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Three dimensional synthetic mats in dike and bank protection

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ABSTRACT: Three dimensional synthetic mats are used on dikes and banks as a reinforcement of vegetation to increase the erosion resistance. In many cases they enable the construction of low-cost protection with high environmental value in stead of more traditional revetments consisting of 'hard' materials. In the design special attention must be paid to the development of vegetation and the hydraulic forces.

1 INTRODUCTION

1.1 *Function of the mats*

Vegetation, such as grass, provides generally a very good protection of the soil against erosion by water and wind. This is realised in several ways:
- a soil/root mat is formed with a higher erosion resistance than soil alone. The mat is anchored to the subsoil by the roots;
- the vegetation provides ground cover and reduces erosive velocities.

Sometimes however vegetation is absent or difficult to establish. Also the loadings may be to high for a plain vegetation to withstand. In such cases a (temporary) protection of the soil to enable the development of vegetation or to give extra strength to the vegetation is desired. Open three dimensional synthetic mats can provide this protection. The vegetation roots bind around the fibres thus forming a dense and continuous system of fibres, soil and roots (Fig. 1). Thus (Hewlett, 1987):
- the soil itself is given extra strength to withstand loadings. The formation of local weak spots is retarded. This certainly is an advantage in situations where the vegetation cover has not fully been developed yet and when bare spots are present;
- the root structure is given assistance in restraining soil particles from washing out;

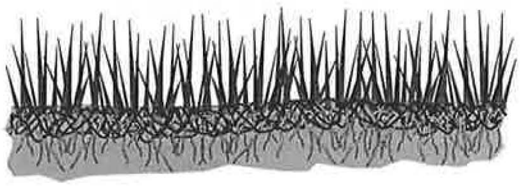

Fig. 1: Soil, roots and fibre form a dense protection.

- lateral continuity of plants is improved which results in a reduction in the risk of localised failure which on its turn may initiate more severe damage.

The main objective of three dimensional synthetic mats is to provide temporary protection to the bare soil to encourage the development of vegetation under circumstances where this is normally difficult or impossible. The second objective is to reinforce vegetation. It gives extra strength to the vegetation so that higher loadings can be withstood than with a plain vegetation.

In fact three dimensional synthetic mats fill in the gap between a protection with a plain vegetation and a more radical protection with materials such as rock, concrete or asphaltic mixtures. The advantages in relation to 'hard' revetments are:
- protection of a ground surface by vegetation is to be preferred from an environmental point of view.

Aesthetically, reinforced grass is indistinguishable from a plain vegetation so it fits in with the landscape. Also, the use of vegetation encourages the development of flora and fauna;

- generally, vegetation reinforcement is cheaper than more traditional constructions using firm materials;
- under normal circumstances, vegetation reinforcement is easier to place than more traditional constructions.

1.2 *Design approach*

Three dimensional synthetic mats are used as a reinforcement for vegetation. They therefore cannot be seen as a separate object, but form a part of an integrated system of soil, vegetation, roots and mat. The design should not only pay attention to whether or not a mat is a proper solution and which mat-type should be used, but also into the conditions to achieve a proper growth of the vegetation.
Further the design should take into account the phase just after placing of the mat in which the vegetation is absent yet and the phase in which the vegetation has been fully developed.

2 MAT TYPES

Open three dimensional mats consist of fibres of polymers (polyamide, polyethylene). In the Reinforced mat also a polyester grid may be present.

These materials provide a good resistance to weather influences. Since a UV-radiation stabilizer is added (carbon black) the resistance against UV-radiation is good. The materials are resistant to all chemicals which are normally contained in the earth and surface water. In Table 1 some properties of the materials used are given.

When placing the mat it is essential to achieve a close contact with the subsoil. This is realised by pinning. The diameter and length of the fixing pins must be chosen to suit the site and soil conditions. Special attention should be given to joints and connections so that no loose ends are present or may develop in coarse of time. Weak joints and loose ends are points of attachment for currents, waves and other loadings. When uni-directional currents are present the mat should be placed by overlapping in the direction of the flow. In case of alternating currents careful pinning or glueing with bitumen is required.

