Geosynthetic lining system in French navigable canals: design of the protective layer

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ABSTRACT: The majority of French navigable canals date from the end of the 19th century. They suffer locally from leaks resulting in the loss of water and risks of internal erosion. For the rehabilitation of such sections, the CETMEF, with the support of the CEMAGREF, has undertaken a study into the use of Geomembrane Lining Systems (GLS). This study essentially concerns the protective structure which is subjected to constraints specific to navigable waterways, and which is of prime technical and economic importance for these canals. Following a brief summary of the operations implemented over the last decade and a review of the protective materials that can be considered, the methods of choice and design for the stability of the protective layer are put forward. These methods take account in particular of the hydraulic conditions encountered and evidence that the worst-case scenario for the stability of the protective layer is the waves from passing barges.

1 GENERAL PRESENTATION

Over the last 10 years, geomembranes and related products have been implemented to waterproof French navigable canals within the framework of their rehabilitation work. This work, already performed over various sections in the North and East of France, has proved to be fully satisfactory. All these geosynthetic lining systems, as well as the specific conditions and the implementation work on each site are presented.

Figure 1. Canal between the Marne and the Rhin

On the basis of this work, an overall study has been carried out by the Centre of Maritime and River Studies (CETMEF) with the support of the *Cemagref* to the use of Geomembrane Lining Systems (GLS) in navigable canals. This study essentially concerns the choice and design for the stability of the protective layer of the geomembrane.

The choice of GLS involves various technical, environmental, and economic criteria as well as to the construction time and conditions (with the canal being taken out of service during the work). Specific constraints related to navigable canals also have to be taken into account to define the particular criteria to be met by GLS; for example, impacts by anchors on the bottom or by a barge on the banks, waves and wash caused by passing barges are parameters to be taken into account in waterproofing design.

Three categories of protection are considered : concrete slabs, which is the system used up to now, gravel, whether treated or not, possibly topped by rip-rap, and suspended elements. The latter category includes all the systems anchored on the top of the embankment, which may be of many different types : they may consist of prefabricated concrete elements of varying geometry, alveolar geocomposites filled with fine or coarse materials, gabions or similar products.

Stability on the slope of each of these categories of protection meets specific criteria and consequently an appropriate design method. Design methods are therefore proposed for each of three protections with the following hydraulic configurations : a canal out of service, with normal navigation water level, and passing barges. In the last case, taking account of quick fluctuations in the level of water not taken into account in the usual calculation methods required the development of specific modelling. The results, applied to usual sizes of French canals, show that lowering the water level when a barge passes is in many cases the most unfavourable configuration for the stability of the geomembrane protection.

2 SUMMARY OF REHABILITATIONS IMPLEMENTED

2.1 *Historical record*

Navigable waterways have been in use in France for several centuries. The majority of the current network dates from the end of the 19th century. The dykes of these canals reveal locally signs of age, such as leakage and erosion phenomena. The initial techniques of rehabilitation, (sheet piles, injections or lining with concrete) have in numerous cases been replaced over the last decade by the use of GLS.

2.2 *Examination of the 7 canal sections recorded*

The rehabilitation of 7 sections sealed by geosynthetic materials was examined in the course of the above-mentioned general study. The lessons learned, presented in detail by Fagon et al. (1999) are summarised below.

The work on these 7 canals was performed between 1989 and 1998. It covered a total area of approximately 20,000 m². The value of the slopes varied from 1/2.5 (1V/2.5H) to 1/1.75.

To ensure sealing, 2 types of bituminous geomembranes (each on 3 sites, 3 to 4 mm thick) and a bentonite geosynthetic material (5 kg/m^2) were used.

In the most frequent case of an old concrete lining, this had to be demolished (4 cases out of 5), given its poor condition. In the last case, the concrete was kept, after filling of the holes and cracks with mortar. It was found that the support structure adopted could vary considerably depending on the specific conditions of the site. This structure includes, as from its base, some or all of the following components :

- an anti-contaminant geotextile (2 cases),
- a layer of treated gravel (thickness = 15 cm ; 3 cases) or a layer of gravel (thickness = 15 to 30 cm ; 2 cases),
- an anti-puncturing geotextile (in only one case).

