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USE OF ASPHALT FOR SLOPE PROTECTION ON EARTH AND ROCKFILL DAMS (*)

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1. INTRODUCTION

In dam construction the use of asphalt as a waterproofing agent can be considered as classical, be it for the construction of an upstream carpet, or of an internal core. In both cases excellent behaviour with respect to impermeability and flexibility are responsible for this qualification.

For slope protection purposes flexibility is also of advantage but impermeability can be a drawback under circumstances.

In the last decades in Holland much experience has been achieved in the use of asphalt for slope protection purposes. Even permeable and yet durable mixtures have been developed. It seems that the Dutch experience in asphalt slope protection works could also be introduced in the construction of high dams and reservoirs.

In the following several techniques are discussed which could be useful in this field :

— it is obvious that in case the impervious element is formed by an upstream asphaltic carpet, this carpet can also serve as a means for slope protection, which is its main purpose on the Dutch Deltadams. The stresses in these dike revetments under wave attack have been studied by the Royal Shell Laboratory but will not be discussed in this paper;

(*) *Utilisation d'asphalte pour la protection de talus de barrages en terre et en enrochements.*

— in general wave attack on slopes of dams and reservoirs is limited, but in some cases sea defense works are incorporated in high dam projects. A good example is the High Island Water Scheme at Hong Kong, which includes the construction of two 100 m high dams, connecting High Island to the mainland, thus forming a drinking water supply reservoir. One of the four cofferdams enabling construction in the dry of the main dams, is directly exposed to wave attack from the Chinese Sea, requiring a full size sea defense.

The Dutch experience in the field of asphalt penetrated rubble constructions in sea defense works could be of use in these and similar instances.

If the impervious element is formed by an internal membrane or core, some type of additional slope protection is required. Generally this type of lining can well be compared with those required for lining of lakes, rivers and canals. Filter constructions are preferred, in order to avoid uplift pressures. Permeable asphaltic constructions have been introduced in the Netherlands and abroad and will be discussed in this paper.

2. COMBINATION OF IMPERVIOUS ELEMENT AND SLOPE PROTECTION

If the impervious element is formed by an upstream membrane, it should also serve as a slope protection. A well known example is asphalt concrete, be it in one layer or in two layers with a control drainage layer between. Rather elaborate and sophisticated equipment is necessary for placing in situ, which for small projects could lead to relative high unit prices. In those cases the use of prefabricated reinforced sandmastic slabs could be considered. These slabs, some 3 cm thick and 1 m wide, reinforced with galvanised steel mesh, can be rolled on a drum in a relatively simple manufacturing yard, transported to the site, and while unrolling be welded together to form a 6 cm thick impervious lining.

In both cases the behaviour of this lining under wave attack depends on the strength and stiffness modulus of the membrane and the subsoil.

In Holland asphalt concrete has been widely used as a means for slope protection of dikes. The stresses in these asphalt concrete revetments under wave attack have been studied by the Royal/Shell Laboratory, using the so-called Bistro-computer programme developed for stress-analysis of multi-layer systems under road traffic loads. Further information should be obtained from the Laboratory.

3. HEAVY DUTY SLOPE PROTECTION

Since long sandmastic asphalt has been used for penetration of riprap in order to stabilize this material against current and wave action. Early examples are the groynes along the North Sea coast of Holland. These groynes used to require considerable maintenance, which after stabilisation with sandmastic asphalt was almost reduced to nil.

The stabilisation was done by pouring hot sandmastic asphalt between the stones, thus keeping the stones in a fixed position.

Due to its visco-elastic behaviour, sand mastic asphalt behaves like a solid mass with high elasticity modulus (up to 10^{12} N/m^2) under short loading times such as wave attack, while as a fluid of very high viscosity under prolonged loading times, thus being able to follow subsoil settlements.

Penetration of rip-rap with sand mastic asphalt has been adopted as standard construction method for protection of the toe of seadikes, by several Government Services in the Netherlands, for instance by the Delta Service. See Figure 1 in which a standard Dutch Deltadam is shown in cross section.

An asphalt penetrated rubble revetment can never be guaranteed as to be 100 % impermeable, for perfect adhesion of the sandmastic to the occasionally moist stones cannot be guaranteed. Nevertheless for design purposes it is recommended to take the consequences of complete impermeability into account.

Uplift pressures under penetrated rubble on earthfill dam.

If the subsoil consists of earthfill and is saturated with water, changes of waterlevel are followed retardedly, because of the low permeability of the subsoil. The accompanying uplift pressures can become dangerous in the case that the changes of waterlevel are slow, for only then sufficient diplacement of water and subsequent deformation of the revetment can take place to cause rupture of the construction.

Modern Dutch dikes mainly are constructed of hydraulic fill, which in most cases consists of fine sand of low permeability; generally they are protected by impervious asphaltic revetments. For the calculation of the uplift pressures resulting from tidal movement, an electrical analogon is used, which is based on the analogy of Ohm's and Darcy's laws for electrical current and laminar groundwater flow respectively.

Uplift pressures under penetrated rubble on rockfill dam.

The permeability of a rockfill subsoil is such that generally slow changes of waterlevel like tidal waves are easily followed, which means that tidally induced uplift pressures are not to be expected. However, short wave induced uplift pressures take their place. Rapid changes of waterlevel like sea and swell are followed retardedly in the rockfill subsoil and their period could in extreme cases even be shifted 180°.