Table 1:Resistance of geosynthetics relevant to erosion control (CUR, 1995)

raw material	Polyamide		Polyethylene		Polyester	
duration	short	long	short	long	short	long
diluted acids	+	0	++	++	++	0
diluted lyes	++	+	++	++	++	0
salt	++	++	++	++	++	++
mineral oil	++	++	+	0	++	++
micro-organism	++	+	++	++	++	++
UV-radiation	++	+	++	+	++	+
heat (100 °C)	++	+	0	-	++	++
waterabsorption	++	++	++	++	++	++
Detergents	++	++	++	++	++	++

short duration: transport and execution
long duration: use of construction
++= well resistant
+ = reasonable resistant
0 = less resistant
- = not resistant

Depending on the situation in which the mats are to be used several mat types are available.

2.1 *Open mat:*

Mat consisting of an entirely open structure of randomly placed monofilaments, available in several thicknesses. The choice for a certain thickness depends on the loading conditions.

This type of mat is used in situations where a proper vegetation can establish by itself in time.

2.2 *Flat-back mat*

Several types are available: as mat identical to the open mat with the exception that the underside of the mat is provided with a flat-back made of a two dimensional layer of filaments (Enkamat) and a mat consisting of two heat bonded mettings of which the upper netting is cuspated and the base layer flat (Tensar mat). The flat-back does not affect the water-permeability.

The flattened underside of the first type allows the mat being filled with mineral chipping. Filling increases the resistance against erosion, convenient in situations in which vegetation cannot develop fully, for instance when the mat is to be placed (partially) under water.

On embankments it is therefore possible to achieve a continuous protection of the entire slope above as well as under water by simply filling the mat on those locations where vegetation growth is difficult or impossible.

2.3 *Pre-filled mat*

A mat factory filled with bitumen bound mineral chipping in such a way that the mat remains open. The waterpermeability and the capacity for vegetation growth are preserved. This mat is much heavier than the other mat types and can withstand high hydraulic loading also under water where a vegetation cover cannot be present.

2.4 *Reinforced mat*

The mat is reinforced and can withstand high tensile forces. It is applicable on very steep slopes and on smooth sublayers. The reinforcement of the mat is achieved by a polyester grid attached to an Open mat or a woven geotextile stitched to an Open mat. The lightest form of reinforcement consists of reinforcing thread in the length direction.

2.5 *Pre-grown mat*

When immediate protection by a grass vegetation is required or when the time available to achieve a dense vegetation cover is insufficient a Pre-grown mat can be applied. This is an Open or Flat-back mat on which a turf is pre-grown under optimum conditions.

3 APPLICATIONS

3.1 *Protection of banks against hydraulic loadings*

Banks along canals, lakes, ponds, rivers, brooks, etc. are subject to attack by waves and currents. The height and duration of the attack may differ from situation to situation. For instance during high water discharges or storm periods large forces are exerted on the embankment lasting only for a short period.

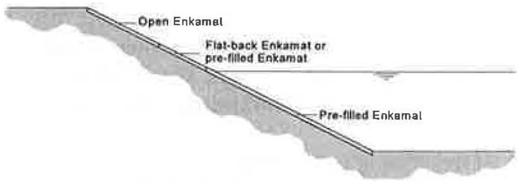

Fig. 2: Bank protection by three-dimensional synthetic mats.

Three dimensional synthetic mats can be applied to give extra strength to the vegetation so that its erosion resistance is increased.

The mats are used as a protection against hydraulic loads in three main situations (Fig. 2):

1. the location to be protected is sufficiently high above the waterlevel, so that a dense vegetation can develop by itself. Hydraulic loadings occur here only under exceptional conditions. In this case the Open or Flat-back mat can be used;
2. the location to be protected is situated lower on the slope and is more often subject to hydraulic forces. Plain vegetation may not develop to a full grown and dense cover. Flat-back mats, filled with stone chipping, are used or when large hydraulic loadings are present, Pre-filled mats;
3. in situations at or below the water line, where vegetation cannot be developed, the Pre-filled mat is used.

Open mats can also be used as a gradual transition between a hard cover and a plain vegetation.