For the sections sealed with a geomembrane, the protective layer consisted of 15 cm thick concrete slabs, cast in situ in shuttering. In one case, a geotextile was installed between the geomembrane and the concrete.

The confinement and protection of the bentonite geosynthetic material was performed with a 10 cm layer of gravel and a 30 cm layer of gravel material. Protection was completed at the top of the slope by elements in prefabricated concrete.

It should be noted that, in 3 cases, sealing concerned only one part of the canal (slope alone or half canal) when it was possible to localise the leaks clearly at the level of the dyke.

2.3 *Lessons learned*

The users are satisfied with the 7 sections, as rehabilitated. The leaks which required the implementation of artificial sealing have disappeared. These users, in the event of a similar problem of sealing, are ready to adopt the same solution.

In comparison with the vertical solutions of sealing (sheet piles or injections), the main comment made by users on the GLS solution relates to the necessity of emptying the canal. This constraint results in very short implementation times, varying from 0.5 to 2 months for the 7 cases examined.

Only one problem was reported, namely lifting under the effect of the wind (approximately 100 km/h) of strips of geomembranes that had not been welded during the work on one of the sites.

3 CONSTRAINTS SPECIFIC TO GLS IN CANALS

3.1 *Constraints zones*

To define the main types of protection that can be used, technically, in navigable waterways, the cross section of the canal has to be divided into homogenous zones as far as constraints are concerned.

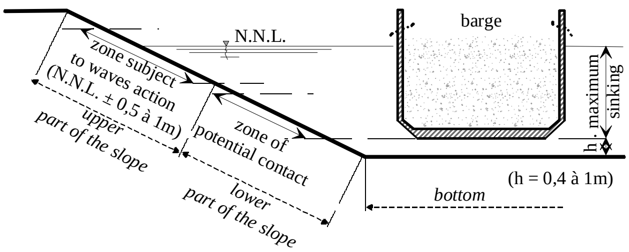

Figure 2. Specific areas of constraints in a canal

Figure 2 shows the 3 zones of constraints specific to GLS :
- the bottom of the canal,
- the lower part of the slope, mainly characterised by the possibility of contact (or impact) with barges,
- the upper part of the slope, subject to wave action.

3.2 *Constraints at the bottom of the canal*

The bottom of the canal is subject to the usual constraints such as propeller streams, and to accidental constraints : falling objects, accidental contact with part of the barge (propeller, anchor, etc.), that are accentuated by propeller streams at the level of the engineering structures (locks, anchorage points, etc.). In this zone, the current is slow in an ordinary cross section, and there are therefore few problems of erosion. In rehabilitation, care must be taken to guarantee the nominal depth, which may involve stripping equal to the thickness of the protection. When sealing is to be performed over the entire wetted perimeter of the canal, the bottom represents just over 50% (depending on the width of the canal) of the sealed area and is in a zone where constraints are low. It is therefore in this zone that the installation of a low cost protection can be justified technically. Implementation constraints must also be taken into account in this zone: a minimal thickness of the protective layer is necessary to prevent the geomembrane from being damaged under the effects of the movement of machines during the work.

3.3 *Constraints on the lower part of the slope*

This is the zone of possible contact with barges. This zone is always under water and the current is generally slow, apart from sections close to the engineering structures. On the other hand, the stability of the GLS and of its protective layer must be examined.

3.4 *Constraints on the upper part of the slope*

This zone is subjected to wave action, resulting from the wind and from passing barges. The majority of this zone is above the normal water level and thus open to atmospheric aggression (UV, frost, ice, etc.). Protection against vandalism also needs to be considered. The aesthetic aspect must be taken into account, as the integration of the canal in its environment is, quite rightly, a major concern of planners. Finally, the stability of the GLS must be ensured.

