimise stress transfer into the geomembrane. An assessment of the stresses induced through the geosynthetic layers is carried out to establish the integrity of each component.

In the assessment of the GCL consideration needs to be given to the possibility of bentonite extrusion through the geotextile; this is of particular concern when a woven geotextile is used. The shear strength of the interface that suffers bentonite extrusion is dramatically reduced and the effect of this should be investigated.

4.4.5 Design flow chart and calculations

See Figures 4.17 and 4.18

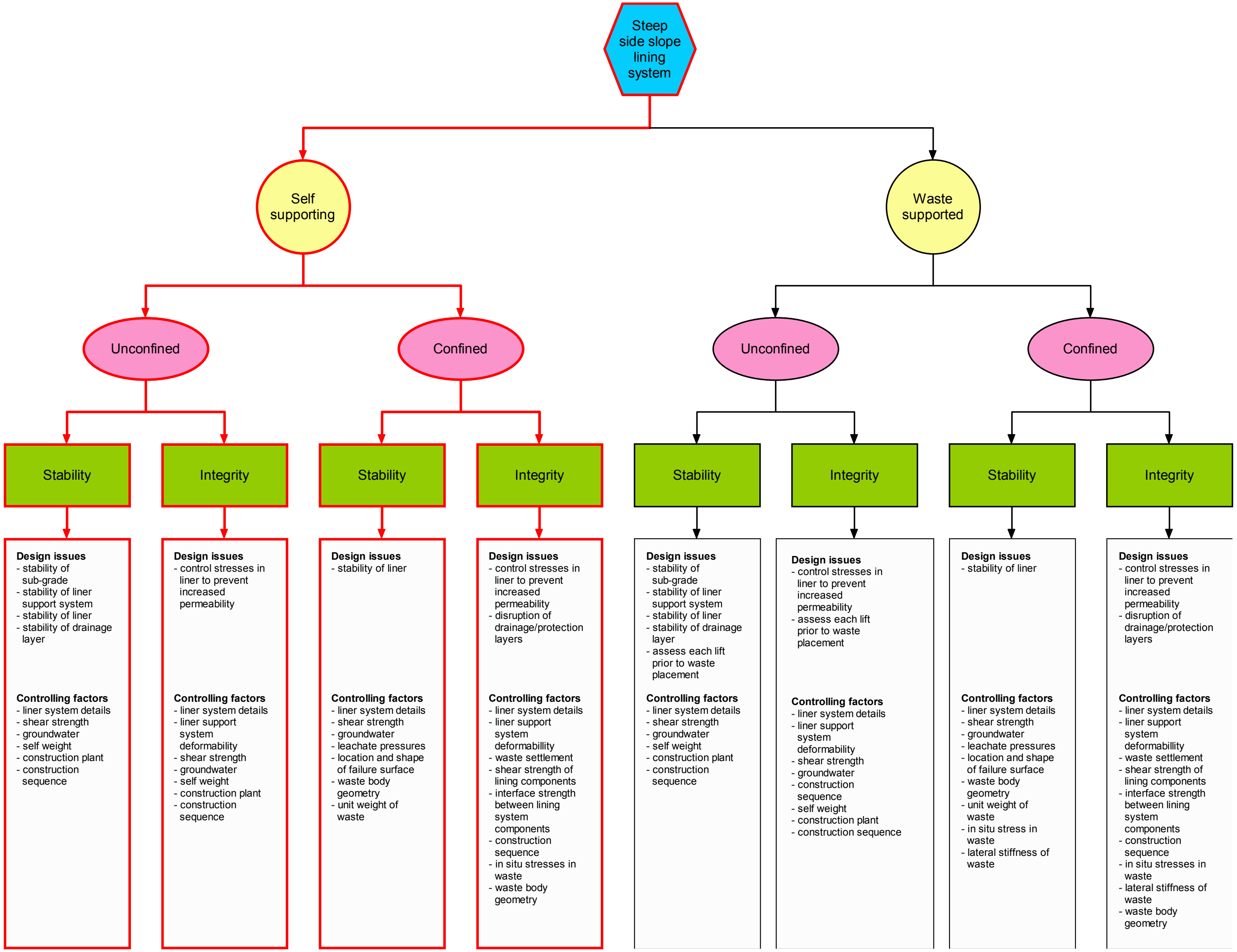


Figure 4.17 Design Flow Chart for Example 4: Steep Side Slope Lining System

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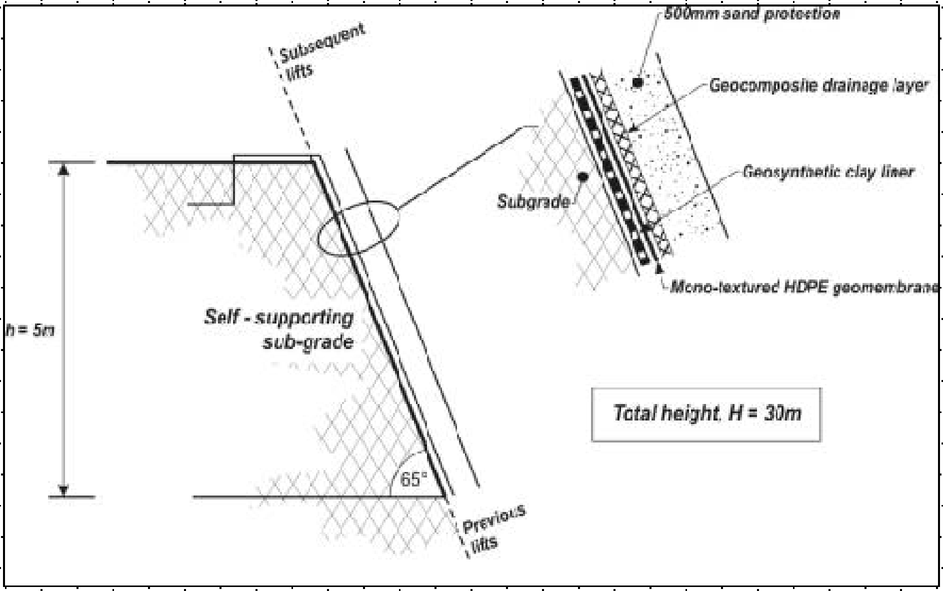