3.2 *Protection of watercourses against hydraulic loadings*

Watercourses are used to transport water for drainage or water supply. The watercurrents cause shear forces on the bottom and slopes of the watercourse, which can result into erosion. A distinction should be made between:

1. watercourses that permanently carry water, such as drain ditches. In this case vegetation cannot be developed to withstand the acting currents. A Pre-filled mat can provide enough resistance to withstand the erosive forces;
2. watercourses that are only subjected to occasional water discharge, such as storm-water runoff channels and spillways. When sufficient time is available for a vegetation cover to recover itself

after a discharge period an Open or Flat-back mat can be used. When high currents are present and the vegetation is poor, the Flat-back mat, filled with stone chipping, or the Pre-filled mat can be used.

3.3 *Protection of waterdefences*

With a waterdefence the following zones can be distinguished (Fig 3):

- zone 1 permanently under water and, in the case of seadefences, within the normal tidal range. This zone is subject to currents and wave attack;
- zone 2 between the mean (high) water level and the design water level. This zone is attacked by higher waves.
- zone 3 between the crest and the design water-level. This zone is subject to wave run-up;
- zone 4, the crest and innerslope. This zone is affected by wave overtopping.

In zone 1 and 2 mostly firm revetments are used such as rock or concrete, but when hydraulic loadings are low, for instance in the case of a polder dike, the Flat-back mat or the Pre-filled mat can provide a good solution.

In zone 3, which is normally protected by a vegetation cover, various mattypes may be used depending on the weight and duration of the loading, etc. Normally the Open mat is adopted.

The rate of wave overtopping in zone 4 can vary from occasional spray to severe overflow of water. Normally a vegetation cover is used in this zone. The Open mat can be used and when the vegetation cover is poor and the overtopping rates are extreme the Flat-back mat, filled with stone chipping, or the Pre-filled mat.

4. VEGETATION

The vegetation itself plays an important role when using three dimensional synthetic mats. The following aspects are important:

- it must root deeply;

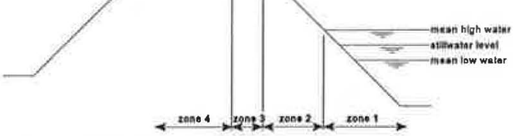

Fig. 3: Zones at waterdefences.

- it must be resistant to dry periods;
- it must grow fast;
- it should keep its quality (depending on whether or not maintenance is carried out).

Which kind of vegetation to use depends on the climate, the type of subsoil and the application which is different for each situation. Aspects to be considered when developing a homogenous and dense vegetation are:

- a good germination of seeds and the establishment of plants. Germination takes place at a soil-temperature of at least 10°C and sufficient humidity of the soil. The growing season in temperate zones is relatively short, whereas in tropical areas it is long.

For perennial crops like grasses the annual rainfall is essential and for annual crops, (e.g. herbs), particularly for those with a short growing period, the seasonal rainfall. Certainly for those crops with a short growing period, it is important to know during which months the required amount of rain falls. The best sowing seasons in temperate regions are april and september. The required time needed for germination is approximately 1 to 3 weeks under good conditions, a complete covering is achieved in the first growing season. A fully grown vegetation is realised after two growing periods;

- maintenance (pasture intensity, mowing, fertilizing). Regular mowing or pasturisation gives a compact and dense grasscovering. The optimum mowing frequency depends on the growing characteristics of the grasstypes used. Ryegrass should be mowed more often than slower growing grasstypes as Fescues or Bents. Overpasturisation or to frequent mowing gives shorter grass and a reduction of the root development. A limited access to preferably sheep is not detrimental to the variety of grass species.

In situations were maintenance is difficult or impossible, for instance on steep or long slopes, a selection of the right grass species is very important. Many grasstypes can be used in combination with reinforcement mats. The composition of grass mixtures determines the intensity of maintenance. When using herbs more specific location bound species are to be used;

- the location of growth: slopes directed towards the south in general show a larger variety of plant species. A large number of species in Western-Europe has a certain preference for steep slopes with an angle between 20 and 30° and with an exposition varying from south-east to west. Tem-

perature fluctuations on southern slopes are also influenced by the type of soil;
- the fertility of the soil. A vulnerable vegetation with much space between the sprouts occurs often on a fertile soil. A dense homogenous vegetation occurs more frequently on more poor soils.

