Accessible design methods for geosynthetics used for erosion control on channel and river banks

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ABSTRACT: The design of geosynthetics used in erosion control on river and channels has evolved over the last 50 years from its early use in land reclamation and protection in fascine replacing willow/brushwood rafts with woven synthetics. Much empirical experience has been gained throughout Europe. Machine made synthetic sheet like materials which have much tighter quality control can be studied in detail in the laboratory in a consistent and systematic way. To add to practical experience testing and design development has occurred and many often complex filter rules have been developed and publicised. However, it is often the case that designers do not have the luxury of sophisticated soil investigation reports for the intermittent embankment erosion schemes they have to design. This paper seeks to point the designer to theestablished design rules but also highlights a new pragmatism developed more recently helping designers focus on more practical elements of installation through service life and maintenance and a greater emphasis on working with nature with a much simpler approach. Designers are given tables and simpler guidelines to cover the majority of designs which have been developed from sound research and experience. A brief preview is given of this new approach which is the basis for latest directive, soon to be published, by the Dutch authorities who have consulted widely highlighting a more realistic and accessible design approach. Reference is also made to the concept of managed overtopping of embankments and the need for reinforced engineered vegetation.

Keywords:geosynthetics, erosion protection, filter, container, turf reinforcement

1 INTRODUCTION

Much of the design in the past has been based on a philosophy of “defending” our infrastructure from the “attack” of nature. The idea is to design embankment structures for rivers and channels to keep nature out with ever higher factors of safety for longer design life periods against overtopping or collapse.The result has been to build higher and stronger structures with a view to keeping nature at bay. There is a shift in thinking within Europe from considering nature as something we can fight using words like attack and defend, a war we are losing especially with the notable increase in global warming and ever rising sea levels. The shift is towards working with nature by first allowing events to cause flooding and to live with the consequences. Ideas such as building better houses which can withstand a flood event rather than try to prevent floods are starting to arise. The use of natural and softer methods to dampen down the effects of high flow or wave attack e.g. planting trees in flood plains to dissipate waves where inundated flood plains could cause wave erosion in storm events. The design would now accept overtopping of the levees which gives a new set of design considerations for Engineers. Geosynthetics are often designed to enhance and work with the strength of nature against the more damaging parts of itself. The flexible and moldable forms that can be constructed with geosynthetics can be used to produce compatible designs with this new thinking.

2 EMBANKMENTS SLOPES

2.1 *Revetments*

Revetments are used to protect often soft and alluvial highly erodible surfaces in exposed conditions on the slopes of protective earth structures such as river or coastal dikes. They are usually layers of rock, concrete units or mattresses designed to be stable in the prevailing conditions. Geotextiles are used to filter the fine materials and act as a separator from the rock layers above. Wave or water current stability design has long been established for armour units for primary and further smaller graded layers beneath to act as a filter. Each layer is designed such they cannot be washed through the gaps between the overlaying armour units thus making a stable interlocked revetment. Guidelines published by CIRIA (2007) give the design methods for sizing of primary and secondary units for stability. The most common form of revetment are loose laid rock tipped into placed and often primary units are placed by grab and where possible interlocked.If the hydraulic forces such as wave attack are sufficiently high the design will demand many layers of filter to dissipate loading and prevent loss of fines.

Figure 1: Rock revetment and geotextile

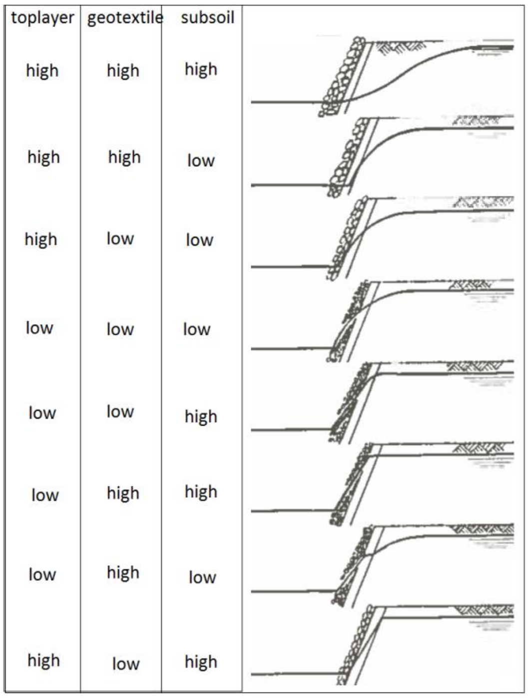
2.1.1 *Geotextile replaces rock filter layers and saves on carbon*

A geotextile can replace one or more layers of the finer sub layers of rock thus saving on cost. The sheet like nature of the material prevents loss of material through the gaps in the rock above it. With the increase in the recognition in many European countries in carbon production and transport costs to the environment authorities are favouring designs which can show a carbon saving over traditional methods. Geosynthetics represent significant carbon saving over rock filter layers.

The design of geotextiles for these applications has developed from the 1970s where site based trials were used to establish suitable use through a more systematic approach to develop filter rules using laboratory and theoretical mathematical modelling in the 1980s.

The basic design requirement for a geotextile under a revetment should give:

a) Sufficient permeability to allow water to flow through without causing physical stress to the geotextile which can then translate to stressing the embankment
b) Suitable filter capability to prevent loss of fine materials
c) Survivability of the filter during construction and durability through design life



toplayer	geotextile	subsoil
high	high	high
high	high	low
high	low	low
low	low	low
low	low	high
low	high	high
low	high	low
high	low	high

Figure 2: Relative permeabilities

2.2 *Required Geotextile Hydraulic Properties*

The filter geotextile under a revetment must allow free movement of water through the boundary layers in either direction. Dependant on loacation the revetment will experience different hydraulic loads at different times. For instance in a tidal esturary there could be currents, wave attack and infiltration on a rising tide and drawdown on a falling tide.

A filter is defined by permeability and soil retention in balance. There needs to be sufficient flow to prevent instability in the embankment due to hydraulic pressure whilst retaining sufficient amount of the underlying soil to maintain its structure.

2.2.1 *Drainage drawdown*

Even in steady river flow levels there maybe drawdown due to high local water tables. If the geotextile presents a lower permeability than the underlying soils pore pressure build up occurs which leads to piping and soil movment. (see gradients in Figure 2) The predominant flow is unidirectional and the design of the filter assumes a loss of the finer fraction of the underlying soil passing through the geotextile leaving larger grains of soil to leave a soil particle skeleton near the surface of the geotextile to build up. The Terzaghi model (1922) criterion adapted to geotextiles filters ny Giroud (2010) Based on laboratory and theoretical modelling there have been a number of filter rules proposed. A useful summary can be found in “Geotextiles in Filtration : A state of the art review” (Palmeira; Gardoni 2000)

Typical retention criteria proposed are

Granular and dispersive soils :

$d_{15} \leq O_{90} \leq d_{85}$

Fine grained soil (PI < 10%)

$d_{15} \leq O_{90} \leq 2d_{85}$

where O_{90} = AOS of geotextile filter measured according to ISO 12956:2010 ; d_{15} and d_{85} = particle size fractions of soil to be retained. Most of the filter retention criteria are summarised in the Figure 3 which have been used in the last 30 years.

Similalry in Figure 3 the graph summarises the permeability criteria used for uni-directional flow.

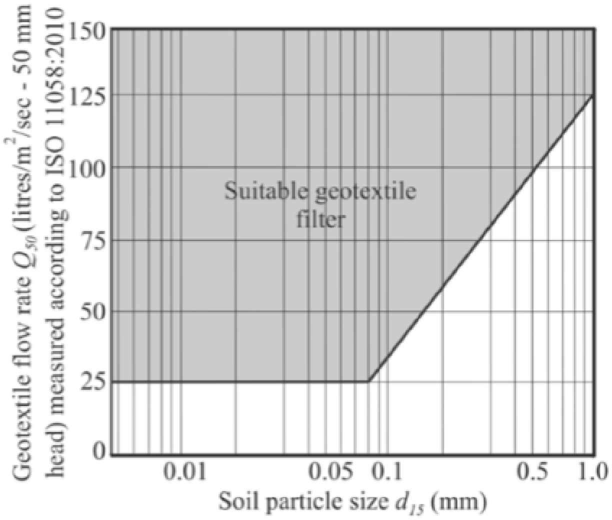


Figure 3: Geotextile filter criteria for unidirectional drawdown

A safe estimate for geotextile retention in water current conditions would be $O_{90} \leq 0.6$mm with a geotextile permeability being $Q_{50} \geq 5$ litres/m^2.sec .