3.5 *Consequences for designing*

In designing protective systems, therefore, the slope will be subdivided into two parts, that may possibly be protected differently. In such cases, the boundary between the protections must be designed on a case by case basis, depending in particular on the specific constraints on the part situated immediately below the Navigation Normal Level (NNL), which can be treated either as the part out of the water or as the lower part of the slopes.

4 TYPES OF PROTECTION ENVISAGED

4.1 *Different types of protection*

Depending on the constraints previously described, the main types of protective structures that can be envisaged in the case of navigable canals are shown in Table 1, which also indicates the degree of matching of these 3 structures with the 3 zones chosen.

The different types of protection, together with the conditions for their use, are described in the following paragraphs.

Table 1. Main protective structures technically meeting the specific constraints of navigable canals

Type of protection	Bottom	Lower slope	Upper slope
Concrete	***	***	***
Treated gravel	***	***	*
Gravel / riprap	***	***	***
Suspended elements			
- cellular elements	-	***	*** (1)
- geo-containers	-	***	*** (1)
- gabions	-	***	*** (1)
-connected elements	-	*	*** (1)

(1) : subject to good erosion resistance of the product used
*** : suitable generally   * : possibly suitable
- : generally not used

4.2 *Concrete*

This is generally cement concrete, occasionally fibre reinforced concrete, or bituminous concrete. In this case, the concrete acts as a mechanical protection, without looking for sealing. Its thickness must therefore be determined according to the force of the impacts from which the protection is likely to suffer.

At the bottom of the canal, given the constraints already defined, the thickness of the protection may be reduced in relation to the 15 cm hitherto implemented over the first sections used, without, however, going below 10 cm.

In the upper part of the slope, in the absence of possible impacts from barges, the mechanical strength is less important. The aesthetic appearance, however, must be taken in account for certain sections (coloured concrete, etc.).

In the 3 zones, the insertion of a geotextile between the geomembrane and the concrete is advisable to ensure protection of the geomembrane, particularly against puncturing, during the casting of the concrete.

4.3 *Treated gravel*

This is gravelly, compacted material with the addition of a binder (asphalt, cement). The cohesion brought by the binder makes it possible, in contrast to untreated gravel, to reduce the thickness to be laid and above all to reduce the eventual problems of erosion. A geosynthetic material will be inserted between the geomembrane and the protective layer, essentially to protect against puncturing.

In the lower part of the slope, this solution can be envisaged only with a continuity of the same material laid on the bottom of the canal : on the slope, the thickness, depending on the quality of the material, will be in the order of 20 cm for reasons of implementation and to ensure sufficient protection.

In the upper part of the slope, the resistance of this type of material to erosion, and especially to climatic aggression (freezing and thawing) implies high constraints and requires a material with excellent cohesion. This solution must therefore be used with care, after checking the resistance capacity of the material.

4.4 *Gravel – Riprap*

This encompasses materials without any binder, of various grain size, from gravel with fines, to riprap proper.

Given the low physical constraints on the bottom of the canal, the thickness of the protective layer can there be limited to values in the order of 30 cm, allowing the passage of lightweight machines for the laying of the material. In the absence of problems of stability and erosion, the use of local gravel materials can be envisaged. An anti-puncturing geotextile must be placed between the geomembrane and the gravel, sized according to the materials used. Particular attention must be paid to the proximity of engineering structures (locks and anchorage points) where manoeuvring accentuates erosion from propeller streams. Excessively fine materials are to be avoided in such places (even gravel is to be avoided within the immediate vicinity of locks where they cause problems of stones caught in the lock gates).

In the lower part of the slope, the grain size constraints of the materials are relatively unrelated to problems of erosion. For economic reasons, a gravel material can be used provided that its internal friction angle is sufficient, in relation to the pitch of the slope. Generally speaking, this type of protection is not to be used on slopes over 1/2. A geosynthetic material is to be placed between the geomembrane and the protective layer, mainly to protect against puncturing. Furthermore, it must meet the resistance criteria corresponding to the anchoring force that may be necessary at the top of the slope (see paragraph 6) to ensure the stability of the protection. This second function can also be met by a second geosynthetic material.

