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Geosynthetic damage - from laboratory to field

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ABSTRACT: Geosynthetic damage has been a major concern since the introduction of geotextiles for civil engineering applications. Mechanical damage occurs to a large extent during the installation and construction phase, as the mechanical impact on the geosynthetics during installation and compaction can be significantly higher than during the service lifetime. The type of damage is divided into six categories: abrasion, splitting, puncturing, stress rupture, fibre cutting and tearing. There are a number of laboratory tests relevant to the evaluation of damage susceptibility. However no single laboratory test has so far been developed which is capable of giving a complete basis for damage evaluation. A combination of different test methods seem to be a realistic approach in most cases and in specific cases full scale field trials can be carried out to provide the required information. The level for evaluation may vary from specification of characteristics based on index tests to full scale trials combined with control during and after construction. Specific examples of testing and evaluation of geosynthetics damage will be discussed in greater length for two applications: separation function for road and filtration function for revetment structures.

1 INTRODUCTION

Ever since geosynthetics have been used in engineering applications the question of installation damage has been a key issue. For about half a century geosynthetics have served successfully as separators, filters, reinforcement, drainage medium and protection layers in a countless number of projects. Among the large number of successful applications there are however examples where the geosynthetic has not fulfilled its intended purpose due to damage created during installation. Most manufacturers and distributors are naturally more interested in focusing on their successes and are not too happy to focus on potential installation damage on their product. It should however be recognized that the strengths of any product cannot be fully exploited without properly accounting for its weaknesses.

When geotextiles were introduced manufacturers and distributors, in their enthusiasm for their fantastic products, sometimes overestimated the ability of the product to survive the construction phase. During site trials in Germany in the seventies relatively thin, lightweight woven geotextiles were installed between sharp edged crushed fill material and then subjected to compaction. When the geotextile was extracted severe damage could be observed (Figure 1).

Figure 1. Severe damage on geotextiles from field trials in the seventies (Wilmers 2002).

These and similar experiences throughout the world triggered the idea of developing criteria for evaluation of geotextile survivability. Since then, extensive work has been performed both by producers and users to develop better methods for evaluation of damage susceptibility, criteria for selection of products and last but not least better products!

Today the possibility for mechanical damage of the geosynthetics is a major issue for the evaluation of ”fit for purpose”. Geosynthetics in civil engineering applications are generally used to fulfil one or more of the following functions: separation, filtration, reinforcement, protection or drainage. Mechanical impact on the geosynthetics may reduce or even totally destroy its ability to fulfil one ore more of these functions. On the other hand it should be noted that the geosynthetic might still serve its intended function despite the damage. As a part of the design it is therefore required to evaluate what kind of mechanical damage might be expected and what are the consequences of the damage in terms of ability to fulfil its intended function in the structure.

In this paper focus is placed on installation damage, i.e. the damage on geosynthetics related to mechanical impact during the installation in the construction process. We want to look into different damage mechanisms and try to correlate them to different applications. We also want to emphasize relevant test methods for evaluation of damage susceptibility and to give some examples from the field.

The subject of installation damage will be presented in the context of two areas of engineering application where geotextiles are widely used – geotextiles used as separators in roads and geotextiles used as filters in water structures. In the process of constructing these structures, the geosynthetics may be subjected to heavy construction stresses commonly by far exceeding the service stresses. The possibility of damaging the geosynthetics during construction is therefore high. This may reduce the long-term performance of the structure. We want to focus on some relevant damage mechanisms and try to link these mechanisms to essential properties of the geosynthetics. We also want to look into how the resistance to damage, commonly named the geosynthetics survivability (Christopher and Holtz, 1988), may be evaluated and how this may be reflected in design and specification.

2 DAMAGE MECHANISMS

Damage from mechanical impact on the geosynthetics may occur all the way from production, in storage and handling, during installation through to the service lifetime. During the construction process the geosynthetics will be subjected to different kinds of damage mechanisms.

The type of damage mechanism will vary with the boundary conditions: subsoil, fill material, construction equipment and procedures and climatic conditions. The geosynthetic characteristics will also influence the type of damage mechanism. The most important factors related to susceptibility for damage are given in Table 1.

Table 1. Factors influencing the damage mechanisms

Subsoil	Stiffness
	Strength
Fill material	Grain size
	Angularity
Construction equipment and procedures	Stressing during installation
	Weight of compaction equipment
	Vibrating compaction
	Layer thickness
Climatic conditions	Temperature
	Water
Geosynthetic characteristics	Polymer type
	Fibre type and dimension
	Manufacturing process
	Thickness
	Mass per unit area

The damage mechanism results from a combination of the boundary conditions, the geosynthetic characteristics and several external factors. During the installation and construction phase the construction equipment, subsoil conditions and the fill material are obviously all important factors. The stress induced in the geosynthetic is obviously different in an installation on soft subsoil with large diameter rounded fill material compared to the installation on a firm ground with sharp edged crushed rock.

However, other factors may also have significant influence. For example, the susceptibility for damage for the geosynthetic caused by traffic of compaction equipment may be significantly different if the temperature is –10ºC compared to the conditions at +30ºC.

The amount but also the mode of damage will vary with the geosynthetic characteristics. A thick heavy weight nonwoven needle punched geotextile (high elongation, relatively low strength, fluffy surface) is, for the same impact, likely to have a different mode of damage compared to an extruded geogrid (low elongation, high strength, smooth surface).

In the following, six damage mechanisms are presented with their typical appearance and related to the situations where they are likely to occur.

2.1 *Abrasion*

Abrasion is typically caused by a repeated sliding action from an abrasive material on the geosynthetic. This type of damage mechanism typically occurs where the geosynthetic is at the surface (canal revetments, sea shores with washing of sediments up and down, sliding masses e.g solid waste dumped on geosynthetics in landfills). This is a common mechanism where there is cyclic relative motion between geosynthetic and contact soil (railroad applications, temporary roads) (Müller-Rochholz 1996). Figures 2-4 show examples of the visual appearance of abrasion damage.

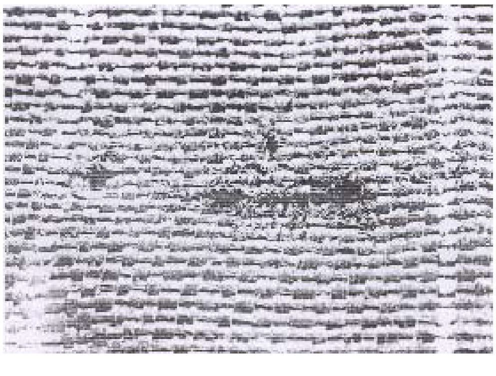

Figure 2. Examples of abrasion of surface of polypropylene woven geotextile (Brady et al 1994).

Figure 2 and 3 are examples from the same test site showing severe damage of a relatively light weight (240 g/m^2) polyethylene woven geotextile while a heavier (400 g/m^2) polyester/polyamide had more surface abrasion leaving the weave itself relatively undisturbed.

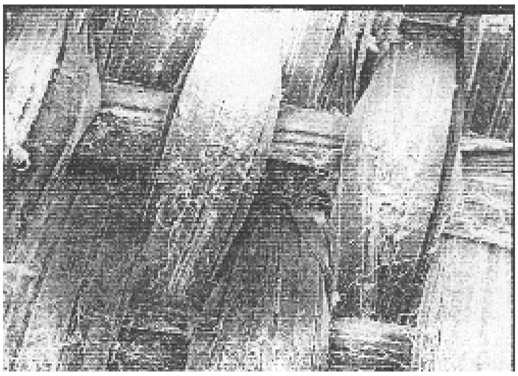

Figure 3. Surface abrasion of woven polypropylene slit film (Brady et al 1994).

Abrasion may occur on all types of geosynthetics, but needle punched nonwovens are especially susceptible to this type of damage as the surface is more easily abraded. Despite what is a common belief and a basic assumption for design and specification, abrasion may also occur with fine grained fill material. Research (Ehrler & Gündisch, 1999) has shown that severe abrasion can occur with relatively small but sharp particles (quartz sand, max diameter 200 µm) in the fill material. This abrasion leads to a considerable loss in strength (up to 50 %) which has to be taken into account.

Abrasion will reduce the thickness of the geosynthetic and hence lead to a local reduction of the strength and possibly also change the filtration properties. Severe abrasion may lead to a total destruction of the geosynthetic as can sometimes be seen, for example when separating geotextiles are exposed in footpaths.

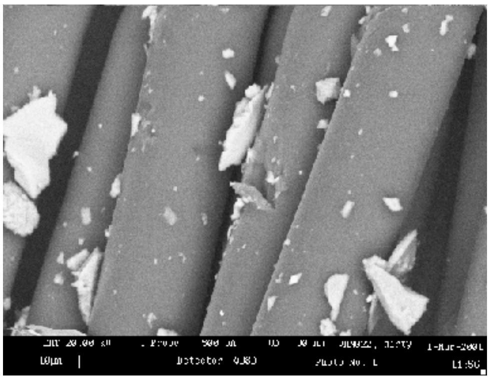

Figure 4. Surface abrasion of polyester yarns after damage testing (Greenwood 2002).

2.2 *Splitting*

Splitting is typically caused when sharp edged fill material is filled directly on the geosynthetic and possibly in combination with compaction with vibrating equipment. It is observed principally in the ribs of extruded polyethylene geogrids. An example from a field trial is presented in Figure 5 (Brady et al 1994).

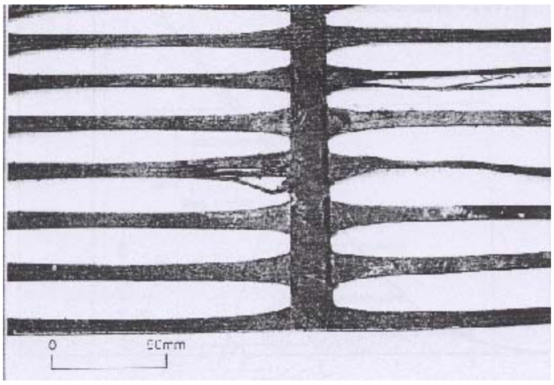

Figure 5. Example of splitting of rib, polyethylene geogrid (Brady et al 1994).

The fill material in this case was a limestone aggregate, which was compacted to refusal using a vibrating compaction equipment. Splitting causes no immediate loss in strength when the split is in the direction of load, but may do so when a biaxial grid splits in the direction transverse to the load.

2.3 *Puncturing*

Puncturing typically occurs when sharp edged fill material is dumped directly on the geosynthetic, or by compaction with heavy equipment over thin layers of the fill material. The situation is likely to occur when geotextiles are used for separation and filtration in coastal revetments or in road and railway structures.

The mechanism is generally related to woven and nonwoven geotextiles (puncturing of geogrids doesn't make much sense). Generally nonwoven geotextiles with a relative low flexibility are more susceptible to this type of damage. The stones will penetrate the geotextile and could reduce or destroy the separation and filtration efficiency. However, investigations in the field (Watn, Eiksund & Knutson, 1998, Chew et al, 1999, Khay, 1998) have shown that even with considerable puncturing damage, the geotextile may still fulfil its function in the structure as the stones will fill the punctured hole.

A typical example of puncturing is presented in Figure 6. This is from a field test (SINTEF report 1997) where a thermally bonded (relatively stiff) nonwoven geotextile is placed on relatively firm subsoil but with a thin layer of soft mud underneath the geotextile. The fill material is a sharp edged stone material. The stones had punctured through the geotextile and into the subsoil. The correspondence of the puncturing of the geotextile and the imprint in the subsoil was clearly visible. During the extraction it could however be observed that despite a number of (relatively small) holes from puncturing the separation function was fullfiled successfully.

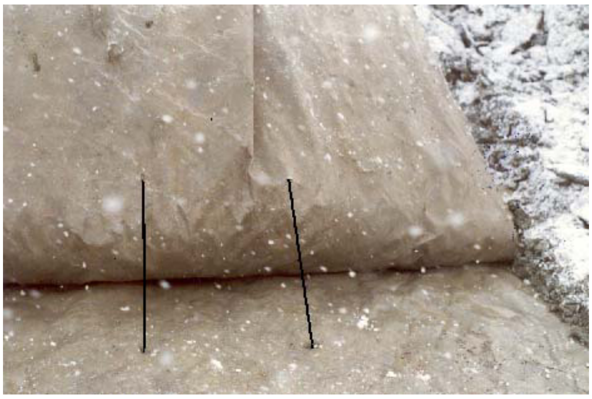

Figure 6. Puncturing of geotextile (SINTEF 1997).

2.4 *Stress rupture*

Stress rupture typically occurs when the geosynthetic is exposed to large loads and deformations, and is typically related to the use of geotextiles for separation on soft subsoil with large diameter fill material. It has also been caused by heavy construction equipment on an access road with a thin layer of backfill over soft subsoil (Richardson 1998). The subsoil will deform and consequently the geotextile will follow the deformation by local elongation. If the geotextile is not flexible the deformation may lead to overstressing of the geotextile causing stress rupture. Following stress rupture the geotextile is no longer capable of fulfilling its function, neither for separation nor for reinforcement.

Figure 7 shows an example of stressing of the geotextile by dumping of large diameter fill material over a soft subsoil. The deformation of the subsoil due to the weight of the fill in this case resulted in local stress rupture of the nonwoven geotextile used as a separator between the fill and the subsoil. The geotextile in this case was a thermally bonded nonwoven whose flexibility was not sufficient to cope with the large deformations of the subsoil.

Figure 7. Geotextile stressed by deformation caused by granular fill material on soft subsoil (Wetting 2002).

Stress-rupture can also occur at the point where a geosynthetic reinforcement is fixed to a rigid structure such as a wall facing. This can cause local stress concentration of strains at the point of fixing.

2.5 *Fibre cutting*

Fibre cutting typically occurs when sharp edged material acts as a "knife" cutting the fibres of the geosynthetics. This mechanism is common if a sharp-edged stone is cutting the geosynthetics resting on a hard base and is most common with woven geotextiles, geogrids and reinforcing strips. The fibres in these geotextiles are relatively thin and may easily be cut, causing a reduction in strength of the geosynthetics (Cancelli and Montanelli 2000). Woven Geogrids and strips are however commonly coated (e.g. by PVC) and the coating will reduce the susceptibility for cutting of the fibres and as such reduce the reduction of tensile strength. Figure 8 shows an example of cutting of fibres in a polyester strip. The strip in this case was covered with a crushed sharp-edged limestone aggregate.

