Bank protection of the Ravenna harbor by a composite filtration system

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ABSTRACT: A new composite system including both a geotextile filtration system and an external protection layer made of concrete slabs was laid and tested on the Ravenna harbor banks. Compared to existing bank protection composite systems, the filtration function was of the highest importance in the development of the new system. The core of the filtration system is a needle-punched nonwoven fabric with excellent hydraulic properties able to stabilize difficult soils : flexibility to reach an intimate contact with the soil surface, small opening size required by this fine soil, homogeneity of the nonwoven obtained by a sufficient number of constrictions, and finally, high normal permeability to prevent excessive pore pressure in the soil. The external protection layer is made of truncated concrete pyramids fixed directly on the geotextile. Its purpose is first to break the hydraulic energy of waves, and secondly to ballast the composite and to apply a normal stress on the geotextile filter at the soil surface. Cables are knitted on the nonwoven to support the weight of the whole concrete structure. Special installation devices improve the accuracy of the placement. 18 months after installation, the composite has worked well.

1 INTRODUCTION

The protection of marine coast or river banks consists both of :

- An external revetment made either of one or several layers of crushed blocs and stones (rip-rap), or of concrete elements. The function of this revetment is to protect the slope against external hydraulic loading due to the waves.
- An underlying filter structure built by superposing several layers of well distributed granular materials designed according to granular filter rules, or by laying a geotextile filter. The function of this filter structure is to avoid the internal erosion of the soil due to water flows inside the soil body due to water movements.

From their experience, Pilarczyk, Breteler (2000) wrote that the placement of a granular filter underwater is usually a serious problem; the quality control is very difficult, especially when placement of thin layers is required. Therefore, banks of rivers, canals or marine coasts are usually built with filtration geotextiles instead of granular filters. Geotextiles are laid on the natural soil to be stabilized, and covered by rip-rap layers made of big stones or rocks. This solution is very efficient and hundreds of kilometers of banks have been successfully protected with this technique.

But rip-rap revetment sometimes raises some difficulties for one or several of the following reasons : 1. Not enough space available to built a rip-rap layer (for example, thickness limitation inside inland waterways), 2. No quarry in the neighborhood of the job site able to deliver the stones, 3. Underwater installation difficult in case of great depth of water or high current velocity, 4. Slope stability, etc…..

In these conditions, the use of a composite filtration/revetment structure which combines into a unique product, on one side the geotextile filtration system, and on the other side the concrete revetment fixed on it, may be helpful. Composites with different combinations of geotextiles and concrete revetment already exist on the market, but the geotextile is often considered as a supporting frame for the concrete revetment. In this case, woven geotextiles are mainly used, because of their high tensile properties, whereas their characteristics required for the filtration function, i.e. fine soil retention and water permeability, may sometimes not be sufficient.

A new composite combining both improved soil filtration properties and required supporting strength has therefore been specially designed and has been tested on the slopes of the Ravenna harbor in Italy. After presentation of the rules used for the filtration function, and the related characteristics required for the geotextile filtration system, the composite filtration/product and the testing zone in Ravenna will be described.

2 THE FUNCTIONAL DESIGN OF GEOTEXTILES

Constituent materials must be carefully chosen in order to ensure that they function correctly for the entire working life of the structure.

The characteristics taken into consideration depend on the function that the particular material has to fulfil. In the case of geosynthetics, for example, the useful characteristics for the separation and reinforcement functions are not the same as those for the filtration function.

Starting with this notion of the role of particular products in a structure, it is possible to list and analyse all the various characteristics that need to be defined for a specific function. This is referred to as functional sizing. These characteristics can be inventoried, by grouping them into three categories:

2.1 *Initial functional characteristics*

These are the initial characteristics enabling a geosynthetic to fulfil its function within the structure.

2.2 *Characteristics connected with installation*

These are the characteristics that are designed to prevent or limit the loss of initial functional characteristics when the geosynthetic is being laid.

2.3 *Characteristics connected with durability*

These are the characteristics enabling the initial functional characteristics to be maintained above the specified values for the working life of the structure.

3 THE FILTRATION FUNCTION

The filtration function, which involves intricate interaction mechanisms between soil particles and geotextile fibers, is certainly one of the most complex of all the functions fulfilled by geotextile products. A lot of studies and research have therefore been carried out around the world in the last decades to clarify the role of a filtration system in contact with natural soils, and to define design criteria based on the right characteristics.

3.1 *Role of a filtration system*

Natural soils are porous media that contain about 30-40% of voids formed by the pores between the soil particles. When a soil is saturated, the water it contains circulates in time with movements of the water table within the pores.