In the design attention must be paid to the density of the vegetation as well as the rootsystem. The rootpenetration through the mat is reduced when the thickness of the mould layer on top of the mat becomes larger than 20 mm, depending on the seed that is used. Also the use of a fertile toplayer on a less fertile subsoil increases this effect, caused by a sharp change over between layers. By milling the subsoil to a depth of 10 to 20 cm before placing a fertile topsoil layer (30 - 40 cm) this is dealt with.

Factors that influence the development of a rootsystem in the subsoil are:
- the humidity rate of the subsoil: a relatively dry subsoil gives a faster development of the root system;
- texture: the development of a rootsystem is reduced when the soil is more heavy;
- temperature: a relatively high subsoil temperature gives a faster and deeper development of the rootsystem;
- nutrients: P and K and most crypto-elements, but certainly N, enhance the growth of roots and offshoots;
- light: the more light the larger the rootsystem;
- acidity: in general plants in an acid environment develop lesser roots than in a basic environment.

5 HYDRAULIC LOADINGS

5.1 *Currents*

Water currents cause shear stresses on slopes and bottoms of watercourses. The acting current velocity or shear stress has to be compared with the critical current velocity or critical shear stress (the current by which soil particles start to move).

Two methods are often used to calculate the mean velocity of the current in watercourses, which are the Chezy and the Manning method.

The Chezy formula:

$$V = C \cdot \sqrt{R \cdot i}$$

$$C = 18 \log \frac{12R}{k_s}$$

Where: V = mean velocity of the current (m/s); C = Chezy's coefficient for hydraulically rough surfaces ($m^{1/2}/s$); R = hydraulic radius (m); i = slope of the energy line (-); k_s = absolute roughness (m).

The Strickler-Manning formula:

$$V = K_m \cdot R^{\frac{2}{3}} \cdot I^{\frac{1}{2}}$$

where: K_m = Manning's roughness coefficient [$m^{1/3}/s$].

In stead of K_m also the retardance factor n ($s/m^{1/3}$) = $1/K_m$ is used.

The relation between Chezy's coefficient and Manning's roughness coefficient is:

$$c = \frac{R^{\frac{1}{6}}}{n} = K_m . R^{\frac{1}{6}}$$

The absolute roughness k_s for an unprotected non-vegetated waterway can be estimated by taking the D_{90} of the soil. The D_{90} is the particle size of the soil which is exceeded by 10 percent of the material (m).

In (Delft Hydraulics, 1977) an absolute roughness k_s = 0,014 m is measured for an unvegetated Flat-back mat filled with chippings. In (Muth, 1983) a Manning's roughness coefficient K_M of 50 $m^{1/3}/s$ or an absolute roughness of k_s = 0,010 m is determined for the Pre-filled mat.

For mats in which the vegetation has fully developed, Manning's roughness coefficient can be taken similar to that of a plain vegetation. In Table 2 some retardance factors are given.

The critical current velocity for unvegetated waterways depends on the grain size and cohesion of the soil. In Fig. 4 the relation is given for the critical current velocity, the mean grain size diameter D_{50} of several soiltypes and for several mat types. In

Table 2: Retardance factors (n) for various slopes (1:x).

Slope (1:x)	Retardance factor (n)
1:10	0.0300
1:5	0.0256
1:4	0.0235
1:3	0.0200
>1:3	0.0200

Fig. 5 a rough indication is given of the time after which 0 % residual soil filling of the mat is reached related to the current velocity.

The data in Fig. 5 and Fig. 6 are derived from tests with a uniform stationary flow. In reality however often a non-stationary flow occurs which gives higher loadings. In practice it has been proven that mats can resist significantly higher currents for shorter periods than indicated by the laboratory results. A possible explanation is that due to sedimentation of silt in the mat the mat is stuck to the silt (Enka, 1983).