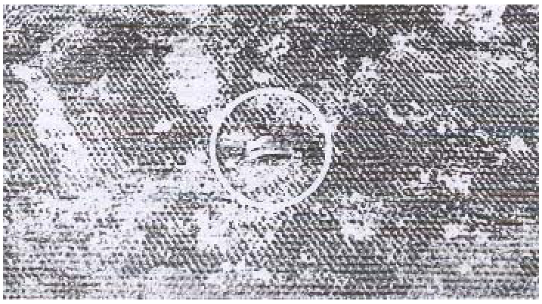

Figure 8. Cutting of fibres in surface of polyester based strip geogrid (Brady et al 1994).

2.6 *Tearing*

Tearing occurs when the geosynthetic is subjected to tearing forces tending to rip the geosynthetic. Tearing is commonly a mechanism occuring once the geosynthetic is initially damaged by another mechanism like stress rupture or fibre cutting leading to a tear propagation from the overstressing of the remaining fibers. Tearing is commonly a failure mechanism in non woven geotextiles subjected to overstressing e.g at a sharp edge. Figure 9 shows an example of tearing of a nonwoven needle punched geotextile which occurred during extraction when the already damaged material was pulled by the excavator grab.

Figure 9. Geotextile with severe damage from tearing (SINTEF report 1997).

Figure 10 shows a close up of a geotextile with tear damage. This occurred when a non-woven needle punched geotextile was used as a separator between a fill material with relatively large diameter stones over firm subsoil. As can be seen the fibres have torn leaving a hole in the geotextile.

Figure 10. Hole in non-woven geotextile caused by tearing of fibers (Wilmers 2000).

3 LABORATORY TESTING

The need for determining the susceptibility to damage for the various geosynthetics has led to several attempts to develop laboratory test methods for this purpose. As previously mentioned there are a number of different damage mechanisms and in combination with a wide range of different products this inevitably leads to the fact that no single test method is able to give the full picture. There are test methods which both in the title and in their set-up are intended to cover the aspect of installation damage. It is however fair to say that there is still a lot of work to be done before a good correlation is established between results found in the laboratory and experiences from the field. The types of tests are divided into index tests and performance tests. The index tests are intended to provide general product properties, i.e for the geosynthetics alone. These properties can then, from experience, be linked to susceptibility to damage. The performance tests are intended to give information of the geosynthetics behaviour in service, i.e typically in combination with a surrounding soil. In this chapter we will give a presentation of some tests which are relevant for evaluation of susceptibility for damage. We will try to link the different test methods to damage mechanisms and their relevance for different product types.

3.1 *Index tests*

There are a number of index tests, which can be used for measuring geosynthetics properties relevant for evaluating damage and damage susceptibility. Table 2 summarises some of the standard index tests that are commonly used for this purpose.

Table 2. Summary of common index test for evaluating damage susceptibility of geotextiles

Classification	Test Name	Reference Code
Indirect test	Mass per unit area	EN 965 : 1995 E EN ISO 9864:1990
	Thickness	EN ISO 9863:1990 EN 964-1 or –2
	Wide width tensile	ASTM D4595 : 1994 EN ISO 10319 : 1993
	Grab tensile	ASTM D 4632
	Burst resistance	prEN 14151
Abrasion test	-	EN ISO 13427
Penetration Test	CBR plunger	EN ISO 12236 : 1996 GRI Test: GS1 BS6906 : Part 4 : 1989
	Rod plunger	ASTM D4833–88
Dynamic or impact test	Cone drop	BS6906 : Part 6 : 1990 DIN EN 918 EN ISO 13433
	Modified drop cone	AS 3706.5
	Pendulum impact	GRI Test: GS2-86

Note : GRI stands for Geosynthetic Research Institute

In the following we will review some of the tests and the extent to which they contribute towards the evaluation of damage susceptibility.

3.1.1 *Mass per unit area*

Mass per unit area can be determined by standardised test methods like EN 965. The test can be used for all types of geosynthetics. A number of studies (SINTEF report 1997, Koerner & Koerner 1990, Watts & Brady 1994, Bräu 1996) have indicated a good correlation between the mass per unit area and the susceptibility to damage. The mass per unit area physically indicates the amount of polymeric material within a unit area. A higher specific mass would suggest a more densely packed structure, hence greater effort and force is required to rupture it. In some countries a minimum value is specified, e.g. for separation functions. It should however be noted that mass per unit area alone is not sufficient as a basis for comparison between different types of products as the susceptibility is also related to polymer type, fibre type, production technology etc. (Troost and Ploeg 1990). The correlation is therefore generally limited to similar types of products. Accordingly the mass per unit area should not be used as a single criterion for evaluation of damage susceptibility.

3.1.2 *Thickness*

Determination of thickness of the geosynthetic can be done either with or without loading according to the standardised test method EN 964-1. The test can be used for all types of geosynthetics. As for mass per unit area there is a logical relationship between the thickness and the susceptibility to damage, which has also been found in several studies (Chew et al 2000, Bonaparte et al 1998). The thickness is especially relevant for abrasion. However there is great variability, depending on the type of product, and it is not possible to establish a general relationship.

3.1.3 *Wide width tensile test*

Wide width tensile tests are generally performed both in the machine and cross directions of the geosynthetic, using the standardised test method EN ISO 10319. The test can be used for almost all types of geosynthetics. The test can be used to determine the tensile stress-strain relationship and also to calculate corresponding figures such as strain energy (area under the stress-strain curve) and the energy index (multiplication of tensile strength by corresponding strain) (SINTEF report 1996, Nancey et al. 2001). As will be reviewed later in this article there is a relationship between the characteristics found in the wide width tensile test and the susceptibility to damage. It should however be noted that this a relative relationship between similar types of products and can not be used to compare different types of geosynthetics.

The tensile test may also be used to evaluate the effects of damage, e.g. after installation trials for reinforcing geosynthetics. It should be noted that determination of reduction factor for the tensile strength after an installation test should preferably be performed using large test samples to give a reasonable representation of the reduction over the geosynthetic (Brady et al 1994).

3.1.4 *Grab tensile test*

The grab tensile test can be performed according to ASTM D 4632. The grab tensile test is commonly used as a relatively quick and cheap quality control for the strength and elongation of a geotextile. As for the wide width tensile test results from the grab test can be used to indicate the relative resistance against damage for the same type of products (Christopher & Elias 1998).

3.1.5 *Trapezoid tearing strength*

Trapezoid tearing strength can be performed according to ASTM D4533. The test is intended to measure the force required to continue or propagate a tear in woven or non woven geotextiles (Christopher & Elias 1998). In the European standardisation work the work item on such a tear propagation test is to be deleted. The reason was that no correlation was found between the characteristic determined by this test and the behaviour in the field.

3.1.6 *Burst resistance*

Burst strength can be determined according to prEN 14151 or ASTM 3786. The test is intended to measure the resistance against failure from an "out of plane" deformation (Christopher & Elias 1998).

3.1.7 *Abrasion test*

The resistance against abrasion can be tested according to EN ISO 13427. The test is intended to measure the resistance against damage for geotextiles as determined by a "sliding block". Testing (Müller-Rochholz 1996) indicated a good correlation between this type of test and results from a rotating drum with basalt stones. However the correlation with field behaviour is questionable.

3.1.8 *Puncture test*

This can be considered as a more direct test that simulates the strength of geotextiles subjected to some deformation. The penetration test measures the maximum force developed as a rod, or plunger, is forced into the plane of the geotextile at a constant rate. The rationale behind such a test is the understanding that the geotextile mobilizes tensile strength to resist rupture as the plunger is being pushed into its plane. A geotextile with greater tensile strength would therefore require a larger vertical plunger force. This tension force developed by the geotextile is a function of the vertical force developed along the axis of the rod (Cazzuffi et al., 1986). Therefore, by measuring force developed in the rod, the resistance of the geotextile against puncture can be quantified. The penetration type of tests can be conducted according to EN ISO 12236 (CBR Plunger test) or ASTM D4833 (Rod plunger test). The tests are suitable for non woven geotextiles and for most wovens. The results from the test can be used to evaluate the relative susceptibility for damage typically caused by stressing of the geotextiles.

The most widely used penetration test is the CBR plunger test. Researches were conducted with the CBR Plunger Test and its results were correlated with the standard wide width tensile test. It was concluded that there was generally good correlation between the tensile strength measured from wide width tensile test and those calculated from CBR Plunger Test (Cazzuffi et al., 1986; Murphy and Koerner, 1988; Moritz and Murray, 1982; Wong et al, 2002).

The Rod Plunger Test follows the same rationale as the CBR Plunger Test. The main difference between the two tests is that the Rod Plunger Test uses an 8-mm diameter chamfered rod tip on a 45-mm diameter geotextile specimen, while the CBR Plunger Test uses a 50-mm diameter flat tip on a 150-mm diameter geotextile specimen. Because the plunger tip is smaller, the Rod Plunger Test suffers from greater inconsistency in its result due to the fact that the fibres of the geotextile can slide around the tip, thereby forcing a piercing action and tensioning effect to enforce a rupture. Furthermore, the smaller rod tip and the smaller geotextile test area will also have a better chance of testing a localised “weak spot” on the geotextile which may not be representative. The standard Rod Puncture test has also been modified to investigate the effect of pre-tension of the geotextile on the puncture resistance (Ghosh, 1998). It was found that a radial pre-tension actually lowers the puncture force and the calculated failure strain of the geotextile (Figure 11).

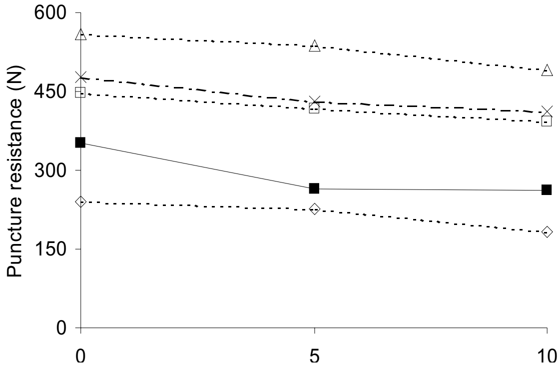

Figure 11. Effect of pretension on Plunger test: Higher pre-strain lead to lower plunger force for 6 non-woven geotextiles (redrawn after Ghosh, 1998).

3.1.9 *Impact test-cone drop test*

The dynamic impact test quantifies the resistance of geotextiles against damage by measuring the amount of damage caused by an impact force with an object. A smaller amount of damage would suggest a higher puncture resistance. The most common test of this nature is the Cone Drop Test. The impact resistance can be tested according to EN 918.

The Modified Drop Cone Test follows the same principle, but is modified to allow for a greater drop height so as to test thicker and heavier geotextiles (Lawson, 1992). The Pendulum Impact Test is another example of a dynamic test, though not so commonly used. This test measure the energy required to penetrate and rupture a geotextile in one of three specified failure types. This test was modified from the Spencer Impact Test (Koerner, 1998) and can be used to test geotextiles, geomembranes and geocomposites (Koerner et al., 1986).

The test is generally most suitable for non-woven geotextiles and some types of wovens. There is a considerable amount of experience with this test method, and many attempts have been made to correlate empirically the field behavior related to damage typically caused by sharp edged stones and this test. An empirical correlation with field behaviour based on damage, typically caused by penetration of sharp edged stones, has been established (SINTEF report 1997). However, actual field condition for a puncture to take place is far more complex than a simply radial clamped condition. Hence, performance tests are recommended.

3.2 *Performance tests*

The performance tests related to damage are intended to provide information directly related to the application of the geosynthetic. In general performance tests are designed to replicate the conditions in the field.

3.2.1 *Laboratory test-Damage during installation*

In the European standardization two work items have been identified to develop test methods to simulate damage during installation. This work is divided into two parts, Part 1: Installation in granular materials and Part 2: Installation on soft subsoil.

The test method for installation in granular materials ENV 10722-1 requires the use of a rigid split box 350 mm x 350 mm x 155 mm. The layout of the box is shown in Figure 12.

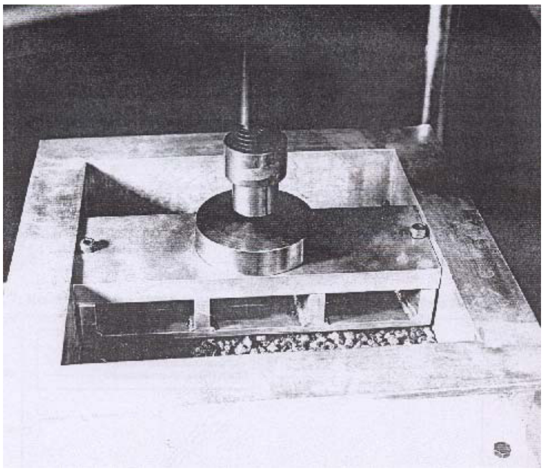

Figure 12. Test box, ENV 10722-1 Damage during installation (Greenwood 1998).

The geosynthetic is placed between two layers of an artificial aggregate (sintered aluminium oxide) and then subjected to a cyclic loading by a rectangular plate. After the completion of the test the geotextile sample is extracted and evaluated for damage by visual inspection and by wide width tensile tests. The test method was initially developed in France to evaluate damage for reinforcing geosynthetics but is now covering all types of applications and geosynthetics products.

Experience with the test method (Cazuffi 2001, Greenwood 1998, Khay 1998) indicates that there is a correlation between the results from the test and the behaviour in the field. However the correlation is not unique, in that a high resistance to damage in the test indicates high resistance in the field, but the contrary is not true. This means that a geosynthetic which loses much of its strength in the test may still have low damage in the field. The test method seems to be more relevant for evaluating the susceptibility to damage caused by abrasion and cutting of fibres. Accordingly the results from the test should be used with caution and not used as a single indication of susceptibility to damage.

ENV 10722, Part 2 installation of soft soil is under preparation and a first draft is intended circulated in the technical committee in 2002.

4 FIELD TESTING

Evaluation of the susceptibility to damage based on laboratory testing, and especially on index testing, can be difficult. The evaluation should therefore be relatively conservative in its approach. If a less conservative approach is required, or when the consequences of damage can be severe, site-specific field trials should be used instead. This is particularly the case for determining the reduction in strength for soil reinforcement.

