

DESIGN OF HIGH STRENGTH GEOTEXTILES FOR BASAL REINFORCEMENT WITHIN EMBANKMENTS

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ABSTRACT

High Strength Geotextiles (HSG's) are commonly used as basal reinforcement within embankments and structures founded upon weak ground. The polymeric composition of these products can bring high magnitudes of tensile strength to the system to prevent against slope instabilities and bearing type failures.

HSG's are "passive" forms of reinforcement, whereby activation of its capacity occurs whence destabilising forces are applied, causing the reinforcement to undergo tensile strain. The polymeric materials in HSG's undergo creep, i.e. deformation under sustained application of constant tensile loads. The combination of strain-dependent and time-dependent behaviours in HSG's are a complex mix of material characteristics, which make them complicated to design with. The complexity of their behaviour has resulted in greatly varying design methods adopted in industry. The source of difference is often linked to how creep is addressed in the selection of HSG, and how its strain-dependent behaviour is accounted for. This paper discusses the design methodologies referred to in BS8006 (Code of Practice for Strengthened/Reinforced Soils and other Fills) – which follows a limit state design process to ascertain the design loads to be carried by HSG's and methods on how to assess the design strength of proprietary products. The authors generally support the methodologies adopted in BS8006 with suggestions on limiting criteria and how these can be assessed.

1 INTRODUCTION

The inclusion of tensile elements to reinforce earthen structures dates back to prehistoric times, where reeds and vines were used in clay bricks to facilitate the construction of large earth structures in 1000 BC (Exxon, 1994). Parts of the Great Wall of China, dating back to circa 200 BC, were constructed with clay and gravel mixtures reinforced with branches of the tamarisk tree (Jones, 1996).

The use of geosynthetic fabrics as reinforcing elements was introduced in the 1970's, following the advent of synthetic polymer-based materials. In industry today, geosynthetics, in particular geotextiles and geogrids, are commonly used to facilitate the construction of embankments founded on soft soils. The ubiquity of these products has spawned numerous guidelines and codes covering the design and selection of proprietary geotextile products. However, the design of basal reinforcements still has elements of ambiguity, resulting in confusion and inconsistency of design outcomes in the industry today.

In recognition of such design variability, this paper discusses various approaches used in Australia, and suggests one that is largely based upon the principles of basal reinforcement design documented within BS8006 and recommendations found in literature.

This paper covers the basic properties of geotextiles, and the mechanisms by which they provide reinforcement in Sections 2 and 3. Section 4 provides a summary of the basic design principles for basal reinforcement recommended by the different design methods – covering the establishment of design tensile loads to stabilise an embankment; and the methods of evaluating the necessary geotextile product(s) to support these loads. To conclude, this paper provides details on how to specify basal reinforcement in a universally acknowledged manner, including the design life, strength and strain criteria of HSG's, to ensure the most suitable product can be selected.

2 APPLICATIONS OF HIGH STRENGTH GEOTEXTILES

2.1 WHAT ARE HIGH STRENGTH GEOTEXTILES

Geotextiles and geogrids (herein collectively called “high strength geotextiles, HSG’s”), comprise highly stable and durable polymers which have been manufactured into planar sheets, either as fabrics or square/rectangular grids, which exhibit high tensile capacity in specified directions and planes (Exxon, 1994). These materials can be placed within soil, rock or earth structures to provide added tensile capacity to the system.

2.2 HOW ARE HIGH STRENGTH GEOTEXTILES USED

The application of embankment loads on earthen foundations will introduce destabilising shear forces in the supporting soil. In soft ground, the stability of the embankment system is governed primarily by the shearing resistance present in the foundation to resist these destabilising forces. The available shearing resistance is typically low in soft ground, and therefore incapable of supporting embankments. This condition restricts the embankment heights that can be constructed.

The introduction of HSG’s can be used to provide tensile restraint into the system, and prevent shear failure in the embankment fill and foundation soil.

2.3 MECHANISM OF REINFORCEMENT

HSG’s in embankments rely on two primary mechanisms of load transfer, which act iteratively and continuously during the load application process:

- Tensile/shear stresses which are introduced in the foundation from the application of embankment loads are transferred to the HSG by means of frictional bond between the geotextile and adjacent soil
- The transferred forces are carried by the geotextile via tension within the polymeric fibres or grid

This behaviour is typical of “passive” reinforcement systems, whereby activation of the reinforcement occurs whence destabilising forces are applied, causing the reinforcement to undergo strain and react in tension. The continued application of load will cause further activation of the geotextile capacity, until such point the system reaches equilibrium. This is described further in Section 3.