For well vegetated mats (Enkamat), with a nominal thickness of 20 mm, the critical current velocity can be established for uni-directional flow using Fig. 6, depending on the loading duration (Hewlett, 1987).

The figures refer to horizontal substrates. For applications on slopes a slope factor has to be used which takes into account the gravity force on a soil grain.

$$v_{cr,slope} = t . v_{cr,hor}$$

$$t = \left(1 - \frac{\sin^2\alpha}{\sin^2\phi}\right)^{1/4}$$

Where: t = slope factor; α = slope angle (dgr); ϕ = angle of internal friction of the soil (dgr).

It is also advised to apply a safety factor of 1.5 for situations with none or poor vegetation and of 1.2 for situations with a mature vegetation.

As can be concluded when comparing the unvegetated situation and the vegetated situation Open mats are preferred on vegetated slopes, while on unvegetated slopes the Flat-back mat or the Filled mat are to be used.

The mats are jointed under water by overlaps in which the mats are placed tilewise onto each other in the direction of the current. It is however possible that for a short period the current attacks from the opposite direction, causing an extra load onto the joint with fear from flapping. It has been shown that a Pre-filled mat will flap at a current directed in an opposite direction with a velocity of 0.6 m/s (Berkhout, 1981). When higher currents are to be expected careful fixing of the overlap by pinning, gluing or ballasting is required.

Situations in which high turbulent currents occur, such as around bridges, narrowing of the watercourse, irregular bottom, should be dealt with separately.

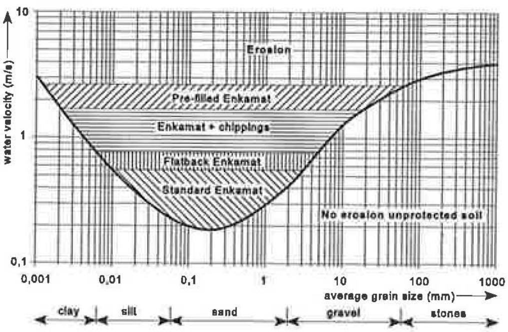

Fig. 4: Critical current velocity in relation to mean grain size diameter and soiltype.

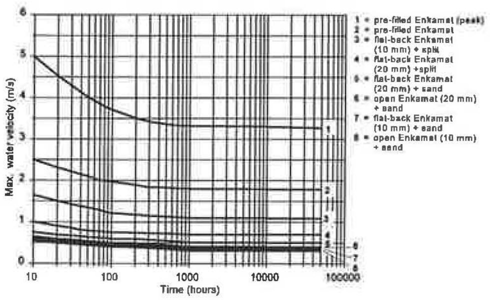

Fig. 5: Time at with 0% residual filling of the mat is reached vs. the current velocity.

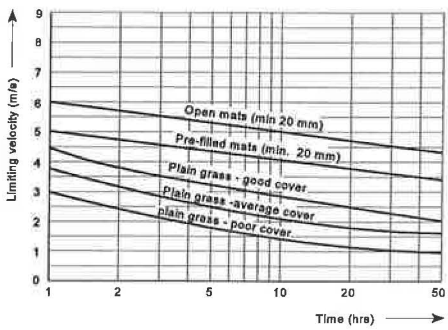

Fig. 6: Recommended limiting values for erosion of plain and reinforced grass (Hewlett, 1987).

5.2 *Waves*

Waves are generated by wind or ships. The wave conditions for wind-induced waves can be established using hindcasting methods. From experience it can be derived that the Pre-filled mat (unvegetated) can withstand regular wave attack with a height of H_s = 0.2 to 0.3 m. Incidental higher waves are allowed.

A vegetated grass slope can withstand wave attack up to a height of H_s = 0.3 m for a duration of several days to a week under the condition that it is well maintained. No information is available on the resistance of grassed slopes in combination with Open mats. Therefore it is assumed that these structures provide similar protection as plain grass. However, the duration before erosion will occur will be prolonged to several weeks. Also the recovering of he grass after the loading is better. The Open mat, when properly vegetated, can withstand a wave attack of 0.3 m for a period of several weeks. Incidental wave attack up to 0.7 m will give no severe erosion.

