GEOSYNTHETICS FOR EROSION CONTROL IN HYDRAULIC ENVIRONMENT

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ABSTRACT

The hydrologic cycle is described. The mechanisms of erosion due to hydraulic action are discussed. A summary of conventional erosion control techniques and systems is provided. This includes the use of vegetation and timber products; rocks and stones; and concrete unit products. The functions of geosynthetic erosion control products may be summarized as ground cover, turf reinforcement, material confinement and material containment. In ground cover, the product minimizes the impact of rain droplets and prevent the detachment of soil particles. In turf reinforcement, the product improves the erosion resistance of vegetation. In material confinement, the product enhances erosion resistance of the soil that they help confine. In material containment, the product when filled with the selected material becomes a structural unit to replace of rock or concrete units to resist the forces of erosion, thereby protecting the base soil below. The application and design of geosynthetics for erosion control in hydraulic environment are presented. Several case studies are described.

Keywords: Hydraulic action, erosion, geosynthetics, application, design

INTRODUCTION

The Collins Dictionary of Geology (Lipidus, 1990) provides a detailed definition of *erosion*. *Erosion*, a noun, is *the wearing away of any part of the Earth's surface by natural agencies*. *These include mass wasting and the action of waves, wind, streams and glaciers. Fundamental to the process of erosion is that material must be picked up and carried away by such agents. Evidence for erosion is widespread; the retreat of marine cliffs, deposition of fluvial material, and the cutting of great canyons, e.g. the Grand Canyon.* This paper discusses the erosion of soil through hydraulic action and the application of geosynthetics for the control of erosion under such hydraulic influence.

HYDROLOGIC CYCLE

Vast currents of water, water vapor, ice, and energy are flowing about us continuously in an elaborate, open global plumbing system (Christopherson, 2000). Together they form the hydrologic cycle, which has operated for billions of years, from the lower atmosphere to several kilometers beneath Earth's surface. The cycle involves the circulation and transformation of water throughout Earth's atmosphere, hydrosphere, lithosphere, and biosphere.

Figure 1 shows a simplified model of the complex hydrologic cycle. The oceans cover over 70% of Earth's surface and contain more than 97% of the Earth's water. Naturally most of the evaporation comes from the oceans. Moisture condenses into precipitation producing clouds in the atmosphere. Although most of the precipitation falls over the oceans, part of it results in continental precipitation as a result of wind shifting of the clouds. When the continental precipitation reaches ground it either flows overland or soaks into the soil.

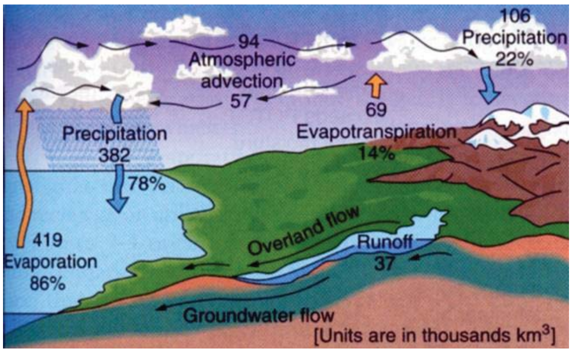


Fig. 1 A simplified model of the hydrologic cycle (Christopherson, 2000)

In any drainage basin, water initially moves downslope in a thin film called sheet-flow, or overland flow. Surface runoff tends to then concentrate in rills or small-scale downhill grooves, which may then develop into deeper gullies and then a stream course in a valley. Streams drain into rivers that eventually flow to the ocean. As water finds its way from high ground back to the ocean under the influence of gravity, there is a constant interexchange of groundwater and fluvial water depending on the landform and subsurface geology. Figure 2 shows the schematic diagram of the runoff process according to Knighton (1984).

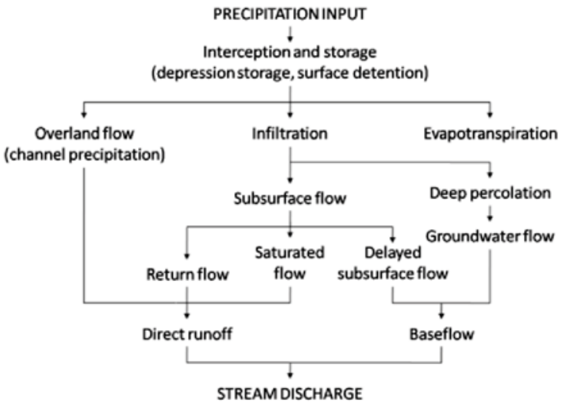


Fig. 2 Schematic diagram of the runoff process (Knighton, 1984)

EROSION MECHANISMS AND PROCESSES

Erosion Mechanisms

Hydraulic action is the work of flowing water alone. Depending on the impacting hydraulic energy, the landform present and the characteristics of the in-situ soil, erosion or deposition may occur. In order for erosion to occur three erosion mechanisms must act in sequence: detachment, entrainment and transport. Detachment is caused by raindrop impact on a soil surface, running water scouring action, flowing debris abrasion and wave breaking action. Entrainment is mainly due to fluid drag. Fluid drag causes particle to move because of horizontal force (from the flow of water) and vertical lift (from the turbulence and eddies). Once a particle is entrained, it tends to move as long as the velocity of the medium is high enough to transport the particle horizontally. Figure 3 shows the erosion and settling velocities for different soil particle sizes.

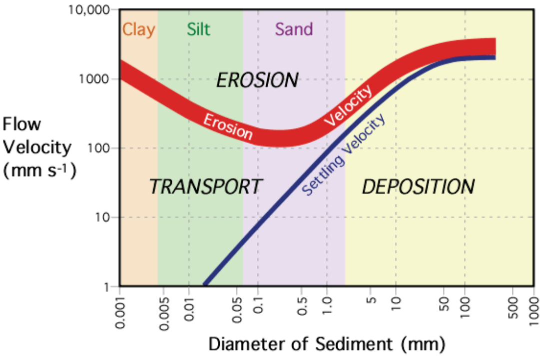


Fig. 3 Erosion and settling velocities for different soil particle sizes (Pidwirny, 1999)

Overland Erosion Process

The overland flow of water erodes the ground surface. Thin, uniform layers of soil are peeled off the land surface in a process called sheet erosion (Cunningham and Saigo, 1997). When little rivulets of running water gather together and cut small channels in the soil, the process is called rill erosion. When rills enlarge to form bigger ravines that are too large to be removed by normal tillage operations, they progress onto the process of gully erosion.

Fluvial Erosion Process

Running water causes hydraulic squeeze-and-release action that loosens and lifts rock particles. As this debris moves along, it mechanically erodes the streambed further, through the process of abrasion, with rock particles grinding and carving the bed like sandpaper (Christopherson, 2000).