The reinforcement mechanisms are illustrated in Figure 1 below, where the geotextile is shown intersecting a critical failure surface in an embankment founded upon soft soil.

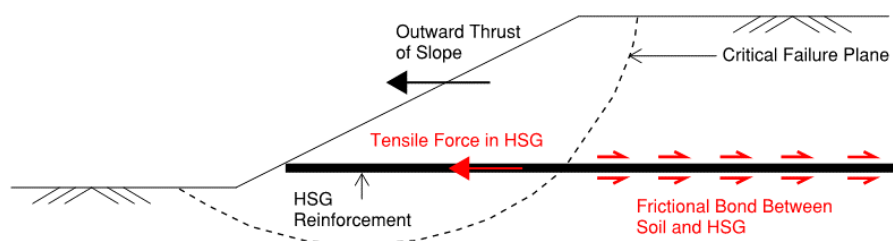


Figure 1: Mechanisms of load transfer in HSG’s (Exxon, 1994)

3 CHARACTERISTICS OF HIGH STRENGTH GEOTEXTILES

3.1 STRAIN DEPENDENT BEHAVIOUR

Due to their “passive” nature geotextiles must be strained in order for their strength to develop. Their tensile strength is directly proportional to the extension they experience. This behaviour is illustrated in Figure 2, containing a plot of the stress-strain behaviour of polymeric materials commonly used in geotextiles, i.e. polyester fibres, polypropylene, and High Density Polyethylene (HDPE) grids.

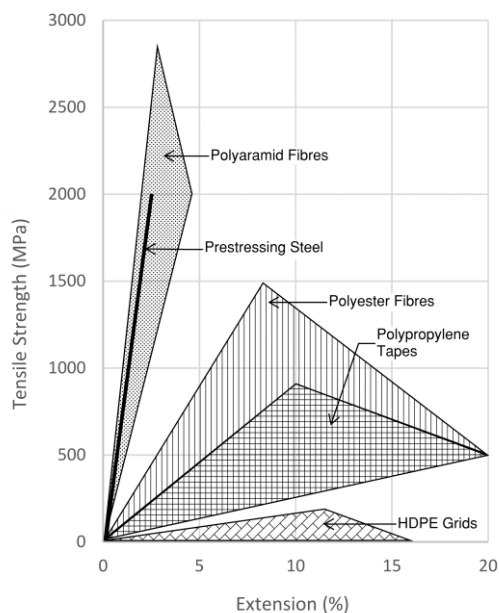


Figure 2: Strain dependent behaviour of geotextiles (Exxon, 1994)

3.2 TIME DEPENDENT BEHAVIOUR

Polymeric materials typically exhibit “visco-elastic behaviour” at ambient temperatures (10 to 30 degrees Celsius). Upon applying a constant and sustained tensile load to the reinforcement at a constant temperature, the material will experience creep, and eventually fail in “tensile creep rupture” after a certain time. Creep is defined as an increase in extension under constant applied load (Exxon, 1994).

3.3 MATERIAL PROPERTY CURVES

In order to fully describe the creep behaviour of geotextiles in terms of stress-strain-time, two material property curves are required – stress-rupture curves and isochronous creep curves. Generic forms of these curves are illustrated in Figure 3 and Figure 4 below.

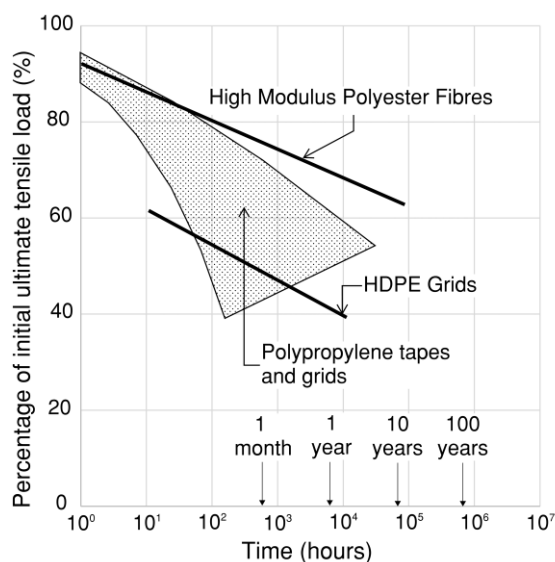


Figure 3: Stress-rupture curve (reproduced from Exxon, 1994)

Stress-rupture curves illustrate the reduction in geotextile rupture tensile loads at different times due to material creep.