By means of the same processes as those associated with surface flows, water may destabilise soil particles, detach them and carry them away (Figure 1).

To prevent destabilisation of the particles situated at the interface with the external medium, a filtration system is applied at the surface (Figure 1).

Its role is:

- to maintain the particles so that they are not carried away by flow coming from inside the soil mass;
- to allow free circulation of water in the long term.

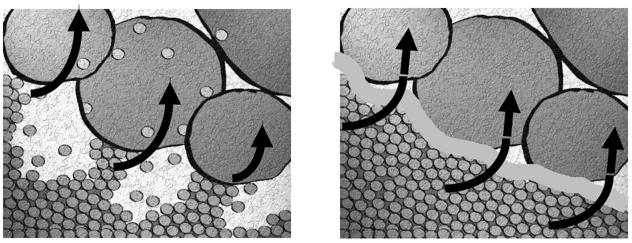

Figure 1. Role of a filtration system. With a filtration system (right), the soil particles at the interface are stabilized while keeping a free water flow. Without filtration system, internal erosion of the soil occurs (left).

It is thus clear that the operation of a filtration system in a hydraulic or geotechnical structure is quite different from that of the filters used in other industrial-type applications (air filters, oil filters, etc.), which are placed across the flow path to trap all particles being carried by the fluid (usually in suspension). The major drawback of this exclusive role is that particles inevitably accumulate at the surface or in the filter, eventually leading to clogging, i.e. the filter becomes less and less permeable. Industrial filters of this type have to be replaced regularly. This is quite unthinkable in the case of a geotechnical structure, where the filtration system is intended to fulfil its role throughout the working life of the structure.

To prevent clogging by particles carried in the flowing fluid, the filtration system in a hydraulic structure must prevent the ground as a whole from moving. It is therefore crucial for the filtration system to maintain the soil so that the particles remain immobile and stable and are prevented from being carried away. However, there are always very fine particles that will be moved along by water. The filter system must therefore allow them to pass.

3.2 *Functional characteristics of geotextile filtration system*

From a wide analysis of the behavior of geotextiles laid in old sites (Delmas et al. 2000), some important points can be made to improve the functional performances of a geotextile filter:

- the geotextile is a catalyst for filtration : it helps to stabilize the coarser particles of the soil (the skeleton) which should not move, otherwise the soil particles are destabilized;
- this catalytic action is an interface phenomenon : only a minimum number of filament layers is necessary.
- this phenomenon is only possible if the geotextile filaments are in intimate contact with the soil surface : the geotextile should be flexible enough to conform to the soil roughness.
- the finest soil particles contained inside the arches at the interface must be washed in suspension through the geotextile (Figure 2) : a very thick geotextile or a geotextile with very low opening sizes may block these particles and increase the risks of internal clogging.
- free long-term water flow through the filtration system with low headloss

These qualitative observations were expressed as optimum values of geotextile characteristics and new specifications of the functional characteristics were defined to improve the performance of the filtration system (Delmas et al. 2000).

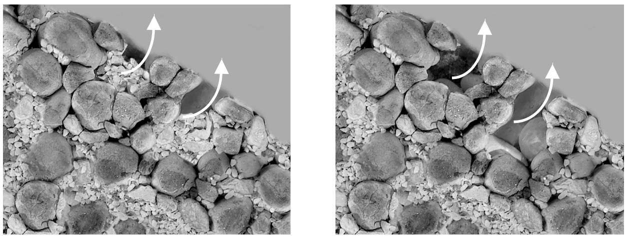

Figure 2. Formation of natural arches between the soil skeleton particles and the filtration system. A stable structure is maintained at the interface while the fine suspended particles inside the arches escape under the effect of water flow.

These new requirements can be summarized as follows.

3.2.1 *Optimum range of opening sizes*

An optimum range of opening sizes has been defined firstly to be able to filter the majority of soils, and secondly to avoid the risk of clogging by the finest particles transported in suspension :

$$50\ \mu m \leq O_{100} \leq 80 \mu m,$$

where O_{100} = maximum opening size of the geotextile. This maximum opening size is approached by standard tests methods such as EN ISO 12596, which measures the filtration opening size of the geotextile by wet sieving, and $O_{100} \approx O_{90,w}$.