The upstream tributaries in a drainage basin usually have small and irregular discharges, and most of the channel's energy is expended in turbulent eddies. As a result, hydraulic action in these upstream sections is at maximum but the suspended load is small.

The downstream portions of a river move much larger volumes of water past a given point and carry larger suspended loads of sediment. Stream velocity determines the rates of erosion and deposition (see Figure 3). Figure 4 shows the fluvial transportation of eroded materials through saltation, traction, suspension, and solution.

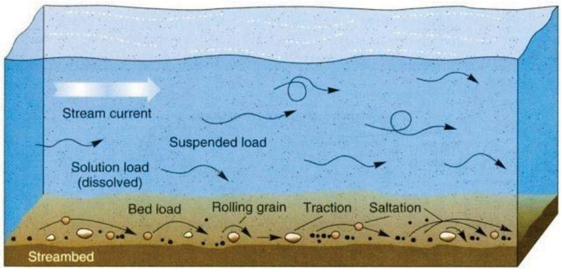


Fig. 4 Fluvial transportation of eroded materials through saltation, traction, suspension, and solution (Christopherson, 2000)

Shoreline Erosion Process

The shorelines of oceans and large lakes are exposed to wave attack. Water waves are predominantly wind created. Friction between moving air and the water surface generates undulations of water surface or waves. Waves appear as water body in migration in the direction of the wave travel. In reality only a slight amount of water is advancing. It is the wave energy that is moving through the flexible medium of water.

Individual water particles move forward only slightly, forming a vertically circular pattern.

When waves approach the shoreline, the orbiting water particles are vertically restricted and this restriction causes elliptical and flattened orbits to form near the bottom. This pattern change slows the affected wave, but more waves continue arriving from behind. The resultant effects are closer-spaced waves, growing in height and steepness, with sharper wave crests. As the crest of each wave rises, a point is reached when its height exceeds its vertical stability and the wave falls into a characteristic breaker, crashing onto the shore. When waves break on the shore, they expend a large part of their energy to erode the land. Figure 5 shows the nature of waves in the ocean and the changes in wave characteristics as it approaches the shoreline.

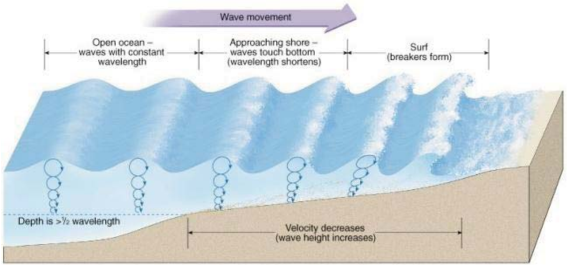


Fig. 5 Changes in wave characteristics as it approaches the shoreline

The action of tides, currents, wind, waves and changing sea level produces a variety of erosional and depositional landforms. Sea cliffs are erosional landforms formed by the undercutting action of the waves. Beaches and mudflats are depositional landforms. At any period of time, a shoreline may be eroding or accreting, depending on changes in tides, currents, wind, waves and disruption to littoral process.

Slope Instability

Slope instability is not an erosion mechanism. However, slope instability can hasten the rate of erosion. Firstly, slides detach large soil masses from otherwise stable conditions and move them closer to sources of erosion. Secondly, detached soil masses usually end up looser than the in-situ soil state.

EROSION CONTROL SYSTEMS

Vegetation and Timber Products

Vegetation provides a protective cover to the ground against surface erosion. Table 1 shows the erosion rates by land use in Malaysia (Sani, 1998). It is evident from Table 1 that different land use, which determines different ground vegetation cover or the lack of it, impacts the rate of erosion.

The removal of surface vegetation which results in the exposure of barren soil as in the case of construction site accelerates the rate of erosion (see Table 1). Grass can be an effective erosion control measure when combined with a system of surface drains (GCO, 1984; Hengchaovanich, 1999; Truong, 1999). The techniques used for planting grass include hydroseeding, sprigging, turfing and broadcast seeding (GCO, 1984).

Table 1 Erosion rates by land use in Malaysia (Sani, 1998)

Land use	Rate of erosion (tonnes/ hectare/year)
Undisturbed lowland rainforest	0.19-3.12
Selective logging, lowland forest	0.2-16.5
Selective logging, steepland forest	11.2-28.5
Shifting cultivation	0.18-0.34
Logging roads	10-550
Temperate vegetables, highlands	2-10.5
Traditional pepper cultivation	80-85
Conversion of forest to oil palm	2.2-2.5
Construction site	400-500
Streams affected by construction activity	12-100

A variety of woody materials, both live and dead, are used in bank protection all over the world (Donat, 1992; Przedwojski et al, 1995; Polster, 2002). Live woody materials include water-tolerant trees and shrubs. They act to impede hydraulic action and their roots act as reinforcement of the base soil. However, they need regular trimming and maintenance to avoid a significant reduction in channel capacity. Timber and other dead woody materials are used in bank protection in the form of poles, stakes, piles, beams, battens, logs, brush, etc.

Successful establishment of vegetation on a newly-formed slope is governed by several factors related to the time of planting, steepness, soil type and the selection of the replanting species (GCO, 1984; Barker, 1999). Durability under successive wetting and drying of the timber product is a key consideration for the design life of the erosion protection system.

Rock and Stone Based Revetments

Rock may be used in the construction of revetments for erosion control applications, as riprap, rock armour or stone pitching (McConnell, 1998). A geotextile filter layer is often used in between the rock layers and the base soil.

Riprap is widely graded rock ($D_{85}/D_{15} \sim 2 – 2.5$), which is placed in bulk to give an armour layer about 2 to 3 stones thick. Rock armour is more carefully selected rock of a narrow size range (D_{85}/D_{15} ~ 1.25 – 1.7.5), which is carefully placed in layers, usually two rock thick. Rubble, which is usually rock or stone fragments, but may sometimes include broken concrete, brick or asphalt, can be dumped to provide protection.

Pitched stone revetments are common in some places where the increased stability afforded to relatively small rock by close packing has allowed the use of local stone. Other techniques that allow smaller stones to be used with improved stability include the use of steel wire gabion and mattress products, and the use of cement grout, bitumen and other materials to bind the stones.

Concrete Product Revetments

A wide variety of precast concrete products are available for use to replace of rock as erosion control cover units (Przedwojski et al, 1995; McConnell, 1998; Pilarczyk, 2000). They either come in the form of block or slab units. Concrete blocks or slabs may be placed to form an armour layer for revetment construction, often with a geotextile filter layer placed between the concrete product or the granular drainage layers and the base soil.