	Ref.	Example 4	Checked:		Sheet:	1
			Reviewed:		of:	9

DESCRIPTION: Steep slope lining system

GEOMETRY:



1. SUBGRADE

From the site investigation, the sub-grade is considered stable.

2. BASAL LINING SYSTEM

This is not considered in this example.

3. STEEP SIDE SLOPE LINING SYSTEM

3.1 Unconfined

a) Stability

Both the sub-grade and the liner support system are stable and not considered in this example.

The geocomposite, geomembrane, and GCL liners are anchored in at the top of each 5 m lift and are therefore stable.

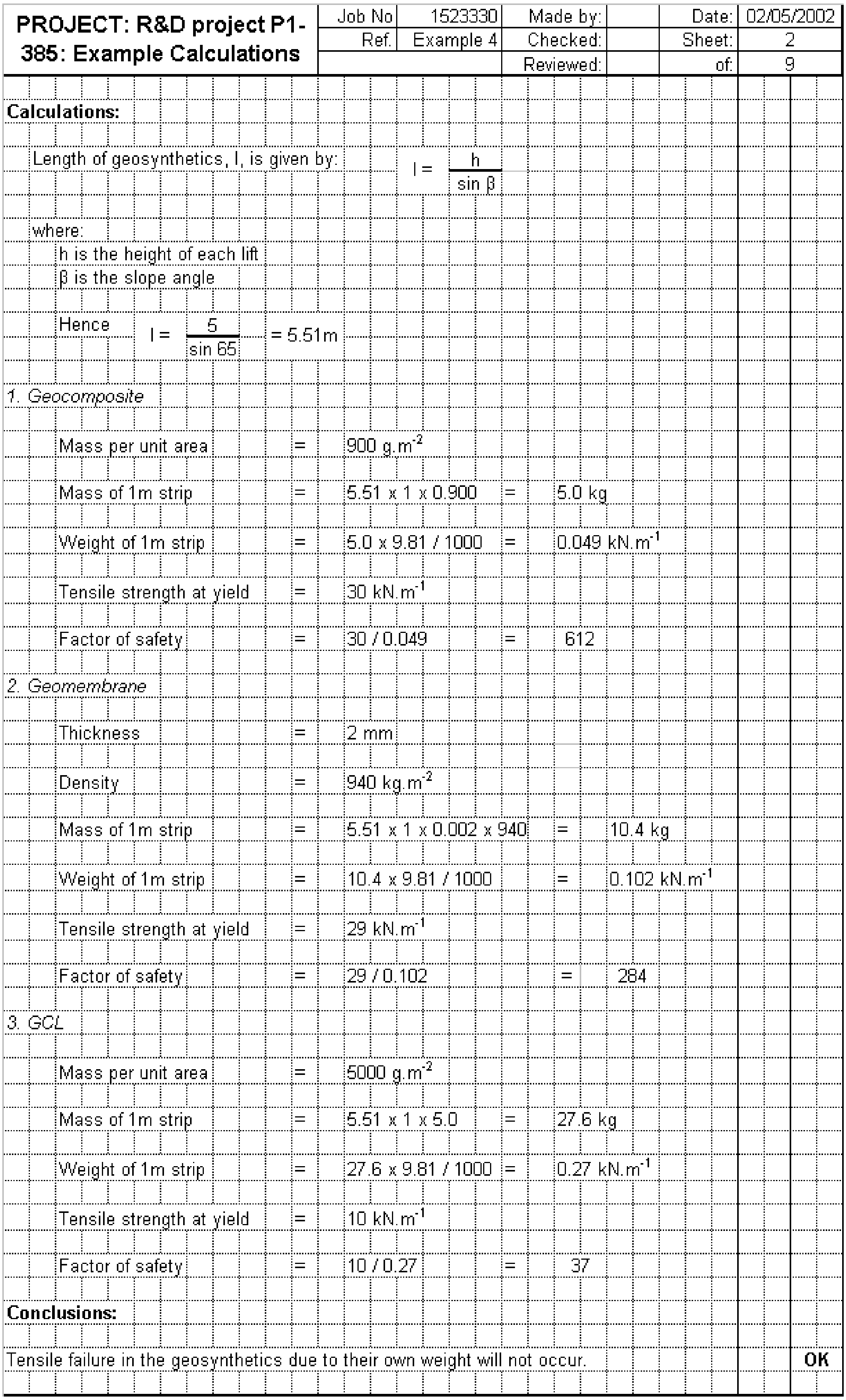
The sand protection layer by inspection will not be stable placed on a slope of 65°. Therefore the sand must be placed in lifts ahead of waste placement to ensure stability.