If the permeability is too high the groundwaterflow in the subsoil is no longer laminar so Darcy's law, expressing proportionality between velocity and difference of head, is no longer valid. This means that an

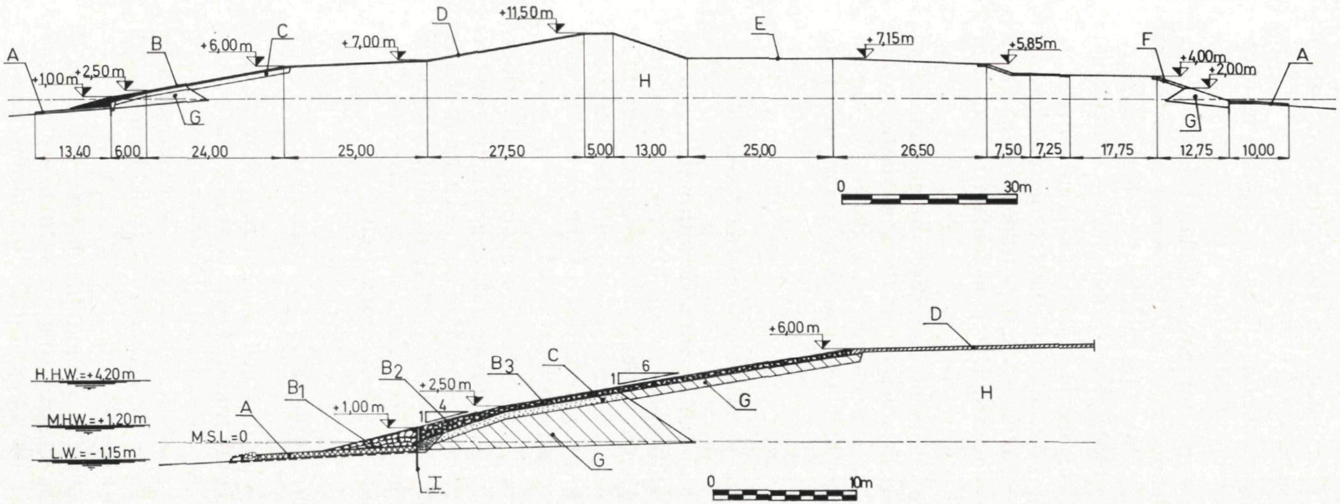

Fig. 1

Typical section-easter scheldt closure-dam.

(A) Fascine mattress.
(B_1) Stone 10/300 kg penetrated with asphalt grout.
(B_2) Stone 10/60 kg penetrated with sand mastic grout, thickness 0,35-1 m.
(B_3) Stone 10/60 kg penetrated with sand mastic grout, thickness 0,35 m.
(C) Sandasphalt, thick 0,5 m.
(D) Asphalt concrete, thick 0,2 m.
(E) Grass on clay.
(F) Concrete blocks.
(G) Mine waste.
(H) Hydraulic fill.
(I) Concrete sheetpiling.

Coupe typique de la digue de fermeture de l'Oosterschelde.

(A) Tapis de défense en fascinages.
(B_1) Enrochements 10/300 kg pénétrés de mastic asphaltique.
(B_2) Enrochements 10/60 kg pénétrés de mastic asphaltique épaisseur 0,35-1 m.
(B_3) Enrochements 10/60 kg pénétrés de mastic asphaltique épaisseur 0,35 m.
(C) Sable bitumineux, épaisseur 0,5 m.
(D) Béton bitumineux, épaisseur 0,2 m.
(E) Argile gazonnée.
(F) Blocs en béton.
(G) Tous venant des mines.
(H) Remblayage hydraulique.
(I) Palplanches en béton.