Simple blocks can be placed freely on the slope relying on unit mass, friction with the under-layer and inter-block friction to provide stability. For some blocks, gravel may be placed in the joints to increase friction and help transfer loads over a wider area. Interlocking blocks can provide greater stability than simple blocks. Blocks can also be connected by cables to form mats. Concrete slabs (generally of plan area 2 m x 2 m or larger) which may be either precast or cast in-situ are also used.

Geosynthetic Products

The functions of geosynthetic products for erosion control applications may be summarized as ground cover, turf reinforcement, material confinement and material containment. A variety of products have been used for erosion control applications (Theisen, 1992; Sprague and Koutsourais, 1995; Kam, 2006; Leong et al, 2006; Lawson, 2008; Heibum et al, 2010; Hornsey et al, 2012; Nemeth et al, 2012).

Erosion control geomats

Erosion control geomat (ECGM) is a rolled ground-covering product that helps to prevent or retard the erosion process. There is a wide variety of products in the market. ECGMs may be classified according to their structural form and degree of biodegradability.

ECGMs function as ground cover to exposed soil. They minimize the impact of rain droplets and resist detachment of soil particles. They also act as a backing for turf roots to grow into resulting in a composite carpet of turf (instead of behaving as individual clumps), thereby enhancing the erosion resistance of grass.

Three-dimensional mats are able to trap some topsoil that can help speed up the process of revegetation. Biodegradable mats may provide nourishment to facilitate growth of vegetation but gradually loses its function as turf reinforcement as biodegradation progresses.

Hybrids (combination of biodegradable and non-biodegradable components) can provide nourishment while retaining the long-term turf reinforcement function. Figures 7(a,b) show the use of two-dimensional biodegradable mat and three-dimensional non-biodegradable mat respectively for erosion protection of excavated slopes.

(a)

(b)

Fig. 7 Use of ECGM for erosion control applications, (a) 2-D biodegradable mat (b) 3-D non-biodegradable mat

Seeding techniques are usually used to establish vegetation. This may be done before or after the laying of ECGM. ECGM integrated with pre-grown turf are sometimes used (Kam, 2006).

Geosynthetic confinement products

Geosynthetic products with material confinement function usually have honeycomb-like cells for in-filling with material. The product is made from polymeric strips assembled and connected by a series of offset, full depth seams aligned perpendicular to the longitudinal axis of the strips. The product comes in a compact accordion-like form and when expanded or stretched out, will form a network of flexible, three-dimensional, cellular confinement system.

The strips are usually solid or perforated polymer straps but may also be made using geogrids or geotextiles. The strip width is varied according to design requirement. They may be in-filled with soil or stones and the confinement function effectively increases resistance of the soil or stone particles to detachment and entrainment.

Figure 8(a) shows the application of soil filled cellular confinement product for excavated slope erosion control. Here, the cells are carefully planted with different types of grass and small flowering plants that will result in an artistic motif. Figure 8(b) shows the application of stone filled cellular confinement product for riverbank erosion control.

(a)

(b)

Fig. 8 Application of cellular confinement product (a) soil filled cells for excavated slope erosion control (b) stone filled cells for riverbank erosion control

Geosynthetic containment products

Geotextile containment products in the form of bags, mattresses, tubes and other container shapes have been used in erosion control applications (Jakobson and Nielsen, 1970; Liu, 1974; Kortsmit and Tutuarima, 1993; Pilarczyk, 2000; Koerner, 2005; Yee et al, 2007; Lawson, 2008) for more than 50 years. The materials used to fill these geotextile containment products include sand, aggregate, cement grout and concrete.

For long term durability, the geotextile containment product may require product surface effect enhancement, establishment of long term vegetation cover or installation of a long term protective cover. Figures 9 a, b, c, d show the use geotextile bag, sand filled geotextile mattress, micro-concrete filled geotextile mattress and geotextile tube respectively for erosion control applications.

(a)

(b)

(c)

(d)

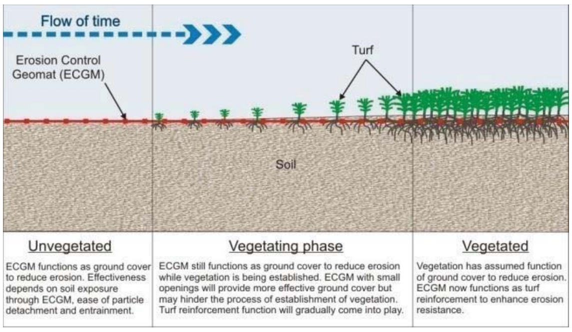
Fig. 9 Use of geotextile containment products for erosion control applications, (a) geobag (b) sand filled geotextile mattress (c) micro-concrete filled geotextile mattress (d) geotextile tube

To a significantly lesser extent, geogrids and geonets have also been used to fabricate containment products for erosion control applications. However, geotextile predominates as the material of choice for the fabrication of geosynthetic containment products for erosion control applications because panels of geotextile can be easily joined with high seam strength and efficiency, as well as contain material over a much wider range of particle sizes.

PERFORMANCE AND SELECTION OF EROSION CONTROL GEOMAT

Vegetation Establishment Phases

When ECGMs are used for erosion control there is a time perspective involved when we talk about the functions needed and performance of the ECGM (see Figure 10).



ECGM functions as ground cover to reduce erosion. Effectiveness depends on soil exposure through ECGM, ease of particle detachment and entrainment.

ECGM still functions as ground cover to reduce erosion while vegetation is being established. ECGM with small openings will provide more effective ground cover but may hinder the process of establishment of vegetation. Turf reinforcement function will gradually come into play.

Vegetation has assumed function of ground cover to reduce erosion. ECGM now functions as turf reinforcement to enhance erosion resistance.

Fig. 10 Phases of vegetation establishment and functions of ECGM as a progression of time (Yee, 2006)

Broadly, we can differentiate three different phases; the unvegetated phase, the vegetating phase and the vegetated phase. During the unvegetated and vegetating phases, ground cover is the most important function. During the vegetating phase, the provision of optimum conditions for vegetation growth is an important function of the product. The length of time of the vegetating phase is very much dependent on the grass species, the ground condition, the topsoil fertility, the planting method and the climate and weather condition during planting and vegetating process. During the vegetated phase the only important function still remaining is turf reinforcement. While a theoretical predictive method for soil erosion and its prevention is still an elusive target, there is no lack of laboratory rainfall simulators and wave tanks to study the situation (Koerner, 2005).