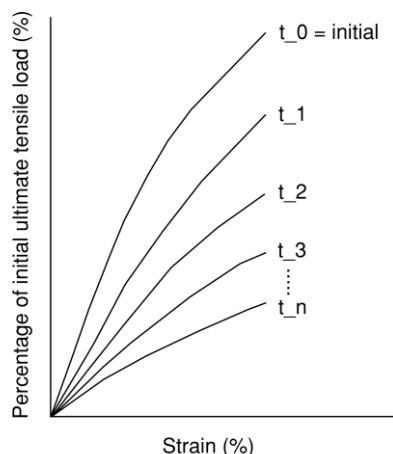


Figure 4: Isochronous creep curves (after Exxon, 1994)

Isochronous creep curves illustrate the geotextile tensile load and strain relationship at various times.

4 DESIGN METHODOLOGY

4.1 DESIGN PRINCIPLES

Three main considerations are required in the design of basal reinforcements to account for their strain and time-dependency characteristics:

- Time, t
- HSG strength, T
- HSG strain, ε

These attributes are neatly summarised in isochronous creep curves, a typical example of which is illustrated in Figure 4. The y-axis relates to the product strength; x-axis to the corresponding strain; and different curves are presented at various times post load application. As the manufacture and polymeric constituents vary between HSG products, their performance and behaviour will differ, resulting in unique isochronous curves for each product.

Different basal reinforcement design methods are adopted in practice today which address these three design considerations in different ways. Details of these methods are provided in Sections 4.3 and 4.4 below.

However, the fundamental steps and principles of design are consistent between all the methods, and can be symbolised with the nomenclature and equations shown in Table 1. A full glossary is provided in Section 4.2.

Table 1: Steps and principles of basal reinforcement design

Step	Symbol	Description
1	T_r	T_r is the calculated load which will need to be carried by the HSG during its design life, t , while subject to a corresponding strain, ε . T_r is determined as the magnitude of tensile force required to maintain embankment stability, as determined from assessments of various embankment failure mechanisms.
2	T_B	A proprietary HSG product is selected with a base (unfactored) tensile strength of T_B .
3	$T_D = \frac{T_B}{f_m}$	The design strength of the selected HSG product, T_D , equates to its base strength, T_B , reduced by reinforcement material factors, f_m , associated with manufacture and installation conditions
4	$T_r \leq T_D$	The selected HSG product strength, T_D , must equal or exceed the calculated loads, T_r .

4.2 GLOSSARY

Table 2 provides a summary of the key nomenclature used within this paper.

Table 2: Glossary of terms

Symbol	Definition
GENERAL	
T_i	Initial tensile strength of HSG
T_D	Design strength of HSG
T_B	Base strength of HSG
f_m	Reinforcement material factors
f_n	Economic ramification factor
LIMIT STATE DESIGN	
$T_{r(ULS)}$	Calculated ULS load at designated time, $t_{(ULS)}$, and rupture strain $\epsilon_{(ULS)}$
$T_{r(SLS)}$	Calculated SLS load at designated time, $t_{(SLS)}$, and serviceability strain $\epsilon_{(SLS)}$
$T_{B(ULS)}$	Base tensile rupture strength at designated time, $t_{(ULS)}$, and rupture strain $\epsilon_{(ULS)}$
$T_{B(SLS)}$	Base tensile serviceability strength at designated time, $t_{(SLS)}$, and serviceability strain $\epsilon_{(SLS)}$
$T_{D(ULS)}$	Design tensile rupture strength, $\frac{T_{B(ULS)}}{f_m}$
$T_{D(SLS)}$	Design tensile serviceability strength, $\frac{T_{B(SLS)}}{f_m}$
$X\%$	Proportion of the initial ultimate tensile load corresponding to design strain limits and time
WORKING STRESS DESIGN	
$T_{r(WS)}$	Calculated working load at designated time, $t_{(WS)}$, and serviceability strain $\epsilon_{(WS)}$
$T_{B(WS)}$	Base tensile strength at designated time, $t_{(WS)}$, and serviceability strain $\epsilon_{(WS)}$
$T_{D(WS)}$	Design tensile working strength, $\frac{T_{B(WS)}}{f_m}$
$R_{(WS)}\%$	Ratio of the design strain value to the initial failure/rupture strain limit