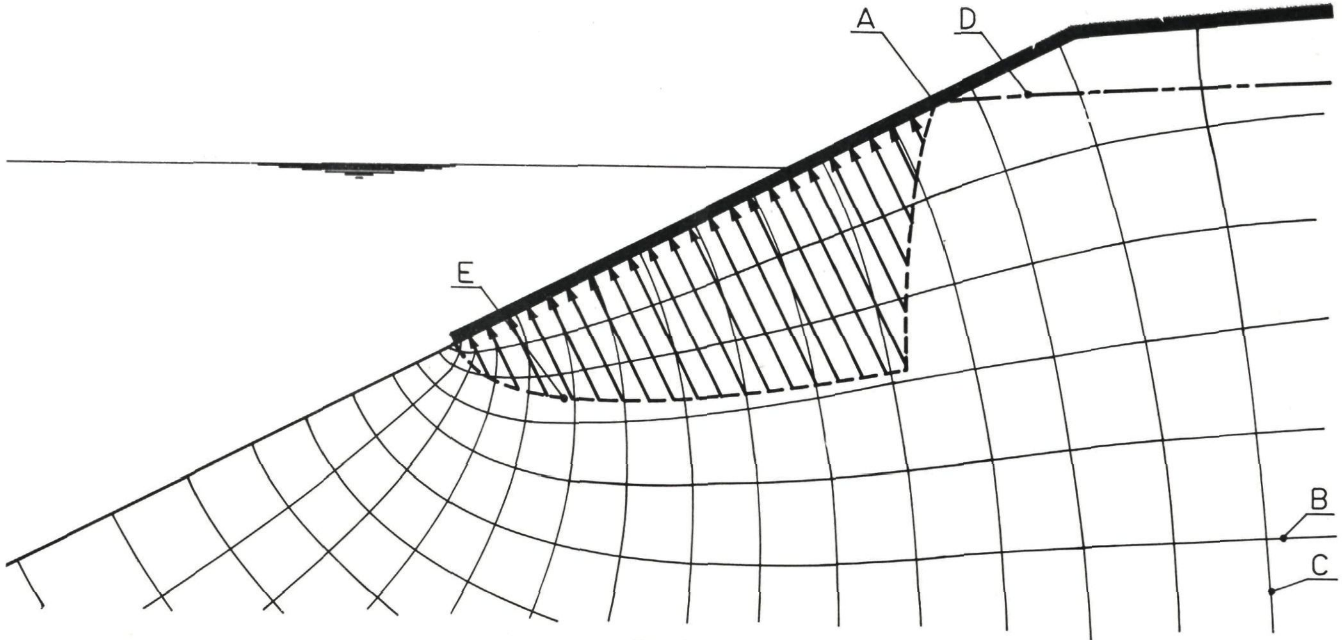

Fig. 2

Groundwaterflow under impervious revetment.

(A) Impervious revetment.
(B) Flowline.
(C) Equipotential line.
(D) Phreatic surface.
(E) Uplift water pressure distribution.

Circulation souterraine d'eau sous revêtement imperméable.

(A) Revêtement imperméable.
(B) Ligne de courant.
(C) Courbe équipotentielle.
(D) Surface phréatique.
(E) Distribution du pression de l'eau au-dessous du revêtement imperméable.

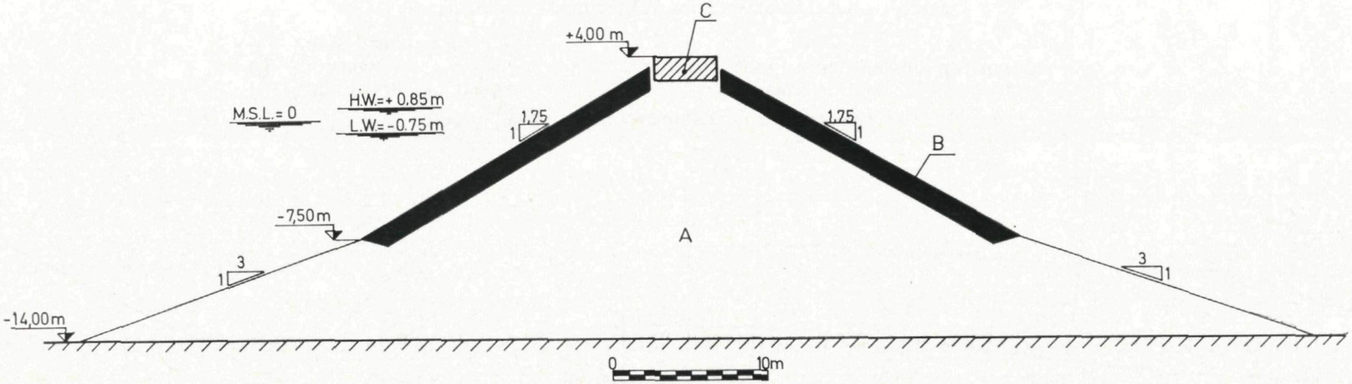

Fig. 3

IJmuiden breakwater section as studied in hydraulic model.

(A) Bund of rock 300-1000 kg.
(B) 2,25 m thick solid stone asphalt armour.
(C) Cement concrete coping.

Section du môle d'IJmuiden étudié en modèle réduit hydraulique.

(*A*) *Levée en enrochements 300-1000 kg.*
(*B*) *Couche d'enrochements remplie d'asphalte ; épaisseur 2,25 m.*
(*C*) *Tête en béton.*

electrical analogon no longer can be used and a hydraulic model should be utilised instead. An example of a breakwater section which has been studied in a hydraulic model is given in Figure 3.

It represents the IJmuiden breakwater, in which the impervious armour protects an extremely permeable bund of rock 300 to 1000 kg, which was chosen because of its stability during construction in the rough North Sea. As a consequence however fairly easy penetration of wave action in the bund was made possible, leading to high uplift pressures under the revetment. It illustrates the desirability of a bund consisting of material of low permeability if the armour is impervious.

RESISTANCE OF PENETRATED RUBBLE REVETMENT AGAINST WAVE ATTACK.

The mechanical properties of asphalt, strength, visco-elastic behaviour, etc., are so complicated that scaling down of these properties, in order to investigate problems like resistance against wave attack in hydraulic models, is hazardous. Full scale tests remain indispensable, which of course holds not only for asphaltic constructions.

A good example is the at the time promising newly developed method of pattern grouting, a method of partial penetration of a rubble mound armour by stone asphalt with the purpose of achieving an open construction (Ref. 1). Hydraulic model tests indicated that the apparent weight of the armour stone could be " upgraded " at least 5 times as stability under wave attack is concerned. A full scale test section was constructed at the head of the Separating Jetty in the Harbour Entrance of Europoort Rotterdam (Fig. 4).

The typical section is given in Figure 5.

According to the well known Hudson formula the 1 to 3 tons stone " upgraded " to 5 to 15 tons armourstone, would resist waves up to :

$$H = \sqrt{\frac{k\ D \cdot \Delta \cdot \cot \alpha \cdot W}{\gamma}} = 5{,}35\ \text{m}.$$

Now during a storm, waves with a significant wave height of the same order of magnitude, hit the head of the Separating Jetty, destroying the armour as indicated in Figure 6. The astonishing fact however was that the underlying sandasphalt bund was only slightly damaged.