Performance Evaluation using Rainfall Simulators

Rainfall simulators are useful tools for the study of erosion of soils due to rainfall and runoff (Dimoyiannis et al, 2001; Wanielista and Chopra, 2010). Rustom and Weggel (1993) performed laboratory soil erosion tests on a number of ECGMs using a rainfall simulator. Results are presented for bare soil slopes and for soil slopes protected by 12 different ECGMs with different products showing varying degrees of reduction in erosion. Such tests are very useful in quantifying reductions in erosion between a specific product against non-use and against other products.

Leong et al (2006) reported the use of rainfall simulator for physical model testing in the laboratory to determine the performance of selected ECGMs. The large scale physical model testing facility was developed in the Hydraulics Laboratory of the National University of Singapore. Figure 11 shows the testing setup.

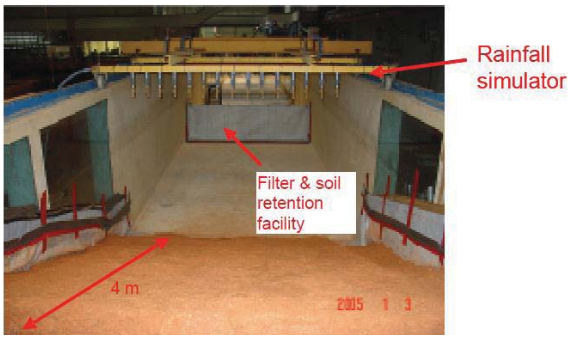


Fig. 11 Large scale physical model testing facility at the Hydraulics Laboratory of the National University of Singapore (Leong et al, 2006)

The 2 m wide flume test setup essentially consists of three components; the rainfall simulator, the model soil slope and the eroded soil retention basin. The rainfall simulator consists of a 2 m long pipe with 15 nozzles at every 100 mm intervals, is placed across the width of the flume and can move along the length of the flume above where the model soil slope is located. The eroded soil retention basin is located beyond the toe of the model soil slope and consists of a geotextile filter baffle across the flume located 4 m from the toe of the model slope. The geotextile baffle allows water to seep through but retains soil particles which can then be quantified.

A series of tests was carried out to quantify the erosion of the model slope in terms of soil collected in the retention basin under different simulated rainfall intensity and duration. These were repeated under the same conditions using 3 different grades of ECGM. Table 2 shows the results.

Table 2 Eroded soil concentration in terms of ppm of runoff (Leong et al, 2006)

Slope preparation		Bare Slope	ECGM 1	ECGM 2	ECGM 3
ECGM unit mass		N.A.	270	400	320
Time (min)	Intensity (mm/hr)	Eroded soil concentration (ppm)			
15	300	3048	610	-	-
15	500	2743	571	80	183
30	300	2667	486	-	-
30	500	2286	446	51	114

The percentage area cover of the ECGM seems to affect the loss of soil prior to establishment of vegetation. A high percentage area cover is more effective in controlling erosion of the barren soil. However, if the percentage area cover is too high it may slow down the process of revegetation.

Turf Reinforcement Performance

Erosion control revegetation mats (ECRMs) and turf reinforcing mats (TRMs) are ECGMs that have the function of turf reinforcement. Figure 12 shows the long term design velocities versus storm flow durations (Theisen, 1992).

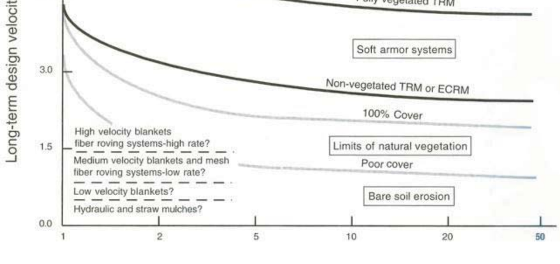


Fig. 12 Recommended maximum design velocities for various classes of erosion control materials (Theisen, 1992)

It should be noted that allowable flow velocities decrease with flow duration. Koerner (2005) remarked that manufacturers of ECGMs often present the erosion resistance of their products in terms of maximum allowable flow velocity and that though unstated, these flow limits are typically for very short duration and may not reflect the potential for severe erosion damage that results from moderate flow velocities over a period of several hours.

Product Selection

If cost is not an issue, the ideal system would be one that provides maximum ground cover erosion resistance, time-wise has the shortest vegetating phase and provides the best performance in terms of turf reinforcement. The definition of system here would include the ECGM, the grass species and the topsoil selection. A wide variety of product designs is available in the market to cater for these engineering objectives. However, cost is always a consideration. Therefore the first question to answer in the product selection process is whether turf reinforcement is required in design. Generally, ECGMs with long term turf reinforcement capability tend to be more costly.

It is desirable to ensure a quick establishment of vegetation, as a good vegetation cover is the key to long-term protection of barren soil. However, ECGMs that have excellent ground cover erosion resistance tend to have low light penetration capability which may slow down the vegetating process. Ultimately, the product selection is best based on a balance between the relevant design objectives and cost.

ECGM Product Specification

The specification process for ECGMs usually covers a variety of product properties and test methods. They generally fall under the category of index or performance. Some of them are properties that rely on established test methods e.g. tensile strength, mass per unit area, water permeability, etc. Others are properties that rely on developing test methods e.g. light transmission, smoulder resistance, porosity, water absorption, protection against evaporation, etc. (Smith and Bhatiar, 2006; Nemeth et al, 2012). Smith et al (2005) indicated that percentage area cover and water holding capacity play important roles in the long term vegetation establishment of ECGMs.

As there are no numerical analytical methods available for design, the usual way to specify is based on past practice and experience. A target type or range of product is first identified, based on past successes and the manufacturer's published data then forms a basis to specify on properties.

REVETMENT DESIGN USING GEOTEXTILE CONTAINMENT PRODUCTS

Structure Performance and Design Life

The design life of the revetment structure should be defined. This is most likely determined on an economic basis and this definition impacts on the product specification for durability requirements. The required level of service of the revetment should also be determined. This may be in terms of an acceptable overtopping limit or risk of damage. Last but not least the design event of a certain return period should be selected. This will generally be longer than the design life of the revetment structure.

Geometry

The definition of geometry is necessary for assessment of both hydraulic and geotechnical stabilities. The definition of geometry would include slope angle, crest elevation, toe levels, etc.

Hydraulic Conditions

Typically, the information required as design input includes water level, wave conditions, wave direction and current flow conditions. Design water levels should include the influence of tides and surges if applicable. The design water level is also referred to as still water level (SWL). SWL is the level that the water surface would assume in the absence of wind waves.