3.2.2 *Optimum range of number of constrictions.*

An optimum range of thickness must also be defined to stabilize the soil skeleton at the geotextile interface and to avoid risks of internal clogging due to deep filtration. But Giroud (1996) and Giroud et al. (1998) have shown that the number of constrictions is a more general characteristic than thickness, because this criterion is the same for all types of nonwoven, independent of their internal structure. The number of constrictions corresponds to the number of "passages" delimited by three or more crossing filaments which are met by a soil particle passing through the geotextile, from one side to the other side (Figure 3).

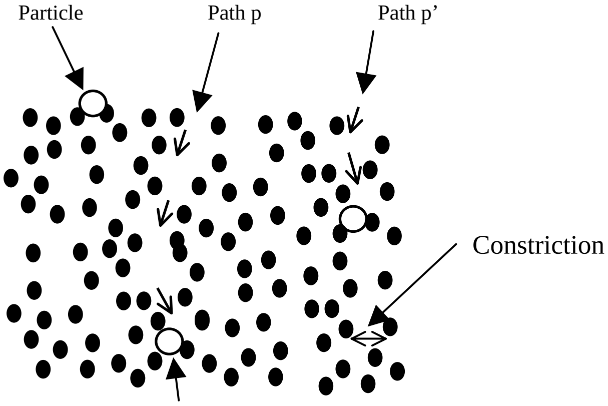

Figure 3. Schematic cross-section of a nonwoven geotextile. The soil particles (white) which pass across the nonwoven meet a given number "m" of constrictions between the filaments (black).

The relationship established by Giroud (1996) to calculate this number of constrictions "m" is

$$m = \sqrt{(1-n)} \cdot \frac{t_{GT}}{d_f} \qquad (1)$$

very simple:
where t_{GT} = geotextile filter thickness (m); d_f = fiber diameter (m); and n = geotextile porosity (-):

$$n = 1 - \frac{\mu_{GT}}{(\rho_f \cdot t_{GT})} \qquad (2)$$

where μ_{GT} = mass per unit area of the geotextile filter (kg/m²); and ρ_f = density of the fiber (kg/m^3)
The optimum range of number of constrictions is:

$$25 \leq m \leq 40, \qquad (3)$$

the lower limit guaranteeing firstly the homogeneity of the filtration opening size of the geotextile, and the upper border guaranteeing the stabilization of the soil skeleton near the soil-geotextile interface to reduce the risk of internal clogging.

3.2.3 *Minimum normal water permeability*

The normal permeability of the filter must be larger than the soil permeability to avoid uplift water pressures causing loss of stability. The permeability of geotextiles is usually greater than the soil permeability. But Pilarczyk et al. (2000) point out the importance of a proper permeability of the geotextile with respect to the stability of relatively less permeable cover layers as, for example, concrete revetments.

Indeed, the reduction of the flow area due to the concrete laid directly on the geotextile should be compensated for by a higher geotextile permeability. The normal permeability of the geotextile filter should meet the following requirement :

$$K_{geotextile} \geq FS_{permeability} \, . \, K_{soil} \, / \, (1-S_{revetment}) \qquad (4)$$

where $K_{geotextile}$ = normal permeability of the geotextile; K_{soil} = permeability of the soil; $FS_{permeability}$ = factor of safety on the permeability; $S_{revetment}$ = percentage of the revetment area.

The factor of safety $FS_{permeability}$ is a function of the soil type and may vary from 2 for a clean uniform sand to 50 for fine soils or risky applications such as dams.

The critical case is a uniform sand having a permeability of about 10^{-3} m/s, where the geotextile normal permeability should be :

$$K_g \geq 2/(1-S_{revetment}) \, . \, 10^{-3} \text{ m/s.} \qquad (5)$$

For example, a composite which has a relative concrete area of about 75% must have a minimum geotextile permeability of $K_g \geq 8.10^{-3}$ m/s.

Practically, the nonwoven needle-punched geotextiles offer the highest permeability among all the geotextile structure available on the market. They are therefore appropriate to fulfill this requirement.

3.2.4 *Minimum flexibility*

Without intimate contact between the soil and the geotextile filtration system, there is no chance to stabilize the soil skeleton, which will then be unable to catalyze upstream the granular self filter. The flexibility of the composite should be as great as possible to adjust to the soil surface irregularities.

3.3 *Characteristics connected with installation*

A perfect filtration system may fail if it is damaged during installation : holes, tears or localized puncturing may be caused by rip-rap stones dropped on the geotextile or by the angular gravel of a drainage trench.

In comparison, the use of a geotextile/revetment composite reduces the localized stresses applied on the geotextile filter, and the usual requirements in terms of minimum elongation or minimum puncture resistance may be considerably reduced.