Careful inspection of the remnants revealed that the asphalt patches were broken apart completely, including the stones in the mixture. The same damage configuration was found as formerly in the IJmuiden breakwaters after summer storms. In IJmuiden these damages had been brought about when preceding high temperatures had accelerated the consolidation process of the stone asphalt armour, during which process cracks would occur. These cracks initiated further damage during following summer-storms.

Fig. 4

Foto general view separating jetty Hook of Holland.

Vue générale de la digue séparant l'écoulement à Hoek Van holland.

Contrary to the stone asphalt armour, which premixed product needs a consolidation period of several years before the stones in the mixture form a skeleton, a penetrated rubble revetment already has formed its internal skeleton before asphalt is even brought in. Thus cracks due to consolidation cannot occur. In the pattern grouting system however, cavities had been formed delibirately, to produce an open armour.

The German investigator Führböter (Ref. 2) found that inside water filled cavities on slopes like joints, cracks, etc., so called plunging breakers could cause high pressure shocks, to be compared with waterhammer, producing a blasting effect. These waterpressures are proportional to the

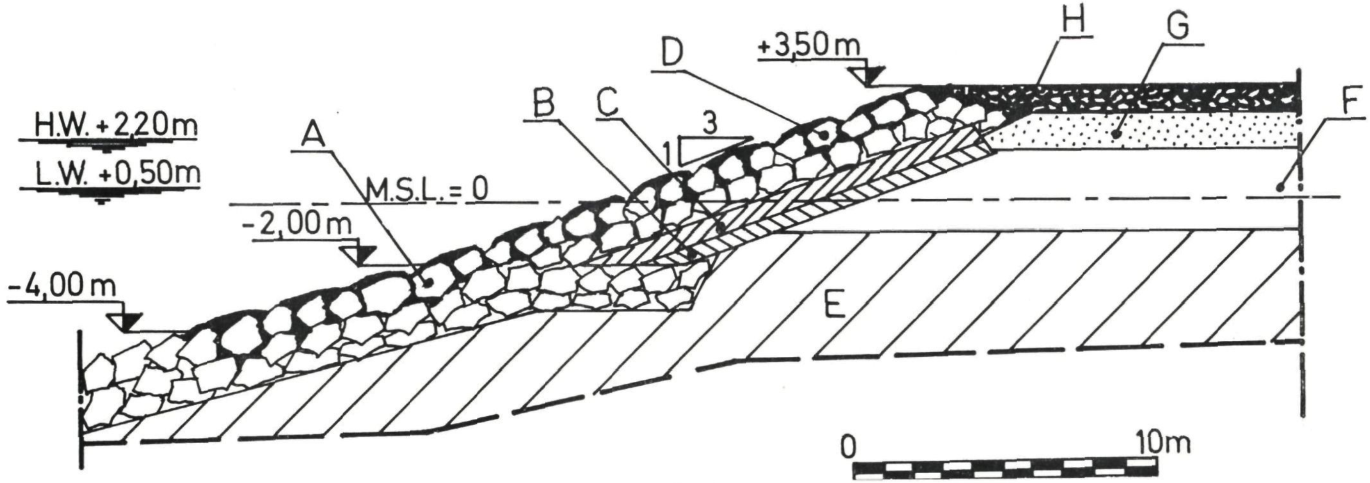

Fig. 5

Trial section pattern grouting breakwater armour Hook of Holland.

(A) Stone 1-6 ton, pattern grouted with stone asphalt.
(B) Masticgravel, 0,5 m thick.
(C) Stone 200-800 kg, 0,7 m thick.
(D) Stone 1-3 ton, pattern grouted with stone asphalt, 1,75 m thick.
(E) Base construction of waste material from cleared away bund.
(F) Sandasphalt bund, mixed with hot gravel.
(G) Sandasphalt.
(H) Stone 10-60 kg, penetrated with asphalt grout.

Section expérimentale d'injections à pénétration partielle d'enrochements à Hoek van Holland.

(A) Enrochements 1-6 t à pénétration partielle de béton bitumineux.
(B) Gravier à mastic asphaltique, épaisseur 0,5 m.
(C) Enrochements 200-800 kg, épaisseur 0,7 m.
(D) Enrochements 1-3 t, à pénétration partielle de béton bitumineux, épaisseur 1,75 m.
(E) Construction de base, composée de matériel de l'ancien môle.
(F) Digue en sable bitumineux, mélangé de gravier chaud.
(G) Sable bitumineux.
(H) Enrochements 10-60 kg, pénétrés d'asphalte.