Erosion is high in the upper part of the slope. Riprap will therefore be better than gravel. The size of the riprap must meet the criteria defined in the bank protection catalogue (STCPMVN, 1995)]. The stability conditions are the same as those in the lower part of the slope (see paragraph 6). A transition layer of gravel may also prove to be necessary.

4.5 *Suspended elements*

Suspended elements encompass systems generally using geosynthetic materials and requiring anchoring at the top when they are used on the slope (cellular elements, geo-containers, gabions, prefabricated concrete elements, etc). Their purpose, with the exception of gabions and certain prefabricated concrete elements, is to retain the soil, enabling grassing over of the upper part of the slope for better integration into the environment. This type of protection may eventually be used at the foot of the slope but only when it also forms part of the protection of the upper part. The main systems are described below.

In the case of cellular systems, the material is confined in honeycombs, enabling the use of materials with a finer grain size and lower mechanical characteristics. A geosynthetic material is to be placed between the material and the geomembrane, for the same purpose as in the case of riprap and gravel (anti-puncturing and anchoring). It will be fixed to the honeycombs to prevent them from lifting under the effect of currents. The anchoring function can be ensured by a second geotextile. The honeycombs may eventually by closed off by a third geosynthetic material to hold the filling material in place.

The gabions envisaged are flat gabions (with a thickness in the order of 25 cm) with a metal or synthetic casing. An anti-puncturing geotextile will be placed between the geomembrane and the gabions. Anchoring of the gabions at the top of the slope, if necessary, can be provided using the same geosynthetic material or by an independent system.

Geo-containers, in this case, are geo-containers anchored at the top of the slope and filled in situ. Concrete is to be preferred to sand for filling, to prevent the pocket from emptying following a tear resulting from an impact. Sand with a small proportion of cement may eventually be envisaged.

All the suspended elements described above can be envisaged over the entire slope, provided they have a sufficient erosion resistance for use on the upper part, where application of this type of protection is particularly suitable, especially from the aesthetic viewpoint (planting of vegetation on the part out of the water, various forms of paving, etc.). In the top part, resistance to climatic aggressions must be ensured.

Connected elements are prefabricated, generally in concrete, anchored at the top of the slope. The size and weight of the elements must enable erosion resistance. A geotextile will be placed, preferably, between the concrete elements and the geomembrane to provide protection against puncturing.

Generally speaking, suspended elements integrate geosynthetic techniques currently being developed. Their erosion resistance when subjected to wave action needs to be carefully examined.

5 APPROACH FOR THE CHOICE OF A PROTECTIVE STRUCTURE

5.1 *Definition of the main typical cross sections*

Theoretically, the diversity of the protective structures that can be used for each of the 3 zones of the canal offers a large number of solutions. A certain number of those solutions do not, however, appear to be technically and economically optimal, and/or are likely to be suitable only for very particular cases. A limited number of typical protection profiles are therefore proposed, meeting the following criteria:

- limitation to two types of protection over one cross section; whilst the use of 3 different protections for each of the 3 zones of the section could be envisaged, the conditions for implementation in situ would become extremely complex, with a resultant increase in cost;
- limitation of the use of suspended elements to be backfilled with soil and grassed to the upper part of the slope; hese solutions offer an aesthetic interest but are not, generally, justified economically outside of the visible areas;
- concrete and riprap protections can be used at the top of the slope only if they are also installed at the bottom of the slope; the concrete protection requires an abutment at the foot and riprap (thickness > 50 cm) is difficult to install on top of a thin protection of concrete or treated gravel placed at the bottom of the slope.

On the basis of the protection of the canal bottom and of the top of the slope, and of the above criteria, 9 typical profiles meet the criteria summarised in Table 2, in which the solutions are ranked from top to bottom according to the increase in cost.