But the tensile strength, which is generally not useful with rip-rap, becomes very important for the composite. The tensile strength in the direction of the panel length must be designed to support the weight of the concrete revetment fixed on the geotextile filtration system. It is a short term property as, if the whole system is stable on the slope (see 3.4.2.), tensile strength is useful only during the installation of the composite.

3.4 *Characteristics connected with durability*

These characteristics must be designed to guarantee the long-term behavior of the composite structure.

3.4.1 *Maximum number of constrictions.*

The number of constrictions (i.e. the thickness) of the filtration system should be lower than 40 to build a stable granular filter at the interface between the soil surface and the geotextile. Otherwise the displacement of the skeleton particles deep inside the filter destabilize the soil structure, and internal clogging may occur (see section 3.2.2.). A number of constrictions $m \leq 40$ is a guarantee for the long term permeability of the filtration system (Bouthot et al. 2000).

Furthermore, Faure et al. (2000) have clearly shown that the thicker the nonwoven, the higher the risk of internal clogging by the finest soil particles transported by the water flow in suspension.

3.4.2 *Soil/geotextile friction angle*

The friction angle between the soil and the geotextile filtration system should be much greater than the slope angle to prevent any risk of slippage of the structure. The common rule for geosynthetic stability on slopes is :

$$\tan \varphi_{soil/GT} \geq FS_{friction} \cdot Slope \qquad (6)$$

and:

$FS_{friction} = 1.35$, according to the last Eurocode draft

where $\varphi_{soil/GT}$ = friction angle between the soil and the geotextile; Slope = slope of the bank to be protected by the composite; $FS_{friction}$ = factor of safety for the stability of the composite on the slope

For example, on a 1v/2h slope, the friction angle between the soil and the geotextile filter should be higher than :

$$\varphi_{soil/GT} = \text{atan}(1/2\text{x}1.35), \text{ i.e. } 34° \qquad (7)$$

Again, the nonwoven needle-punched geotextiles offer in general the greatest friction angle with soils among all the geotextile structure available on the market. They are still the most appropriate to fulfill this requirement.

3.4.3 *Resistance to the external environment*

The composite must be resistant during its whole working life to UV, if directly exposed to sun, and to all type of chemicals found in the water or in the soil (oil, salt, etc …). The chemical compatibility of the composite must be adjusted according to the UV intensity, to the chemical concentrations and to the exposure period of the site.

4 THE COMPOSITE FILTRATION SYSTEM FOR EROSION CONTROL

4.1 *The optimized filtration layer*

From the previous discussion it appears that the best compromise to meet all the requirements for the filtration layer is a nonwoven needle-punched geotextile. The production parameters of this

filtration layer (fiber size, density) have therefore been optimized. The requirements listed previously are summarized below:
- Filtration Opening Size : $50\ \mu m \leq O_{100} \leq 80 \mu m$,
- Number of constrictions : $25 \leq m \leq 40$,
- Normal permeability : $K_g \geq 8 \cdot 10^{-3}$ m/s,
- Friction angle with a soil : $\tan\varphi_{soil/GT} \geq 0.8 \cdot \tan\varphi_{soil}$
- The nonwoven needle-punched geotextile is made of UV stabilized polypropylene. This polymer shows a wide resistance spectrum to resist to the majority of chemicals found in hydraulic applications to usual concentrations.

4.2 *The new geotextile/revetment composite*

From this filtration base, the composite has been defined to meet the other requirements.

The revetment structure and fixing are the same as for existing woven based composite : the structure is made of concrete slabs having the shape of a truncated pyramid with a square base of about 34 cm, and a height between 12 and 20 cm, depending on the composite weight needed to resist the hydraulic gradients of the site (Figures 4-5). The distance between the slabs is about 7 cm, which corresponds to a relative revetment area of about 70%.

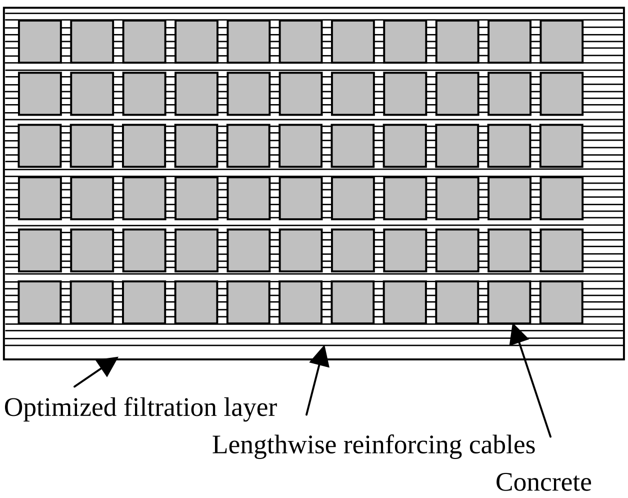

Figure 4 : Schematic top view of the revetment composite

In the case of the new composite based on a nonwoven filtration layer, the remaining open space allows :
- sufficient water flow for soils having a permeability $K_{soil} \leq 10^{-3}$ m/s according to (4), which covers the wide majority of soils to be filtered.
- sufficient flexibility of the composite which may easily adapt to unplanned surface