b) Integrity

Aim: Assess the integrity of the geosynthetics prior to waste placement.

Approach: Calculate the self-weight of each of the geosynthetics and compare with the yield strength of the materials. Assume that the geosynthetics have no frictional support beneath.

Figure 4.18 Calculations for Example 4



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Calculations:

Length of geosynthetics, l, is given by: $l = \frac{h}{\sin \beta}$

where:

h is the height of each lift

β is the slope angle

Hence $l = \frac{5}{\sin 65} = 5.51\text{m}$

1. Geocomposite

Mass per unit area = 900 g.m^{-2}

Mass of 1m strip = 5.51 x 1 x 0.900 = 5.0 kg

Weight of 1m strip = 5.0 x 9.81 / 1000 = 0.049 kN.m^{-1}

Tensile strength at yield = 30 kN.m^{-1}

Factor of safety = 30 / 0.049 = 612

2. Geomembrane

Thickness = 2 mm

Density = 940 kg.m^{-2}

Mass of 1m strip = 5.51 x 1 x 0.002 x 940 = 10.4 kg

Weight of 1m strip = 10.4 x 9.81 / 1000 = 0.102 kN.m^{-1}

Tensile strength at yield = 29 kN.m^{-1}

Factor of safety = 29 / 0.102 = 284

3. GCL

Mass per unit area = 5000 g.m^{-2}

Mass of 1m strip = 5.51 x 1 x 5.0 = 27.6 kg

Weight of 1m strip = 27.6 x 9.81 / 1000 = 0.27 kN.m^{-1}

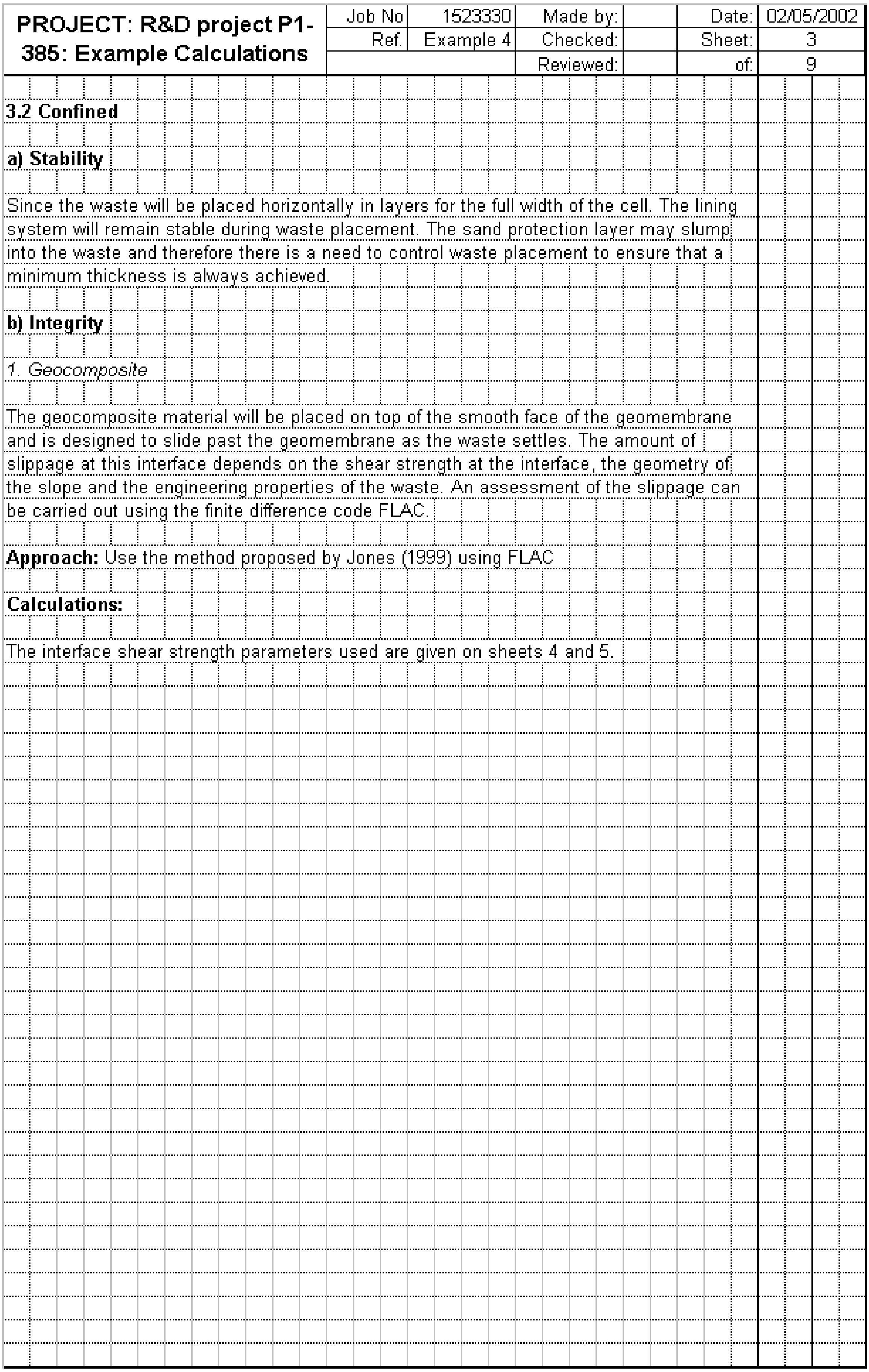
Tensile strength at yield = 10 kN.m^{-1}

Factor of safety = 10 / 0.27 = 37

Conclusions:

