BITUMINOUS BANK REVETMENTS
IN RIVERS AND CANALS.

December 1968

by Ir. A.J. Woestenek.
CONTENTS.

1. INTRODUCTION

2. FACTORS INFLUENCING THE DESIGN OF BITUMINOUS REVETMENTS

   2.1. Forces acting on bank revetments
       2.1.1. Mechanical forces
       2.1.2. Physico-chemical action

   2.2. Stability considerations
       2.2.1. Overall stability of a slope
       2.2.2. Local stability of a slope
       2.2.3. Stability of revetment

   2.3. Methods of execution

3. ACTUAL DESIGN OF BITUMINOUS REVETMENTS - EXAMPLES.

APPENDIX. INFLUENCE OF EMERGING GROUNDWATERFLOW ON LOCAL SLOPE-STABILITY.
LIST OF FIGURES.

1. Groundwaterflow - Impermeable revetment.
2. Groundwaterflow - Permeable revetment.
5. Bank revetment Rotterdam:
   Inland navigation canal.
BITUMINOUS BANK REVETMENTS IN RIVERS AND CANALS.

1. INTRODUCTION.

In many countries inland navigation is taking a high flight nowadays. The increase of number, size and speed of inland shipping calls for reconstruction of existing bank revetments and installation of new protective works on navigable rivers and existing or newly built canals. New methods of bank protection are developed to speed up production and reduce costs at the same time by mechanisation.

Asphalt mixes are very suitable for a mechanised production, though up till recently several problems prevented its general use in the field of bank protection. The main problems originated from the difficulty of application under water and from the watertightness of the product. In Holland, where the use of asphalt mixes in hydraulic engineering is attractive not only for technical reasons, but also from an economical point of view because of the scarcences of raw materials such as stone, this was a challenge for industry to design new asphalt mixes and application methods.

BITUMARIN, a Dutch company specialising in asphalt applications in hydraulic engineering, made extensive studies also on methods of bank protection, and already developed several techniques and application methods in this field, which might be worth mentioning. In this note some observations are made on design requirements for bituminous revetments and its consequences for the actual design in practice.

2. FACTORS INFLUENCING THE DESIGN OF BITUMINOUS REVETMENTS.

2.1. Forces acting on bank revetments.

2.1.1. Mechanical forces.

Protection against wave attack is generally the main purpose of bank revetments, though in most cases protection against erosion by water currents is also an important item.

Waves can be generated either by wind or by the movement of ships. Because of the limited length of the so-called "fetch" wind-waves in rivers and canals are generally of short period (not exceeding 1 or 2 seconds) and relatively low (order of magnitude several decimeters). The bow-and rear-waves of sailing ships mainly depend on form, dimensions and speed of the ship, and are of about the same order of magnitude, though mostly more turbulent. The angle of attack in both cases is rather oblique.
The sink of the waterlevel caused by the passing by of a ship (downdrag) which could also be regarded as a wave phenomenon, will be considered in paragraph 2.2. Though wave-attack on bank protection works is by far not as severe as in coastal defense works it should not be underestimated.

The required thickness of the protective layer depends on the force and loading time of the waveimpact, the mechanical properties of the layer (including fatigue resistance) and the nature of the subsoil. It is difficult to access for calculation, but from experience the required thickness of an asphaltic layer of good quality, for instance well compacted concrete or light stone-asphalt, could be estimated to be about 1 decimeter.

The wave-runup of a revetment depends on the angle of the slope, the roughness and porosity of the revetment and the wave-characteristics. From tests carried out at the Delft Hydraulics laboratory by commission of Bitumarin it appears that for waves at right angle of a slope varying from 1 : 1,75 to 1 : 2,25 the wave-runup of a stone-asphalt grouted rubble-revetment is 1,40 to 1,45 times the wave-runup of a non grouted rubble-revetment and 0,75 to 0,80 times the wave-runup of a smooth revetment. It should be remembered that a stone-asphalt grouted rubble can be regarded as rough but impermeable.

The low runup of a rubble-revetment is not only due to its higher degree of roughness but also to its porosity. So it can be expected that an open light stone-asphalt will have a smaller wave-runup than a similar grouted rubble-revetment.

Watercurrents can be the result of a slope of the watersurface, as is the case in rivers, or be caused by shipping. The displacement of water generated by moving ships results in temporary reverse currents, the magnitude of which is depending on form and speed of the ship and the ratio of wetted area of ship and river- or canal-section. 1).

Whereas reversecurrents act on the whole wetted perimeter, currents caused by the action of the ship-screws are limited to a fairly restricted area of the banks, but possess a high degree of turbulence.

1) XVIIth International Navigation Congress Lisbon 1969
XVIIIth International Navigation Congress Rome 1953
As most asphalt mixes can resist velocities up to several metres per second, the use of asphalt mixes below the water surface generally causes no difficulties in this respect.

2.1.2. Physico-chemical action.
In the hostile environment of "water and wind" the durability of asphalt mixes is of vital importance, the more because of the desirability of using open mixes in view of the stability criterion which will be discussed in par. 2.2.