An example of lack of attention to detail in the construction phase s shown in Figure 4. The designer has selected the correct geotextile to match the sandy subsoil but had not taken account of an access road constructed by the installer made from course road stone. In a storm event that occurred during construction the geotextile was not sufficiently permeable to allow water out of the slope as it has a lower permeability than the course access track below it. The track should have been removed and the geotextile placed on the original beach material.

Figure 4: Mismatch of permeabilites of geotextile and underlying layer

There are current research projects on refining these filter rules. Exceptions to these rules may be found on some sites, assuming sufficient soil data is available, show particle distribution curves where a high silt content combined with certain granular fractions can be a problem. Moraci et al (2012) shows that whilst the model of a skeletal structural build up of particles is sufficient for soil retention for most soils, those with high silt content in a fluidised soil could be in danger of piping. This work is part of continuing research in defining the critical diameter D_c of suffusion, where particles can freely move within the skeleton. Once defined the O_{90} can then be defined more accuratly for these type of soils. The second goal of the research is to redefine the upper limit of O_{90} for the geotextile filter for stable granular soils. Findings so far suggest that for internally unstable soils the limiting value to give a geotextile opening size seems to be the lower limit value of D_c. It must not be lower than D_c or blinding will occur.

Concerns are expressed by Palmira & Gardoni (2000) of the danger of severe clogging or surface blinding of geosynthetics in their state if the art paper looking at all types of geosynthetic filters. This, however is more releavant to single directional seepage flow in earth structures or drains and is often used as a reason for dismissing their use in revetment applications. Later in the summary he points to general rules of thumb differentiating for hydraulic structures referencing Carroll (1983); Christopher & Holtz (1985) , Corbet (1993) who recommend $k_f \geq 10k_s$

Where k_f - filter coefficient of permeability ; k_s– soil coefficient of permeability

Corbet (1993) in addition recommends $k_f \geq 100k_s$ for thicker (> 2mm) non wovens

2.2.2 *Currents*

Water currents create a surface shear stress on the revetment. A geotextile will help resist this shear stress due to its sheet like nature. Anchoring mid slope can sometimes enhance this effect still further. This action is different from the drawdown effect which is related to a free surface associated with flow parralel to an embankment.

2.2.3*Wave and tidal*

In rivers and channels where waves caused by windblown or bow waves from vessels or in tidal estural channels a reversing flow condition is created with greater turbulanece in water conditions causing ersion in soils. Earlier design models assumed that there was a need to tighten geotextile retention which ended in some revetments failing through uplift or the breakdown of the goetectile through stress. Often geotextiles were designed out of revetments as they were considered a stability hazard (Van de Meer 1988) where ALL geotextiles were given a permeability factor of as low as 0.1 which made all goetetiles appear virtually impermeable. In the last 10 years more sophistiacted modelling has been undertaken and a recognition of the wide variety of geotextiles which have been produced with very differing permeabilities and retention criterias. Models now include differing wave periods, hydraulic grasientsand varying confining pressures at soil/geotextile filter intefaces.

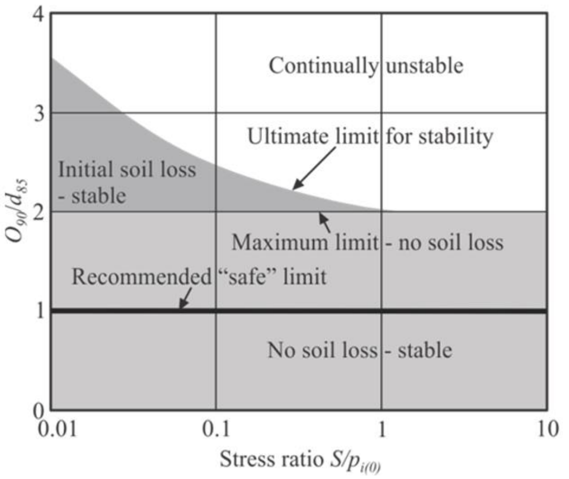


Figure 5: Geotextile retention criterion for waves and tides condition (Srikongsri, 2010)

Srikongsri (2010) has carried out laboratory modelling on sandy soils , different geotextiles types which have different hydraulic properties. He simulated doffernt wave heights and periods and overbruden pressures (armour weight) showing the filter performance for retention ration of O_{90}/d_{85} plotted agaisnt stess ratio. The stress ration is the ratio of the seepage pressure (destabilisaing effect) and the mean effective stress in the proted soil at the soil/geotextile filter interface (stabilising effect).

For stress ratios less than 1 the performance is governed by the stabilising effect of the rock armour. If the stress ration is greater than 1 then the performance is governed by the destabilising effect of the seepage flow.

The different regions of filter performance in Figure 5 are:

1. For retention ratios $O_{90}/d_{85} \leq 2$ there was no observed soil loss through the geotextile filters over a wide range of stress ratios.
2. For stress ratios less than 1 there was a transition zone where initial soil loss through the geotextile filters was observed but this stabilised after a period of time. For stress ratios greater than 1 no transition zone was evident resulting in an abrupt change from stable to unstable conditions at O90/d85 = 2.

3. Based on the filter performance regions shown in figure 5, Srikongsri (2010) recommended a “safe” retention criterion of O90/d85 ≤ 1.0 which would ensure the retention limit was well distant from any unstable piping conditions.

Srikongsri (2010) also compared the results shown in figure 5 with other published laboratory and field results and found good agreement. The overriding implication of the results shown in figure 5, and its recommended “safe” retention limit of $O_{90}/d_{85} \leq 1.0$, is that appropriate retention criterion for the waves and tides condition is very similar to that for the unidirectional drawdown condition, and that the stabilising effect of the armour weight counteracts the increased destabilising effect of the wave-induced seepage pressure. More recently, Kachan et al. (2012) have reached similar conclusions.

2.3 *Required Geotextile Mechanical Properties*

Whilst there has been much work carried out in filter design on the micro level it is often the case that macro effects dictate the actual functioning of the geotextile. Having a perfect match for retention and permeability with the underlying soil is totally negated if while installing several holes 300mm wide have been made in the middle of the revetment by some sharp rock points above or below the geotextile.

Figure 6: Site based rock drop tests & damaged geotextile

This concern was recognised in the 1980s but not universally and maybe a symptom of looking at the micro when the macro dominates. Some methods were devised from a simple site specific rock drop test usually required on the site itself simulating the actual installation conditions. This is useful but often impractical especially on new sites where selected geotextiles are needed on the first day of construction and the delay of selection of the correct geotextile and then supply lead time to send product to continue. If the rock armour has been selected and is locally sourced the tests can sometimes be carried out at the quarry this could solve the lead time problem.

Attempts have been made to carry out controlled rock drop tests to relate an index test (short term laboratory test) to observed damage from a particular rock dropped from a set height. Various manufactures published their results to give an indication of the grade of geotextile suitable. This was repeated for different rock sizes resulting in an energy value of rock weight multiplied by distance dropped.

Figure 7: Suitable geotextile after first layer installation

Some related this to product mass per square metre Lawson (1992)

$$M_A \geq 1200 \sqrt{H} \, . \, D_{85}$$

where, M_A = mass per unit area of the geotextile filter (in g/m^2) measured according to ISO 9864:2005; H = height of rock placement on the geotextile (in m); and D85 = 85% rock size on geotextile (in m).

Shercliff (2005) proposed CBR puncture resistance as opposed to mass per unit area specifically for thick non wovens geotextiles reading from an empirically based chart for different rock drop energy values.

Experience has shown that the greatest damage is done to a geotextile when dropping a primary armour unit causes more damage to a geotextile after a bedding layer has been placed than when dropping the bedding layer. Dropping a stone on a geotextile over soft soil causes less damage than over a hard surface.

Good site practice is to minimise any rock drop to a practical minimum of 1-1.5m. This is determined by the practicalities of the site and a designer should seek advice about the buildability of the site before specifying the geotextile based on mechanical strength.

Other mechanical properties such as tensile strength should be specified to indicate ability of the material to be manoeuvred or even dragged on site often by machine.