4.3 LIMIT STATE DESIGN APPROACH

4.3.1 BS8006 – ULS and SLS

In the absence of a national guideline for the design of basal reinforcement in Australia, designers commonly refer to British Standard BS8006 – Code of Practice for Strengthened/Reinforced Soils and other Fills. In particular, for the design of HSG's for basal reinforcement, reference is made to Section 8 of BS8006 – Design of Embankments with Reinforced Soil Foundations on Poor Ground. There are two versions of this code used commonly in industry today, namely, the 1995 and 2010 edition. The basic design principles for basal reinforcements in these codes are largely the same, with one major difference as discussed in Section 4.3.6.

BS8006 follows a Limit State Design approach, whereby the selected reinforcement requires satisfaction of two design limit states, Ultimate Limit State (ULS) and Serviceability Limit State (SLS).

Attainment of ULS design requirements safeguards against collapse and catastrophic failure conditions. Postulated mechanisms of failure are assessed from which the necessary tensile capacity of the HSG required to meet or exceed the destabilising loads is determined, i.e. ultimate design tensile load to be resisted by basal reinforcement, $T_{r(ULS)}$. Subsequently, the designer must select the proprietary HSG product which has the capacity, T_D , to achieve design tensile load, $T_{r(ULS)}$.

Attainment of SLS design requirements safeguards against deformation and excessive strain of the structure. Postulated mechanisms of deformation are assessed from which the induced tensile loads in the HSG are

determined, i.e. serviceability design tensile load to be resisted by basal reinforcement, $T_{r(SLS)}$. Subsequently, the designer must select the proprietary HSG product, T_D , that conforms to the prescribed serviceability limits under the subjected loads, while accounting for strain in polymeric materials that will result from creep strain under constant load.

The design strength, T_D , may be governed by either ULS or SLS conditions, and hence both limit states must be checked.

The authors recognise there are other international design codes that cover the design of HSG's on soft soil, such as EBGEO (2011), the German code governing the design of earth structures. However, particular focus is paid to BS8006 due to its comparative popularity in Australia.

4.3.2 Partial Factors

Partial factors are “multipliers” applied to various components of the embankment and HSG system to formulate a margin of safety against failure or excessive deformation. The partial factors of interest include Load and Material Factors applied to the embankment elements, and Reinforcement Material Factors applied to the HSG.

Load Factors and Material Factors

For each of the limit states, ULS and SLS, a series of partial factors are applied to the components of the structure as part of the assessment.

Destabilising forces on the system, e.g. surcharges and earth loads, are increased by Load Factors, to account for the likelihood of variability in the applied loads. Material strengths providing restoring forces to the system, such as soil cohesion, are reduced by Material Factors to account for uncertainties and variabilities in the ground materials.

Details of Load Factors and Material Factors can be found in BS8006.

Reinforcement Material Factors, f_m

Reinforcement base strengths, T_B , are reduced by reinforcement material factors, f_m , to generate the reinforcement design tensile strength, T_D . Refer to Equation 1. Reinforcement material factors are product-specific values which account for variabilities in the manufacture, installation and applied environmental conditions of the HSG. According to BS8006, f_m is the multiplied product of several partial factors accounting for the following HSG attributes :

- intrinsic properties of reinforcement material, e.g. consistency of manufacture, possible reductions in material capacity based on control of specimens, and extrapolation of test data for long term capacity assessments relating to base strength
- construction and environmental effects, e.g. susceptibility to damage during installation, and environmental conditions impacting on the degradation rate.

For example, f_m can equate to:

$$f_m = RF_M \times RF_{IN} \times RF_{CH} \times RF_{EX} \quad (1)$$

Where RF_M , RF_{IN} , RF_{CH} and RF_{EX} equate to reduction factors for manufacture, installation damage, chemical/environmental effects and extrapolation of data respectively.

Note that these reinforcement material factors vary between different HSG products and manufacturers, and are usually provided on product-specific technical datasheets. In the absence of this information, clarification should be sought from the product supplier.

4.3.3 Economic Ramification Factor, f_n

In BS8006, the consequences of failure for the embankment is captured by means of an Economic Ramification Factor, f_n . This factor accounts for the importance and impact the structure may have on life and the provision of services, by allocating factors to decrease the reinforcement design strength, T_D , for structures of higher importance and impact, i.e. T_D / f_n

f_n ranges from 1.0 to 1.1 for structures with “medium” to “high” ramifications of failure respectively. For structures falling within the “low” category of failure, partial factors are not applied.