Tensile failure in the geosynthetics due to their own weight will not occur. **OK**

Figure 4.18 Calculations for Example 4 continued



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3.2 Confined

a) Stability

Since the waste will be placed horizontally in layers for the full width of the cell. The lining system will remain stable during waste placement. The sand protection layer may slump into the waste and therefore there is a need to control waste placement to ensure that a minimum thickness is always achieved.

b) Integrity

1. Geocomposite

The geocomposite material will be placed on top of the smooth face of the geomembrane and is designed to slide past the geomembrane as the waste settles. The amount of slippage at this interface depends on the shear strength at the interface, the geometry of the slope and the engineering properties of the waste. An assessment of the slippage can be carried out using the finite difference code FLAC.

Approach: Use the method proposed by Jones (1999) using FLAC

Calculations:

The interface shear strength parameters used are given on sheets 4 and 5.

Figure 4.18 Calculations for Example 4 continued

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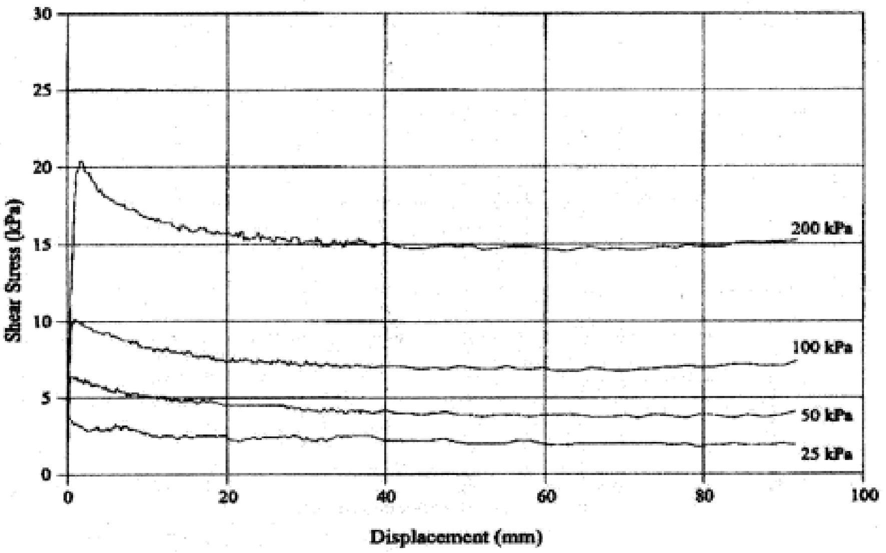
Interface shear strength distribution used for smooth geomembrane/ geotextile interface along slope