In the special case of the use of a laying technique especially used where large areas of geotextile are placed under water the fascine mattress which is a prefabrication on a dry embankment will be dragged by towing vessels as a raft and attached to an embankment or channel bed. Rocks are dumped onto the square matrix of fascines which then push the mattress on a mat form in a controlled way onto the bed. These mattresses often use woven geotextiles which have the ability to incorporate handing loops in the weaving process to facilitate prefabrication and avoid puncturing the geotextile. The dilemma then comes when a restrained woven has dropped on it from some height, especially when dropped from water surface to bed. Figure shows the terminal velocities of rocks dropped in water which can still result in quite high impact loads. It is likely therefore that some fascine mattresses were damaged. The traditional method to overcome this was to create a protective mattress of brushwood over the woven geotextile under the fascines or to increase the tensile strength and robustness of the woven to as much as 200kN/m. The latest proposal by the Dutch, who are the major users of fascines worldwide, is to combine a woven with a nonwoven. Reference is made to this in their new directive previewed later in this paper.

Figure 8: Fascine mattress with woven geotextile with tie loops

Figure 9: Flexible concrete mattress laid on filter geotextile

2.4 *Alternative revetments*

Concrete units are sometimes made often on site and interlocked as single units and should be considered as rock armour from the design point of view for geotextiles. For lighter applications or in urban areas the use of concrete block mattresses has been very popular especially as these can be topsoil and grass filled as well as gravel filled. The key design consideration for concrete mattresses is their sheet like nature at the surface and whilst flexible can adapt to settlement they act as a unit and under heavy hydraulic load can be peeled off the surface. Special attention should be made to anchorage on the perimeter or even mid slope using soil anchors attached to the block face. With the relatively thin layer the section of an open enough geotextile is essential as drawdown forces due to wave attack and the reduced opening area at the surface through the holes in the blocks compared to a rock armour surface. The design limits and procedures for geotextile mattresses are defined by Dutch publication s Pilarczyk (2000) and CUR 174 (2012)

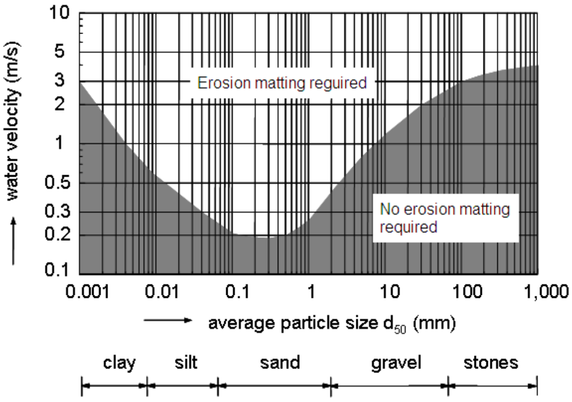


Figure 10: Particle transportation velocities

2.4.1 *Geotextile mattress,*

In some areas current (<1.5m/s) or wave attack (Hs<1.0m) is reduced but soils are still highly erodible sand mattresses maybe considered. A geotextile mattress is made from two sheets of geotextile sewn together to form a series of long tubes which can be prefilled or more often site filled with pumped sand. The front face of the tube is a composite of non woven and woven whilst the back face is woven. The woven geotextile provides the reinforcement needed for placement and anchoring into a trench. The non woven assists with surface abrasion protection and encourages sediment entrapment leading to natural growth of local grasses etc. Sometimes additional topsoil and seed are needed to protect the above water section. Designers need to apply the same design rules for mattresses as noted above. Detailing on maximum fill of mattress to 0.1 to 0.2m ensures good surface contact to the soil preventing piping. Overfilling can create back of revetment channels and therefore piping. As with all thin revetments attention to detailing of toe crest and edge anchoring is essential. Calculations on down slope “veneer” stresses need to be considered.

2.4.2 *Turf Reinforcement Mattresses (TRM)*

When rivers and streams are slow flowing but where silts and sands are easily transported ideally a natural vegetated river bank is the ideal where a grass sward is sufficient to handle the flows as long it is protected. The challenge is the establishment and then maintenance of the vegetation over a long period. For slopes that become wetted frequently or occasionally a TRM can be a good solution as they reinforce the roots of a grass sward when under increased flow and cover for any weak spots in the grass where die back may have occurred. TRM’s are usually a three dimensional extruded polymer matrix which acts as a preformed and permanent artificial root system which is design to minimise movement of organic particles at the surface encouraging root growth to establish. Some TRM/s contain a mixture of asphalt and chippings (see lighter grey section in Figure 12) and some can be filled with small stones when placed under water or in the frequently wetted zone.

Figure 11: Open and asphalt filled TRM

Figure 12: Early growth of reinforced grass

Key design considerations with TRMs similar to thin revetments is good anchorage details at crest and toe and as these are sometimes light materials they need to be pinned to make intimate ground contact at all places. Mats should be installed in a roof tile fashion working from downstream to up stream. Short leafed varieties or grass which are compatible with the indigenous varieties in the area should be used with spread rates for seeding. Fast establishment of grass is essential.

3 STATE OF THE ART – LATEST DESIGN GUIDELINES

3.1 *SBRCURnet – Draft guideline for the design ofgeotextiles under stone coverings, 2016.*

A Dutch committee of Government, consultants, contractors and geosynthetics experts have been working on what appears to be a major shift in the design approach to designing geotextiles which receive stone and rock.

3.2 *Influences for new design guidance*

Much of the work in the design of early filters was undertaken by Dutch colleagues based on the traditional Dutch weaving experience where specialist wovens have been used successfully over many years.
New technology - Over the last 20 years non woven needle punched technology has been developing which has changed the role of geotextiles as filters due to their more flexible and extensible nature and filter characteristics. Non wovens have been developed for these applications in UK, France and Germany along with filter rules.

There has been much resistance in the past from contractors who have seen geotextiles as a nuisance especially when asked to install what is perceived as flimsy sheet like materials which are incompatible with the heavy rock placing equipment they use.

More robust damage resistant geotextiles and developed experience has given more confidence to the contractors and has driven the design and buildability element of the guidelines being produced.

Another influence on design has been a systematic study made on Dutch failing revetments containing geotextile filters to try to identify the cause of failure. The overwhelming conclusion was failure was due to holes punched in the geotextile at installation stage leading to piping and eventual loss of structure in the embankment.

It was recognised that the numerous filter rules were somewhat confusing to a designer who may only design a revetment at maximum once a year and more likely much less and the investment in time to research and select the correct method was too onerous. Engineers were much more likely to make mistakes which led to failure which inevitably was bad for geosynthetics industry. An additional reality is that although Dutch geology is more homogenous than most European countries there is still a reasonable variety of soil types with their variable permeabilities and filter behaviour. Designers often have little knowledge of the soil types as these are difficult to capture in a marine or river environment.

They prompted the committee to adopt a three tier approach and classification system to give the designer the option to make reasonably safe designs so that at least designers had some more universal design methods which would reduce the risk of failure.

3.3 *The three methods*

3.3.1 *The Simple Method*

This is for where standard properties of geotextiles are required to overcome the macro influences of installation damage and universal filter characteristics. There is no calculation required and a series of look up tables are provided using standard soil- and stone classifications developed for typical soils; using the detailed method for average soils and an outline knowledge of the soils on the site. Limiting factors are defined which must not be exceeded. It is thought that this method will cover the majority of installations.

3.3.2 *The Detailed Method*

This uses existing filter design calculations and assumes more superior soils knowledge. These rules are defined in the CUR publication 174 “Geosynthetics in hydraulic engineering”. This gives the designer the opportunity to make their own calculations where there may be known variations and greater soil details where, soil types such as changes in permeability may occur along the slope or hydraulic loadings are variable such as flow and wave attack in the tidal region of an estuary. There may be proprietary block systems used which are placed in different ways requiring less robustness from the geotextile by giving greater concerns for permeability and stability considerations. Shape of revetment away from the simple slope may create hydraulic stress points to be individually considered. Consideration of any installation requirements such as tracking of the surface for access or fabrication methods on the foreshore.

3.3.3 *The Advanced Method*

This is where there is a special case such as a large project or where the failure of the geotextile would have a major impact. At this level it is likely there will be laboratory, model and performance testing. It could be that one characteristic of the geotextile is researched and the other characteristics are defined by the simple method.