4.3.4 Design Loads

Design loads for ULS and SLS can be determined as described below.

Determination of $T_{r(ULS)}$

According to BS8006, basal reinforcements must be designed to withstand the ULS failure mechanisms listed below.

- Local stability. Stability of embankment slopes within the embankment fill material.
- Rotational stability. Stability of the combined embankment and foundation system.
- Lateral Sliding. Resistance of the reinforcement against the outward thrust of embankment fill on the upper surface of the basal reinforcement.
- Foundation Extrusion and Bearing Capacity. Lateral extrusion of foundation soil beneath the embankment.
- Overall Stability. Deep seated failures involving instability of the overall embankment.

The designer must ascertain the necessary tensile capacity of the HSG to ensure prevention of these mechanisms, i.e. attainment of a factor of safety (FOS) of unity, against failure. Assessments include slope stability analyses and equations provided in the code. The minimum required HSG tensile capacity equates to $T_{r(ULS)}$. Note that under ultimate limit state conditions, driving forces and resisting forces are increased and reduced respectively with partial factors, as described in Section 4.3.2.

Determination of $T_{r(SLS)}$

According to BS8006, the SLS conditions which must be designed against are, excessive reinforcement strain and settlement. The induced HSG forces required to prevent exceedance of the limiting strains equates to $T_{r(SLS)}$.

The assessment of reinforcement strain can be undertaken directly with finite element analyses. However, in the absence of which, designers can use an indirect method of determining $T_{r(SLS)}$; the analyses for ULS can be re-run, using unfactored loads and material properties (consistent with SLS conditions), and the necessary HSG tensile loads determined to ensure prevention of the failure mechanisms listed above. This value equates to $T_{r(SLS)}$.

Suggested strain limits to which the assessed $T_{r(SLS)}$ must adhere to are summarised below.

Table 3: Suggested maximum reinforcement strain limits from BS8006

Design Life	Maximum Strain Limit (%)
Short Term	5
Long Term	5-10

Settlement estimates are typically undertaken as a separate exercise, and will not be discussed herein.

4.3.5 Evaluation of Product Design Strength

According to BS8006, the design strength of reinforcement, T_D , is calculated according to the formulae below.

$$T_D = \frac{T_B}{f_m} \quad (2)$$

Reinforcement base strengths, T_B , are derived from the “characteristic initial tensile strength”, T_i of a product, which equates to the immediate tensile capacity of the product without accounting for creep nor material factors. Values of T_i for HSG products can be readily obtained from geotextile manufacturers in the form of product technical datasheets.

The paragraphs below describe how the ULS and SLS design strengths of HSG can be determined from the material behavioural curves that are characteristic of polymeric materials. Note that these methods of determining geotextile capacity are not described explicitly in BS8006, but are inferred in the text. The actual method of assessment is referenced from Exxon, 1994.

Determination of $T_{D(ULS)}$

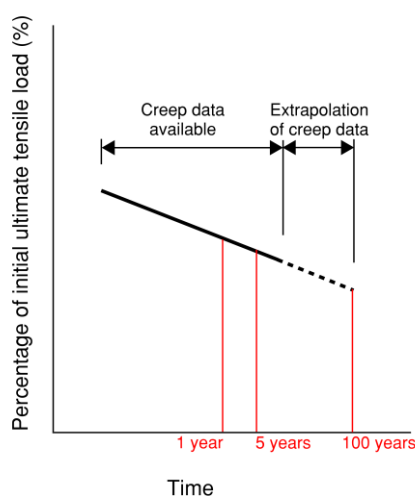
T_D for ULS conditions, $T_{D(ULS)}$, can be derived from the reinforcement base strength, T_B , established from ULS conditions, $T_{B(ULS)}$. BS8006:1995 stipulates T_B for ULS conditions is equal to the “...extrapolated tensile creep rupture strength... at end of the selected design life...”. A similar definition is provided in BS8006:2010. Application of loads in the HSG less than this base strength will ensure the reinforcement does not fail in tension during its design life.