The maximum value of the slopes is indicated for each of these typical systems where they can be applied, given the necessity, for gravel and riprap protections, of ensuring their internal stability.

Table 2. Typical geomembrane protection types

N°	Bottom	Lower part of the slope	Upper part of the slope	Condition – Value of slope
1	Gravel		Riprap	P < 1/2
2	Gravel		Concrete	
3	Gravel	Gravel/riprap(1)	Grassing (2)	P < 1/2
4	Treated gravel		Riprap	P < 1/2
5	Treated gravel		Concrete	
6	Treated gravel	Treated gravel	Grassing (2)	P < 1/2
7	Concrete		Riprap	P < 1/2
8	Concrete		Concrete	
9	Concrete	Concrete	Grassing (2)	P < 1/2

(1) addition of riprap over the layer of gravel to ensure the internal stability of the material on a steep slope

(2) suspended elements backfilled with soil for grassing of the bank

5.2 *Criteria of choice between the different solutions*

Generally speaking, 2 inputs were chosen to define the GLS, namely the characteristics and constraints of the project at the top of the slope and the bottom of the canal. This choice was dictated by the following reasons :

- the top of the slope is the area of the GLS where the specific constraints of each site are the most variable (possibility of anchoring, landscaping constraints, value of the slope);

– the bottom of the canal represents the largest area and is also subject to extremely variable constraints depending on the site (necessity of maintaining the draft after rehabilitation, manoeuvring areas, locks, quays, etc.);
– protection of the lower part of the slope is determined by knowing the protection of the other two parts of the canal (Table 2).

The criteria of choice are, for the top of the slope, the landscaping constraints, the possibility of anchoring and the pitch of the slope, and for the bottom of the canal the constraints of draft and the proximity of engineering structures (locks, quays, etc.).

The approach for the designer in choosing a geomembrane protective structure can therefore be as follow : (a) step 1 – choice of the cheapest solution technically suitable for the bottom; (b) step 2 – choice of the cheapest solution suitable for the top of the slope; (c) step 3 - selection, from table 2, of the typical profile corresponding to the choices of the 2 previous steps.

6 STABILITY OF THE PROTECTIVE SYSTEM ON THE SLOPE

One of the factors to be taken into account in designing a GLS is the stability of the geomembrane protective structure on the slope. This protection is likely to slip down the slope under the impetus of its own weight if the friction force between the geomembrane and the cover (it's generally the interface with the lowest friction) is insufficient. In such cases, the solution usually adopted is the installation of an abutment at the foot and/or of a reinforcement geotextile anchored to the top of the slope to prevent slippage of the protection.

In such conditions, for sealing systems installed on a slope, the slippage stability of the protection needs to be assessed, by determining in particular the friction forces likely to be mobilised. This approach should make it possible to define a safety coefficient for the stability of the GLS and, if necessary, the anchoring force at the top of the slope. For canals, we propose a sizing approach for the three types of protection retained. The hydraulic conditions specific to canals are taken into account by considering three cases for calculating the stability of the protective structure: canal empty, canal at its normal navigation level (NNL), and a rapid variation in the water level resulting from the wave of passing barges. As far as the latter point is concerned, the worst-case scenario for stability is the phase of a rapid drop in the water level, which can reach an amplitude of 0.5 to 1 m, depending on the width of the canal and on the barge size.

We have presented below the main elements of the methods adopted for protections in concrete and in gravel/riprap, together with examples of the results obtained. In particular, the hypotheses adopted to take account of rapid variations in the water level are given. The same methodology can be applied to calculate the anchoring forces at the top of the slope of the suspended elements.

The notations of the characteristic orders of magnitude of the canals, as used in the calculations, are given in figures 3 and 4, namely :

– β : angle of the slope to the horizontal
– e : thickness of the geomembrane protective layer,
– $h_1 + h_2$: water height at the normal navigation level
– h_2 : maximum drop following a passing barge,
– h_3 : freeboard
– $h = h_1 + h_2 + h_3$: total height of the slope.