In addition to the installation forces on the geotextile the directive focusses on other stresses on the geotextile in the short medium and long term in terms of the life time of the structure. For instance, fascines are being deployed where tensile stiffness is important whilst manoeuvring the mattresses into place.

The robustness of the geotextile is addressed far more fully than in previous guidance and a series of drop tests have helped determine the Energy Absorption Level (EAL) in a geotextile laid out ready to receive dumped stone. A distinction is made between conditions above and below water and in the varying water level in either intertidal or seasonal water level fluctuations. The apparent incompatibility of the need for stiffness when manoeuvring and the need for deformation when placing stones is also addressed by making use of composites combining woven and non woven geotextiles.

Table 1: Key features of the geotextile, with reference to the relevant sections in the Guideline

Requirements	**Characteristics geotextieles**	**Unit**	**Requirement / reason**	**Norm**	**Section in guideline**
Functionality	Openingsize	mm	Prevent leaching of the base layer	EN ISO 12956	5.2.1, table 5.4
	Permeability	m/s	Caring for good water permeability to prevent water overpressure and suppressure	EN ISO 11058	5.2.2, table 5.5
	Lifetime	jaar	Minimum service life > 50 year, to prevent failure during life time	EN ISO 13438	5.2.3
Robustness	Tensile strength, at break	kN/m^1	Absorbing forces during the installation phase	EN ISO 10319	Minimum breaking strength: 5.3.2, table 5.6
	Minimum elongation	%	Elongation of the geotextile to be able to follow the deformation of the underlying soil as result of the energy absorption of the falling stone	EN ISO 10319	Minimum elongation at break: 5.3.3, table 5.7
Additional requirements at installation using a mattress	Maximum elongation at required tensile strength	ε	When using a mattress, the strain in the geotextile may not exceed a certain value at the maximum strength level, during installation	EN ISO 10319	Maximum elongation at required strength: 5.4.1, table 5.8
	Energy Absorption Level	kJ/m^2	The Energy Absorption capability of the geotextile (EAL) is the relationship between tensile strength and elongation at break, which with	EN ISO 10321	5.4.2, table 5.9

			each other multiplied, give an indication of the deformation capacity		
	Seam strength	kN/m	Strength over the sewing seam, if applicable		5.4.3, table 5.10

The proposed Directive is based on CUR 174 (2009): Geosynthetics in hydraulic engineering,revised edition. Additional references are made to the life expectancy of geosynthetics CUR243: Durability of Geosynthetics and to CUR 115:2011 :Guideline for installationof geosynthetics in hydraulic engineering.

Central to the draft directive is the recognition of the subsurface, stone revetment and geotextile working together in partnership each having an effect on the other.

3.4 *Requirements for the geotextile*

To allow the geotextile to function as a filter it must take account of:

Filter/separator requirements - Soil density, and aperture size, permeability and resistance

Robustness requirements – minimum tensile strength and elongation

Special case for a sinking (fascine) mattress maximum elongation at a given tensile load and seam strength. In addition, the mattress must be able to withstand falling stone impact loads. This may lead to non woven geotextile used on steep dry slopes and composite woven/non woven composites in submerged slopes and bed protection applications.

The tables below shows the properties to be specified with references to later in the report to determine these. The two properties which are characteristic for the functioning of the geotextile is ground density and water permeability.

It is interesting to note that the CBR test and Cone Drop test are omitted from the specification as they are determined to be less suitable for the determination of robustness, which is a departure from the recommendation in the CIRIA manual (2007)

The directive gives a flow chart method to help designers decide on the design method applicable to their site. These ask questions of available information and risk levels involved in the design and the cost savings which may be attainable with closer detailed design for a given project. These then lead to the steps to be taken in terms of calculation or even performance testing. The result is a priorised specification.

3.5 *Simple method summary*

3.5.1 *Key Conditions for Simple Method*

1. Estimate ground density and water permeability of soil at site location
2. Determine direction of flow through geotextile: one or two (reversing);
3. Design life is minimum 50 years
4. The slope itself is geotechnically stable determined by slope angle and toe detail
5. Maximum drop height on site 2m.
6. Maximum of 15 tonnes site plant tracking over minimum 300mm of cover
7. Two layer revetment with a specification for the lower layer of 90/250mm, 5-40kg , 10-60kg, 40-200kg. Stone density 2300kg/m^3
8. Factory of Safety throughout is 1.5

Classifications of soil are to EuroCode 7 and cover stones to BS 13383-1: 2013 – Armour Stone. Rock armour is defined up to a maximum of 200kg typically used in rivers and channels. If wave attack is significant then larger stones maybe used but would need the advanced design approach.

3.5.2 *Selection of O_{90}*

Using the following table, choose the lower O_{90} between two categories

Table 2: Opening size for different soils in single and reversing flows

Opening size O_{90} (mm)	Stationary (single direction flow)	Dynamic (reversing flows)
Soil		
Heavy clay	0.10	0.10
Sandy clay	0.30	0.14
sand	0.34	0.12
Sandy gravel	0.50	0.50
gravel	0.50	0.50

3.5.3 *Selection of Permeability*

Using the table below with an estimate of the predominant soil type select the required permeability of the geotextile.

k_g : Permeability coefficient of geotextile (m/s)
k_b range : Permeability coefficient of base material (m/s)
C_m : Safety factor, depending on base material

Table 3: Required minimum permeability of geotextile

Soil	D_{50} (mm)	Range k_b (m/s)	Chosen notional value k_b (m/s)	C_m	Required k_g (m/s)
Heavy clay	0.010	$10^{-10} – 10^{-8}$	10^{-8}	100	10^{-6}
Sandy clay	0.038	$10^{-8} – 10^{-6}$	10^{-6}	100	10^{-4}
sand	0.17	$10^{-6} – 10^{-3}$	10^{-4}	10	10^{-3}
Sandy gravel	3.0		10^{-3}	10	10^{-2}
gravel	9.3	$10^{-3} – 10^{-1}$	10^{-2}	10	10^{-1}

3.5.4 *Selection of robustness – minimum tensile strength*

1. Minimum tensile strength in 2 directions when installing a woven ≥ 35kN/m (eg in fascine installation)
2. Minimum tensile strength in 2 directions when installing a nonwoven ≥ 15kN/m

These apply also to composites of wovens and nonwovens in case of mattress installation. The concept is that if a woven is pierced by receiving high local stress the nonwoven will compensate with its high localised strain.
Selection of robustness – minimum tensile elongation

For direct installation - Minimum elongation ≥ 60% in both directions
When using sinking mattresses to allow for transportation and immersion – woven component – Maximum elongation ≤ 20% in both directions at maximum tensile strength level.

A note on sewing of adjacent panels on site maybe allowable for efficiency to create a large towing mattresses but there should not be excessive load on the seam and it is assumed that a seam can only provide 50% maximum of the original sewn joint.

Energy Absorption Level for sinking mattresses is determined by the area under the Stress / strain curve for the geotextile and is matched to the EAL level of a dumped stone

Table 4: Energy Absorption Levels for typical stone grades

Stone class	Energy Absorption Level (EAL) (kJ/m^2)
90/250 mm	3
5-40 kg	3.5
10-60 kg	7
40-200 kg	9

EAL is derived from:

$EAL = 0.5 * T_{max} * \epsilon_{max}$ [kJ/m^2 or kN/m)

Where

T_{max} = Average of machine and cross machine direction strength at break
ϵ_{max}= Average of machine and cross machinedirection elongation at break

The directive gives guidance on the calculation of EAL for geotextiles with elongations at break greater than 60%.
The guidelines were based on actual site results from various countries including Germany, France and UK.

3.6 *Detailed method summary*

This method is an expansion from reading from standard tables to calculation methods and higher levels of complexity which include the effect on the key parameters:

1.Stable and unstable ground
2.Cohesiveness of soil
3.Relative quantities of sand and silt fraction and grain mobility
4.Limiting clogging conditions
5.Uniformity coefficient of substrate
6.Thick geotextiles should have a permittivity value – can be difficult to determine before the actual geotextile is selected as only then the geotextile thickness is known
7.Relative water levels on each side of a revetment. In a falling water application (tidal) it is possible that the water head behind the revetment is high due to the relative impermeably of the geotextile especially in situations where fine particles dictate a small opening size thus lowering the permeability. Where this occurs "C" factor of Safety for geotextile permeability 10 x permeability of subsoil for granular should be 100 x for fine subsoils.