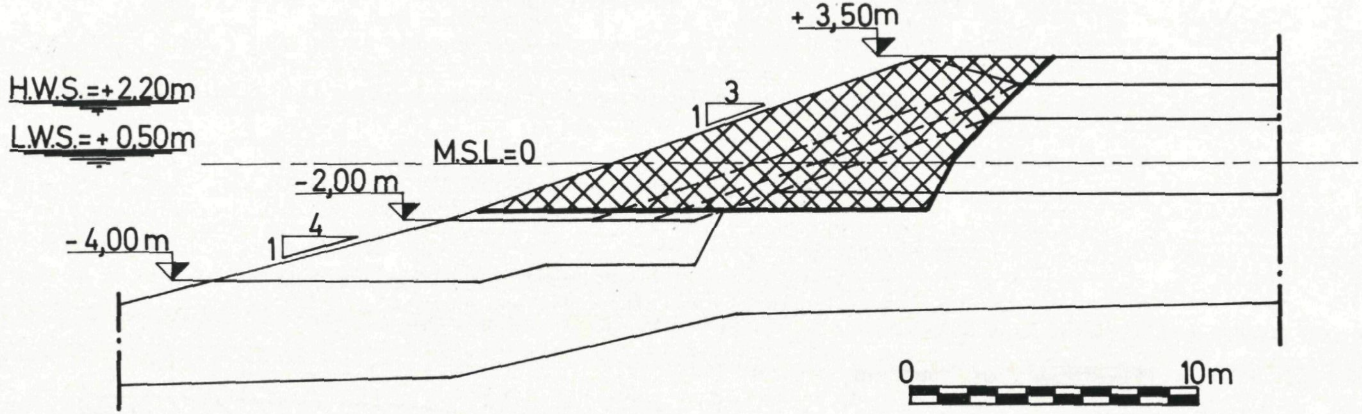

Fig. 6

Damaged trial section separating Jetty Hook of Holland.

H. W. S. and L. W. S. : High water and low water at storm of 19-21 november 1971, during which damage occurred.
Significant wave height estimated at $H_s = 5{,}25$ m.

Section expérimentale endommagée de la digue séparant l'écoulement à Hoek Van Holland.

H. W. S. en L. W. S. : eau haute et eau basse de la tempête du 19-21 novembre 1971, causant les dégâts.
Hauteur de vague significative, estimée à $H_s = 5.25$ m.

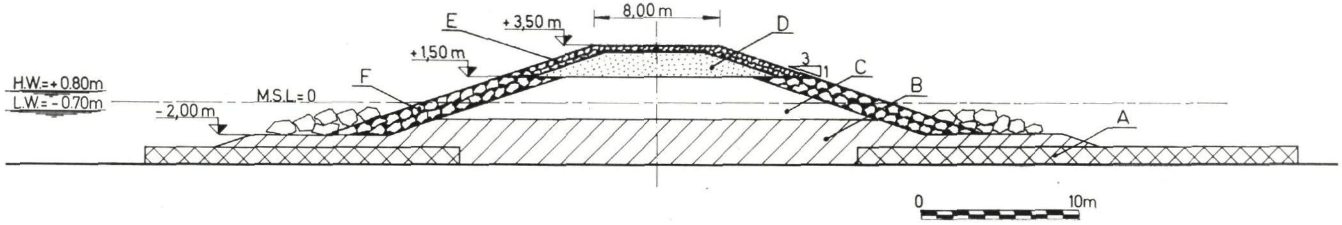

Fig. 7

Typical section separating jetty Hook of Holland.

(A) Fascine mattresses.
(B) Base construction consisting of re-used rubble from ancient bunds cleared away.
(C) Bund of sandasphalt, mixed with hot gravel to prevent deep penetration in subconstruction.
(D) Sandasphalt.
(E) 0,60 m stone 10-60 kg penetrated with sandmastic grout.
(F) 1,20 m stone 600-1,000 kg penetrated with stone asphalt grout.

Coupe typique de la digue séparant l'écoulement à Hoek van Holland.

(*A*) *Tapis de défense en fascinages.*
(*B*) *Construction de base composée de maçonnerie et enrochements de l'ancien môle.*
(*C*) *Digue en sable bitumineux, mélangé de gravier chaud, empêchant la pénétration dans la construction de base.*
(*D*) *Sable bitumineux.*
(*E*) *Enrochements 10-60 kg pénétrés de mastic asphaltique épaisseur 0,60 m.*
(*F*) *Enrochements 600-1 000 kg pénétrés de béton bitumineux, épaisseur 1,20 m.*

wave height. They occur just under the still waterlevel, and are little depending on the slope angle, though at gentle slopes, less than 1 : 6, a water cushion is formed on the slope by retreating water, by which the pressures are greatly reduced.

This phenomenon is responsible for both the damage at the Ijmuiden breakwaters and at the experimental section on the head of the Separating Jetty at Hook of Holland. It explains also that the sand asphalt bund, though of limited strength, showed only little damage, for there were little cracks to produce the blasting effect.

The conclusion is that for heavy wave attack around the still water level a closed surface is essential. A fully penetrated rubble revetment in this area is therefore recommended and measures should be taken that no cracks or even potential cracks are likely to occur.

Among other things this means that the slope should not be too steep, 1 : 2,5 could be considered to be the limit, and the mixture should be composed in such a way that optimum flexability is combined with the necessary minimum stability on the slope.

In this way very strong revetments can be designed and constructed as has been proved by the North Sea Groynes at the Dutch Coast, the Deltadams, etc. One of the most recent designs being the already mentioned Separating Jetty at Europoort, of which the typical cross section is given in Figure 7.

4. PERMEABLE ASPHALT REVETMENTS

Slope protection of earthfill dams can well be compared with slope protection of banks of rivers and canals. When uplift water pressures under the revetment should be avoided filter constructions should be used meeting the following requirements :

— stability under the action of waves and currents;
— prevent the washing out of fines in the subsoil.

The washing out of fines from outside is caused by pressure fluctuations resulting from wave or current action, penetrating into the subsoil and putting the fines into suspension. It can be stopped by either preventing the suspended fines to drop out or by decreasing the pressure fluctuations to such an extent that the fines do not come into suspension at all.