6.1 *Protections by concrete slabs*

These generally involve concrete cast in situ directly on the geomembrane or with the insertion of a geotextile. In this case, the main objective is to define the force exerted by the protection of the slope on that of the bottom of the canal and in particular to ensure there is no slippage of the foot inwards.

6.1.1 *Canal empty*

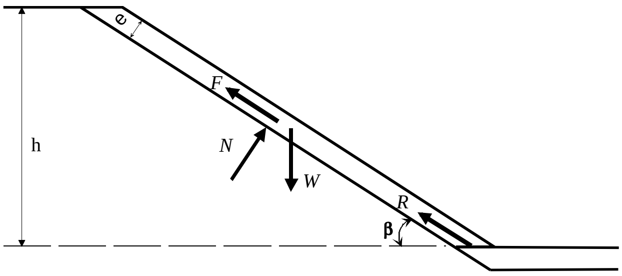

Figure 3. Stability of a concrete slab – forces involved when the canal is empty.

Figure 3 shows the forces involved when the canal is empty. These are distributed between a driving force which tends to cause slippage of the concrete slab (component parallel to the slope of the weight : $W\sin\beta$) and a stabilising force F corresponding to the mobilisation of friction at the interface between the geomembrane and the concrete slab or geotextile, to which the force R of the foot abutment is eventually added. These forces are defined by the following relations :

$W.\sin\beta = h.e.\gamma_b$ where γ_b is the unit weight of the concrete

$N = W.\cos\beta$ is the normal contact force at the interface

$F=N.\tan\delta$ where δ is the angle of friction at the geomembrane/concrete interface (zero cohesion is presumed at the interface).

Slippage stability is given by the relation:

$R + F = W.\sin\beta$

The following expression of R can be deduced:

$R = h.e.\ \gamma_b.(1\text{-}\cot\text{an}\beta.\tan\delta)$

This expression shows a balance without any abutment being required ($R<0$) when $\beta<\delta$, and otherwise, when the value of the slope is higher than the angle of friction, makes it possible to define the strength of the abutment required, broken down between a vertical force $R\sin\beta$ and a horizontal force $R\cos\beta$ giving the risk of slippage from the foot of the slabs into the canal.

6.1.2 *Canal at its normal level*

When the canal is full, to its NNL, the same type of relation is obtained by taking the submerged weight of the concrete below the NNL. In these conditions, a check is made that the force R is systematically lower than that obtained in the previous case, with the canal empty.

6.1.3 *Drop in water level with a passing barge*

The rapid drop in water level with a passing barge can have a negative effect on the stability of the concrete slab, as a result of the imbalance of the hydrostatic forces on each side of the slab (fig.4).

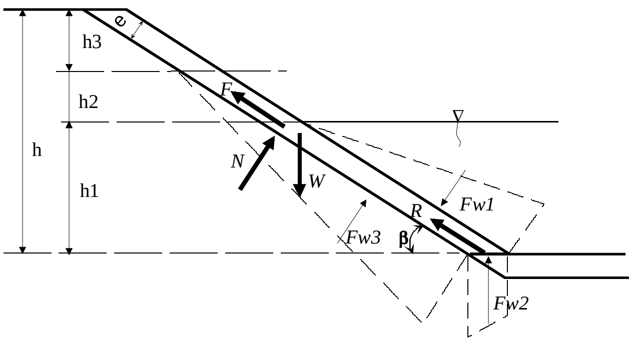

Figure 4. Stability of a concrete slab– forces involved with a passing barge

As the purpose of the concrete protection is not to ensure sealing, it can be considered, when the canal is at its NNL, that the hydrostatic pressure is identical on both sides of the concrete. On the other hand, following a rapid drop in the water level, the pressure of the water above the concrete decreases immediately, whereas the hydrostatic pressure from underneath can be considered as stable over the short period of the drop in water level (the time of the wave) given the low permeability of the layer of concrete. The result of this action is to decrease the contact force, N, and consequently the force of friction between the slabs and the geomembrane.