The method considers in more detail the lifetime of the geotextile and puts forward a procedure to

1. Determine the relevant degradation mechanisms of the geotextile
2. Determine the reduction factors
3. Gives the parameters to be stated in a specification

Aging mechanisms include
1.Chemical resistance: oxidation in PP materials
2. Chemical resistance: hydrolysis in PET materials
3.UV radiation and weathering
4.Creep
5.Damage during installation – its effect on aging in the long term expressed as a reduction factor
6.Clogging due to chemical process
7.Blocking due to a biological process
8.Time-dependant penetration into the filter (particles fixed over the useful life of the filter)

3.7 *Example Reduction factors*

The reduction factors are to be considered for extended design life from the 50 years target to 100years.

3.7.1 *When considering permeability*

$K_{\text{long term}} = k_{g\ \text{index}} / RF_{CH}.\ RF_{WE}.RF_{IN}.RF_{CC}.RF_{BC}.\ RF_{CR}/RF_{ID}$

3.7.2 *When considering opening size*

$O_{90}\ \text{long term} = O_{90\ \text{index}} / RF_{CH}.\ RF_{WE}.RF_{IN}.RF_{CC}.RF_{BC}.\ RF_{CR}/RF_{ID}$

Table 5: Reduction factors to extend design life from 50 to 100years

Reduction factors for filter applications, based on a useful life of 100years		
	Reduction value	CUR 243: Durability of geosynthetics [1])
RF_{CH}	To be determined by performance test	Chapter 1.5.5.2
RF_{WE}	1.4	CE-Acc. Doc
RF_{CR}	1.0	Table 1.11
RF_{IN}	1.0	Table 1.11
RF_{CC}	1.0	Table 1.11
RF_{BC}	1.0	Table 1.11
RF_{ID}	1.1	Table 1.9

[1])Reference is made to the chapter and tables in CUR 243: Durability of Geosynthetics, 2016

Where:
RF_{WE} – Reduction factor for UV and weathering
RF_{CH} – Reduction factor for time-dependant compression of the geotextile (compressive creep)
RF_{IN} – Reduction factor for time-dependant penetration of soil particles
RF_{ID} – Reduction factor for installation damage
RF_{CC} – Reduction factor for blocking due to chemical processes
RF_{BC} – Reduction factor for blocking due to biological processes
RF_{CR} – Reduction factor for chemical degradation effects

There are separate strength reduction factor tables apply to the tensile load for wovens and nonwovens.

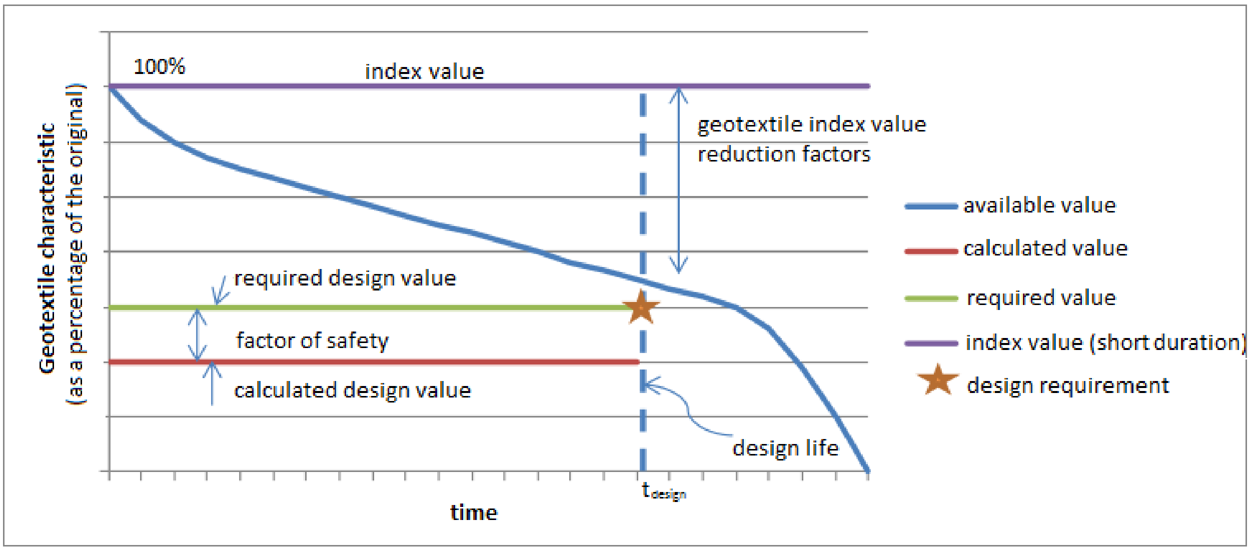


Figure 13: Establishing design requirement - long term design value < available long-term value

3.8 *Determining the tensile strength required*

Calculation methodsare given to establish the required geotextile strength for 6 different loading cases during the installation of the geotextile on dry slopes or in cases of installation under water by means of a fascine mattress.

Calculations are given for the shearing effect of a loaded revetment which is anchored at the top of the slope and is being stressed as the stone are placed.

Consideration is given to the installation method and any reduction factors due to damage during installation. When considering a fascine mattress installation factors include:

- The size of the mattress
- Loads whilst transporting mattress
- Loads during sinking of mattress
- Stresses cause to mattress which is submerged to additional dumped stone
- Rollout of a geotextile on a dry slope
- Impact of stone on a dry slope
- Load due to site trafficking

References are made to earlier design methods to determine tensile forces to pull fascine mattresses from embankments where they have been constructed (Pilarczyk 2000). They include:

- Wiep number per m in each direction (wiep is the bundle of twigs that are made placed cross hatched across a fascine
- Wiep weight
- Soil / textile friction angles
- Inclination of the embankment

3.9 *Determining maximum elongation*

Modelling the distorted shape of the distorted geotextile when one or several rocks are placed directly onto the surface which then deforms

The stone types were categorised into two types:

1. Stone with a predominantly round shape

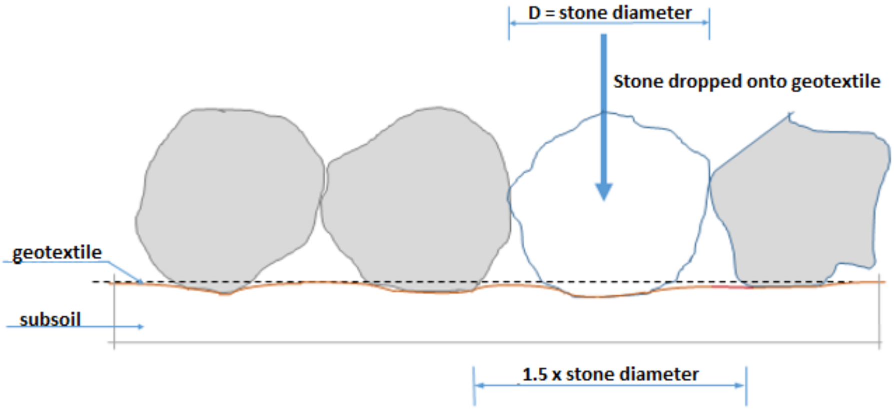


Figure 14.a: Schematic of dropped rounded stone surrounded by static stones giving maximum impact to geotextile

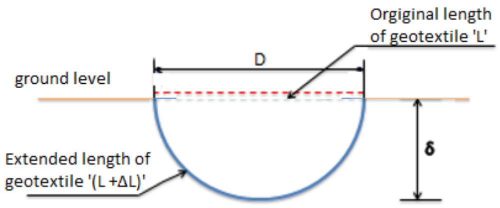


Figure 14.b: Actual likely and theoretical maximum extension of a geotextile overlain by a single rock

δ = Depression in the surface (m)
D = Maximum D_{n85} stone (according to EN 13883) (m)
ΔL = Extension of geotextile (m)
L = Original length (= D) (m)
In Figure 14: Schematic showing the maximum impression of a stone with a $\delta = 0.5$ D

This theoretical model is above 57% elongation. Whilst there may be other forces which determine the indentation of the stone it is the underlying soil properties which determine the degree of indentation. With sand the indentation is less than with clay.