Two loading parameters will feature in the stability equations for wave attack. One of them is the significant wave height (H_s) which is defined traditionally as the mean wave height of the highest third of the waves. The other is the breaker parameter (ξ), given in the following equation:

$$\xi = \frac{\tan \alpha}{\sqrt{2\pi H_s / g T_p^{2}}} \qquad (1)$$

One loading parameter will feature in the stability equations for flow attack. The critical velocity (u_{cr}) is the current velocity when erosion or hydraulic instability starts to occur on channels and is usually expressed as a depth averaged velocity.

Structural Units

The geotextile containment products are usually supplied as flat units although they may come in a roll or folded form. These products come in a prefabricated form but with filling positions that are closed by seaming or other means. When they are filled with the specified fill material and closed properly on site, they form structural units that are used for the construction of revetments.

Effective revetment thickness

When filled with the intended material, these products will shrink in width and length as they gain in thickness. The product filled thickness depends on the product design and the degree of filling. The surface of the filled unit is also not even. However, for design a nominal thickness is estimated. Manufacturers usually would provide information with regards to such filled unit dimensions and nominal thickness achieved after filling.

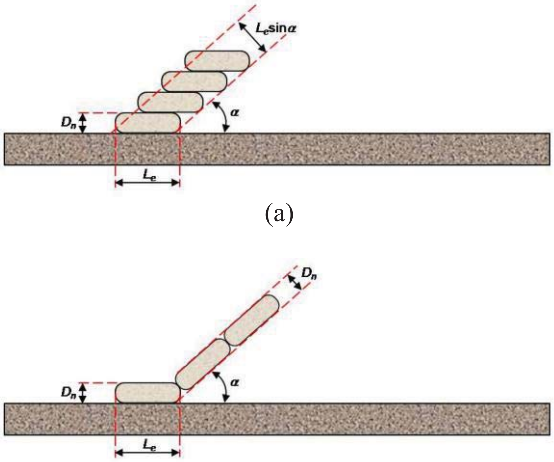
The effective thickness of the geotextile mattress revetment is equal to the nominal thickness of the filled mattress. The effective thickness of the geobag revetment is dependent on the nominal thickness of the filled geobag, the method of placement on the slope and the slope angle.

The effective thickness of the geobag revetment, D_e, for placement method 1 and placement method 2 (see Figure 13) are given in Equations (2) and (3) respectively (CUR 217, 2006).

$$D_e = L_n \sin \alpha \qquad (2)$$

$$D_e = D_n \qquad (3)$$

where:
L_n = nominal length of geobag unit [m];
α = slope angle of revetment [deg] ;
D_n = nominal thickness of geobag unit [m].



(a)

(b)

Fig. 13 Geobags placement (a) method 1 (b) method 2

Fill material

The fill used is usually sand or concrete. However, other fill materials may also be used depending on the product and application.

Buoyant relative density

The buoyant relative density of the structural unit, Δ, is given by:

$$\boldsymbol{\Delta = \frac{\rho_f}{\rho_w} - 1} \tag{4}$$

where,
ρ_f = density of fill material [kg/m^3];
ρ_w = density of water [kg/m^3].

An initial estimation of the buoyant relative density of the structural unit, Δ, for design is shown in Table 3 where the density of water, ρ_w, is assumed as 1000 kg/m^3.

Table 3 Initial estimation of buoyant relative density of structural unit for design

In-fill material	Filling method	Density of fill material, ρ_f (kg/m^3)	Buoyant relative density, Δ
Sand fill	Hydraulic	1900	0.9
	Mechanical	1800	0.8
Micro concrete mix	Hydraulic	2400	1.4

Stability under Wave Attack

Geobags

Figure 14 shows the applicability zones of stability criteria for geobag revetment.

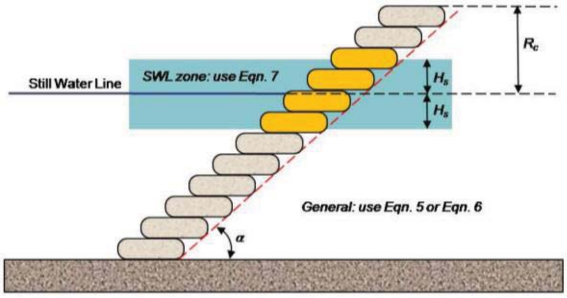


Fig. 14 Applicability zones of stability criteria for geobag revetment

The stability criteria of geobag revetment under wave attack are given as follows (CUR 217, 2006):

For irregular waves, slope 1:3 or less,

$$\frac{H_s}{\Delta D_e} \leq \mathbf{1.4} \tag{5}$$

For slope 1:3 or steeper,

$$\frac{H_s}{\Delta D_e} \leq \frac{2.75}{\sqrt{\xi}} \tag{6}$$

For zone from H_s below SWL to H_s above SWL,

$$\frac{H_s}{\Delta D_e} \leq \mathbf{0.79 + 0.09}\frac{R_c}{H_s} \tag{7}$$

Geotextile mattresses

The stability criterion of mattress revetment under wave attack is given as follows (Pilarczyk et al, 1998; McConnell, 1998; CUR 217, 2006):

$$\frac{H_s}{\Delta D_e} \leq \frac{S_m}{\xi^{2/3}} \tag{8}$$

where,
H_s = significant wave height [m];
Δ = buoyant relative density of structural unit [-];
D_e = effective thickness of revetment [m];
ξ = breaker parameter [-];
α = slope angle of revetment [deg];
L_o = wave length in deep water [m];
g = gravitational acceleration [m/s^2];
T_p = peak wave period [s];
S_m = stability factor of mattress [-].

Table 4 shows the recommended values of S_m for different geotextile mattress products. The recommended values for concrete filled geotextile mattress are based on Pilarczyk (1998). The permeability of concrete filled geotextile mattress depends on the design of the filter points. The recommended values for sand filled geotextile mattress are based on CUR 217 (2006). The permeability of sand filled geotextile mattress depends on the permeability of the sand fill and the geotextile used to manufacture the mattress product.

Table 4 Recommended values of S_m for different geotextile mattress products

Product	Stability factor, S_m
Concrete filled geotextile mattress with low permeability	2 - 3
Concrete filled geotextile mattress with high permeability	3 - 4
Sand filled geotextile mattress	4 - 5

Stability under Flow Attack

The stability criterion of structural units under longitudinal flow attack is as follows (Pilarczyk, 1990; CUR 217, 2006):

$$\boldsymbol{\Delta D_e \geq 0.035\frac{\Phi}{\Psi}\frac{K_T K_h}{K_s}\frac{(u_{cr})^2}{2g}}$$
(9)

where:
Δ = buoyant relative density of structural unit [-];
D_e = effective thickness of revetment [m];
Φ = stability parameter [-];
Ψ = Shields parameter [-];
K_T = turbulence factor [-];
K_h = depth parameter [-];
K_s = slope parameter [-];
u_{cr} = critical flow velocity [m/s];
g = gravitational acceleration [m/s^2].