The last method is to be preferred, for the first method would imply the use of a very fine meshed cloth, which easily will clog up from inside, thus losing its permeability.

If some sort of textile fabric is used the best results are obtained with " three-dimensional " fabrics, having a certain thickness and rigidity which have a damping effect on the pressure fluctuations. Of course a sandasphalt layer is an ideal filterlayer in this respect because of its thickness and pore structure providing maximum damping of pressure fluctuations without the building up of uplift pressures.

Local loss of stability under the revetment can be caused by groundwaterflow emerging from the bank. If the subsoil is saturated with water and the waterlevel outside the bank sinks, the phreatic line in the bank will touch the slope above the waterlevel and coincide with the slope down to the waterlevel outside. Thus in this " wet " region between the tangential point and the outside waterlevel the flowlines emerge essentially in a horizontal direction whilst the equipotentials are vertical. This only holds for the upper layers of the slope, where the emerging groundwaterflow runs down the slope under a free watertable of an inclination equal to the inclination of the slope.

For the local stability of the slope in this region, consider a slip path parallel to the slope at a depth d_s which is small compared with the length of the slip path (Fig. 8).

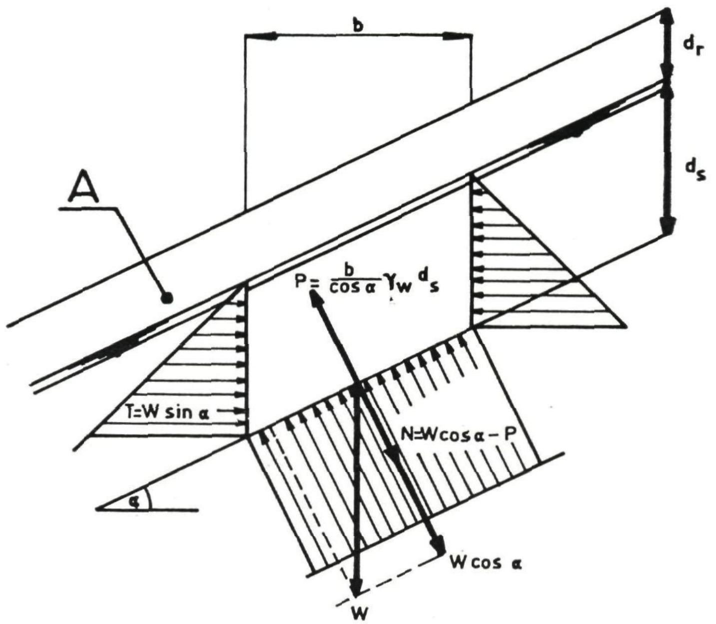

Fig. 8

Local slope stability : emerging groundwaterflow.

(A) Permeable revetment.

Stabilité locale du talus : circulation souterraine d'eau, sortant du talus.

(A) Revêtement perméable.

The equipotentiallines being vertical, the waterpessure varies hydrostatically with the depth under the slope, so the force P normal to the slip path of the length $\frac{b}{\cos \alpha}$ due to waterpressure can be written :

$$P = \frac{b}{\cos \alpha} \cdot \gamma_w \cdot d_s;$$

which can be considered as the resultant force of the vertically directed water-displacement :

$$b \cdot \gamma_w \cdot d_s,$$

and the horizontally directed " seepage force " :

$$b \cdot \gamma_w \cdot d_s \cdot \tan \alpha.$$

Now for the plane considered it can be written :

shearforce $= T = b \sin \alpha \, (d_s \, \gamma_s + d_r \, \gamma_r)$,

normal force $= N = b \cos \alpha \, (d_s \, \gamma_s + d_r \, \gamma_r) - \frac{b}{\cos \alpha} \, d_s \, \gamma_w$.

From these expressions for any depth of the slip path d_s and for any surface weight $d_r \, \gamma_r$ the required normal and shearforces can be calculated and represented in a diagram (Fig. 9).

It appears that the influence of d_s is given in a system of straight lines parallel to $T = N \tan \alpha$, whereas the influence of surface weight is given by a system of straight lines parallel to $T = N \tan 2 \alpha$.

By comparing this with the enveloping line of the circles of stress :

$$T = C + N \tan \varphi,$$

the stability in the planes under consideration can be judged.

It can be concluded that :

— in loose sand (no cohesion) and without surface weight the slope angle α should not exceed half the angle of internal friction φ;

— surface weight can force the critical slippath down;

— cohesive soil will permit steeper slopes but surface weight should be kept to a minimum if $\alpha > \varphi$.

This means that steep slopes in loose sand can either be protected by heavy surface weight, or by adding cohesion to the upper layers. The last is done by using sandasphalt as a filter layer.