The field tests are generally site specific, but guidelines for the installation and extraction of samples from a simulated site environment have been developed (Bush 1998, Watts and Brady 1990). Visual damage is classified in terms of holes, cuts, scuffs etc, and converted to numbers per square meter. Based on these guidelines some national standards have been developed for this purpose (British Standard BS 8006, annex D, ASTM D 5818).

4.1 *BS 8006- annex D. Site damage test*

The guidelines in BS 8006, annex D, are intended for the determination of the material or reduction factor for damage for soil reinforcement. They describe the layout and procedure for a site damage test. The approach in these guidelines is:

a) to place the reinforcement under a range of fills that conform to grading limits of the Specification for Highway Works (Department of Transport 1993) and to compact those fills in accordance with and in excess of that specification

b) to recover the reinforcement and measure its tensile strength and stiffness, and assess the damage

c) quantify any loss of strength of the reinforcement due to the construction process.

The test site consists of nine bays each 3.5m x 3.5m. The geosynthetic reinforcement is installed and compacted with three different types of fill material in layers with a minimum thickness of 150 mm or 1.5 times the maximum particle diameter of the fill material, whichever is the greater. This is combined with three levels of compaction: standard compaction, overcompaction and double layer compaction.

After the installation and compaction the geosynthetics reinforcement is recovered with due care and the level of damage is evaluated based on visual inspection and standardised tensile testing of samples from the extracted geosynthetic. The results from the tensile tests of specimens from the exhumed geosynthetic are compared with those from tensile tests on virgin control samples from the same batch. For the visual assessment the damage is classified into four categories: general abrasion, splits, cuts and bruises.

The method described in BS8006 gives satisfactory guidelines for the installation and compaction of the fill. However major deficiencies are the lack of guidance for selecting the specimen for the tensile test from the exhumed sample, and for the determination of the partial factor (Austin, 1998).

Field tests generally give a good basis for site specific evaluation of susceptibility to damage. However performance of field tests are time consuming and expensive and relate only to the conditions under which they have been performed

5 GEOTEXTILES FOR SEPARATION IN ROADS

5.1 *Installation damage in the construction of road pavements*

The most common use of geosynthetics is as geotextiles for separation and filtration in roads. For this application there is generally no risk of loss of life even though that may be so in some specific cases. The geotextile may fulfil its function even with a moderate level of damage. Accordingly the evaluation of susceptibility for damage is not as critical as in a structure where the consequence of failure caused by damage are more severe. The evaluation of damage for these "low risk" applications will typically be based on experience and on the requirements in the geotextile specification based on index tests.

Experience had shown that the damage to a geotextile used in a permanent road originates mostly in the installation and construction phase. For temporary roads the design aims to provide sufficient performance of the geotextile for a limited period and at a lower level than for a permanent road. However, in both cases the typical damage mechanisms are the same and damage susceptibility can be evaluated according to the same principles.

Typical damage mechanisms for this application are the punching of stones through the geotextile during installation and compaction of fill material and tensile rupture caused by heavy construction traffic.

In the Nordic countries there is more than 20 years' experience with a classification system for non-woven geotextiles for separation and filtration in roads. The original system used by the Norwegian Directorate of Roads divides the geotextiles for separation and filtration in roads into four application classes, 1-4 (Alfheim og Sørli 1977, SINTEF report 1996). Application class 1 is used only for filtration purposes while application classes 2-4 are used depending on the grading and angularity of the fill material. Class 4 is used for the most severe conditions. The criteria for evaluation of the relevant application class are based on the results of the static puncture test (CBR-test) and the cone drop test. Four types of criteria are used: minimum tensile strength (calculated from the CBR-test), minimum tensile strain strength (calculated from the CBR-test), strength increase from 20-70% strain (calculated from the CBR-test), and hole size from the cone drop test. The tested geotextile obtain points dependent on the results related to these criteria and the total number of points is then the basis for the evaluation of relevant application class.

Over the years there has been a considerable development both related to products and test methods and there was a clear need for a revision of the system. In 1994 a research project was started in Norway aiming at preparing a new set of specification requirements for this application. A major part of this project was focused on the deformation and damage of geotextiles during the installation and compaction phase. In 2000 a new project was started as a continuation of this aimed at developing common Nordic guidelines for specification and control. A collection of experience related to geotextile damage, combined with laboratory tests, model tests and field tests was carried out as the basis for the development of these new specification systems. The following is a summary of the results obtained in these projects and how they can be implemented into the evaluation of damage susceptibility.

5.2 *Laboratory index tests*

The index tests included cone drop tests, static puncture tests and wide width tensile tests. The tests were performed on virgin samples and on samples extracted after the puncture and cone drop tests. In addition the effect of thermal cycling and stress-strain behaviour under frozen conditions were studied. Six different non-woven geotextiles were tested, three corresponding to class 2 and three corresponds to class 3. The geotextiles used in the laboratory tests corresponding to class 3 are listed in Table 3.

Table 3. Class 3 geotextiles used in the laboratory test.

Ref.	Type of product	Nominal mass per unit area (g/m^2)
SNP 3A	Staple fibre, needle punched, polypropylene	190
CNP 3B	Continuous filament, needle punched, polypropylene	160
CTP 3C	Continuous filament, thermally bonded, polypropylene	190

A summary of the results from the static puncture tests and the falling cone test on virgin samples for class 3 products is shown in Table 4.

Table 4. Results from initial index testing of the geotextiles.

Ref	Measured mass per unit area	Static Puncture test		Falling cone
	(g/m^2)	Max. force (N)	Displacement (mm)	Average hole diameter (mm)
SNP 3A	197.8	2380	57	14
CNP 3B	171.5	2252	44	24.2
CTP 3C	190.8	1970	50.8	19.1

Typical load-displacement curves from the static puncture test are shown in Figure 13. Observe the differences in initial stiffness between the different geotextiles.

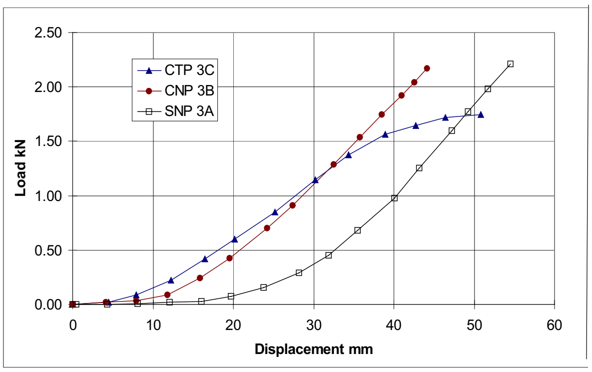

Figure 13 Results from CBR testing of geotextiles

5.3 *Model tests*

The large scale laboratory testing was performed in a 12.5 m long and 1.8 m wide test bin filled with a 650 mm thick layer of soft clay with 2-3 kPa undrained shear strength. The geotextiles were placed on the clay and covered with 150 mm of crushed stone as shown in Figure 14. The geotextile test samples were 2 x 1.8 m. Cyclic and static load was then applied to the bearing layer by means of a circular plate with diameter 250 mm. The geotextiles used in the large-scale laboratory test are listed in Table 3.

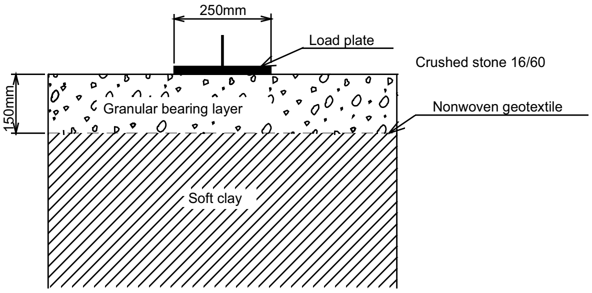

Figure 14. Model test. Bearing layer structural layout.

A cyclic load with frequency 1 Hz and amplitude 0-4 kN was applied to the load plate. A load of 4 kN corresponds to an average applied stress under the load plate of 81.5 kN/m^2. The gradual increase in displacement of the geotextile beneath the load plate was measured during the test, the resulting deformation profiles after 1000 cycles are shown in Figure 15.

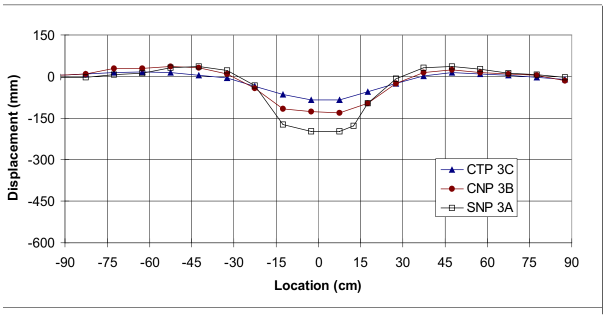

Figure 15. Measured vertical displacement profile of the geotextiles after completed load test.

There are considerable differences in the measured deformations and strains in the geotextile in the load test. The observed relative deformations in the model test, Figure 15, correspond well with the load displacement relations, Figure 13, measured in the static puncture test. The calculated average strains of the geotextiles after 1000 cycles were measured to be 10.3%, 4.6% and 1.4% for SNP 3A, CNP 3B and CTP 3C, respectively. Converted to displacement in the static puncture test these strains correspond 19 mm, 12 mm, and 7 mm displacement. Figure 16 shows that the load corresponding to these strain levels is approximately 0.08 kN for all the three geotextiles. In the same figure, the area under the load displacement curve, named as the deformation energy, is shaded. Note that the deformation energy based on these results is about the same for all the tested geotextiles, even with large differences in the deformation level.

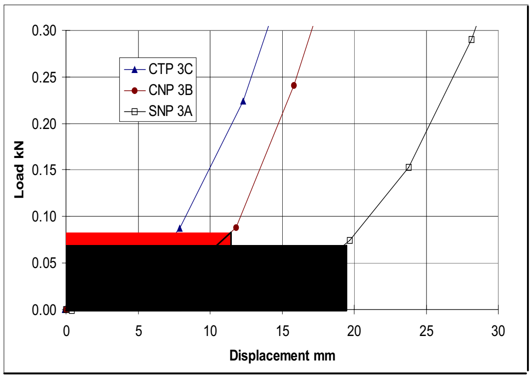

Figure 16. Force-displacement relationship related to measured deformation for the geotextiles in the model test.

5.4 *Field tests*

The field tests were performed to try to correlate the results of the laboratory index tests and the model tests with observations in the field.

5.4.1 *Test set up*

The test was performed outdoor on frozen uneven ground. The material in the ground consists of fill masses containing silt, sand, clay and occasional stones. Due to rainfall just before and during the installation the upper 50-100 mm of the subsoil was saturated and muddy during installation. As the temperature decreased during the test, by the time the geotextile was extracted this upper layer had frozen. Geotextiles corresponding to class 4 used in the field test are listed in table 5.

Table 5. Geotextiles involved in the field test.

Reference	Type of product	Mass per unit area (nominal) (g/m^2)
CNP 4A	Continuous filament, needle punched, polypropylene	320
SNP 4B	Staple fibre, needle punched, polypropylene	330
SNP 4C	Staple fibre, needle punched, polypropylene	320
CTP 4D *)	Continuous filament, thermally bonded, polypropylene	350
SNP 4E	Staple fibre, needle punched, calendered on one side, polypropylene	300
CTP 4F **)	Continuous filament, thermally bonded, polypropylene and polyethylene	350

*) Not previously classified in class 4 in Norway
**) Tested in a separate field test

The results from the performed index tests on these geotextiles are presented in Table 6.

Table 6. Results index test for geotextiles in field test.

Ref	Mass per unit area (measured)	CBR-force	CBR-strain (calculated)	Cone drop
	g/m^2	N/mm	%	mm
CNP 4A	310.7	34.32	60.86	15.90
SNP 4B	359.0	38.28	70.78	12.10
SNP 4C	314.4	26.17	87.08	10.10
CTP 4D	353.1	33.87	70.12	13.90
SNP 4E	302.3	28.44	85.46	13.10
CTP 4F	345.9	38.9	51.4	20.9

The geotextile CTP 4F was tested separately together with CTP 4D, which was also tested together with the other products. The results for CTP 4D are used as reference basis for comparing the results. The field test also included five geotextiles of class 2. The level of damage on three of the geotextiles of class 2 were so severe that evaluation was not possible. The qualitative evaluation is therefore restricted to the geotextiles of class 4. The load deformation curves from the static puncture test are shown in Figure 17.

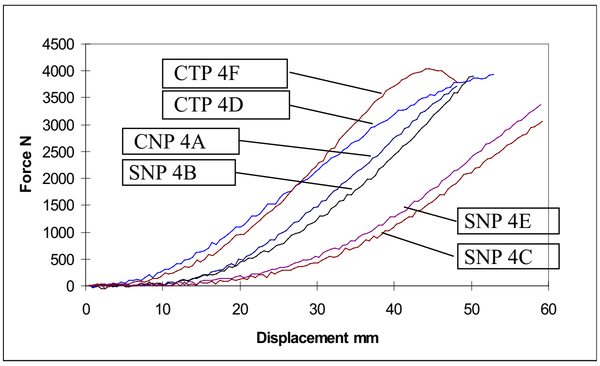

Figure 17. Load-deformation curves from CBR-testing.

The set-up for the test fill is shown on Figure 18.

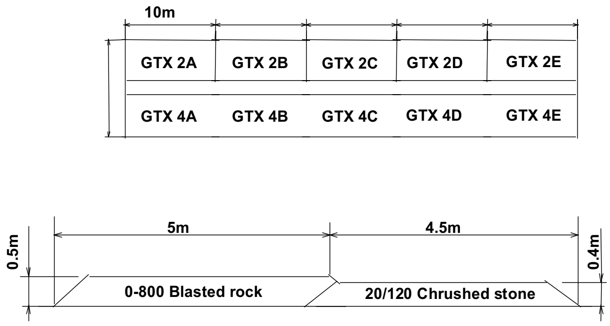

Figure 18. Test set-up of field test.

The geotextiles were placed directly on the ground and then covered with fill material by the use of a pay loader. The covering was performed sideways to ensure that each of the geotextiles was treated equally. For the class 4 material, blasted rock with a maximum diameter of 800 mm was used for the fill. Since the largest rock fragments were flake shaped, a fill height of 500 mm could be achieved. The fill material was compacted with a heavy vibrating roller with three overpasses along the centre line and three on the shoulders of each fill, Figure 19.