$T_{B(ULS)}$ can be determined from stress-rupture curves of HSG products, as shown in Figure 5(a). These curves define the rupture capacity (load carrying capacity) of the geotextile when sustained load is imparted on the geotextile for prolonged durations. The tensile strength of reinforcement decreases over time due to creep effects, until a point where they undergo tensile rupture. Stress-rupture curves can be used to ascertain the available tensile strength at a point in the future, as shown in Figure 5(a). For long design lives, e.g. 100 years etc., creep rupture reduction factors are often determined from extrapolated data. Manufacturers often do not supply stress-rupture curves, and prefer to present the stress rupture strength of HSG in the form of a Creep Reduction Factor, RF_{CR} , which varies depending on the design life of interest, as shown in Figure 5(b).

$T_{B(ULS)}$ and $T_{D(ULS)}$ can be calculated according to the equations below.

$$T_{B(ULS)} = \frac{T_i}{RF_{CR}} \quad (3)$$

$$T_{D(ULS)} = \frac{T_{B(ULS)}}{f_m} \quad (4)$$



Design life	Creep rupture reduction factor, RF_{CR}
5 years	1.33
10 years	1.37
120 years	1.5

(a) Example of stress-rupture curve

(b) Example of stress-rupture factors

Figure 5: Determining T_B for ULS conditions, $T_{B(ULS)}$, using stress-rupture curves

Note that stress-rupture curves are product specific, and differ between the polymeric composition and geometry of HSG's.

Determination of $T_{D(SLS)}$

T_D for SLS conditions, $T_{D(ULS)}$, can be derived from the reinforcement base strength, T_B , established from SLS conditions, $T_{B(SLS)}$. BS8006:1995 stipulates T_B for SLS conditions is equal to the "...extrapolated tensile load... which gives rise to a creep strain, between the end of construction and the end of the design life, which does not exceed prescribed serviceability limit strains." A similar definition is provided in BS8006:2010. Attainment of this base strength will ensure reinforcement strains do not exceed the prescribed value during its design life.

$T_{B(SLS)}$ can be determined from isochronous creep curves of HSG products as shown in Figure 6. Isochronous creep curves provide a representation of the degree of strain sustained when HSG's are subjected to constant load, over prolonged periods.

The serviceability performance of reinforcement, $T_{B(SLS)}$, can be calculated by firstly identifying the strain limits which need to be met for the design life of interest, for example:

- 100 year design life
- Long term total strain $\leq 8\%$

Reference can then be made to the isochronous creep curves to ascertain the allowable load which can be imparted onto the HSG correlating to these strain limits. The load is determined as a proportion of the initial ultimate tensile load, T_i , which equates to $T_{B(SLS)}$ according to Equation 5 below. Once $T_{B(SLS)}$ is established, $T_{D(SLS)}$ can be determined according to Equation 6.

$$T_{B(SLS)} = X\% \text{ of } T_i \quad (5)$$

$$T_{D(SLS)} = \frac{T_{B(SLS)}}{f_m} \quad (6)$$

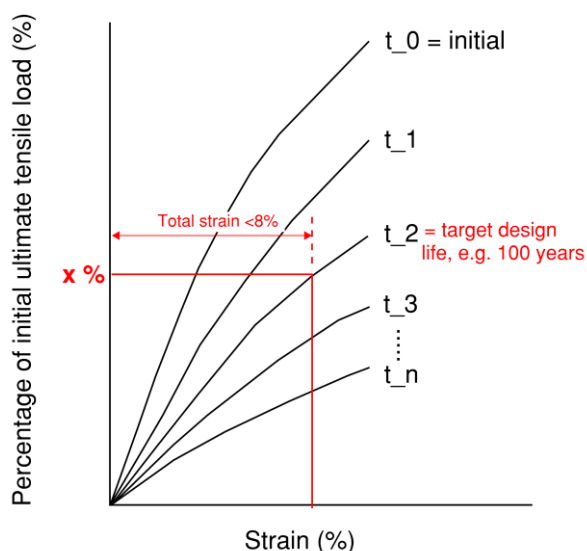


Figure 6: Determining T_B for SLS conditions, $T_{B(SLS)}$, using isochronous creep curves

Note that isochronous creep curves are product specific, and differ between the polymeric composition and geometry of HSG's.

4.3.6 Selection of Proprietary Products

In selecting the proprietary product, the designer must ensure the following relationship is satisfied.

$$T_r \leq \frac{T_D}{f_n} \quad (7)$$

Sections 4.3.2 to 4.3.5 described the basic framework to ascertain design loads, T_r , and HSG product strengths, T_D . However, the way in which these values are used and compared differs between the 1995 and 2010 editions of BS8006. The following sections provide a brief description of how HSG loads (T_r) and strengths (T_D) are calculated and compared.