Table 5 shows the values of Φ to adopt in design. Table 6 shows the values of Ψ to adopt in design. Table 7 shows the values of K_T to adopt in design.

Table 5 Stability parameter

Revetment location	Stability parameter, Φ
For continuous top layer	1.0
For edges	1.5

Table 6 Shields parameter

Revetment type	Shields parameter, Ψ
Geobag revetment	0.05
Mattress revetment	0.07

Table 7 Turbulence factor

Hydraulic situation	Turbulence factor, K_T
Normal turbulence in rivers	1.0
Higher turbulence: river bends	1.5
Strong turbulence: hydraulic jumps, sharp bends, local disruptions	2.0
Turbulence as the result of propeller jets and other water jets	3.0 to 4.0

By introducing the depth factor, K_h, the depth-averaged flow velocity is translated into a flow velocity just above the revetment. The depth factor, K_h, is given as follows (Pilarczyk, 2000; CUR 217, 2006):

For developed current profile,

$$\boldsymbol{K_h = \frac{2}{\left(\log\left(\frac{12h}{k_r}\right)\right)^2}} \tag{10}$$

For undeveloped current profile,

$$\boldsymbol{K_h = \left(\frac{h}{k_r}\right)^{-0.2}} \tag{11}$$

For a very rough current,

$$\boldsymbol{K_h = 1.0} \tag{12}$$

where,
h = water depth [m];
k_r = equivalent roughness according to Nikuradse [m].

The value of k_r depends on the type of revetment. For geobag revetment, the value of k_r can be taken as equal to D_n. For mattress revetment, the value of k_r can be taken as equal to D_e.

The slope factor, K_s, is a function of the influence of the angle of shearing resistance between the structural unit and the subsoil, and is given as follows (Pilarczyk, 1990; CUR 217, 2006):
For units not anchored at the top of the slope,

$$\boldsymbol{K_s = \sqrt{1 - \left(\frac{\sin\alpha}{\sin\delta}\right)^2}} \tag{13}$$

For mattresses anchored at the top of the slope and geobags designed with tail reinforcements,

$$\boldsymbol{K_s = 1.0} \tag{14}$$

where,
α = slope angle of revetment [deg];
δ = friction angle between structural unit and the subsoil [deg].

Sand Tightness Criteria

There is a need to check for sand tightness of sand filled geobag and goetextile mattress units. Table 8 shows the recommended design criteria for sand tightness requirement (CUR 217, 2006). There are two approaches to fulfilling the sand tightness requirement.

If the sand fill source and particle distribution is known, the pore size of the geobag or geotextile mattress can then be specified for the contract documents. Alternatively, if the pore size of the geobag or geotextile mattress is known, the particle distribution of the sand fill can then be specified for the contract documents.

Table 8 Recommended design criteria for sand tightness requirement

Hydraulic load	Requirement 1	Requirement 2
Stationary load (current)	$\boldsymbol{O_{90} < 5D_{10}\sqrt{C_u}}$	$\boldsymbol{O_{90} < 2D_{90}}$
Dynamic load (wave)	$\boldsymbol{O_{90} < 1.5D_{10}\sqrt{C_u}}$	$\boldsymbol{O_{90} < D_{90}}$

O_{90} = pore size of geobag or geotextile mattress;
D_{10} = sieve size through which 10% fraction of the sand material passes;
D_{60} = sieve size through which 60% fraction of the sand material passes;
D_{90} = sieve size through which 90% fraction of the sand material passes;
C_u = uniformity coefficient (=D_{60} / D_{10})

Mechanical Strength Requirement

The mechanical strength requirement is usually dictated by stresses experienced during handling, installation and in-service. They should be strong and robust enough to prevent rupture during filling and placement.

Durability Requirement

The durability of the structural units should outlast the design life of the revetment. This includes resistance to abrasion, UV attack, debris impact, vandalism, etc.

Other Considerations

Geotechnical stability

Information on the geotechnical properties of the slope and foundation materials should be known or determined to enable an assessment of the geotechnical stability. The materials may include naturally occurring subsoil or imported fill material. The relevant properties include particle size, shear strength, permeability and others.

Toe protection

Toe protection will provide some sliding resistance to the revetment and help to prevent failure of the revetment from scour. Typical forms of toe protection are:

(a) *buried toe* – the revetment cover layer is extended beneath the bed level to beyond the predicted scour depth;
(b) *sheet piling* – this may be used alone or with a concrete toe beam;
(c) *toe retaining structure* – this may be in the form of a gabion toe, precast concrete mini-wall or geotextile tube dyke unit;
(d) *extension of cover layer along bed* – the cover layer may be extended along the bed in front of the structure; if scour occurs, then this extra length of revetment will drop into the scour hole providing protection (this should not be used where severe scour may occur as some undermining or loss of sub-layer material may occur).

Trenching and anchoring details

The top of sand filled and concrete filled geotextile mattresses are generally anchored in a trench. The trenching and anchoring details may differ from case to case, depending on the product, the revetment geometry and the anchoring resistance force required. When there is a possibility of significant overtopping or overflow of the structure, erosion protection of the back face may need to be provided for.

Termination details

Appropriate termination details should be adopted at the ends of the structure to prevent undermining at the end of the structure. Such details are usually very much site-specific. The termination details may involve butting against a solid structure; e.g. concrete walls, wing walls of culvert openings, concrete discharge drains along the bank slopes, etc. or involve the revetment curving back in plan into the bank slopes.

Geotextile Containment Product Specification

Physical properties

This relates to dimensions of the unfilled product to enable the ultimate filled product to conform to specific engineering requirements.

Mechanical properties

Relevant mechanical properties include tensile strength, seam strength, puncture resistance, etc.

Hydraulic properties

The key property here is pore size of the geotextile used in the manufacture of the containment product. A minimum permeability is also often specified although this is seldom a critical issue given that geotextiles are often permeable enough.

Durability properties

Relevant durability tests include abrasion test that simulate site conditions, UV resistance test, etc.

Fill Material Specification

Specification for sand fill

Specification of sand to be used as fill material is usually based on a gradation that conforms to the sand tightness requirement. The sand generally should not contain any unwanted material such as:

(a) material susceptible to volume change, including marine mud, swelling clays and collapsible soils,
(b) peat, vegetation, timber, organic, soluble or perishable material,
(c) dangerous or toxic material or material susceptible to combustion, and
(d) metal, rubber or other unsuitable material.