Figure 19. Compaction of fill.

One week after the installation the fill material was removed. The upper part of the fill material was removed carefully with an excavator. The end of each geotextile was then tied to the excavator and carefully lifted out.

The amount of damage and deformation of the geotextiles were observed during extraction. Visual inspection during extraction identified some damage in terms of holes on all the geotextiles. The degree of damage varied. The geotextiles SNP 4B and CTP 4D were less damaged than average, SNP 4C and CNP 4A received an average level of damage, while SNP 4E and CTP 4F were the most severely damaged.

In Figure 20 the extraction of geotextile CNP 4A is shown. The geotextile is a continuous filament, needle punched, polypropylene geotextile, which has a mass per unit area of about 310 g/m^2, a medium tensile strength (CBR: 60 N/mm), medium to low elongation at break (60%), and a medium to large hole diameter in the cone drop test (15 mm). During excavation it was noted that the surface under the geotextile was relatively even, and that the geotextile had an average level of damage compared to the other geotextiles.

Figure 20. Extraction of geotextile CNP 4A.

Figure 21 shows the extraction of geotextile CTP 4D. This is a continuous filament, thermally bonded, polypropylene geotextile. It has an area weight of about 350 g/m^2, medium tensile strength (CBR-34 N/mm), medium elongation at break (70%) and medium hole diameter with cone drop (14 mm). During the extraction it was noted that the surface under the geotextile was quite even and the level of damage was low.

Figure 21. Extraction of geotextile, CTP 4D.

Figure 22 shows the extraction of geotextile SNP 4E. The geotextile is a staple fibre, needle punched, polypropylene geotextile which is calendered on one side. It has an mass per unit area of about 300 g/m^2, a relatively low tensile strength (CBR-28 N/mm), high elongation at break (85%) and a medium hole diameter in the cone drop test (13 mm). During extraction it was noted that the surface under the geotextile was quite uneven and the level of damage was moderate to high.

Figure 22. Extraction of geotextile SNP 4E.

During extraction it was observed that there was a clear difference in the evenness of the subsoil under the geotextiles. In general the subsoil was more even under the products with a high initial stiffness than under the others.

The general level of damage on some of the geotextiles corresponding to class 2 was too severe to be able to make a quantification of the damage. Considerable differences in damage susceptibility between the different geotextiles could however be observed from the visual observation, Figure 23.

Figure 23. Extraction of class 2 geotextiles.

It should be noted that all the class 4 geotextiles, even though there were differences, had fulfilled the separation function reasonably well. The most severely damaged geotextiles would however have failed to act as a filter.

The observed damage susceptibility for the class 2 geotextiles follwed the same pattern as the observations on the class 4 geotextiles. The two geotextiles having the least damage had fulfilled their separation function reasonably well, while the three most damaged had not.

After extraction the samples were brought to the laboratory where the damages (number and size of holes) were counted and measured. Other types of damages could be observed, such as abrasion and deformation, but the quantification is only related to holes. The distribution of holes within different diameter ranges is shown in Figure 24.

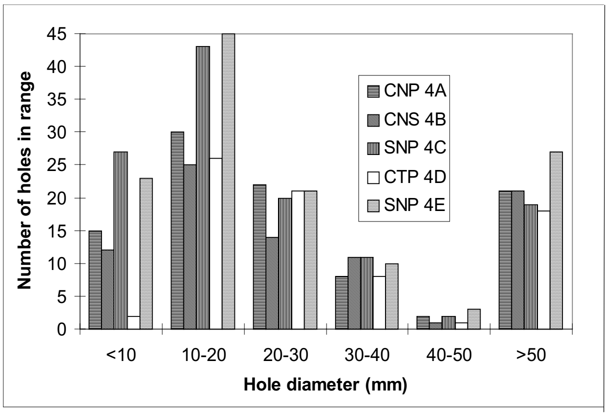

Figure 24. Distribution of holes related to diameter .

It can be noted that the small diameter holes (less than 20 mm) generally relate to puncturing from stones through the geotextile, while the larger diameter holes generally represent stress rupture and tearing.

In order to correlate the observed damage with the results of the index tests, the degree of damage on a geotextile is defined as the sum of the measured hole diameters in mm. The resistance to damage for a product can then be defined as the average damage for all the geotextiles (in mm) divided by the damage for the individual geotextile in mm. Table 7 shows the results of these calculations, in which the resistance to damage is a dimensionless number which is greater than unity for the less damaged materials and less than unity for the more heavily damaged products. A factor of 1.15 means 15 % less damage than the average. A verbal classification of the resistance to damage (low-medium-high) based on overall evaluation of the geotextiles is also included.

Table 7. Resistance against damage.

Material	*Damage* (mm)	*Verbal classification*	*Resistance to damage*
CNP 4A	2793	Medium	1.07
SNP 4B	2613	Low	1.15
SNP 4C	3157	Medium	0.95
CTP 4D	2655	Low	1.13
SNP 4E	3759	Medium/High	0.80
CTP 4F	-	High	0.40*)

*) Based on a scaling of the results using CTP 4D as a reference material

As CTP 4F was tested in a separate test the results can not be compared directly with the others. The additional field test with geotextiles CTP 4D and CTP 4F used less heavy compaction equipment resulting in considerably less damage on CTP 4D compared with the other materials.

However, by using the results for CTP 4D as a reference, a comparative level of damage has been estimated for CTP4F. This method of estimating the degree of damage is quite uncertain, since it is based on the damage in only one reference geotextile, but still it illustrates the much higher degree of damage found for CTP 4F compared to the other products tested.

The resistance to damage and the results from the index tests are used to evaluate the requirements in the original classification system. The relevance of an index test with regard to survivability of the geotextile is studied by correlating the parameter with the resistance against damage as defined above. The mass per unit area is included in the correlation. The results of the correlation are shown in Table 8. The test results from geotextile CTP 4F were not included in the correlation.

Table 8. Correlation index test results and damage resistance.

Parameter	Correlation
Weight/m^2	0.81
Strength incr. 20-70%	-0.11
Failure strength	0.84
Strain to failure	-0.77
1/(Cone drop hole diam)	-0.26
Number of points	-0.36

The parameters showing the best correlation with the resistance against damage is the *push through strength* from the CBR test and the *mass per unit area.* The criteria for *strength increase*, and *the number of points used as classification criteria* show poor correlation. The *strain to failure* and the *cone drop hole diameter* show a fair negative correlation. The poor correlation for the number of points is remarkable. The low correlation is mainly caused by the fact that the two geotextiles with the most damage have full score based on the criteria in the index test.

The results of the index test do not indicate an obvious candidate among the parameters that would explain why CTP 4F should be so severely damaged. In the primary tests the best correlation with the resistance to damage was found for the mass per unit area and the tensile strength. This was not the case for CTP 4F, which has a high score for both parameters. Geotextile CTP 4F has, however, relatively low values both for elongation at break and the inverse of the cone drop hole diameter. These low values may partly explain the higher degree of damage for the CTP 4F geotextile.

Both CTP 4D and CTP 4F are thermally bonded geotextiles, having a high initial stiffness. As shown in Figure 16, the force-displacement relations from the static puncture test are relatively similar for these two geotextiles compared to the other geotextiles tested. The large difference in degree of damage between CTP 4D and 4F is not reflected by similar differences in the index test results, with a possible exception for the deformation at failure and the results from the cone drop test. The damage on CTP 4F is therefore probably caused by material properties not measured in the index tests. A possible explanation may be properties related to the brittleness of the geotextile and may possibly be correlated to the tear propagation properties.

5.5 *Conclusions from the project*

The project has provided useful information for evaluating relevant properties and requirements for geotextiles to be used for separation and filtration in roads. There are considerable differences in stress-strain properties of the geotextiles, which are reflected in the behaviour in the field. Noticeable differences are found in the susceptibility to damage during installation. The criteria used in the old system (Alfheim & Sørli 1977) for classification and specification do not appear to reflect correctly the behaviour in the field. A revision of the criteria was therefore clearly needed.

The deformation of the geotextiles when subjected to loading, that is rutting during installation and construction, is clearly linked to the initial tensile stiffness of the geotextile. The criterion for geotextile survivability has to reflect the behaviour during installation, construction and service lifetime. A criterion has therefore been developed based on a combination of requirements for deformation energy and remaining stress and strain to failure. The criterion is based on the assumption that the geotextile acts together with and deforms with the subsoil. A soft subsoil will have relatively low resistance to deformation and the geotextile should then either deform together with the subsoil (be highly flexible) or be able to withstand the deformation (have high strength) to avoid damaging the geotextile (Rathmayer 2000).

The principle for a strain related energy criterion is presented in Figure 25.

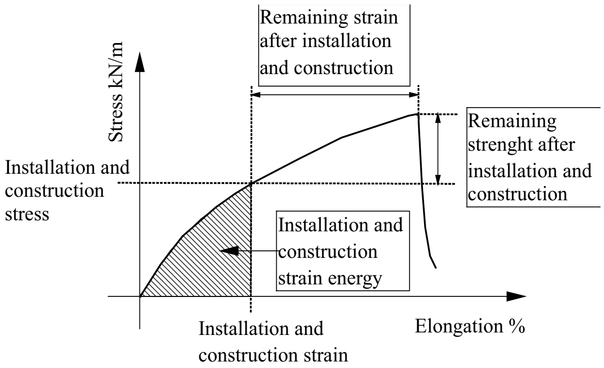

Figure 25. Survivability criterion principle.

The deformation energy should be chosen with regard to the type of fill material, construction equipment and type of subsoil.

On a more firm subsoil the damage mechanisms are likely to be more related to abrasion or puncturing and these requirements have to be covered by other characteristics of the geotextile.

6 COASTAL REVETMENT STRUCTURES APPLICATION

6.1 *Installation damage for coastal revetment applications*

Geotextiles are gradually replacing traditional graded granular filters used in coastal revetments, dams, riverbanks and breakwaters to protect these structures against wave erosion. This is because it is more cost effective to install a geotextile filter than laying a graded granular filter, and yet does not compromise the hydraulic performance of the finished structure to long term wave erosion. Extensive research on the hydraulic behaviour of geotextiles filters has aided the task of selecting geotextiles with the right opening size to meet the filtration criteria. However, there is inadequate information to help engineers choose appropriate geotextiles that have sufficient mechanical robustness to resist damage during construction.

This lack of knowledge has made it difficult for engineers to know whether a geotextile that has been designed for filtration function can survive the installation process without being damaged. In most coastal revetment and river bank protection projects, heavy rocks, more commonly known as armour stones, are often placed above the geotextile filter, which is laid over the site soil that is to be protected from wave erosion. In many instances, the armour stones are usually dropped onto the geotextile from some height. Such a practice is economical and fast, but brings with it a very high chance of puncturing the geotextile if an improper geotextile was selected and/or too heavy an armour stone was released from too high a height. The hydraulic performance of the geotextile may be affected as a result of a puncture, and hence the stability of the finished hydraulic structure may be compromised in the long term. In some reported cases, this has led to subsidence of the ground along the coastline where the geotextiles have been punctured (Lawson, 1992).

Often very general and uneconomical guidelines have been used to guide engineers and contractors in selection and installation of geotextile filters to prevent extensive installation damage occurring. This conservative approach has often resulted in designers specifying unnecessarily thick geotextiles or in contractors adopting a construction procedure that is uneconomical and not productive. The approach usually originates from past experience and often stems from a too simplistic approach in understanding how and why geotextiles are punctured when armour stones are dropped. This has led to the incorrect use of standard index tests to quantify the puncture resistance of geotextiles and an incorrect assumption that geotextiles with certain higher mechanical properties are more resistant to puncture.

Typical damage mechanisms, for this application, are punching of holes during the rock dropping stage. These holes, depending on the subsoil condition, can be of tensile failure type (i.e. puncture failure mode) or cutting failure type (i.e. cutting failure mode). Some minor variation in-between the two is also possible (e.g. tearing failure mode) or the combination of these.

Singapore has been expanding the area via sea reclamation. Up to now more than 10% of the nation's area was reclaimed through the major sea reclamation projects over the last 25 years. In 1998, a research project was initiated at the National University of Singapore, with support from the government agencies and the industrial partners, to review and come out with a new specification for revetment filter design pertaining to safeguard against installation damage. A major part of this project was focused on appropriate laboratory tests and the field performance test to evaluate the damage susceptibility of geotextiles from the installation phase. More than 800 instances of rock dropping were conducted in order to develop a standardised drop test for this application (Chew et al, 1999; Wong et al, 2000). The concept of tensile-elongation energy was reviewed and considered to be more appropriate in evaluating the damage resistance of the geotextiles during the selection stage. The selected product also needs to satisfy the drop test based on the proposed Standardised Drop Test conducted prior to the selection of the products. An exhumation test is also included in the contract period to gain more confidence in the selected products and in the construction procedure. All these were incorporated into a new specification for the new generation of major reclamation projects in Singapore (e.g. Tuas Reclamation Project by Jurong Town Corporation, and Tekong Reclamation Project by Housing Development Board).

This section will give a brief review of the development of laboratory tests, model tests and field tests carried out for the development of these new specification systems. We will give a review of the results obtained in these projects and proposed how they can be taken into account for evaluation of damage susceptibility.

6.2 *Types of damage for revetment filter constructions*

The prevailing damage in this application is due to the impact of rock onto the geotextile when it is released from a height. This form of mechanism that causes perforation of textile materials can be considered as part of penetration mechanics. When a textile material is subjected to impact by a projectile, the textile material may respond in one of two extreme ways. The first is to resist deformation by instantly mobilizing very high tensile forces under very low strain to counteract the sudden surge of force exerted by a fast moving projectile upon impact. For this to happen, the textile must possess very high modulus and be tightly woven together. The fibres of the textile must also pos-sess high strength individually. The wave speed of the textile, which is a function of its modulus, indicates the textile's ability to resist perforation (Laible, 1980). If the wave speed of the tex-tile is of a magnitude lower than the stress wave velocity created by the impact, the fibres will break and penetration of the textile will occur. This puncture mechanism is more relevant for high strength materials, like silk or Kevlar textiles, subjected to a ballistic impact by a small but high velocity projectile, like a bullet. These textiles are typical materials used in ballistic armour for law enforcement and military personnel.