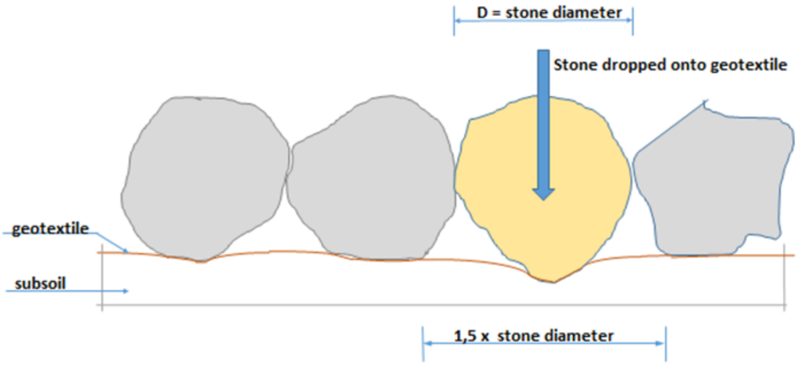


Figure 15.a: Schematic of dropped sharp cornered stone surrounded by static stones giving maximum impact to geotextile

2. Stone with sharp corners

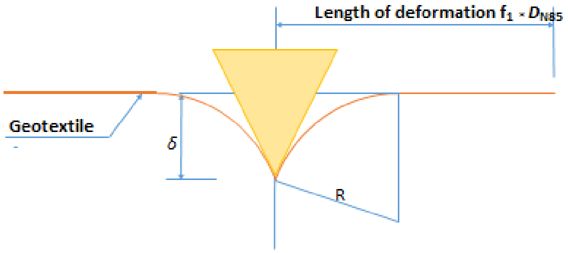


Figure 15.b: theoretical extension of a geotextile under sharp cornered stone with partly circle shaped deformation of the subsoil and the geotextile

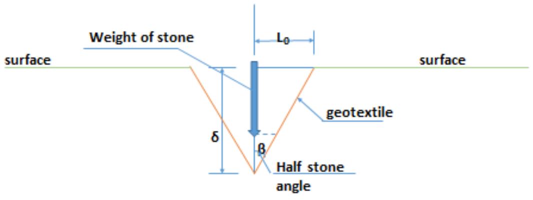


Figure 15 c: theoretical extension of a geotextile overlain by a single rock with sharp edged deformation of the subsoil and the geotextile

A similar theoretical indentation is modelled using a conical shape representing a sharp ended stone resulting in a maximum strain combined with the result from the rounded stone the determined maximum 60% specification was derived.

This modelling method was also used to determine limiting elongations for a sinking mattress.

The Guidelineis a comprehensive state of the art study itself and brings much experience and practicality to the design of geosynthetics in river and channel construction. The involvement of consultants and contractors as well as geosynthetics experts will enhance the use of geosynthetics in these environments.

The Guideline will be available in print at the end of 2016.

4 OVERTOPPING

4.1 *Designing in overtopping*

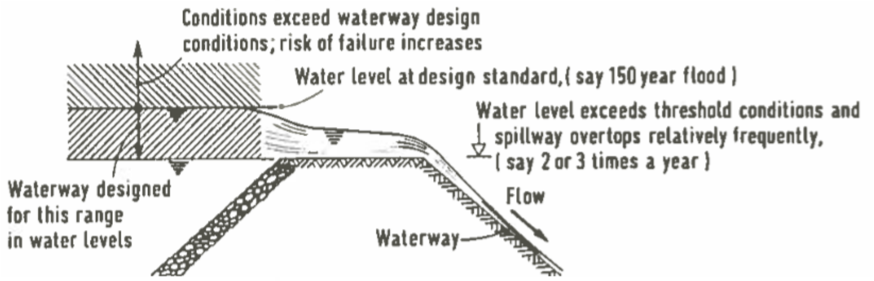


Figure 16: Designing for overtopping of river embankments

There has been a growing change in design philosophy in the construction of river and flood embankments. In a growing number of areas in Europe with the increase in tidal levels and climate changes to higher and more intense rainfall events resulting in a number of countries being extensively flooded. 2014-2015 saw extensive floods in UK and France is currently suffering from high flood levels. Designers are using more holistic approach to water control by employing sustainable drainage methods such as temporary use channels (swales) and attenuation ponds which have valves which retain and attenuate flows within the urban environment. Grass surfaces are used as infiltration and cleansing tools and road drainage is slowed down and retained. Green and blue roof systems are being used. These measures all reduce flooding but now designers are allowing and controlling over topping of river and channels into flood plain areas. In addition, they are now thinking in terms of deliberately allowing flooding of housing and changing the design or refurbishing houses to withstand flooding as opposed to constantly raising crest levels.

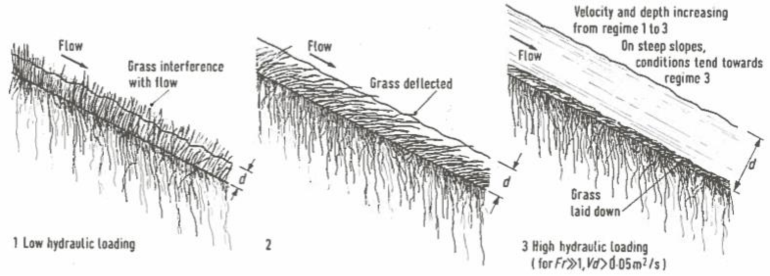


Figure 17: Well maintained grass provides protected reinforcement against erosion

Overtopping of crests poses specific design considerations. Firstly, flow down the back face of a dike must be controlled. It has been long recognised that for occasional inundations a well-established grass sward is remarkably good at withstanding sheet flow of water at speed for a limited time period through a flood event. Water flow accelerates over the crest to supercritical flow flattening the grass blades presenting a relatively smooth surface minimising shear on the surface soil.

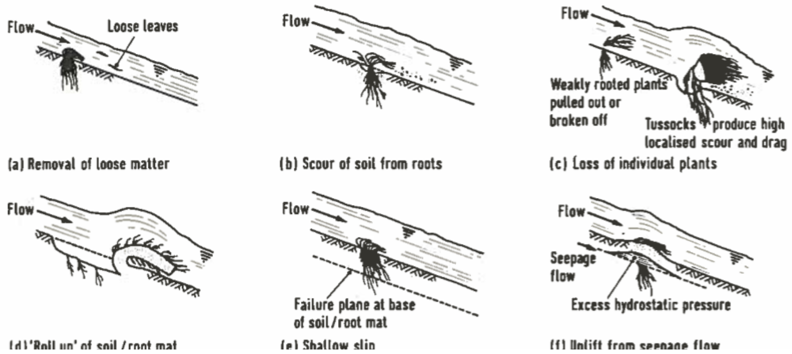


Figure 18: Weak spot in turf can lead to rapid failure

4.2 *Failure of turf in high flow*

A grass sward is however vulnerable in high flows to die back or weakened root structure which following an initial soil loss results in pluck out and then local rapid erosion.