Specification for micro concrete fill

Specification of micro concrete to be used as fill material is usually based on a mix formula that provides workability and ultimate target compressive strength. McConnell (1998) provides one such mix formula.

CASE STUDIES

ECGM for Riverbank Erosion Control in Batangas, Philippines

The San Isidro Homes development project in Batangas, Philippines borders a river and is susceptible to erosion. The height of the riverbank is about 6 m. The conventional solution is to construct a revetment.

At this site, a hybrid solution was adopted. The lower riverbank slope was protected with a gabion and stone mattress structure while the upper riverbank slope was covered with an ECGM to reinforce the final turf cover to the slope. Steel 'J' pins were used to pin down the ECGM onto the riverbank slope. This solution was about 70% of the cost of providing a full revetment for the riverbank slope.

The ECGM used was a three-dimensional fully synthetic product of tensile strength greater than 7 kN/m and a UV resistance of more than 90% strength retention after 500 hours of exposure in a xenon-arc test apparatus according to ASTM D4355 test method.

According to manufacturer provided information the product when fully vegetated has a limiting shear stress of 0.23 kPa and the design velocity is 4 m/s for a sustained exposure of 50 hours. Figure 15 show the cross-section of the riverbank slope protection design adopted. Figure 16(a) shows the installation of the ECGM while Figure 16(b) shows the fully vegetated surface.

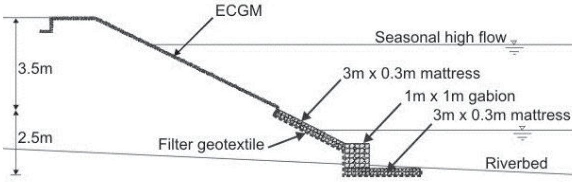


Fig. 15 Cross-section of riverbank slope showing use of ECGM as turf reinforcement

(a)

(b)

Fig. 16 ECGM for riverbank protection in Batangas (a) installation of ECGM (b) fully vegetated river bank after installation of ECGM

Geobag Revetment for Protection of Endicott Island, Alaska, USA

Endicott Island is a 0.2 km^2 artificial island located 4 km offshore of the Sagavanirktok River Delta in the Alaskan Beaufort Sea. It is 1,900 km from the North Pole and 400 km north of the Arctic Circle. The island was constructed in 1987 for the purpose of extracting and processing oil reserves of the Endicott Oilfield and is still in use today.

It consists of an offshore oil production facility, a desalination plant and a wastewater treatment plant. This was the first continuously producing offshore oilfield in the Arctic, producing around 20,000 barrels of oil per day. Processed oil is sent from Endicott Island through a 38 km pipeline to the Trans-Alaska Pipeline, and then to Valdez, Alaska.

The island was created using locally dredged gravel. The gravel was also used to fill geobags to form the revetment protecting the shoreline of the island. These geobag units had to survive freezing conditions for the most part of the year as well as resist wave attacks during the summer storms. Figure 17 shows an aerial view of the geobag revetment protecting Endicott Island.

Fig. 17 Aerial view of geobag revetment protecting Endicott Island

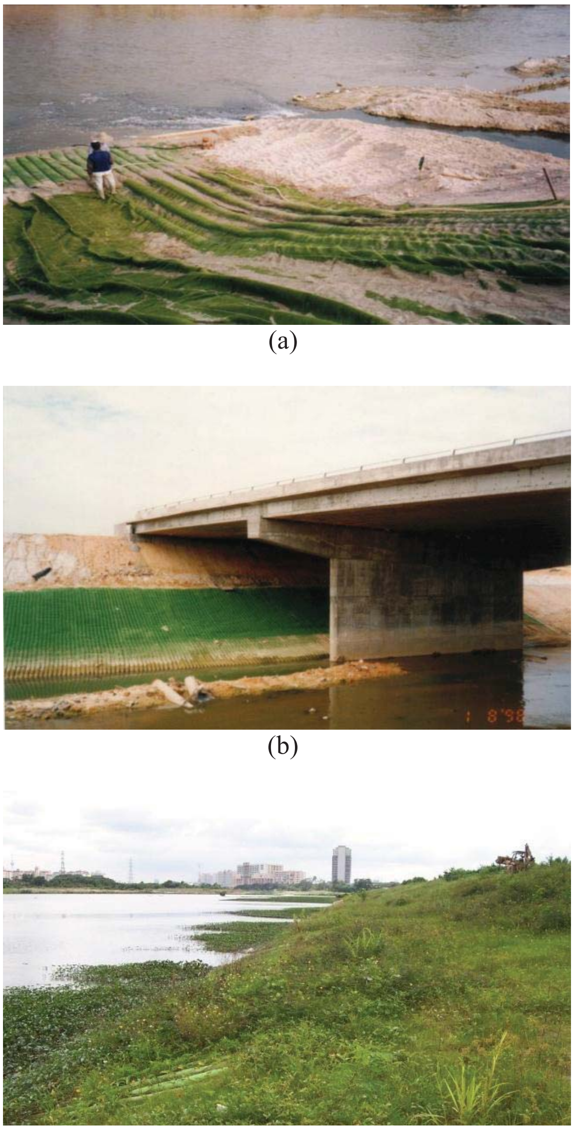
Sand Filled Geotextile Mattress Revetment for Klang River Integrated Flood Mitigation Project, Kuala Lumpur, Malaysia

This case study involved the use of sand filled geotextile mattress for the erosion protection of a stretch of Klang River that passes through the capital city of Kuala Lumpur in Malaysia. Klang River originates from the Ulu Gombak Forest Reserve, about 25 km northeast of the city and flows a distance of 120 km before it drains into the Straits of Malacca at Port Klang. With a catchment area of nearly 1,300 km^2, it is the fourth largest river basin in the state of Selangor.

Located at 3°17’N, 101°E to 2°40’N, 101°17’E, it covers areas in Sepang, Kuala Langat, Petaling Jaya, Klang, Gombak and Kuala Lumpur (Suzana et al). However, due to intense city development, the section of the river passing through the city remains as a narrow walled channel that resembles a large storm drain. Further downstream, the river would resume a natural course again near Kampung Pantai. The surrounding and downstream areas were prone to flooding and flood control dykes were constructed to protect the surrounding areas from flooding.

Sand filled geotextile mattress was used to protect the banks of the re-profiled river channel created with the construction of the flood control dykes along Klang River. Sand filled geotextile mattress was a cost effective and convenient solution because the river sediment was sand and could be used to fill the geotextile mattress. The system also allowed the establishment of vegetation through natural process. Riprap and other rock based revetment systems would cost more and would have been less aesthetically appealing. The area is practically fully developed and populated and transportation of rock for construction of revetment would have been problematic.