The second way in which a textile material may respond to impact is to develop a large elongation around the projectile. In the process of elongation, kinetic energy from the projectile is being transferred to the fabric. Kinetic energy is gradually expended to mobilise tensile forces and strains in the fabric. If the kinetic energy from the projectile is greater than the maximum possible energy that can be developed to mobilize the tensile forces and strains, then the fibres will break and perforation of the textile will occur. This puncture mechanism is more relevant for textiles that have high elongation and low modulus subjected to a low velocity projectile. Such textiles are typical of most geotextiles. Stress waves are unlikely to play a dominant role in this case as the projectiles are travelling at low velocities, in contrast to the velocities that bullets usually travel (around 300m/s). A rock free falling from a height of 2m to 3m, having a particle velocity below the order of 10 m/s, would be classified as a low velocity projectile.

In the case of a free falling rock hitting the surface of a geotextile, stress waves would not be of concern as the stress wave velocity is of several order of magnitudes lower than the wave speed of the geotextile. The wave speed of a fabric is given as:

$$c = \sqrt{\frac{E}{\rho}} \tag{1}$$

where E is the stiffness modulus of the textile, and ρ is the density of the textile. Assuming that a typical 400 g/m^2 nonwoven needle punched geotextile of 3 mm thick would have a tensile strength of 30 kN/m and strain limit of 80 %, and that the stress-strain relationship is linear, the modulus of the geotextile would be 12500 kN/m^2. The typical non-woven geotextile would possess a density of about 133 kg/m^3. Hence the wave speed of the geotextile would be about 307 m/s. For a rock free-falling from a height of 3 metres and hitting the geotextile surface, the maximum velocity of the stress wave passing through the geotextile cannot be greater than the speed at which the rock hit the geotextile, which is at most 8 m/s. Since the magnitude of the wave speed of the geotextile is about 38 times greater than the velocity of the stress wave, it is highly unlikely that individual fibres of the geotextile would break under the stress wave induced by the impact force, as described by the first mode of failure. Instead, it is likely that the puncture mechanism follows closely to the second puncture mechanism. When the falling rock impacts the geotextile, the area of geotextile around the projectile elongates upon impact. The energy that is expended in elongation of the geotextile and in the deformation of the soil base is absorbed from the kinetic energy of the projectile. In this way, kinetic energy from the projectile is transferred to the geotextile. If the kinetic energy of the projectile is less than the maximum possible energy that can be mobilised in the process of deformation, then no breakage of fibres would have occurred and the geotextile would not be punctured. Since this involves a tension-elongation action, it is possible that the average stain energy term, which is ½ $T\varepsilon$, might accurately describe the puncture resistance of the geotextile against this mode of puncture failure.

The shape and type of the puncture can also provide some information on the puncture mechanisms that were involved. At least two types of punctures on geotextiles were observed when rocks were dropped upon it: holes that were confined to a localized area and holes that were made in a straight line (Antoine and Druelle, 1990). While the localised holes were clearly caused by a tension-elongation action, a straight cut is due to a 'cutting' action instead of a tension-elongation action. An existing hole on the geotextile can also be propagated by a 'tearing' action like that described by Lawson (1982). In this case, tension stress applied in the plane of the geotextile causes an existing hole to tear open.

It is also probable that a puncture on a geotextile is neither caused by a sudden impact force nor by the stresses in the plane but rather by an oscillating action. It has been reported that oscillating wave action can actually cause the fibres of nonwoven geotextile to unravel without breaking (Rankilor, 1984). The oscillating wave action on the top armour stone might cause the fibres to be gradually pushed apart laterally and around a pointed tip of a rock, as the latter is forced into the geotextile.

Among the four mechanisms described in the preceding paragraph, it is the author's opinion that the tension-elongation action and the cutting action will most probably be the main mechanisms that will induce damage on the geotextile during the rock dumping operation. Damage caused by the tear action and the oscillating action are to be the dominant damage mechanisms during the in-service stage.

6.3 *The energy concept for damage*

The energy of the geotextile is proposed to describe the geotextile's ability to resist a tensile-elongation action and the cutting action without rupture to its structure. Hence, it can be used to quantify the puncture resistance of geotextile in the field. The section will briefly trace the development of the energy concept of geotextiles.

To the best of the author's knowledge, the use of energy to quantify the property of a geotextile began in the beginning of 1980s by the French Geosynthetic Committee, or *CFG* (the French chapter of IGS) (Blivet, 1999). The idea behind this energy concept follows that a material, when placed into the ground, would experience some forces and undergoes some elongation, and hence dissipates some energy in doing so. It is assumed that a material will continue to perform its function satisfactorily if the energy dissipated during placement and while in-service does not exceed the threshold energy of the material. This threshold energy, or the "energy level", of a geotextile is estimated to be *½* x *ultimate tensile strength* x *ultimate elongation*, or more accurately the area under the tension-strain curve. Incidentally, this term is also known as toughness of the geotextile in North America (Koerner, 1997). Not surprising, the concept of Constant Energy was first used to quantify geotextiles used in applications of separation. It essentially suggests that a geotextile needs to possess a certain amount of deformation energy in order to perform the role of a separator effectively in a particular type of structure, besides having the right opening size in the structure. This requires the minimum energy level to be defined for each application for each type structure. In situations where the geotextile has to perform a primary separation and secondary reinforcement function, a minimum tensile strength of the geotextile has to be defined along with the minimum energy level required of a geotextile. This is necessary because an extremely deformable geotextile could meet the energy criterion without providing any reinforcement to the structure. Since the proposal of the energy concept, a few experiments have been conducted to validate it (SINTEF 1997, Rathmayer 2000, Diederich 2001, Chew et al., 1999, Wong et al., 2002). These tests have shown that geotextiles with certain energy levels used in specific roadway structures suffer an acceptable degree of deformation (Blivet, 1999). Though there are some experimental verification, there has yet to be a thorough mathematical proof of its authenticity.

6.3.1 *Theoretical approach*

Giroud (1999) presents a detailed mathematical expression to describe the separation action of a geotextile. Giroud begins by assuming that a geotextile, sandwiched between two soils with a distributed load applied above it, deforms into a spherical shape with a circular area (Figure 26a). Based on the geometry of the deformed shape (Figure 26b), an equation describing general profile of the geotextile can be derived to be:

$$1+\varepsilon=\frac{1}{2}\left(\frac{2y}{B}+\frac{B}{2y}\right)\arcsin\left[\frac{1}{\frac{1}{2}\left(\frac{2y}{B}+\frac{B}{2y}\right)}\right] \tag{2}$$

where ε is the geotextile strain; y is the geotextile deflection; and B is the diameter of the circular zone under which the geotextile deforms. By equilibrating the static forces acting on the geotextile (shown in Figure 26c), a force equilibrium equation can be derived to be:

$$F = P + W - Q = \pi BT\sin\theta \tag{3}$$

where F is the resultant of forces acting on the geotextile; W is the weight of the soil above the geotextile; Q is the soil reaction beneath the geotextile; T is the tension in the geotextile, and θ is the angle the force T makes with respect to the horizon. By combining the geometric equation and force equilibrium equations, it was shown that the relationship between the tension and strain in the geotextile can be described by the following equation:

$$1+\varepsilon=\frac{\pi BT}{F}\arcsin\left(\frac{F}{\pi BT}\right) \tag{4}$$

Equation 4 can be shown graphically in Figure 27, and is known as the characteristic curve of the geotextile. The characteristic curve represents the relationship between the tension and strain that must be satisfied when a geotextile is subjected to a distributed load; a geotextile resist the distributed load if the peak of its tension-strain curve is above the characteristic curve. This is explained more graphically in Figure 28; geotextile (a) does not meet the relationship whereas geotextile (b) resist the load because the peak of its tension-strain curve is above the characteristic curve. This demonstrates that stiffer geotextiles having higher tensile strength do not always resist ruptures better than more ductile geotextiles of lower tensile strength. Using similar assumptions, Giroud also derived characteristic curves for geotextiles under concentrated loads.

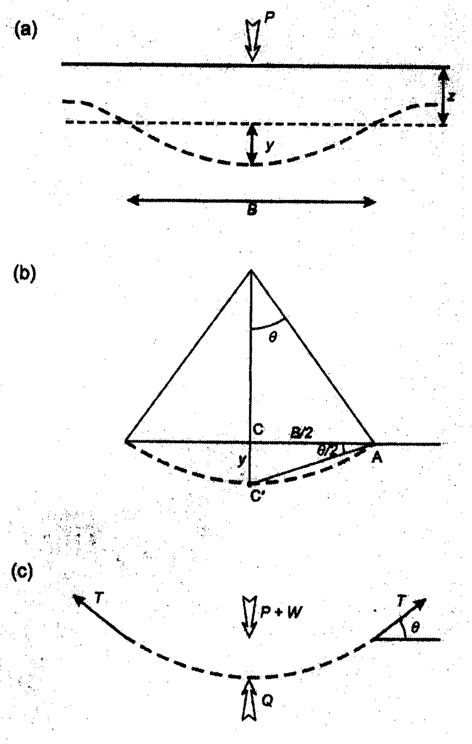

Figure 26 Assumed deformation of geotextile acting as a separator. (a) General deformation profile of geotextile, (b) geometry of the geotextile, and (c) forces acting on the geotextile (after Giroud, 1999)

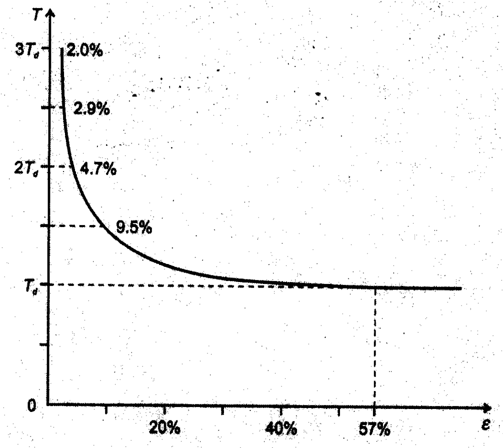

Figure 27. Characteristic curve of geotextile (Giroud, 1999).

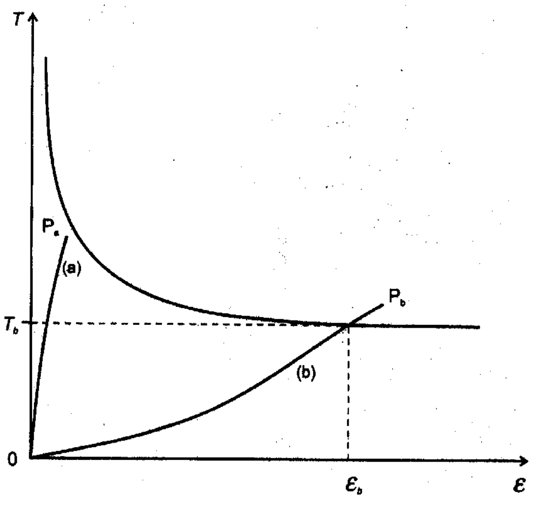

Figure 28. Comparison between two geotextiles on the characteristic curve (Giroud, 1999).

The characteristic curve and equation 4 proposed is a sound mathematical expression of the separation action of geotextiles. This mathematical model was based on the assumption that the geotextile could not slide laterally. Such an assumption is reasonable for the application in roads; but in the case of a rock dropping action where a point load being applied over a larger area, one can imagine that the geotextile would deform in a conical shape, gravitating towards the tip where the load is applied. Hence, lateral sliding around the tip is possible.

To successfully implement the characteristic curve as a specification guideline for geotextile for various applications, the ultimate tensile strength T and elongation ε must be well defined. The tension and elongation terms described in the equation and those that occur in the field are isotropic in nature. Most mechanical laboratory tensile tests induce a uniaxial or biaxial stress state on the geotextile. Soderman and Giroud (1995) proposed an equation that relates the stress and strain of a geotextile in an isotropic biaxial stress state to the equivalent stress and strain of the geotextile in a plane strain biaxial stress state. Thus, the isotropic tensile strength and elongation of geotextiles can be calculated using the tensile strength and elongation values obtained from standard wide width tensile test. However, because the modulus of the geotextile in a uniaxial stress state may not be the same as the modulus in a biaxial stress state, it is rather difficult in ensuring that the calculated isotropic strength and elongation values are accurate. This would complicate the use of the characteristic curve, despite the fact that a large database of uniaxial test results are readily available. Watn and Eiksund (1999) suggested that the use of an isotropic index test, like the CBR Plunger Test, could be a possible alternative.

6.3.2 *Laboratory tests for Energy Concept*

In the previous sections, it was mentioned that the two predominant mechanisms that responsible for the puncturing of geotextile filter are the tensile-elongation mode of failure and the cutting mode of failure. To resist a tensile-elongation failure, the geotextile must have the mechanical ability to stretch without rupture of the fibres. To resist a cutting failure, the geotextile must have the mechanical robustness to resist a slicing action without allowing the cutting edge to penetrate through. While, "tensile energy" of the geotextile is a parameter that indicates the puncture resistance against a tensile-elongation failure mechanism, a new "Cut Energy" is a parameter that indicates the puncture resistance against a cutting failure mechanism. Research into the laboratory testing to quantity these two energy terms were conducted, and experimental data that shows the direct correlation between the puncture resistance of geotextiles and these energies were obtained.

A 5m high test rig, terms "impact rig", was erected to deliver a consistent impact load onto the geotextile samples (Figure 29). The apparatus of the test was configured in such a way that a tensile-elongation mechanism was mobilised to make a puncture on the geotextile upon impact by the impact head. The tensile energy that the geotextiles possess to resist the puncture was also estimated and measured through various standard index tests. The tensile energy could be estimated using reported ultimate stress and strain results of the EN ISO 10319 wide width tensile test, commonly found on many geotextile product brochures. It could also be accurately measured using the EN ISO 12236 CBR Plunger Test.