(a) Shear Stress vs. Displacement



(b) Shear Stress vs. Normal Stress

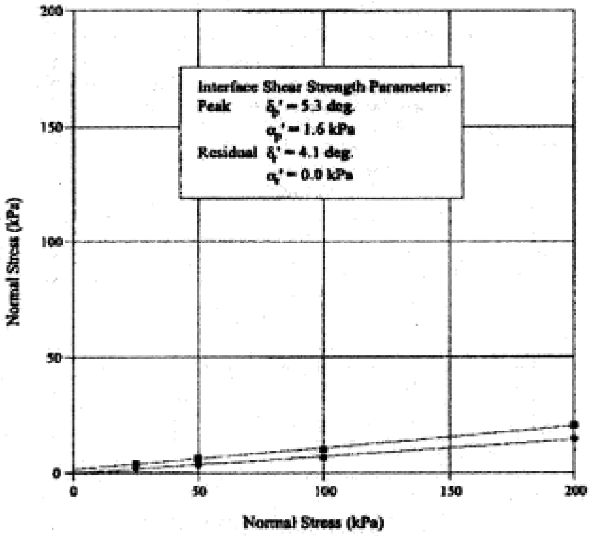


Figure 4.18 Calculations for Example 4 continued

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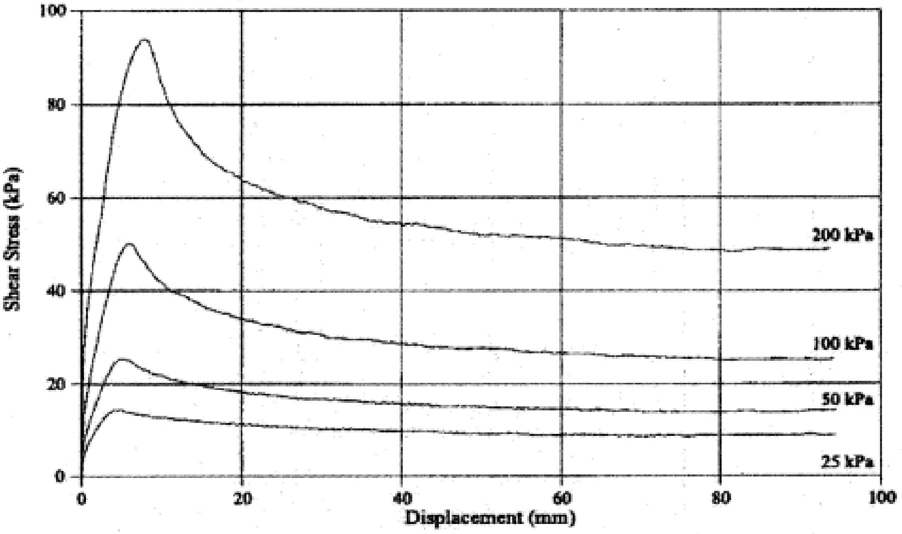
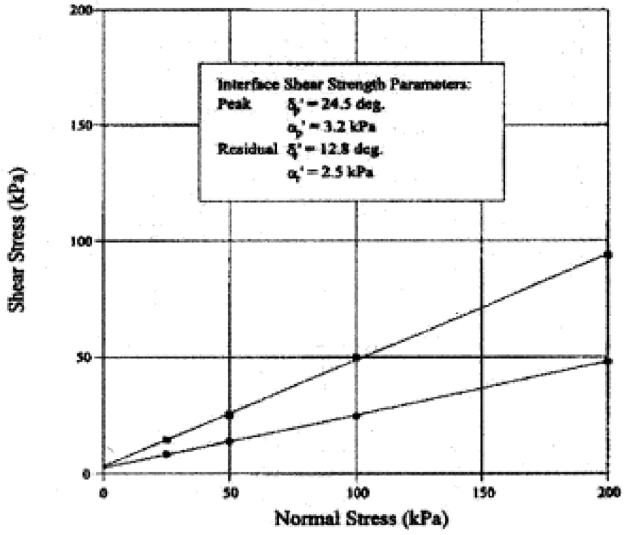
Interface shear strength distribution used for textured geomembrane/ geotextile interface on base

(a) Shear Stress vs. Displacement



(b) Shear Stress vs. Normal Stress



Engineering properties of the waste have been chosen to produce a long-term settlement equal to 20% of the thickness.