4.3 *Turf Reinforcement Mats (TRM)*

Designers are called upon to design structures which blend with nature. Turf reinforcement mattresses (TRM) have been used with mixed results over the last 30 years. The most common and successful TRMs used in hydraulic applications are three dimensional extruded threads heat bonded together to form a matrix which simulates a root structure which in turn allows and encourages root growth through and within it causing an entanglement of reinforced roots. This increases their capacity to withstand inundation preventing pluck out. When there is die back in any area the synthetic root structure remains permanently as a back up to stop local failure. This method has been tested on several trial sites. CIRIA 1987 sponsored a multi discipline full scale trial on types of grass

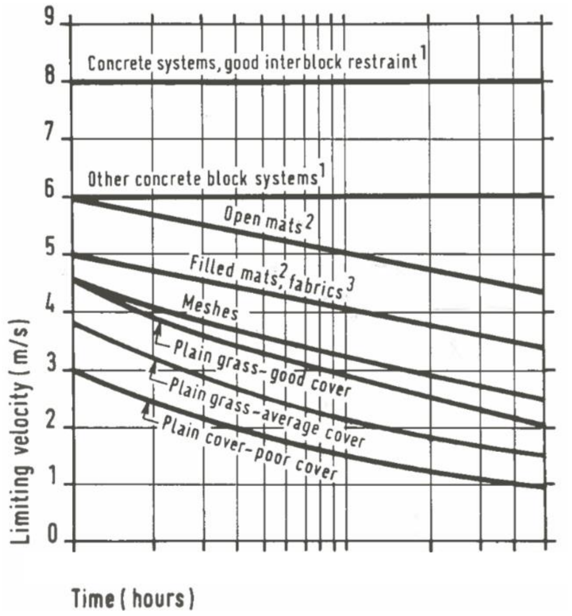


Figure 19: Limiting design velocities for TRMs

reinforcement including TRMs, TRMs with asphalt filling, meshes and plain geotextiles as well as concrete block revetments as previously described. The aim was to find limiting velocities to give designers a methodology for design to allow for flood events lasting several hours. A large capacity water tank was constructed with gates above a series of reinforced grassed channels and one unreinforced (plain grass). Each channel was inundated with water at a constant rate from low flows to higher flows and from short time periods to longer over a period of time allowing the grass to recover between inundations. The programme continued until the turf failed by a notable scouring of the surface or uplift of turf. A summary for designers on limiting velocities was published. It was notable that the more impermeable turf reinforcement mattress failed the earliest due to the pressure difference below and above the turf. Once the mattress is displaced it forms a protrusion which increases the pressure difference across the mat leading to progressive failure. Therefore, the more porous the mattress the easier the pressure relief. For instance, an asphalt filled (heavier mat) failed before an open lighter mat. The common mistake designers make is that it is believed the reinforcement does the work of protection. This is not the case as the reinforcement helps the turf and root structure do the work and acts as the “fil safe” for weak patches in the turf sward. The designer should give as much attention to proper The design guidance includes notes on correct grass mixes and maintenance.

4.3.1 *Importance of pinning detailing*

Pinning of the TRM in early stages of root growth is essential to maintain good surface contact with the underlying soil should a flood event occur before the grass sward is established. Special consideration should be given to changes in hydraulic shape such as bends or at the base of an embankment. Thought should be given to where a hydraulic jump will occur as there will be much turbulence in this area. This often occurs near the base of the embankment and therefore is a critical part of the geotechnical stability of the embankment and needs protecting. CIRIA give a number of solutions to crest and bottom of spillway details.

4.3.2 *Case study example, Somerset, UK*

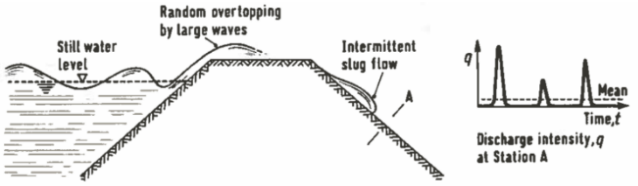
An example of an inundation of a spillway reinforced with a TRM between two rivers in Somerset UK. Extensive flooding and damage occurred in Sommerset,UK in January 2014 where over 6900 hecatres of land was flooded. On this site the inundation was monitored by consultants Black and Veitch who had designed the grass reinforced slope between two rivers one higher than the other. The 20mm thick extruded polypropylene matting containing a geogrid was pinned with U pins at half metre centres along overlaps of 100mm and 1 - 1.5m centres elsewhere. The embankment was only constructed late in the growing season of 2013 and the flood came in January 2014.Monitored speeds reached 4.33m/s and flooding overtopping lasted 62 days at various intensities. The TRM whilst loosing surface topsoil in some places (see Figure 20) managed to maintain the surface profile and prevent major erosion as opposed to embankment failures elsewhere.

Figure 20: Flood event on overtopped embankment

Figure 21: Worst area where only surface topsoil lost and synthetic root structure maintained a hydraulic shape to prevent further erosion whilst in grassed areas as it reinforced the existing roots

4.4 *Additional forces - Wave overtopping*

In addition to overtopping due to inundation in larger open areas where wind blown wave attack such as in estuaries or where flood plains are big enough to allow waves to build up the surging effect or "slug" wave should be considered down the backface. A comprehensive study - Wave Overtopping Simulator (Figure 23) was set up in the Netherlands and reported on by Van de Meer (2006) A large vertical header tank (cap 14m^3) was set up which was fed contiuously with pumped water to simulate dumped water caused by waves that run up and over a dyke or channel embankment simulating a 6 hour storm. For channels and rivers this is less likely a factor however for larger schemes refer for design guidance from the EurOtop Assessment manual : Wave Overtiopping of Sea Defences and Related Structures. (2007) pulished by the EuroTop team a cooperation between UK, Dutch and German experts.



(a) Still water level below crest; major wave activity

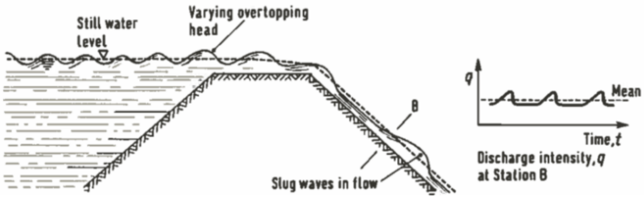


Figure 22: Surge or "slug" waves adding shear loads to surface

Figure 23: Wave overtopping simulator

5 TRANSITIONS

5.1 *Hard Infrastructure meets flexible embankments*

Geosynthetics by their nature are laterally flexible and therefore form flexible structures. This feature is highly compatible with the flexible environment of soils and soil/water interfaces. However, when a river embankment is crossed by a bridge or other infrastructure there is potentially an abrupt change the nature of the structure from soft/flexible/adaptable to hard/rigid/immobile. Designers need to take account of this change structure. Taking the example of a bridge pier or abutment across a river which is either permanently or occasionally submerged the flow of the water is disturbed usually causing a greater propensity to erode any surrounding soils around the bridge and quite often downstream or even upstream of the structure. Bridge designers will shape the potentially submerged parts of the structure to present as smooth hydraulic shape as possible, avoiding turbulence to defend the bridge from undermining by erosion. This however tends to speed the flow between peers and cause erosion. A holistic approach to design would be to aim to cause no erosion by creating as smooth and effective transition as possible from soft to hard and then hard to soft.

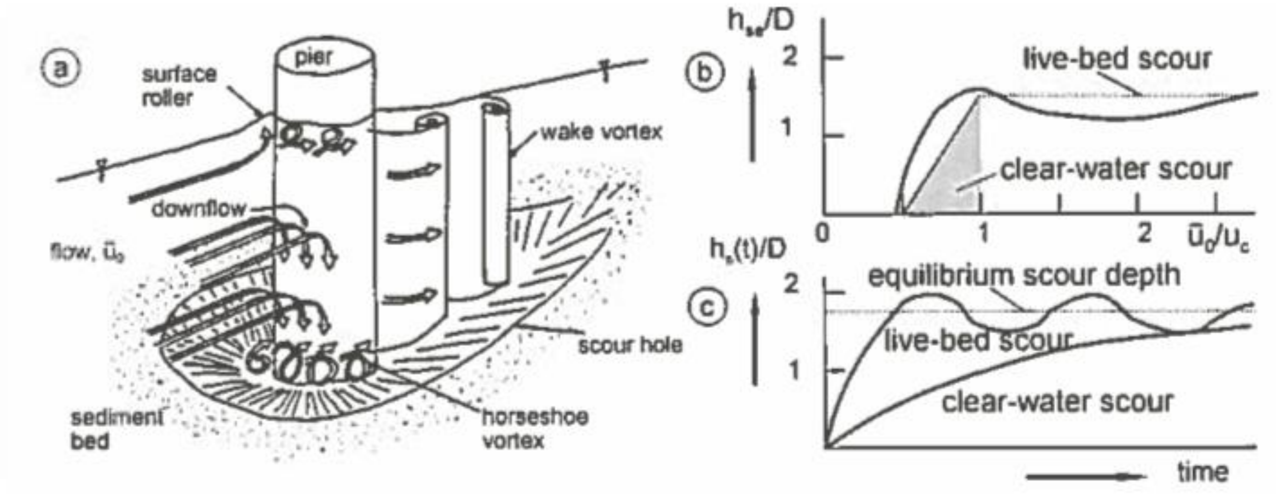


Figure 24: Soft sediment meets hard structure needing a transition using a flexible transition

In the instance of the bridge peers the below water leading edge could be filled with large filled placed bags overlain with a protective thicker non-woven geotextile overlain with rock armour

5.2 *Training walls*

Geosynthetics are well disposed to provide this necessary transition as they have the ability to contain soil as a flexible structure and present an intermediate structure between the two extremes. In the example of the bridge structure from upstream and downstream training works using flexible revetments underlain by geotextile filters me made to provide a flexible

If for the same bridge a training wall is used to funnel water through the bridge the is an acceleration leading are and a decelerating following training area. A TRM maybe used as the start of the upstream training works leading to a rock armour defense followed by the concrete training walls and the reverse in the downstream training works. The concept being a transition from a soft/flexible→semi-soft/flexible→hard/inflexible→semi-soft/flexible→soft/flexible

5.3 *Toe details*

Toe details are dictated by the slope of the revetment and the location of the river or channel bed along with water current speeds. The most common is a buried toe away from the erosive effects of current. Should erosion near the toe take place a buried flexible toe will fall into the scour hole and protect itself. Other toe details include strip toes and hung toes (more unusual) where beds are too soft to support a revetment. In this instance a wrapped reinforcing geosynthetic is used to anchor the revetment at the crest and on the slope in more stable ground.