The geotextile test specimen is secured by the clamp ring that has an internal diameter of 500 mm. The clamp ring has twelve nut-and-bolt system and has grooves along the clamp surface to ensure that the geotextile is gripped tightly. The clamp ring simulates a geotextile that is perfectly anchored around the edges so that no slippage will occur upon impact (Figure 29). This will allow the geotextile to develop an in-plane tension and in-plane elongation as the impact head intrudes into the plane of the geotextile. The clamp ring is secured onto the metal sand drum so that the geotextile is resting on the sand surface. The metal drum is filled with medium sand at a relative density of 70%. The metal sand drum is 700 mm in diameter and 400 mm deep and this allows the sand to have sufficient space to deform upon impact.

The impact head (Figure 29) was designed to stretch the geotextile in a particular direction upon impact. The impact head has a 47.5 mm cutting edge that is angled at 72.5 degrees. This arrangement of the impact head, the clamp ring and the sand-filled metal drum will force the geotextile to fail in a tensile-elongation action predominantly in one direction. By orientating and clamping the geotextile along the direction of the cutting edge of the impact head, it is possible to cause the geotextile to stretch in the perpendicular direction. Thus the rupture of the geotextile is resisted predominantly by the fibres perpendicular to the cutting edge. This allows the puncture resistance of the geotextile against a tensile-elongation action in a particular direction to be investigated. The kinetic energy at rupture must therefore be correlated with the tensile energy of geotextile measured in the direction perpendicular to the cutting edge.

To measure the kinetic energy of the impact head just before impact on the geotextile, a pair of laser emitters and photodiodes and a high-speed oscilloscope was used. The kinetic energy of the impact head just prior to impact can be calculated.

To determine the magnitude of kinetic energy required to make a puncture on the geotextile, the release height of the impact head was increased in steps of 0.5m until a puncture was observed on the geotextile. For each new increment of the release height of the impact head, a new geotextile specimen was tested and the sand was replaced within the metal sand drum to the right density again. The kinetic energy corresponding to the last incremented release height was deemed to be the kinetic energy required to make a puncture on the geotextile. By conducting the test according to these procedures, the kinetic energy required to make a puncture in the machine and cross-machine direction of each geotextile was experimentally determined. This kinetic energy is found to be well correlated with the tensile energy of the geotextile calculated from wide width tensile tests or CBP Plunger test.

The test setup, procedures and results for this test ware described in Wong et al. (2002).

The methodology to prove that the puncture resistance of geotextiles against a cutting failure mechanism can be quantified by the cutting energy of the geotextile is similar to the methodology described above. The Impact Test Rig was used but with a major modification to force the geotextile to puncture by a cutting mechanism.

Figure 29. The 5m Impact Rig (left), the impact head (right top), and the metal sand drum with the clamp ring and geotextile sample secured onto it (right bottom).

6.4 *Field Drop Test*

A direct ways to investigate the puncture resistance of geotextiles against rock dumping operation is to conduct field drop tests. If the procedures of the drop test are similar to the construction sequence employed for the coastal structures, the field drop test is a very effective way to show how the geotextile will survive during the construction process. The selection of the appropriate geotextile filter can then be based on the results of the field drop tests.

The procedures used to conduct a field drop test can vary in many ways. The results of a drop test is influenced by many factors (Wewerka, 1984). The factors that can possibly influence the results of field drop tests are as follows:

a. Geotextile characteristics; which includes the polymer type, weave structure, specific mass and other mechanical properties of the geotextile
b. Primary armour stone; size, weight, angularity
c. Height of release of the stone
d. The characteristic of the secondary armour stones placed on the geotextile; mass, distribution of sizes and angularity
e. The anchorage on the geotextile
f. Characteristic of the soil base; density, consistency, presence of stones
g. Angle of inclination of the base soil
h. Whether the base soil is above or below water
i. Number of test that were conducted

Drop tests can be conducted with many combinations of the above parameters. Therefore, when results of different drop tests are compared, it is not surprising to observe conflicting, confusing and even misleading conclusions reported. To complicate matters, the occurrence of punctures on geotextiles caused by armour stones is a statistical event and the individual test results are subjected to statistical variation.

The occurrence of punctures is basically a statistical event. Certain parameters, like the height of drop and density of the base soil, are within the operator’s control, and can be made invariant. However, some of the parameters are subjected to probabilistic variation. For example, the angle or the face of the armour stone that hits the geotextile cannot be easily controlled as it is almost impossible to prevent the armour stone from spinning as it free-falls. Therefore, it is imperative that the evaluation of the puncture resistance of a geotextile must not be based on one or two drops alone. It must be evaluated statistically with an adequate number of drop tests to arrive at the right conclusion regarding the suitability of the geotextile with a high level of confidence.

Conducting a drop test to evaluate the puncture resistance of geotextile can be a complex task. Depending on the way the test was carried out, the results can be different from other drop tests that were carried out differently. This tends to make the task of comparison between test results difficult. Needless to say, field tests are always expensive because of the heavy logistics, manpower and time involved. Hence, there is always the temptation to simplify the test procedure so that the test can be conducted with the least effort. However, it is very important to ensure that the procedure of the drop test simulates the way in which actual construction will take place. It is also very desirable that the test procedure will yield results that are reproducible and consistent.

A standardized field drop test was proposed (chew et al.,1999) to evaluate the puncture resistance of geotextiles. It essentially consists of two aspects: (*i*) the standardised procedure of conducting the drop test, and (*ii*) the standardised way of evaluating the damage on the geotextiles. It was shown that the results obtained using this test method are quantifiable and reproducible, and that the puncture resistance of the geotextile can be evaluated with a high level of confidence.

6.4.1 *Proposed Standardization of Testing Method*

The basic procedure of the field drop test is summarized as follows:

i. A standard impact concrete block (say, having the same weight of the armour rocks) with a flat impact area shall be used in the field test to deliver a constant impact energy onto the geotextile at a particular drop height. Figure 30 shows a photograph of the impact blocks. The use of these standard concrete blocks ensures that the geotextile was always subjected to the same impact force on the same contact area so that a fair comparison can be made between drops.
ii. All the tests were to be conducted with the appropriate layer of secondary armour stones laid cautiously over the geotextiles according to the design of the structure. The size of the rock can also be quantified by defining a new term known as the equivalent diameter of the rock, or L_R . The term L_R is defined as the average of the length and width of the rocks. From the measurement made on about two hundred rocks that were randomly selected, the equivalent diameter of the rocks were about 30 cm.
iii. Each geotextile test sample measured 5m x 5m and was to be sub-divided into 16 cells of 1.2m x 1.2m area where the impact block was allowed to fall. Sixteen drops were made for

each drop height tested. This permitted a statistical analysis to be made on the results for each test condition. Figure 31 shows the lifting of the standard impact block up to the specified height, setting it in position and releasing it onto the centre of the test cell.

iv. After the drop, the secondary stones were to be carefully removed. The damage inflicted on the geotextile were assessed by counting the number of punctures as well as measuring the length of the straight cut or area of each puncture by inserting a calibrated and graduated cone through the puncture (see Figure 32). The cone ensured that the method of measuring the puncture size was consistent and yet efficient.

Figure 30. An example of a standard impact blocks.

Figure 31. Dropping of standardized stone for Field Drop Test.

6.4.2 *Description of Assessment Method*

The evaluation of the puncture resistance of the geotextile was based on the 95th percentile cumulative area of damage per drop, 95th percentile of the number of punctures and the 95th percentile of the size of all individual punctures on all the cells of the geotextile. The 95th percentile cumulative area of damage per drop, or D_A^{95}, is a statistical representation of the total area that was damaged by one impact from the concrete block. It is obtained by measuring and summing up the areas of all the punctures in each test cell. The D_A^{95} is then obtained by the taking the 95th percentile from all the summed areas of damage from all the test cells. The 95th percentile number of punctures, or N^{95}, is a statistical representation of the number of punctures that were inflicted by one impact from the concrete block. The N^{95} is obtained by counting the number of punctures found in each cell. The 95th percentile of the size of all individual punctures, A^{95}, is a representation of the size of each puncture. It is calculated by dividing the 95th percentile cumulative area of damage per drop by the 95th percentile number of punctures, or D_A^{95} divided by N^{95}. The equivalent length of the puncture, indicated by the term L_p , can also be calculated. This is done by assuming that the punctures are circular in shape. The equivalent length of the punctures is half of the circumference of the circular area. The equivalent length of the punctures, or L_p , allows the size of the punctures to be compared with the size of the adjacent armour stones that caused the punctures. The hole-to-rock size ratio, or *H/R ratio*, indicates the relative size of the size of puncture as compared to the rock. The H/R ratio is the ratio of the equivalent length of the punctures L_p over the equivalent diameter of the rock L_R. A H/R ratio of 1 indicates that the size of the puncture is as large as the rock, while a H/R ratio of 0.5 indicates that the size of the puncture is half as large as the rock. The H/R ratio is useful because it can be used to evaluate if the puncture can be effectively plugged by the rock sitting above it so that soil will not be washed out though the puncture.

The 95th percentile ensures that two standard deviations about the mean are taken into account. Evaluating the puncture resistance of the geotextile using the 95th percentile mark ensures that a conservative approach is adopted.

Figure 32. Technique to quantify the damage on the geotextiles - measuring the size of the puncture using cone.

6.5 *Results of an Evaluation of Puncture Resistance of Geotextiles using the Standardised Test Method*

Using the standard method of conducting a field drop test described in the previous section, a field drop test was conducted in Singapore to evaluate the puncture resistance of geotextiles under varying boundary conditions.

A total of five geotextiles were tested. Details of the geotextile specimens are given in Table 9. W1 and W2 are woven geotextiles with W1 being isotropic and W2 being anisotropic in terms of mechanical properties. Geotextiles NW1, NW2 and NW3 are non-woven geotextiles that was made of two layers of fibres of different diameter. The top protection layer was purposely manufactured with larger diameter fibres so that it possess higher mechanical properties to protect the bottom filter layer against large impact forces. The bottom filter layer was manufactured using smaller diameter fibres so that a dense structure can be optimized to enable its permeability criterion and soil retaining criterion at the same time.

Table 9. Technical details of geotextiles for Field Drop Test 2.

	W1	**W2**	**NW1**	**NW2**	**NW3**
Weave Pattern**	W	W	NW-NP	NW-NP	NW-NP
Polymer	PP*	PP*	PP*	PP*	PP*
Mass per unit area (g/m^2)	400	625	400	600	800
Thickness (mm)	1.6	1.8	3.5	5.0	6.5
Tensile strength MD/CD # (kN/m)	80/80	200/40	23/23	30/30	35/35
Maximum elongation MD/CD # (%)	12/13	15/15	85/85	85/85	85/85
CBR puncture resistance (N)	10000	11000	3300	4500	6500

* PP – Polypropylene,

MD – Machine Direction, CD – Cross Direction

** Weave pattern: W – Woven, NW-NP – Nonwoven needle punched

Following closely to the proposed standard test procedure, tests were carried out with six different test configurations, designated as T1 to T6. The five geotextiles were tested at five different drop heights ranging from 0.5m to 2.5m. Each drop height was accompanied by about 16 drops. A wide variation of ground conditions was also tested. A total of 784 drops were made and 1129m^2 of geotextiles were tested. Table 10 summarizes the variation of key parameters in the test program.

Table 10. Summary of the test program for Field Drop Test.

	Description of boundary conditions and impact block	Condition of base soil	Thickness of secondary stone layer (cm)	Drop height (m)
T1	Loose sand Series Horizontal bed, 0.9 ton impact block	Sand RD 40%	20	0.5, 1.0, 1.5, 2.0, 2.5
T2	Dense sand Series Horizontal bed, 0.9 ton impact block	Sand RD 70%	20	0.5, 1.0, 1.5
T3	Double armor Series Horizontal bed, 0.9 ton impact block	Sand RD 40% & 70%	50	1.5
T4	Silty-sand base Series Horizontal bed, 0.9 ton impact block	Sandy-silty Clay	20	1.5
T5	Slope Series Inclined bed 1V:3H, 1 ton natural rocks	Sand RD 70%	50	1.5
T6	Heavy Block Series Horizontal bed, 1.6 ton impact block	Sand RD 40%	20	0.5, 1.0, 1.5, 2.0, 2.5

The test results from the field tests were consolidated and analysed. The test results were examined by looking at three indicators that describe the amount of damage that was found on the geotextile. These indicators are the total area of damage, the number of punctures, and the typical size of each puncture.

6.5.1 *Influence of the Height of Release of the Impact Block*

Figure 33 and Figure 34 present the amount of damage at varying drop energies. The results were extracted from Test Series T1 and Test Series T2. The abscissa is represented by Drop Energy, or E_{drop}, which represents the potential energy of the impact block in kilo-joules. The y-axis shows the 95th Percentile cumulative area of damage per drop, indicated by the term D_A^{95}. Figures 33 and 34 show clearly that the amount of damage on all the five geotextiles is proportional to the drop energy of the impact block. This is not surprising as higher drop energy means that more energy is transferred to the geotextile upon impact, resulting in a greater amount of damage on the geotextile.

However, it can be seen that D_A^{95} and E_{drop} relationship may not be linear. For weaker geotextile, e.g. NW1, the amount of damage was especially sensitive to the drop energy.

The test results can also be analysed by examining the number and sizes of punctures found on each geotextile for the test conducted on sand base at a relative density of 40% and 70%. Figure 35 shows the 95th percentile number of punctures per drop (or N^{95}) against the drop energy (or E_{drop}) for the test series T1. Figure 36 presents the sizes of the punctures for test series T1. Contrary to the area of damage D_A^{95} and number of punctures N^{95}, the equivalent length L_p is less sensitive to the drop energy. It seems that the equivalent length of punctures remains fairly constant even with increasing drop energy. This is because the size of the puncture is very much affected by the size of secondary stones, which is deliberately kept constant in these series. The H/R ratio for the two test series is also consistently less than 0.5. This implicitly means that the size of the puncture is less than half the size of the secondary armour stones. This hole size is also consistence with the size of hole observed on the exhumed geotextiles from coastal revetments in Southeast Asia after 12 years of service (Wong et al., 2000). It is also interesting to note that based on the filtration study conducted in National University of Singapore, positive dynamic arching or networking phenomena will develop across geotextile punctured holes of up to this size under cyclic wave condition. Hence, the present of a limited number of holes up to this size will not necessarily lead to stability problem (Tien et al, 2002, and Zhao et al., 2000).