The sand filled geotextile mattress with developed vegetation acts as a revetment to protect the flood control dykes. More than 30,000 m^2 of sand filled geotextile mattress was installed and completed in 1999. Figure 18(a) shows the filling of geotextile mattress with sand introduced hydraulically. Figure 18(b) shows the partially completed sand filled geotextile mattress revetment. Figure 18(c) shows the sand filled geotextile mattress revetment overgrown with vegetation.



(a)

(b)

(c)

Fig. 18 Sand filled geotextile mattress revetment for Klang River bank protection, (a) filling of geotextile mattress with sand (b) partially completed geotextile mattress revetment (c) geotextile mattress with vegetation established

Geotextile Tube and Concrete Filled Geotextile Mattress for Construction of River Wharf at Pulau Muda, Indonesia

This case study involved the use of geotextile tube and concrete filled geotextile mattress for the erosion protection in a river wharf project in Pulau Muda, Indonesia. The wharf is located along the bank of Kampar River that is subject to tidal bore effect which can create waves of up to 4 m traveling upriver. The subsoil profile from two boreholes, BH1 and BH2, is shown in Figure 19 and generally consist of a top stratum of a mixture of sand and round wood underlain by soft clay that is interrupted with thin sand layers or lenses. The soft clay generally increases in shear strength with depth.

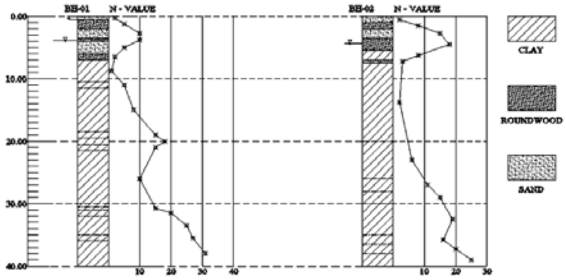
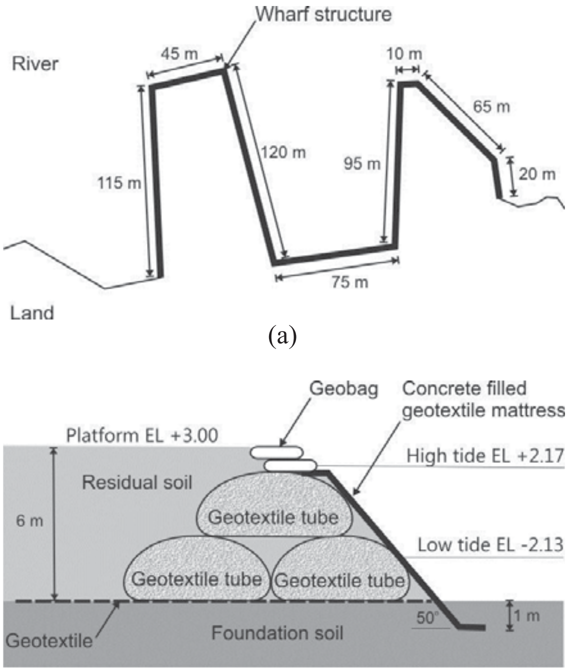


Fig. 19 Subsoil profile (Suhendra et al, 2011)

Figure 20(a) shows the plan view of the river wharf. Figure 20(b) shows the typical section through the river wharf.



(a)

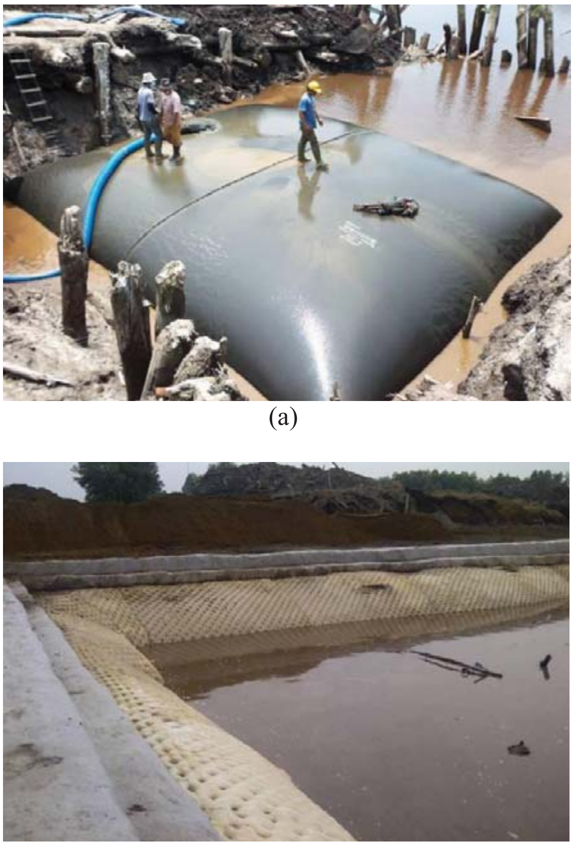
(b)

Fig. 20 River wharf at Pulau Muda (a) layout plan (b) typical cross section through river wharf (Suhendra et al, 2011)

Geotextile tubes were used to form the dyke structure to improve the global stability. This improvement in global stability is achieved by the forcing of the critical slip plane behind the geotextile tube structure to cut deeper down to the layers of higher shear strength. By this way a minimum factor of safety of 1.28 was achieved. Analysis was carried out with Bishop's method using Slope/W program.

The exterior face of the geotextile tube structure was profiled to a slope angle of 50° to the horizontal before a concrete filled geotextile mattress revetment structure was constructed. The concrete mattress was extended downwards by 1 m and outwards by another 1 m to protect against toe scour effects. The concrete mattress was anchored by sandwiching between the geotextile tube structure and two layers of geotextile bags placed above.

Figure 21(a) shows the installation of the geotextile tube at site. Figure 21(b) shows the completed concrete filled geotextile mattress revetment constructed at high tide conditions. This innovative construction allowed the wharf to be constructed under tidal conditions. During the tidal bore event, the geotextile tube was stable enough to resist the waves as well.



(a)

(b)

Fig. 21 River wharf construction at Pulau Muda (a) installation of geotextile tube (b) concrete filled geotextile mattress over installed geotextile tube (Suhendra et al, 2011)

CONCLUSIONS

This paper described the mechanisms and processes of erosion in hydraulic environment. The application of geosynthetics for erosion control was discussed. The process for the selection of erosion control geomats and the process for the design of geotextile containment products were presented. Finally, several case studies involving the application of geosynthetics for erosion control were presented.

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