To support the weight of the concrete revetment during the installation of the composite, reinforcing cables are knitted lengthwise on the nonwoven filtration layer.

A strip of geotextile of 50 cm width is free on one side of the composite to overlap the filtration layer of to adjacent panels and to guarantee the continuity of the filtration function across the whole area.

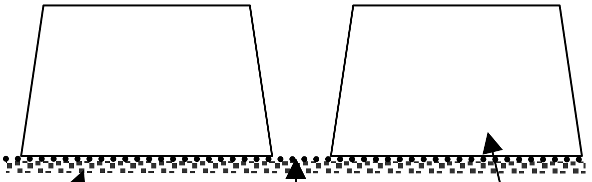

Figure 5 : Schematic cross section of the revetment composite

4.3 *Installation*

The composite carpet may be installed either on a bank slope or at the bottom of the water. The common installation device is a an hydraulic crane installed or the bank or on the pontoon (Figure 6). But a specific floating cylinder has also been developed for the carpet transportation from its construction site to the installation site. This device has been used for the Ravenna harbor project (Figure 7).

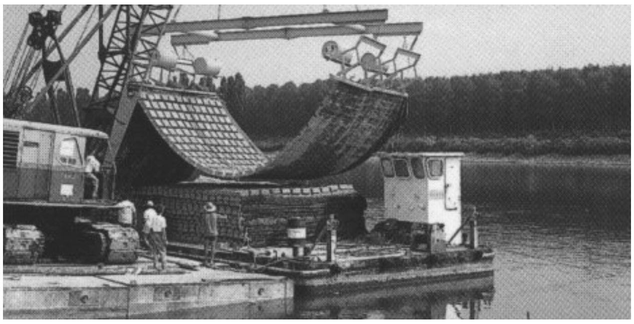

Figure 6 : Underwater composite installation with the pontoon crane

Figure 7 : Ravenna harbor. Installation of the composite on the slope with floating cylinder

5 THE RAVENNA HARBOR TESTING SITE

5.1 *The Ravenna harbor*

Ravenna is a major harbor on the Adriatic Sea which receives a lot of large ships. This intense traffic creates frequent waves which destabilize the excavated banks of fine sand along the channel between the sea and the harbor. The extension of the harbor requires stabilization of the bank and erosion control.

The slope of the bank is 1v / 2.5h and the slope length to be stabilized was between 15 and 25 m, three quarters being underwater.

The height of the waves due to the ships is about 50 cm.

5.2 *Composite for bank erosion control*

The composite geotextile/revetment has been chosen as it was the most economical solution for this bank protection. The composite with concrete slabs of 20 cm height was prepared on an existing platform on the opposite bank of the channel as the space around the bank to be protected was very small. Each panel was rolled on a 4 m diameter floating cylinder and pulled to the installation location where it was unrolled (Figure 7). With this system it is possible to install carpets of 8 m width and 50 m length. This procedure guarantees a safe placement of the system on the soil.

The new composite has been installed on a part of the job site near an existing system based on a woven geotextile for more than 18 months where it works successfully. A comparative study of the behavior of the two products will be carried out after several years of functioning.

6 CONCLUSION

Composite systems combining both a filtration layer to prevent internal erosion control and an external revetment structure are a useful alternative when the conventional solution of the rock rip-rap layer is not possible for technical reasons (space, underwater placement, slope stability) or economic reasons (rip-rap expensive, duration of the project).

If the external structure purpose is to break the hydraulic energy, the main function of the geotextile layer is the filtration to prevent internal erosion of the subsoil. Therefore, the development of the new composite for bank erosion control has focussed on the optimization of the characteristics of the filtration layer to increase its long-term efficiency and its safety for the majority of the soils to be filtered. In particular, optimum ranges of opening sizes and of numbers of constrictions have been defined. Furthermore, the use of a nonwoven needle-punched filtration layer improves the permeability and the stability of the composite on the slope. The spacing and the size of the concrete slabs of the revetment also give also greater flexibility and permeability.

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