6.5.2 *Influence of the Relative Density of the Sand Base*

The test configuration for Test series T1 and Test series T2 are identical except for the density of the sand base on which the geotextile was tested upon. Comparing the results of Test T1 and Test T2, will reveal the effect of the density of the sand base onto the puncturing of geotextiles. Figure 37 shows the 95th percentile cumulative area of damage per drop, or D_A^{95}, against the drop energy E_{drop} for Test series T1 and Test series T2. It can be seen that the damage on the geotextile is more severe when the test was conducted on a denser sand base. This observation is true for all the five geotextiles tested. It was also found that the difference in the amount of damage on the geotextile between the density sand bed is greater at higher drop energies, and at low drop energies, the density of the sand base has less influence on the degree of damage on the geotextile.

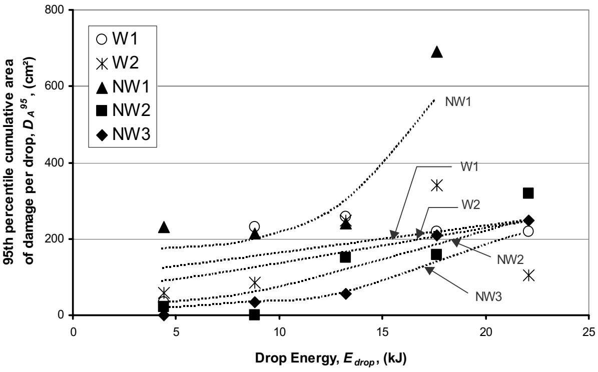

Figure 33. Amount of damage versus drop heights for Loose Sand Series (T1).

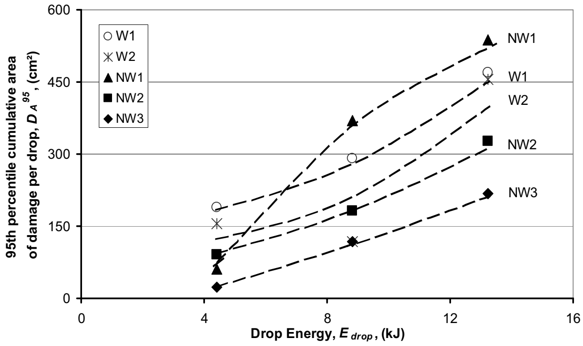

Figure 34. Amount of damage versus drop heights for Dense Sand Series (T2).

6.5.3 *Influence of the Thickness of Secondary Armour Layer*

The influence of the thickness of the secondary armour layer on the amount of damage on the geotextile was investigated in Test series T3 (with the secondary armour stone layer of 50 cm), as compared to the results of T1 and T2 series (thickness of the secondary armour stone is 20 cm).

Figure 38 shows the 95th percentile cumulative area of damage per drop at different thickness of secondary armour stone layer. It can be seen that the amount of damage on the geotextile is drastically reduced when the thickness of the secondary armour stone layer is increased from 20 cm to 50 cm. This is true for both tests carried out on sand bases at relative density of 40% and 70%. The reason for this could be due to the fact that a thicker secondary armour stones layer has greater voids. Therefore, a lot more kinetic energy from the concrete block is dissipated to displace the stones upon impact, thereby reducing the magnitude of energy that is actually absorbed by the geotextile and sand base.

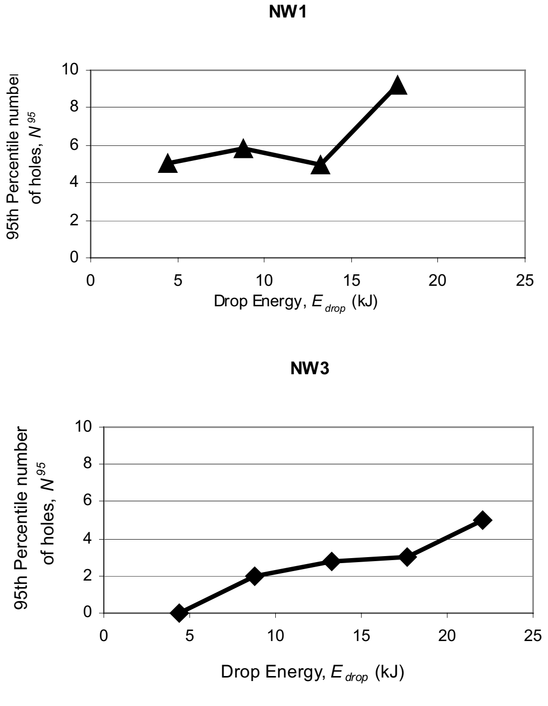

Figure 35. Number of punctures for NW1 and NW3 for Test series T1.

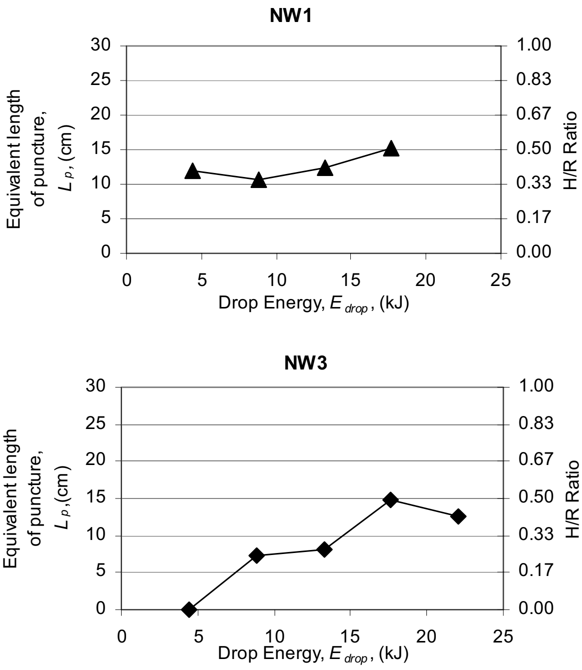

Figure 36. Sizes of punctures for NW1 and NW3 for Test series T1.

Figure 39 and Figure 40 shows the 95th percentile numbe punctures and equivalent length of puncture at different sec dary armour layer thickness respectively. It can be seen fr Figure 39 that increasing the thickness of the secondary arm layer from 20 cm to 50 cm lead to a 60% and 85% reductio the number of punctures on a sand base of 40% and 70% relat density respectively. The equivalent length of the puncture decreases with an increase in the thickness of the secondary mour layer, as shown in Figure 40. On a sand base at a relat density of 70%, this H/R ratio is reduced from 0.39 to 0. which is not a very significant reduction in size. However, equivalent length of puncture on a sand base at a relative den of 40% shows a drastic decrease; the H/R ratio reduces fr 0.35 to 0.025. This is advantageous, because a small H/R r means that the puncture is small and therefore can be ea plugged so that the hydraulic performance of the geotextile is reduced significantly.

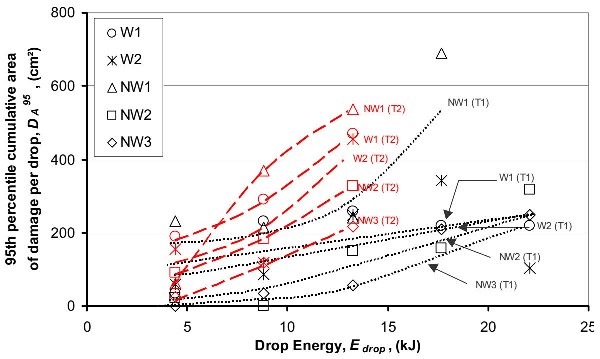

Figure 37. Comparison of the amount of damage for Test series T1 T2.

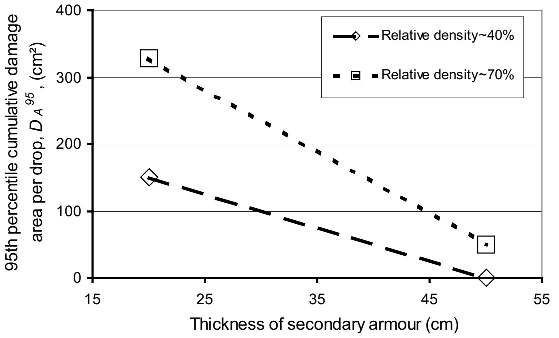

Figure 38. Amount of damage at different thickness of secondary arm stones.

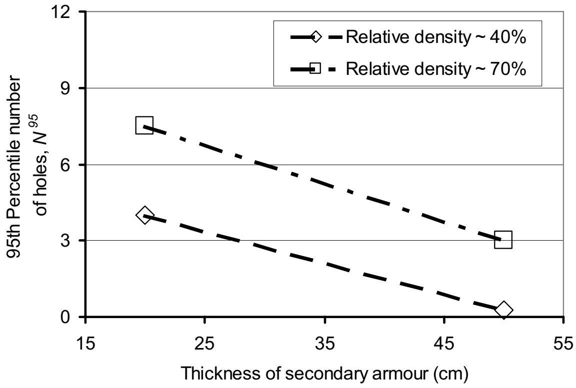

Figure 39. Number of punctures at different thickness of secondary mour stones.

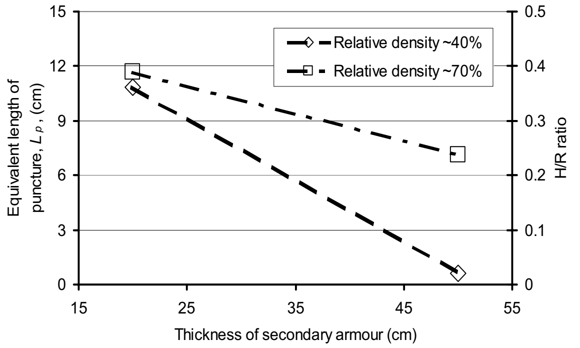

Figure 40. Sizes of punctures at different thickness of secondary armour stone.

6.5.4 *Correlating Field Results Using CBR Energy as Resisting Energy*

Reinterpreting the 95th Percentile cumulative area of damage per drop (D_A^{95}) against the drop energy (E_{drop}) of the Test series T1 and T2, it can be shown that the amount of damage on each geotextile is inversely proportional to the CBR energy of each geotextile.Therefore, the results of Test series T1 and T2 can be normalised by the CBR energy of the respectively geotextile, or E_{CBR}. Figure 41 shows that after normalising that data with the respective CBR energy of each geotextile, all the data points of Test series T1 converge into a single line. This is also true for the data points of Test series T2. Thus, The relationship between D_A^{95} is directly proportional to E_{drop} and inversely proportional to E_{CBR}, or:

$$D_A^{95}\ \alpha\ \frac{E_{drop}}{E_{CBR}} \qquad (5)$$

The difference in boundary conditions between Test series T1 and T2 is the density of the sand base in the test. The data of Test series T1 and T2 shown in Figure 41 can be further analysed to find an empirical relationship between the amount of damage, drop energy, CBR energy and the relative density of the sand base. Figure 42 shows the amount of damage D_A^{95} as a function of the drop energy, CBR energy and relative density of the sand base. A linear equation with an acceptable R^2 regression value of 0.83 was obtained. The equation of the linear correlation is as follows:

$$\left[\frac{D_A^{95}}{RD^{1.41}}\right] = 8.55\left(\frac{E_{drop}}{E_{CBR}}\right) - 190 \qquad (6)$$

where the units of E_{drop} and E_{CBR} are in joules and D_A^{95} is in cm^2. *RD* is the relative density of the sand base. The value of *RD* is between the limits of 0.4 and 0.7, which is typically the density of the sand near the surface. In a typical land reclamation project that involves a sand pumping operation using a sand dredger barge, the density of the sand near the surface just after the sand pumping operation is at loose state, typically at around 40% relative density. If the installation of the geotextile is carried out immediately, it will be more logical to use a *RD* value that is around 0.4 to select the appropriate geotextile using equation 6. However, if the installation of the geotextile is carried out at a much later stage, and sufficient time has been given for the sand to be densified under repeated exposure to wave action or by other mechanical means, it might be more reasonable to assign a *RD* value of around 0.7 to select the appropriate geotextile. A design chart based on Equation 6 is presented in Figure 43. This chart allows the engineer to determine the amount of damage to be expected during a rock dumping operation involving primary armour stone. This design chart is one of the end results of the continuous research conducted to better understand the damage mechanisms, and to develop appropriate laboratory and field testing procedures. It enable engineers to select and design geotextile against installation damage in actual revetment applications.

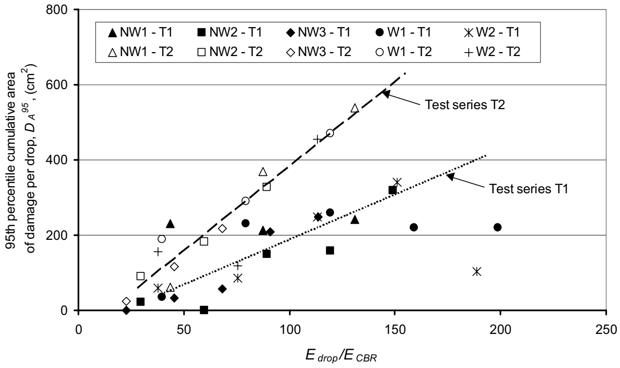

Figure 41. Amount of damage versus the normalised drop energy and CBR energy of Field Drop Test.

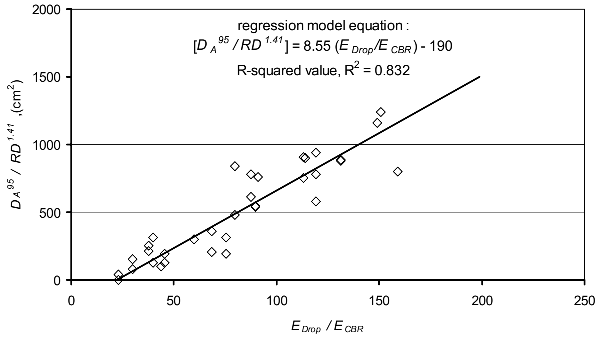

Figure 42. Empirical relationship between the amount of damage, relative density of the sand base, drop energy and CBR energy.