5.4 *Upstream and downstream downslope edge details*

As with crest and toe details the leading and following edges must be anchored to produce a hydraulic and smooth transition. Trenched in buried details should be specified with pins or anchors as appropriate. This may be necessary during construction with temporary edge details to cover for events occurring overnight. An unprotected leading edge and even following edge can see major erosion occur quickly and even revetments being stripped from the surface.

6GEOTEXTILE ALTERNATIVES TO ROCK ARMOUR

6.1 *Geotextile bags*

Figure 25: hand filled bags ready for loading onto a barge for dumping

Where there is no rock armour locally and costs of import is difficult and expensive such as in large Delta areas or where a softer landscape is desirable such as beach areas geotextiles can be used in the form of bags. These can be made from woven or non-woven geotextiles and are stitched using specialist sewing methods designed to allow for impact when dumped. The designer should understand the design of the seam when these bags are filled or installed as well as service life loading. Bags can burst at the seam and burst strengths should be proven by drop trials. This affects the material the bag is made of. Modern trends seem to favour non wovens for smaller hand dumped bags and wovens are needed often for larger bags when handling or in service requirements dictate a reinforcing function such as effective reinforced wall constructions.

6.2 *Geotubes*

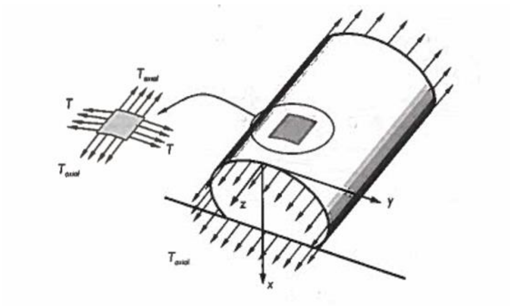


Figure E.4 Axial tensile load in the geotextile.

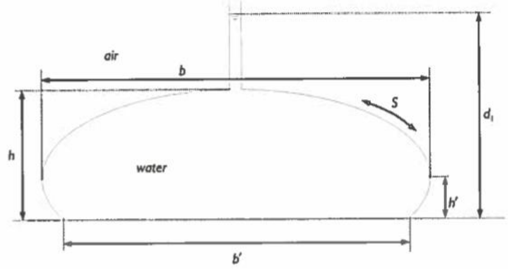


Figure 26: Geotube stress loads

Wovens are more commonly used in large tubes which can be made to suit the site with some practical upper and lower limits. (typically 8m diameter and up to 100m long). These are reinforced structures in service and use their low elongation and reinforcement function for containment on a large scale. The tubes are placed in position and usually filled with hydraulically pumped sand.

It is beyond the remit of this paper to consider the reinforcement aspects of geotubes but the outer walls of a tube form part of the revetment. The design still demands the filter considerations of retention and permeability relative to the content and overall stability of the unit as a structure. Sometimes the geotubes are filled with a pumped sludge material where through either natural filter or flocculation techniques the fill becomes a dense clay like mass. Checks should be carried out on the geotechnical stability of the layer as well as permeability uplift issues.

The designer will need to be aware of the tensile forces in the tube when hydraulically filled and to specify maximum fill levels so as not to exceed geotextile or seam strengths in the tube.

6.3 *Geocontainers*

Geocontainers are formed by lining a split bottomed barge with a woven geotextile, filled with dredged material and sewn to form a 20m long enclosed giant bag.

Containers are used in river bed erosion where these can be dumped in areas of bottom bed scour and due to their large bulk can be target dumped into any large eroded cavities on the river bed dropping them in rows as discrete reinforced units. They can be filled with materials from other areas of deposition in the river thus can be very compatible with dredging operations which produces spoil which needs to be disposed of.

Designers should be aware of the handling and impact loads at all stages of an operation to ensure geotextile and seams strengths are adequate. For instance, as a geocontainer emerges from a split bottom barge the container takes up a very different shape as it passes through the jaws of the barge hold as it opens. (see Figure 26)

Calculation methods for designers are available pub Bezuijen (2002) considering stresses in geotextile during the opening of a split bottomed barge, dropping and impact loads on river bed.

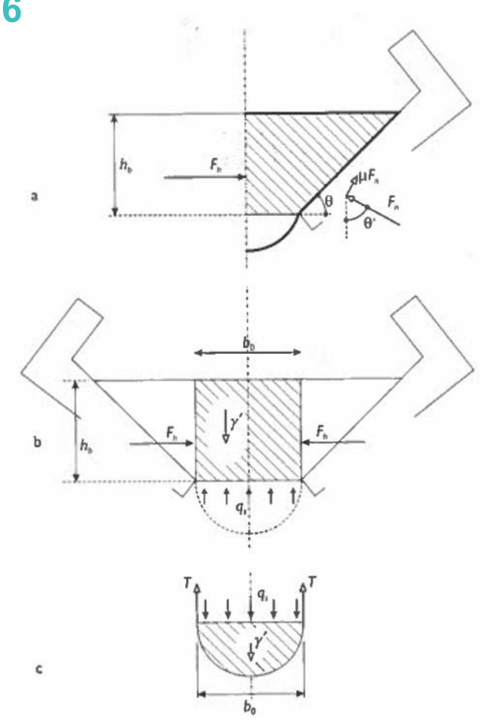


Figure 27: Gecontainer stress

6.4 *Durability*

Tubes and bags are often used as revetment in themselves. As primary armour units durability issues become very important and geotextiles are exposed to UV light. Either these units need additional cover or are treated with high UV resistant additives. Additional design considerations would be bag stability (i.e. a set pattern of overlapping should be designed), overall revetment stability, internal stability, stability within the bags, abrasion resistance to debris transported by current or wave attack and abrasion due to particle abrasion due to wave run up. Defined in Lawson (2012)

7 CONCLUSION

The design of geosynthetics for use in rivers and canals embankments under rock armour has evolved over the last 30 years from an early experimental approach through to sophisticated filter laboratory and mathematical modelling at the particle size level to try to understand the limiting factors which would guarantee a stable structure in what is oftena rough and flexible environment. There are still areas of research on filter required especially when dealing with certain soil types where piping can have a major detrimental effect if not addressed. However, as shown by the draft directive of the Dutch committee, a more pragmatic approach has been shown. Mistakes in design were still being made by designers as the more sophisticated design rules could be seen as too confusing for busy multi-disciplinary designers. Recognising the fact that these harsh environments are often dictated by macro effects such as installation damage which previously had not been adequately addressed has meant that a greater success in the use of geosynthetics in rivers and channels will lead to gaining even more advantages of these versatile materials.

Design methods have been developed to allow the use of contained structures, artificial armour units in the form of bags, tubes and geocontainers. Design philosophy changes in allowing more overtopping of embankments and the need to work with nature has led to design of Turf Reinforced Mattress systems which can sustain periods of inundation preventing erosion in a controlled flood event. The design of geosynthetics in erosion control continue to keep pace with the needs of a flexible, sometimes harsh natural environment and will bring further solutions in the revetments are used to protect often soft and alluvial more highly erodible surfaces in exposed conditions on the slopes of protective earth structures such as river or coastal dikes.

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