In these conditions, the friction force becomes :

$F = N.\tan\delta$ where $N = W.\cos\beta - (Fw3-Fw1) - Fw2.\cos\beta$

where Fw1, Fw2, Fw3 are hydrostatic forces shown in figure 4.

The calculation, not repeated here, is then the same as in the case of the empty canal, taking the new value of N. In the case of the classic dimensions of French canals, it can be seen that the theoretical value of N is negative, which corresponds physically to the fact that the water pressure counterbalances the weight of the concrete slab, thus in fact giving N=0, i.e. the total cancellation of the friction along the slope.

In these conditions, the value of the abutment at the bottom of the slope is expressed simply by the relation:

$R = e.(h.\gamma_b - h_1.\gamma_w)$

where e is the thickness of the slab and γ_b and γ_w are the unit weights of the concrete and of the water respectively.

As an example, this approach, applied to an average sized canal (slope 4 m high with a slope of 1/2) gives the following results per linear meter of the canal:

R = 5.5 kN when the canal is empty,

R = 15.5 kN, a value three times greater, with the passing of a barge creating a drop 0.75 m high.

To define the connection between the slab of the slope and the slab of the bottom, the designer must therefore take into account a force $R.\cos\beta$ of 13.9 kN likely to cause the slippage of the concrete slab into the canal.

6.2 *Protections in soil, gravel and riprap*

The classic approach for the stability to failure of this type of protection is based on dividing the protective layer into two blocks. Such methods are proposed in particular by Soong and Koerner (1996) and by Giroud (1995). The block forming the abutment at the foot of the slope is called the passive block (BCD in figure 5) whereas the block forming the protective layer on the slope is called the active block (ABDE in figure 5). The stabilising force consists of the friction forces along the geomembrane at the base of the active and passive blocks, to which can be added if necessary an anchoring force at the top of the slope. The driving force of the potential slippage is the weight of the protective layer (by its component $W_a.\sin\beta$ parallel to the slope).

We shall not revert here to the detail of the calculations in the case of an empty canal and therefore in the absence of water in the geomembrane protective materials. Such calculations can be performed in accordance with the relations proposed by Koerner (1996) with the blocks method. As in the case of the concrete protection described earlier, the situation with the canal at its NNL is more favourable for the stability of the protective layer, part of the weight of which is then submerged. Furthermore, we have not considered the case of an empty canal and of a saturated protective layer, since such a situation is highly unlikely, given the slow speed of emptying a canal compared to the permeability of the materials generally used for the protective layer.

6.2.1 *Calculation of stability with a passing barge*

On the basis of the blocks method, we have tried to define a method for calculating the stability of the protective layer, taking account of the rapid drop in water level with a passing barge. This type of occasional hydraulic condition is not addressed by the authors quoted above.

The passage of a barge causes a very rapid drop in the water level in the canal within the immediate vicinity of the protection. The rapidity of the phenomenon leads us to estimate, conservatively, that the upper part of the protection remains saturated, especially if the materials used are semi-permeable or more or less clogged by deposited fines. In such conditions, the hydraulic conditions are as follows :

- the height of the water in the canal is h_1 ;
- the height of the water table in the protective layer remains at the normal navigation level, namely $h_1 + h_2$;
- in that part of the protection, of height h_2, which is saturated but out of the water during the brief drop in level, the flow can be presumed to be horizontal (the equipotentials are therefore vertical, and the worst case scenario can therefore be envisaged).

On the basis of these hypotheses, the result of the forces involved on the active block is defined in figure 5 ; on the passive block, the conditions are identical to the case of the empty canal by taking the submerged weight of the material of the block. Furthermore, note will be taken of FSa ($Fa=N.\tan\delta/FSa$) and FSb, the respective safety coefficients for slippage of the active and passive blocks.