Figure 4.18 Calculations for Example 4 continued

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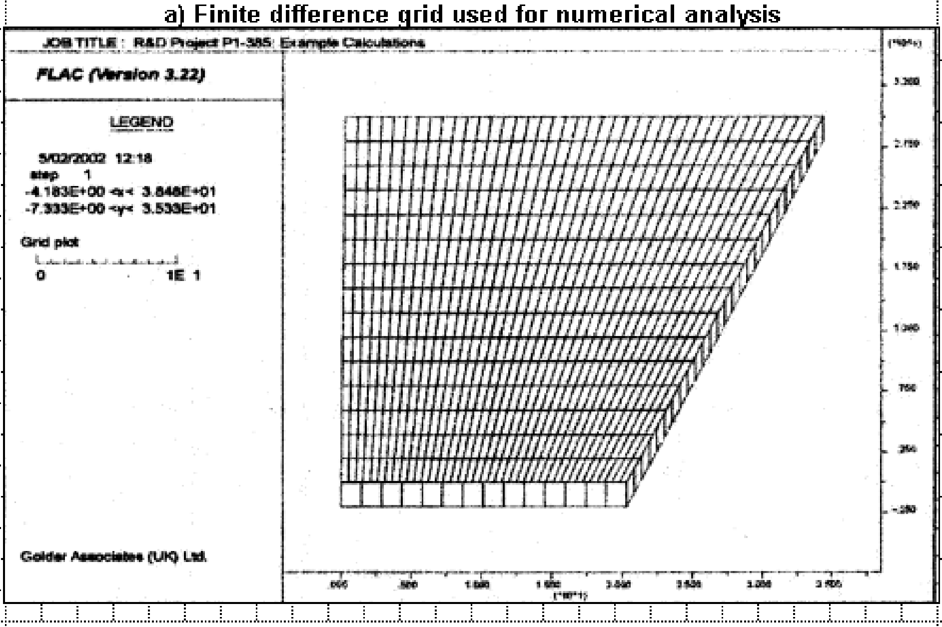
The finite difference grid used and the deformed grid are shown below;

a) Finite difference grid used for numerical analysis



JOB TITLE : R&D Project P1-385: Example Calculations

FLAC (Version 3.22)

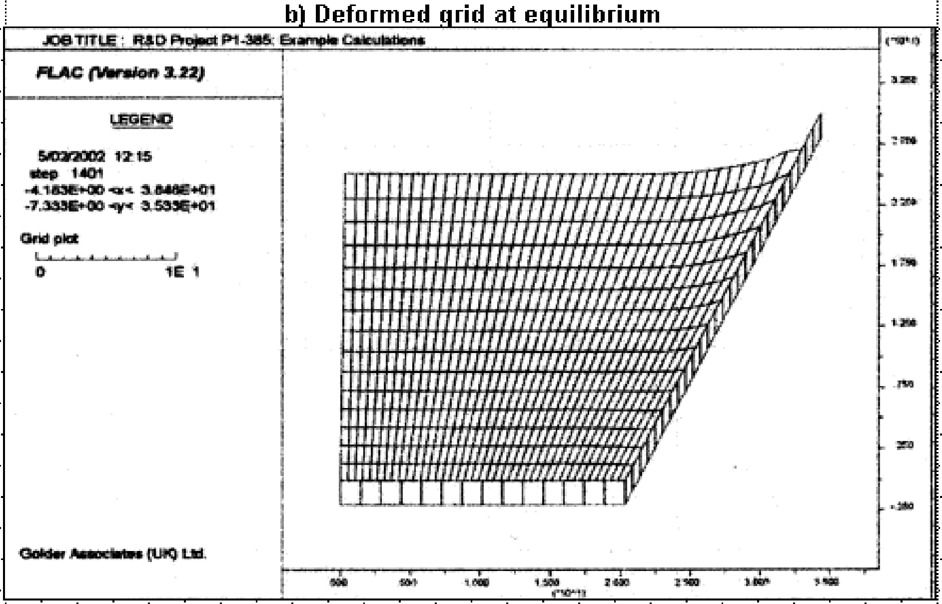
LEGEND

5/02/2002 12:18
step 1
-4.183E+00 <x< 3.848E+01
-7.333E+00 <y< 3.533E+01

Grid plot

Golder Associates (UK) Ltd.

b) Deformed grid at equilibrium



JOB TITLE : R&D Project P1-385: Example Calculations

FLAC (Version 3.22)

LEGEND

5/03/2002 12:15
step 1401
-4.183E+00 <x< 3.848E+01
-7.333E+00 <y< 3.533E+01

Grid plot

Golder Associates (UK) Ltd.