The upper layer of the filterconstruction should be strong enough to withstand the action of waves and currents. Permeable asphalt mixtures generally are falling off in quality if directly exposed to atmospheric condi-

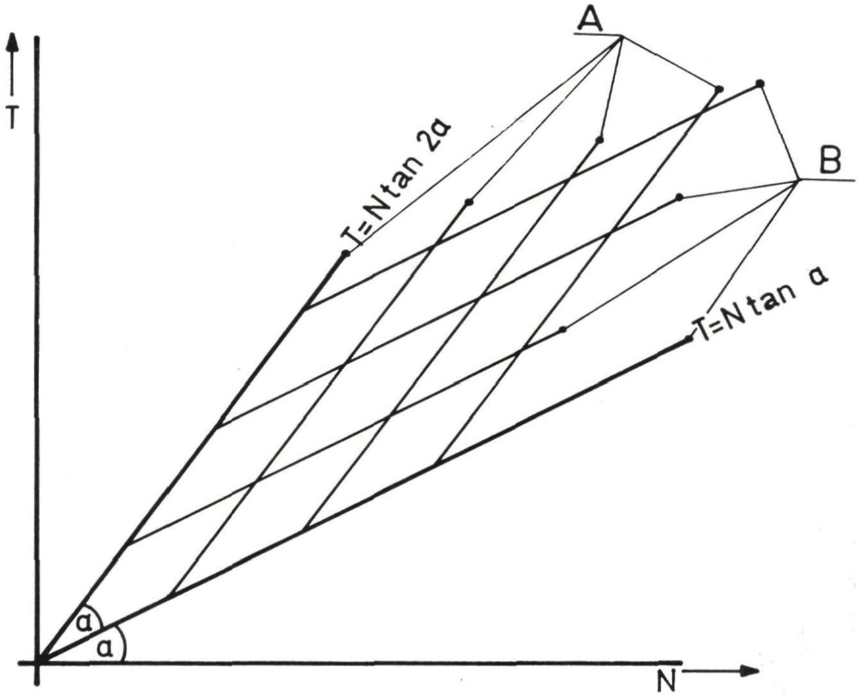

Fig. 9

Relation between normal and tangential stresses in slippath parallel to slope.

(A) Lines of equal surface weight.
(B) Lines of equal depth of slippath.

Relation entre les tensions normales et tangentielles dans lignes de glissement parallèle au talus.

(A) Lignes de poids égales.
(B) Lignes de glissement de profondeurs égales.

tions. In Holland however permeable asphalt mixtures have been developed which are durable, based on a double mixing procedure in which stones of for example 4 to 6 cm diameter are heated and mixed with premixed sandmastic mortar. In this way the stone is coated with sandmastic in a thickness of the order of 1 mm instead of pure bitumen with a layer thickness to be expressed in microns.

This product, called " Mastic-mac " has been investigated with great success on several trial sections :

— on the River IJssel as prefab bankprotection in mattresses of 8×20 m², 0,1 m thick (Fig. 10);

— on the Rhine-Main-Danube Canal in Germany, brought in situ 0,18 m thick on a 0,12 m sandasphalt filter layer (Ref. 3) (Fig. 11);

— on the Harbour side of the Separating Jetty at Hook of Holland 0,5 m thick on a sandasphalt bund (Fig. 12).

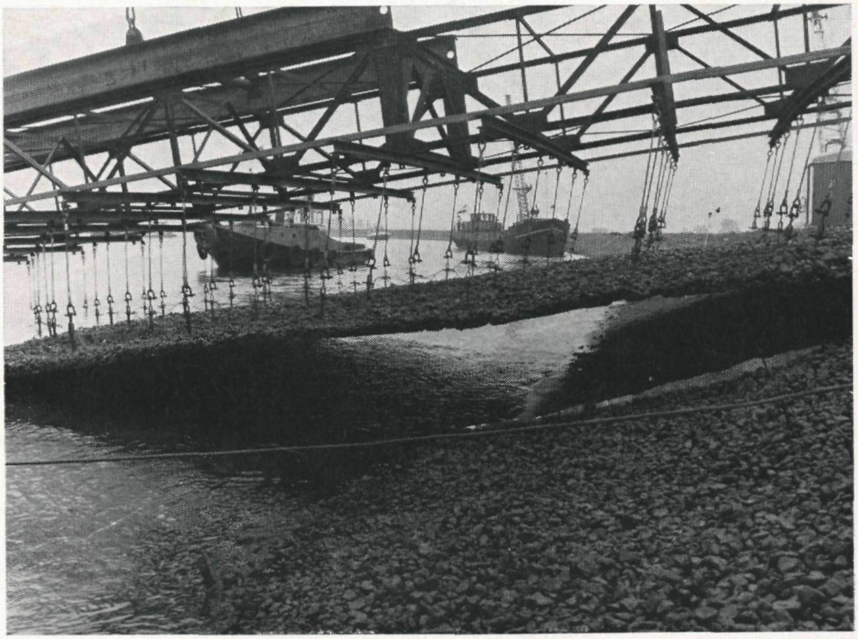

Fig. 10

Placing of prefab masticmac mattress on bank of river Ijssel.

Placement d'un tapis mastic-mac préfabriqué sur le bord du fleuve Ijssel.

In the German tests an 800 HP screw jet of a freighter was directed immediately on the slope but could not cause any damage whatsoever.

The Dutch Government Delta Service is very much interested in the product for eventual use as a seabed protection. In a high discharge flume a prefab mattress was investigated, consisting of 0,12 m mastic-mac put on a polypropylene filter-fabric (0,75 kg/m²), protecting a bed of fine seasand (d_{50}-100 μ).

Velocities up to 7 m/s could not produce any damage, no loss of bed material was found.

Successfull tests have been performed to bring a 6 $\times$ 50 m² mattress in position on the seabed in 10 m and 20 m of waterdepth respectively.