BS8006:1995

According to BS8006:1995, T_B equates to the lesser of $T_{B(ULS)}$ and $T_{B(SLS)}$. That is, the base design strength of the proprietary product is determined based on the lesser value ascertained under ULS and SLS conditions. This leads to T_D being the lesser of $T_{D(ULS)}$ and $T_{D(SLS)}$.

$$T_B = \min(T_{B(ULS)}, T_{B(SLS)}) \quad (8)$$

$$T_D = \min(T_{D(ULS)}, T_{D(SLS)}) \quad (9)$$

T_D/f_n of the selected product must then exceed the design load T_r , being the maximum of $T_{r(ULS)}$ and $T_{r(SLS)}$, i.e.,

$$T_r = \max(T_{r(ULS)}, T_{r(SLS)}) \quad (10)$$

BS8006:2010

One of the biggest differences from the 1995 version, is that in 2010, the product base strength, T_B , is split into two separate assessments, pertaining to ultimate limit state, $T_{B(ULS)}$, and serviceability limit state, $T_{B(SLS)}$. The code stipulates that these capacities, $T_{D(ULS)}$ and $T_{D(SLS)}$, are compared with the respective design tensile loads, $T_{r(ULS)}$ and $T_{r(SLS)}$, as shown in the equations below.

$$T_{r(ULS)} \leq \frac{T_{D(ULS)}}{f_n} \quad (11)$$

$$T_{r(SLS)} \leq \frac{T_{D(SLS)}}{f_n} \quad (12)$$

4.4 WORKING STRESS APPROACH

One of the commonly adopted methodologies in industry today utilises the Working Stress design approach. In determining the design tensile load (working stress), $T_{r(WS)}$, the same failure mechanisms must be designed against, as summarised in Section 4.3.4. However, the margin of safety against failure is calculated by targeting a minimum factor of safety (FOS) greater than unity, as opposed to the application of Load/Material Factors used in the limit state approach (and targeting $FOS \geq 1.0$). For example, in the assessment of rotational stability for long term design conditions, a minimum FOS of 1.5 is normally targeted.

The reinforcement design strength of proprietary products, $T_{D(WS)}$, is determined via the following steps.

1. Reduce the characteristic initial tensile strength, T_i , by the creep reduction factor, RF_{CR} , and proportion of the initial tensile strength correlating to the desired strain limits, $R_{(WS)}\%$ based on the isochronous creep curves. (In some design approaches, strain limits are not accounted for). The outcome equates to the base strength, $T_{B(WS)}$. Refer to Equation 13 below.

$$T_{B(WS)} = \frac{T_i \times R_{(WS)}\%}{RF_{CR}} \quad (13)$$

$R_{(WS)}\%$ equates to the ratio of the limiting strain value to the failure/rupture strain limit at time, $t = 0$.

E.g. for limit strain of 5%, and rupture strain of 10%, $R_{(WS)}\% = \frac{5}{10} = 50\%$

2. The base strength is reduced by reinforcement material factors, f_m , to generate the design strength of the product, $T_{D(WS)}$. Refer to Equation 14 below.

$$T_{D(WS)} = \frac{T_{B(WS)}}{f_m} \quad (14)$$

3. The reinforcement design strength, $T_{D(WS)}$, is then reduced by the economic ramification factor, f_n ; the outcome of which must meet or exceed the design tensile load, $T_{r(WS)}$, according to Equation 15 below.

$$T_{r(WS)} \leq \frac{T_{D(WS)}}{f_n} \quad (15)$$

5 DISCUSSION

5.1 SUGGESTED DESIGN METHOD

Between BS8006:1995 and BS8006:2010, the 2010 version recommends ULS design loads, $T_{r(ULS)}$, to be compared with ULS reinforcement strength $T_{D(ULS)}$, and SLS design loads, $T_{r(SLS)}$ to be compared with SLS reinforcement strength, $T_{D(SLS)}$. The 1995 version selects the lower of the HSG ULS and SLS strengths, and compares this with both the ULS and SLS design loads – resulting in a less justifiable assessment where ULS strengths may be compared with SLS design loads and vice versa.