Figure 4.18 Calculations for Example 4 continued

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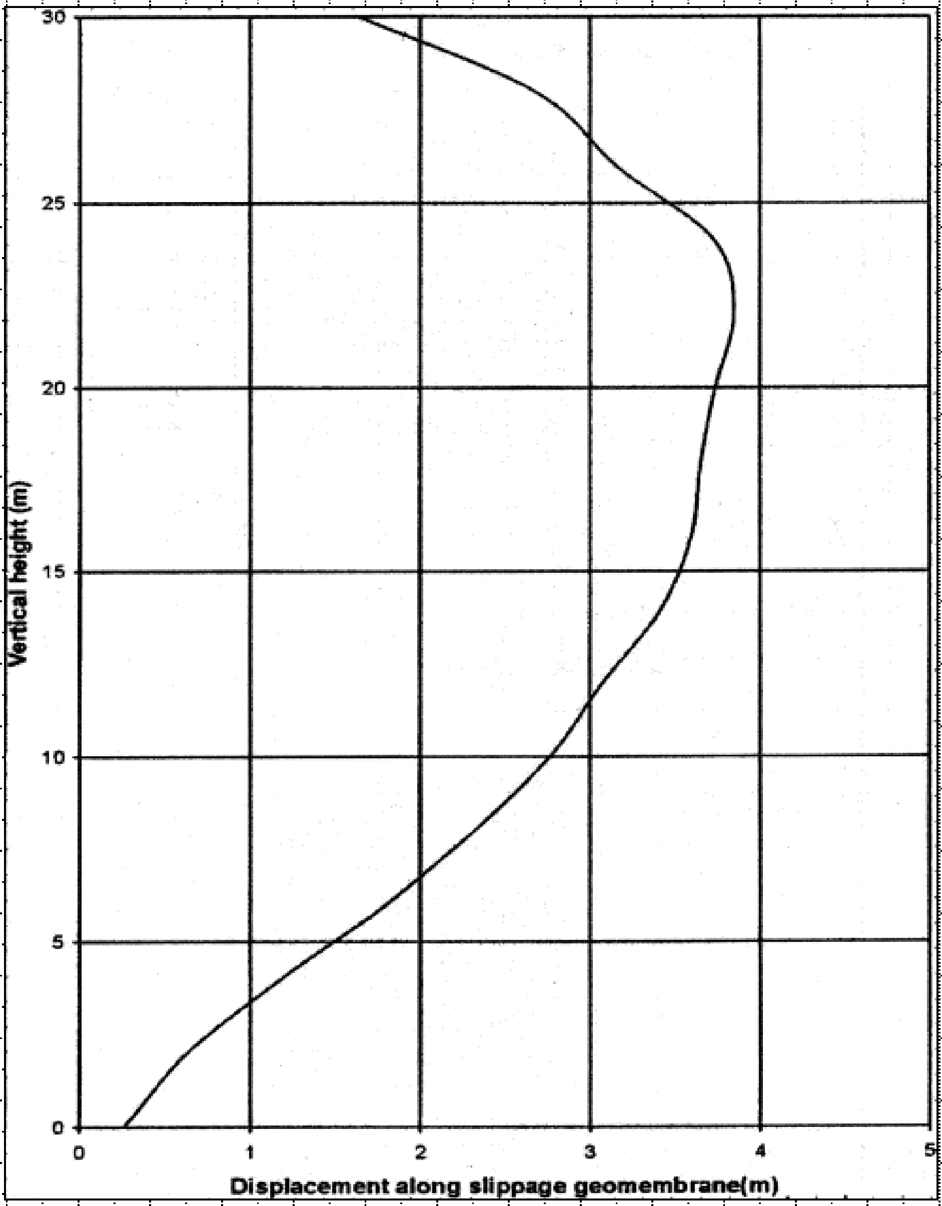
Results:

The maximum slippage at the interface is 3.85m the full profile is set out below;



Conclusions:

An allowance of 4 m of additional geocomposite will provide sufficient material to ensure that there will be no loss of geomembrane protection during the waste settlement. **OK**

2. Geomembrane

Since the geomembrane is a mono-textured material and will be placed with its smooth surface upwards, all the sheet force will be transferred through the geomembrane and there will be no tension developed in the geomembrane. **OK**

Figure 4.18 Calculations for Example 4 continued

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3. GCL

Aim: Assess the integrity of the GCL, by considering the transfer of stresses through the material.