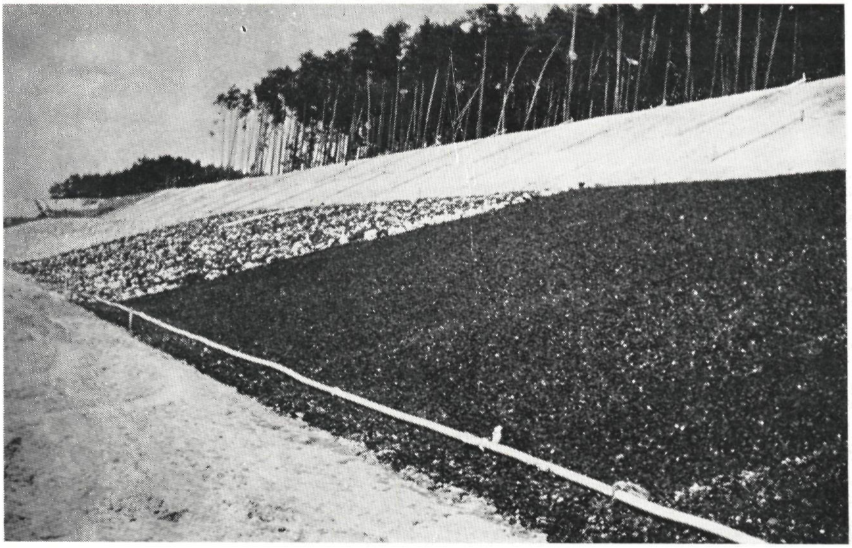

Fig. 11

General view of trial sections Rhein-Main-Donau Kanal.

Vue générale des sections expérimentales du canal Rhein-Main-Donau.

Fig. 12

Placing mastic gravel on trial section separating jetty.

Placement de gravier à mastic dans la section expérimentale de la digue séparant l'écoulement à Hoek van Holland.

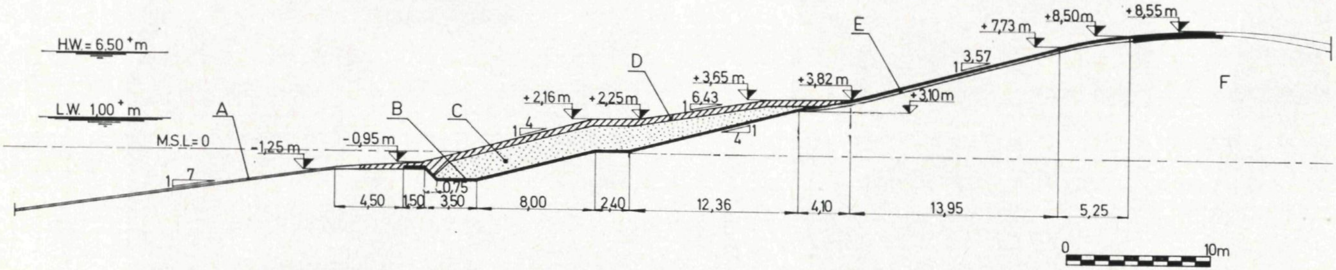

Fig. 13

Embankment drinking water supply basin Rotterdam.

(A) Silt layer.
(B) Nylon reinforced bituminous membrane, 5 mm thick.
(C) Sand for ballasting membrane.
(D) Rubble, penetrated with 50 kg/m² sand mastic grout.
(E) Asphalt concrete in two layers : binder course 225 kg/m²; toplayer, dense asphalt concrete 120 kg/m².
(F) Hydraulic fill.

Barrage du bassin d'eau potable à Rotterdam.

(*A*) *Couche argileuse.*
(*B*) *Voile imperméable en asphalte renforcé de nylon, épaisseur 5 mm.*
(*C*) *Sable, ballast sur la voile.*
(*D*) *Enrochements, pénétrés de 50 kg/m² sable à mastic.*
(*E*) *Béton bitumineux en deux couches : couche de liaison 225 kg/m²; couche supérieure en béton bitumineux dense 120 kg/m².*
(*F*) *Remblayage hydraulique.*

An alternative asphaltic solution for the upper layer is the partial penetration of rubble (pattern grouting). In the German trial sections (Ref. 3) apart from the mastic-mac protection this was the only flawless construction tested. The method is extremely useful for instance in those cases where a loose rubble revetment does not satisfy increased requirements. By pattern grouting the existing revetment is " upgraded " to withstand higher requirements.

In this class also reference can be made to a low cost protection : gravel or small sized riprap can be fixated by penetrating with a sandmastic of extremely low viscosity to enable equal distribution of a small quantity (50 kg/m^2).

An example of this low cost type of slope protection is given in Figure 13 showing the embankment of the Biesbosch drinking water supply basins for Rotterdam. Up till now 10 kilometres of this slope protection have been constructed.

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SUMMARY

Three different types of slope protection are discussed :

— combination of impervious element and slope protection (asphalt concrete, prefab mastic mattresses);

— heavy duty slope protection (penetration of loose riprap, basic design principles, examples);

— bituminous filter construction : sandasphalt filter-layer, mastic-mac protective layer, partial penetration of riprap and rubble; design principles.

RÉSUMÉ

Trois types de protection différentes sont traités :

— combinaison de l'imperméabilité et de la défense du talus (béton bitumineux, tapis de défense préfabriqué en mastic);

— protection lourde de talus (pénétration des enrochements de protection, critères de base des projets, exemples);

— filtre bitumineux : couches en sable bitumineux, couche de défense mastic-mac (enrobés de mastic asphaltique), pénétration partielle des enrochements de protection; critère de base des projets.