The crest and innerslope of waterdefences are normally protected by a vegetation to withstand overtopping waves.

In this respect the duration and frequency of the overtopping should be considered. For instance: overtopping at seadefences takes place during storms with a relatively short duration but with high overtopping peaks while for riverdikes overtopping is less but for a longer period.

No data are available for the maximum allowable overtopping rate for three dimensional synthetic mats. The following indications may however be used:

- the vegetation is given extra strength so the allowable overtopping rate may be higher;
- for riverdikes: the quality of the grass cover (density and rootstructure) can be lesser than with plain vegetation;
- for seadikes a mat can be applied when a slight increase in vegetation strength is required to withstand the overtopping rate or when a plain vegetation is poor or cannot be maintained properly.

5.3 *Waterlevel*

An important factor is the duration of the hydraulic loadings, since the choice of the mat is largely determined by the fact whether or not a dense vegetation cover can be established or maintained. The duration depends largely on the waterlevel. The following guidelines can be used:

- at locations below approximately 0.3 m above the mean waterlevel vegetation growth is considered absent or very poor;
- when the slope is regularly under water for more than a few days (two or three times a year) or a few weeks in exceptional circumstances (once per year) vegetation should there be regarded as poor;
- when waves are present vegetation cannot develop in the normal wave zone. The upper limit of this zone (distance above the mean (high) water level) can be established by calculating the wave run-up;
- when waves are present grass vegetation will generally be poor in the lower part of the zone between the mean water level and the design water level. The length of this part depends on the wave height, the frequency of occurrence of high water levels and the slope angle.

In order to design a mat construction first the position and length of the mat on the slope have to be established. This is done as follows.

Establish the high and low water level. The high water level is estimated as:

- for slightly varying levels (non tidal), the normal high water level;
- for largely varying waterlevels (non tidal) the level that is exceeded with a maximum of three times a year;
- for tidal conditions the mean high water spring level.

The low water level is:

- for varying levels (non tidal), the normal low water level;
- for tidal conditions, the mean low water spring level.

The upper boundary of the mat is 0.5 m measured along the slope above the high water level to which the wave run-up is added (Fig. 7).

The wave run-up can be established using Table 3.

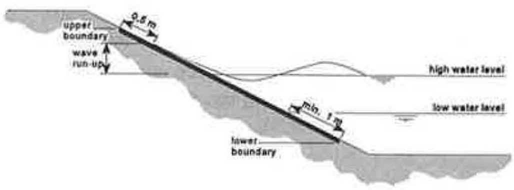

Fig. 7: Upper and lower boundaries

Table 3: wave run-up (m) depending on the significant wave height (H_s) and the slope angle (measured vertical above the high water level)

H_s (m)	slope		
	1:2	1:3	1:4
0.1	0.40	0.25	0.20
0.2	0.80	0.55	0.40
0.3	1.20	0.80	0.60

The lower boundary of the mat is to be established as:

- when the mat is loaded by currents the entire slope or bottom is to be protected;
- when the mat is attacked by waves the lower edge is to be calculated as 1.5 to 2 times H_s, measured vertical opposite the low reference level, with a minimum of 1 m measured along the slope.

6 GEOTECHNICAL ASPECTS

When a mat is applied on slopes geotechnical aspects are to be taken into account. The mat itself can in general be placed under very steep and even vertical conditions, but the subbase itself may not be geotechnically sound.

Although the mat contributes to the stability of slopes since it reduces erosion, the main rule is: the slope itself must be initially stable and not subject to large deformations. Two situations have to be distinguished:

1. the slope is relatively unsteep: the mat can be placed on the slope without fear for sliding off. The mat is not subject to tensile forces which may damage the mat.

This situation generally is present in case of earth substrates if the slope is not steeper than 1:1 for dry slopes and embankments and 1:1.5 for under water applications (Akzo Nobel, 1994). This implies that the mat can be used on nearly every normal earth structure;

2. the slope is relatively steep. The mat is subjected to tensile forces. In that case the Reinforced mat is to be used. The tensile force acting on the mat has to be calculated and the thickness of the mat chosen.

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