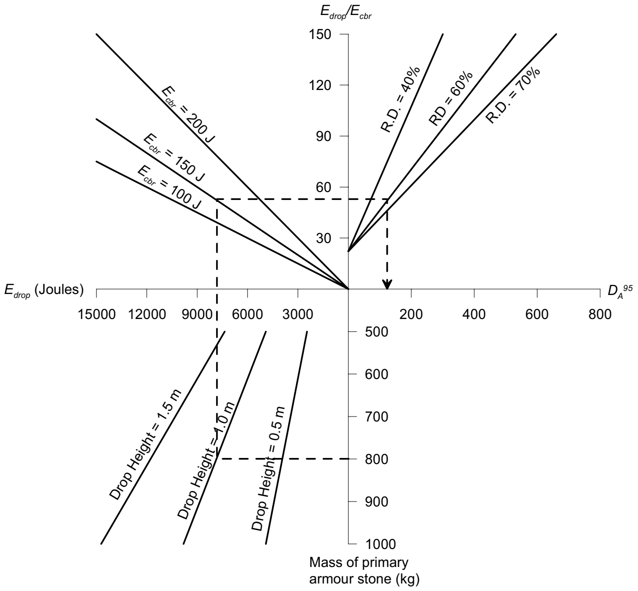

Figure 43. Design chart for the geotextile filter against tensile-elongation failure mechanism.

7 DAMAGE CONSEQUENCES AND EVALUATION

7.1 *General approach*

Prior to design the level of the damage evaluation has to be decided. The level of damage evaluation obviously should reflect both the possibility of damage and the consequences of damage. Level of damage evaluation may vary from no special evaluation at all to a full set of specification of characteristics, pre-trials before installation and control of damage during and after installation and construction. Recommendations for the level of evaluation based on the possibility and consequences of damage are given in Table 11.

Table 11. Recommendations for level of damage evaluation in terms of the possibility and consequences of damage.

Possibility for damage	Consequence of damage		
	Low	Medium	High
Low	No special precautions	Specification of characteristics	Specification of characteristics Pre-installation trials
Medium	Specification of characteristics	Specification of characteristics Pre-installation trials	Specification of characteristics Pre-installation trials. Control during installation.
High	Specification of characteristics	Specification of characteristics Pre-installation trials	Spec. of characteristics Pre-installation trials Control during and after installation and construction

Based on these recommendations, some typical levels of evaluation for some examples of applications and functions are presented in Table 12.

Table 12. Recommended level of evaluation of damage.

Function and type of structure	Possibility of damage *)	Consequence	Level of evaluation
Separation in road, soft subsoil, gravel fill	M.	L	Specification of characteristics
Slope surface erosion control	L	L	No special precautions
Reinforcement in concrete block retaining structure Sand backfill	M.	M/H	Specification of characteristics Pre-installation Trials
Separation and filter in waterways	M	M	Specification of characteristics Pre-installation trials
Reinforcment in bridge abutment, crushed rock backfill	H	H	Spec. of characteristics Pre-installation trials Control during and after installation and construction

*) L-Low, M-medium, H-High

7.2 *Damage mechanism and relevant test methods*

A link between the damage mechanism, the relevant geosynthetic characteristics and thetest methods is required as the basis for evaluation of damage susceptibility. Table 13 gives a proposal for evaluation of the relevance of a number of geosynthetic characteristics and test methods to the damage mechanisms presented in chapter 2. The relevance is rated from 0-3 where 0 indicates no relevance and 3 indicates very good relevance.

Table 13. Geosynthetic characteristics and test methods related to damage mechanisms.

Characteristic and test method	Damage mechanism					
	Abrasion	Split	Puncture	Rupture	Cut	Tear
Weight	2	1	2	1	2	1
Thickness	2	1	2	2	2	1
Strength	1	1	2	2	2	2
Elongation	0	0	1	2	1	2
Grab	0	1	1	2	1	2
Trap. tear	0	1	2	2	1	3
Burst	0	1	2	1	1	2
Abrasion	3	0	0	0	0	0
Impact	0	2	3	0	1	0
Puncture	0	1	3	1	1	1

7.3 *Geotextiles for separation in roads*

The separation function in roads is typically an application where the possibility for damage is medium to high while the consequences generally are low. Accordingly the evaluation of consequences of damage is based on a specification of geotextile characteristics.

The ongoing internordic project "NorGeoSpec" is aiming at developing a common Nordic system for specification and control of geotextiles for separation and filtration in roads (Watn Eiksund & Rathmayer 2002). The possibility for mechanical damage during installation and construction is crucial for this application and has been a major element in the development of the new set of specification criteria. The basic approach for these requirements is that the major damage mechanisms for this application are related to puncturing and to stress rupture of the geotextiles. The puncturing is covered by a set of criteria based on the cone drop test. For the stress rupture mechanism it is assumed that a certain amount of ”strain energy” is used during the installation and construction phase and that the remaining stress and strain should be in reserve for the service lifetime. The characteristics, which have been included to take care of damage susceptibility, are: mass per unit area (maximum variation), tensile strength, strain at failure, energy index and cone drop diameter.

The energy index is calculated as the multiple of the maximum tensile strength and the corresponding strain and divided by two, i.e. the area described by the triangle determined by the point of maximum stress and corresponding strain. The requirement is related to the average of the energy index from themachine and crossway direction. The principle for calculation of the strain energy index for two different geotextiles are presented in Figure 44

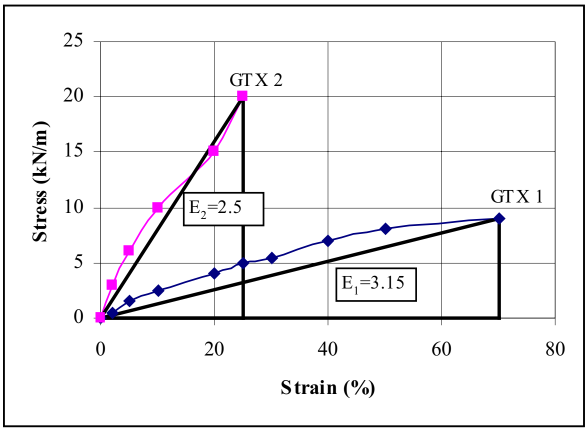

Figure 44. Calculation of energy index.

The reason for using the energy index prior to the strain energy (area under the curve) is that the correlation with the with the field experience are similar. Also the use of the energy index as the basis for the requirement is supported based on a theoretical approach (Giroud 1999).

These requirements are then combined into specification profiles which are linked with the relevant conditions on site. The proposed five specification profiles for NorGeoSpec with the corresponding requirements are presented in Table 14.

Table 14. Specification profiles with required properties.

Profile no.	Max tolerance	1	2	3	4	5
Max tolerance for mass per unit area ∓ %		12	12	10	10	10
Min.tensile strength kN/m	- 10%	6	10	15	20	26
Min failure strain %	- 20%	15	20	25	30	35
Max cone drop diam mm	+ 20%	42	36	27	21	10
Min strain Energy kN/m		1.4	2.6	4.0	5.5	7.5

Other systems for the separation function are based on an evaluation of required geotextile characteristics to ensure the function of the geotextile. The required characteristic may sometimes be very simple, for example Koerner and Koerner (1990), based on the examination of excavated geotextiles from the field, recommend that the area weight of the geosynthetic should be minimum 270 g/m^2 to ensure a sufficient resistance to damage. Most requirements for these applications tend however to set up a combination of requirements, where a main element is the combination of tensile strain and tensile strength (Wilmers & Saathof 1995, Diederich 2001, Nancey et al 2001, Blivet 2000). In principle the basic approach in these requirements is that the required tensile strength is reduced with increased flexibility, i.e. increased tensile strain. A theoretical background for this approach is given by Giroud (1999). He concludes that although a constant energy approach cannot be fully theoretically justified it gives an acceptable practical approach for a specification.

7.4 *Reinforcement applications*

When geosynthetics are used for reinforcement application the evaluation of possible damage is obviously of major importance. The reduction in geosynthetic strength due to damage may at worst lead to rupture of the reinforcement with possible very serious consequences. In some cases the tensile strain is cruciial for the reinforcement function. However a number of studies (Greenwood 1998, Flum et al 2001, Watts and Brady 1994, Cancelli & Montanelli 2000) indicate that mechanical damage primarily influences the tensile strength and only marginally the tensile strain characteristics.

In design a common way of coping with the possibility for damage during installation is therefore to reduce the geosynthetic strength by a partial safety factor. The level of the safety factor is typically dependent on the type of reinforcement and the type of surrounding material. Recommendations for determining relevant reduction factors are given in guidelines from public authorities (British Standard 8006, AASHTO). The basic approach for using a material factor for installation damage is that the installation damage acts independently of other factors to reduce the tensile strength of the reinforcement. Further studies have examined the synergy between damage during installation and the stress rupture behaviour of the geosynthetic reinforcement (Pinho Lopes et al 2000). Schröer et al. (2000) propose that the current practice of multiplying the reduction factors for damage and creep is sufficient. However, the possibility of a further factor is included as a "subfactor" in BS8006 (British Standard BS 8006). Recent studies (Greenwood, personal communication) suggest that in general there is no significant effect on the creep behaviour from the damage and that the two partial safety factors may therefore be treated independently.

7.4.1 *ISO/CEN Guidelines*

ISO TC221/WG5 (2001) is preparing a draft of a guide to derivate design strength for geosynthetics used for soil reinforcement. These guidelines also include the evaluation of effects on tensile strength from damage during installation. These guidelines recommend full-scale installation trials as basis for evaluating the effect on strength and elongation characteristics of the reinforcing geosynthetics. The relevant reduction factor for damage, RF_{ID}, is then expressed as the ratio of tensile strength of the control (undamaged) material to the tensile strength of the exposed material.

However the proposed guidelines also give two alternative procedures for determining the relevant reduction factor when results from field trials are not available:
-interpolation of results with different soils
-interpolation of results between products of the same product line

Interpolation of results with different soils can possibly be used when the reduction factor for the relevant geosynthetic is known for soils with grain size both less and greater then the soil to be used. The medium grain size, d_{50}, is recommended used as the reference for the soil unless other soil gradation characteristics is considered more relevant.

Interpolation of results between products of the same product line can be used provided a relationship can be established between the unit weight, tensile strength or other property of the product and the RF_{ID} of the product for each given d_{50} of the soil used, and provided the data is available for products which are both lighter (weaker) and heavier (stronger) than the product in question. An example of interpolation of RF_{ID} based on this principle is presented in Figure 45.

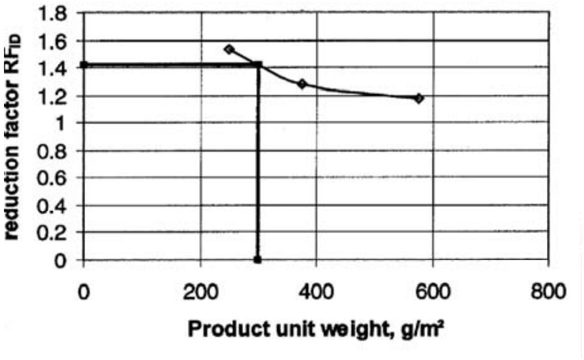

Figure 45. Interpolation RF_{ID} on from damage measurements on products from the same line with different weights (ISO/CEN 2001).

7.4.2 *Default values of factors for installation damage*

In everyday design the use of default values to cover for installation damage on the tensile strength is quite common. The material factor for installation damage may vary significantly dependent on the boundary conditions and the actual geosynthetic reinforcement. Experiences from the field indicate that a variation range from 1.1 to 3 is realistic (Koerner 1998, Flum et al 2001, Hsieh et al 2000). Default values should be applied with great care and should be based on well-documented relevant experience with the specific product type of product and the fill materials in question. Also the default values should be chosen in a way that more specific investigations and documentation of the damage susceptibility are encouraged. If relevant documentation for damage susceptibility is missing, the material factor for damage for geosynthetic reinforcement should be set to 2.5 as a minimum.

8 CONCLUSIONS AND FURTHER WORK

Geosynthetic damage and damage survivability is a major issue in the evaluation of "fitness for purpose" for all applications. The evaluation of susceptibility and possible consequences of damage should be based on the dominating damage mechanisms. The damage mechanisms then indicate which geosynthetic characteristics, test methods and requirements are relevant. The damage mechanisms are primarily related to the boundary conditions (fill material, subsoil, construction equipment and procedures) but will also vary with the type of geosynthetic.

A number of laboratory test methods are available and may provide useful information for evaluating the damage susceptibility. So far no laboratory test method exists that can provide a complete "picture" of the damage susceptibility. A full-scale field trial is technically the best way to provide the required information but this is commonly not possible due to time and economical restrictions. In the absence of field trials a combination of characteristics and test methods is therefore likely to be the best option. This is especially relevant for applications and functions where the consequences of damage are limited. For some applications such combined requirements are already developed, e.g. as specification profiles for separation and filtration in roads (Watn et al 2002).

For revetment filter application, particular attention has to be paid on the appropriate mechanism of failure, which is a function of base soil type, geosynthetics type, boundary and operation conditions. Appropriate laboratory performance tests, or better still, standardised field drop test has to be conducted for the proper evaluation of the damage potential. Evaluation of damage incurred should include the frequency as well as the size of holes on a statistical basis. One such procedure was proposed (Chew et al., 1999). Simplified design chart, developed based on energy concept, was found to be useful and applicable for the selection of appropriate geotextile for such application.

For other applications and functions more thorough evaluations are required. The level for evaluation of damage susceptibility should be based on a combination of probability and consequences of the damage. For reinforcement applications the consequence of damage is generally of high priority and the effect of the damage is primarily related to the tensile strength (in some cases also the tensile strain). For reinforcement applications it is recommended to take into account the effects of damage during installation by reducing the tensile strength with a partial material factor RF_{ID}. Guidance for choosing the value of RF_{ID} can be found in guidelines from public authorities (BS8006, AASHTO). There is currently under preparation a guideline for derivation of design strength for geosynthetics used for soil reinforcement including evaluation of installation damage (ISO 2001).

A number of research projects have been carried out and a lot of experience already exists related to mechanical damage on geosynthetics. However it is fair to say that compared to other topics on geosynthetic design and construction there is still a lot missing. It is strongly recommended that future work on geosynthetic damage should emphasise the linking between results from results in the laboratory and experiences from the field, both from field tests and from real sites. A good correlation between damage mechanisms, geosynthetic characteristics and test methods should be established for a wide range of applications and products in this way. This is believed to be beneficial both for the producers, the designers and the contractors. This is also believed to be crucial to improve the overall confidence in geosynthetics to serve as useful products to solve a wide range of civil engineering problems.

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