Regarding the Working Stress approach, it is apparent that the evaluation of HSG product strengths (refer Section 4.4) are overly conservative. This method accounts for creep reductions in a similar fashion to the SLS approach to determine $T_{B(SLS)}$, however, the derivation of $T_{r(WS)}$ was ascertained by targeting a factor of safety greater than 1.0 – whereas $T_{r(SLS)}$ was derived using FOS of unity.

In the authors' opinions, the limit state approach documented in BS8006:2010 provides the more logical approach for the design of HSG and best caters for the behavioural characteristics of HSG's. Accordingly, the authors suggest adopting the design approach in BS8006:2010, in conjunction with the suggestions made in the discussion points below.

Some of the finer details associated with HSG design pertaining to selection of strain limits and HSG layer quantities are contained in the sections below. While design codes offer suggestions for these conditions, the authors offer their opinion on the suitability of these conditions, and values/quantities they generally adopt, based on their experience and engineering judgement.

5.2 STRAIN LIMITS

Recommended maximum strain limits vary between different standards and codes. The sections below summarise these differences and include the authors' suggestions.

5.2.1 Short Term Strain Limit

A short term strain limit of 5% is recommended in both versions of BS8006.

5.2.2 Long Term Strain Limit

According to BS8006:1995, the suggested strain limit should lie between 5% to 10% for long term applications. However, in the 2010 version of BS8006, for basal reinforced embankments constructed over soft sensitive foundation soils, the maximum allowable reinforcement strain is suggested to be reduced to <3% to ensure strain compatibility with the foundation soil.

In the authors' opinion, a long term strain limit of 8% should be adopted, as this conforms to the range of strain limits presented in BS8006:1995, and is supported by the authors' experience. The authors consider that adopting small strain limits of < 3% for the purposes of strain compatibility seems contradictory to the large deformations and settlements which can be expected from soft soil foundations.

5.2.3 Creep Strain Limit

According to the Roads and Maritime Services Specification for High Strength Geosynthetic Reinforcement (R67), reference is made to BS8006:1995, and states "...maximum creep strain must not exceed 1% over a design life of 100 years at the maximum operating temperature in the derivation of T_{CS} ." The definition of T_{CS} used in R67 equates to $T_{B(SLS)}$ herein.

Strain limits of 1% are recommended in BS8006 for reinforced soil walls supporting bridge abutments and stand-alone retaining walls. There do not appear to be creep strain limits for basal reinforcements supporting embankments stipulated in BS8006.

It is the authors' opinion that ULS and SLS assessments of design strength adequately address strain limits and creep behaviour. No further creep strain limits are required to ensure the proprietary products meet strain criteria.

Accordingly, the authors would suggest that no creep strain limits are used in the determination of $T_{B(SLS)}$ for HSG's.

5.3 MULTIPLE LAYERS OF HSG

According to field trials documented in BS8006:2010, the inclusion of multiple layers of reinforcement in embankments have been found to generate the following conditions:

- Where reinforcements of varying capacity have been installed, the stronger reinforcements attract a disproportionately greater magnitude of load.
- If two identical layers of HSG are incorporated as basal reinforcement, the lowest layer attracts a higher proportion of the loads

In RMS R67, the maximum number of layers of HSG is specified at four layers. However the origin of this specification is not clear.

The authors suggest:

- Using as few layers of HSG as possible, i.e. choose higher strength layers where possible
- Trying to maintain consistency between layer strengths

5.4 PROVIDING PRODUCT SPECIFICATIONS

In the event designers are required to provide specifications for HSG only, e.g. in design only projects, one must clearly specify the necessary design tensile loads, limiting strains and design lives under ULS and SLS conditions in order for the correct HSG product to be selected.

6 CONCLUSIONS

High strength geotextiles (HSG's) are often used as basal reinforcement to improve the stability of embankments constructed on soft soils. International design code BS8006 is commonly used for the design of HSG's and stipulates a limit state design approach. Design outcomes using the 1995 and 2010 editions of BS8006 vary significantly due to differences in the comparison of design loads and design strengths between the two editions. Details of HSG design using the Working Stress approach has been discussed in this paper, which is a commonly adopted methodology in practice. In the authors' view, the design approach recommended in BS8006:2010 is considered to be one of the most rational methods, and is suggested by the authors to be used in conjunction with serviceability strain limits of 5% short term and 8% long term. In the design of HSG's and provision of HSG specifications, practitioners are urged to keep in mind the three primary considerations of HSG behaviour – time, t , strength, T and strain, ε .

7 REFERENCES

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