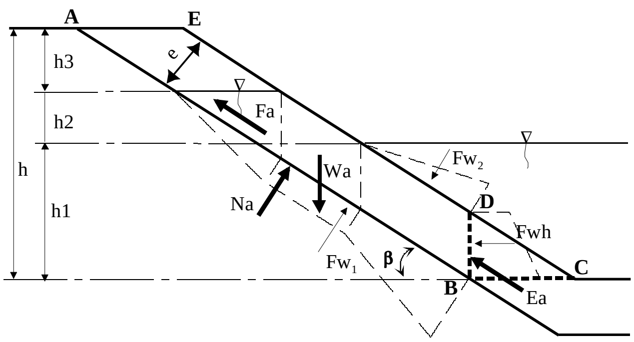

Figure 5 : Stability of a layer in gravel/riprap – forces involved on the active block during the drop in water level

The hydraulic forces on this block are :

$Fwh=e\ \gamma_w\ [h1-e/(2\cos\beta)] / \cos\beta$
$Fw1=\gamma_w\ (h_1^2\cos\beta+2h_2e)/\sin2\beta$
$Fw2=\gamma_w\ (h1-e/ \cos\beta)^2/(2\sin\beta)$

Ea represents the force exerted by the passive block on the active block and vice versa for E_p ; overall equilibrium requires the equality of Ea=Ep which enables us, by taking $FS_a=FS_p=FS$, to define, by following the same approach as in the case of the empty canal, the overall safety coefficient FS as the solution to an equation of the second degree.

If the safety coefficient FS obtained by the previous calculation is insufficient, anchoring of the protective layer at the top of the slope is necessary. The effort to be absorbed to obtain a safety coefficient FS is called T. The value of T is determined by adding T to the result of the forces of the active block. This gives:

$T=W_a\sin\beta-F_{wh}\cos\beta-N_a\tan\delta/FS-W'_p\tan\varphi/(FS\cos\beta- \sin\beta\ \tan\varphi)$

where φ is the internal friction angle of the protection material.

6.2.2 *Example of application*

The application of the calculation methods presented above to a medium sized canal (slope 4 m high and β=26.6°) sealed by a geomembrane protected by a layer of gravelly materials 50 cm thick (internal friction φ=30°) gives the following results for an angle of friction δ=25° between the geomembrane and its protective layer :

a – in the case of an empty canal FS=1.12 without anchoring at the top of the slope ; an anchoring force of 5.6 kN/ml is required to reach FS=1.3

b – in the case of a rapid drop of 0.75 m in the water level, FS=0.95 without anchoring at the top of the slope ; an anchoring force of 9 kN/ml is required to reach FS=1.3

This example evidences the importance of the hydraulic phenomena specific to navigable canals for the stability of their protective structures. The stability of a protection in gravelly materials can in fact be ensured when the canal is empty or at its normal navigation level, and there is instability with passing barges causing a rapid drop in the water level.

Furthermore, it should be recalled that the safety coefficients mentioned above concern only the calculation of the anchoring force that may prove necessary. The geosynthetic material used to absorb the stress as calculated must be defined in a second stage with its own safety coefficient, taking account of its mechanical characteristics (stiffness, tensile strength, nature of the polymer). Consequently, the forces as calculated must not be assimilated to the maximum tensile strength of the geotextile used.

7 CONCLUSION

The present study is based on the experience acquired over the last ten years along 7 rehabilitated sections of a GLS and on an analysis of the various geomembrane protective structures that can be envisaged. It puts forward an approach for the choice of the protective structure according to technical and economic criteria specific to navigable canals.

A method for calculating the stability of the protective structure on the slope has been elaborated. It takes account of the three major types of protection proposed (concrete slabs, gravel and riprap, suspended elements) and examines different hydraulic configurations (canal empty, canal at its NNL, waves from passing barges). The results, applied to the usual sizes of French canals, evidence that the drop in water level with the passing of a barge is in many cases the worst-case scenario for the stability of the protection.

Experimentation in situ is planned to validate the hypotheses and the parameters of the calculations proposed. It would consist of implementing three experimental plots on a canal bank, fitted with instruments and subjected to the hydraulic configurations studied.

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