Approach: Consider the stresses in the lining system at the base of the side slope.

Calculations:

The following peak interface shear strengths were measured:

Geocomposite/smooth geomembrane interface	$\alpha' = 1.6$ kPa	$\delta' = 5.3°$
Textured geomembrane/GCL interface	$\alpha' = 0$ kPa	$\delta' = 26°$
GCL/sub-grade interface	$\alpha' = 0$ kPa	$\delta' = 18°$

a) Stress acting normal to the interface

$\sigma_n = \sigma_v \cos\beta + \sigma_h \sin\beta$

σ_n is the effective stress normal to the lining system

σ_v is the vertical effective stress at the base of the lining system

σ_h is the horizontal effective stress at the base of the lining system

β is the slope angle

The unit weight of the waste is taken as 10 kN.m^{-3}

$\sigma_n = (30 \times 10)\cos 65 + (0.2 \times 30 \times 10)\sin 65 = 181$ kPa

b) Geocomposite/geomembrane interface

The shear strength at this interface, τ_{max}, is

$\tau_{max} = \alpha + \sigma_n \tan\delta$

$\tau_{max} = 1.6 + 181 \tan 5.3 \quad = 18.4\ \text{kN.m}^{-1}$

As the waste settles, there will be movement along this interface and this maximum shear stress must be overcome before movement takes place. The shear stress is then transferred to the interface below.

c) Geomembrane/GCL interface

The shear strength at this interface, τ_{max}, is

$\tau_{max} = 0 + 181 \tan 26 \quad = 88.3\ \text{kN.m}^{-1}$

Since 88.3 > 18.4, there will be no tension in the geomembrane (as discussed in 2 above)

Figure 4.18 Calculations for Example 4 continued

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d) GCL/sub-grade interface

The shear strength at this interface, τ_{max}, is

τ_{max} = 0 + 181 tan 18 = 58.8 kN.m^{-1}

Since 58.8 > 18.4 there will be no tension in the GCL.

However, if the woven surface of the GCL, is placed on the sub-grade and there is some extrusion of saturated bentonite, then this will reduce the interface shear strength significantly, to a friction angle of 5°.

The shear strength at this interface then becomes;

τ_{max} = 0 + 181 tan 5 = 15.8 kN.m^{-1}

Since 15.8 < 18.8, there will be a tension force induced in the GCL.

Tension in the GCL = (18.4 - 15.8) x length of GCL

Tension = (18.4 - 15.8) x 5.51 = 14.3 kN.m^{-1}

The strength of the GCL is 10 kN.m^{-1}, and so the factor of safety against tensile failure is

F of S = 10 / 14.3 = 0.7

Conclusions:

From the above calculations, it is clear that a needle punched GCL with two non-woven geotextiles should be used. In this instance, the integrity of the geosynthetic components of the lining system are considered to be satisfactory. **OK**

Figure 4.18 Calculations for Example 4 continued

5. SUMMARY

Assessment of landfill liner and waste body stability is a key element of the Landfill Directive. Both stability and integrity of the lining components must be assessed in order to demonstrate performance of the barrier system during the design life of the facility. This report gives recommendations and provides guidance. It should be used in conjunction with Report No. 1: Literature Review, which provides a detailed summary of the key issues - controlling landfill stability assessment based on the international state-of-the-art.

This document (Report No. 2) consists of three main sections; design philosophy, design assessment criteria and example calculations.

Design philosophy includes guidance on the selection of appropriate safety factors and of characteristic values. It stresses that a prescriptive approach is not appropriate and highlights the need for sound engineering judgement of site specific factors by an experienced geotechnical engineer. Appropriate ranges of factors of safety for common assessments are introduced. The importance of waste/barrier interaction and the need for appropriate monitoring in order to assess design assumptions and performance are stressed.

Guidance on design assessment has been provided in the form of design flow charts and aide memoir of key issues for consideration. Design is considered through six main landfill elements; sub-grade, basal lining system, shallow side slope lining system, steep side slope lining system, waste slope and capping lining system.

Flow charts for each element list the main design cases and design issues. It is proposed that these charts can be used to identify the key design cases and hence to ensure that all potential failure modes are assessed as part of the design process. The aide memoir of key issues can be used to check that all factors influencing behaviour are considered in the analysis.

The methodology presented in this report is designed to provide a logical comprehensive framework for the selection of all relevant design cases and their analysis.

LIST OF FIGURES

LIST OF TABLES

REFERENCES

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