The durability of an asphalt mix is determined by the durability of the bitumen-skin enveloping the mineral aggregate, which on its turn is favoured by a low (micro) voids content of the mixture. Durable asphalt-mixtures are thus designed in such a way that the voids in the mineral aggregate are just filled with bitumen, be it after compaction (asphalt-concrete), or overfilled with bitumen, so that no compaction is needed (sand mastic). The result is always a watertight, impermeable product.

In its development of stone-asphalt (patents pending) Bitumarin discovered that oven-dried and heated stones could be covered with a relatively thick skin of "overfilled" and therefore durable asphalt mixture, even in the presence of so-called "macro-voids" in the total mix. Thus by the process of dual mixing the possibility arose to design open asphalt-mixes still having excellent durability-properties, owing to the concentration of voids in a relatively small number of macrovoids with a relatively small surface of attack. A further advantage of this type of mixture is that as a result of the "gap-grading" of the mineral aggregate hardly or no artificial compaction is needed to obtain nevertheless a good stability of the mix.

If applied under water the durability-requirements of an asphalt-mix are much lower as has been proven by the decade-long application of "wet sand" in the Amsterdam-Rhine-Canal, where this product has been used to restore the stability of the existing sheet-piling.

"Wet sand mix", a cold mixture of wet sand, lime and Special Road Oil can be considered as an artificial stiff clay, which has, however,
the advantage of being permeable, so that it can be applied as an ideal filter-layer. If applied in the zone of "wind and water" it has to be covered with a protective layer, below the watersurface further protection is hardly necessary in most cases.

2.2. Stability considerations.

2.2.1. Overall stability of a slope.
The overall stability of a slope depends on a number of factors, of which can be mentioned: the length and inclination of the slope, the soil-mechanical properties of the subsoil and the prevailing waterlevels. Each case will have to be investigated separately for it is difficult to give general rules. Generally the weight of the revetment is relatively low, so that the choice of type of revetment will not considerably influence the overall stability, except for the case when sheetpiling is involved.

2.2.2. Local stability of a slope.
Locally the stability of soilparticles can be endangered by influences from outside the slope (waves, currents) or by influences from inside the slope (ground-waterflow). A further distinction is to be made between watertight and permeable slope revetments.

If an impermeable revetment is applied direct action of turbulent pressure-fluctuations on the subsoil is excluded, provided the stiffness of the revetment is sufficiently high. In the case of an impermeable revetment the local stability of the subsoil can be seriously effected by groundwaterflow. In particular at the toe of the impermeable revetment a concentration of flow and equipotential-lines occurs having a unfavourable effect on the stability of soil particles in this area. This concentration of flow lines is caused either by steady seepage from the bank into the river or canal, or by a sudden downdrag when ships are passing, or by a superposition of both phenomena (see fig. 1).

Displacement of soil-particles could also occur under an impermeable revetment if the seepage-pressure of the groundwaterflow exceeds the maximum possible shear in the subsoil.
In the case of a permeable revetment the main local stability problem is shifted from the toe of the revetment to the waterlevel. Depending on the thickness of the protective layer and the size of the voids, pressure-fluctuations due to current- and wave-action can propagate into the layer and have an unfavourable effect on the stability of the underlying soil-particles.

So it appears that to prevent washing out of soil-particles a proper filter-construction has to be designed, in such a way that the upper layer is stable enough to resist the wave and current forces, whereas the underlying layer(s) consist of such grain diameter that these cannot be washed out through the coarser upper layer(s), the permeability of the layers increasing in outside direction. Depending on the nature of the attack and the diameter of the soil particles this principle often leads to a filter-construction consisting of several (three or even more) layers requiring lots of material and elaborate handling techniques.

In order to decrease the number of filter-layers required, the use of a filtercloth can be considered. The meshes of such a cloth should be small enough to prevent washing out of the majority of the underlying soil-particles. Especially if the underlying soil consists of uniform graded particles the danger of clogging up of the cloth should be considered.

The local stability of the subsoil is not only affected by pressure-fluctuations from outside, also groundwater flow as a result of downdrag or steady seepage can have an unfavourable effect. In figure 2 the stream- and equipotential lines are computed for the case of a permeable revetment of a slope 1 in 4 under the influence of downdrag and steady seepage. The typical section is taken from a recently carried out bank revetment of the "Hartelkanaal", the inland navigation canal of "Europoort" Rotterdam.

These computations have been executed on the Bitumarin-owned electrical ground-water flow-analogon. It is clear that near the surface of the slope the flowlines emerge essentially horizontally under a gradient equal to the slope-gradient, causing a horizontally directed seepage-pressure on the upper soil particles. Apart from the influence of surface-weight this consideration leads to the well known result that for a cohesionless soil the slope angle $\alpha$ should not exceed half the angle of
internal friction $\varphi$ of the soil to prevent instability of the surface-layers. For steeper slopes ($\frac{1}{2} \varphi < \alpha < \varphi$) surface-weight can improve local stability, whereas for $\alpha > \varphi$ surface-weight is unfavourable and local stability can only be achieved by calling on the cohesion of the soil (see appendix).

In the light of the foregoing it is clear that permeable bituminous mixes are very suitable in the design of filter-constructions. By choosing a bituminous mixture with small voids (equal or slightly larger than the subsoil) such as lean sand-asphalt or so called "wet-sand", a primary filter layer can be constructed having the following advantages:

- almost complete damping of pressure-fluctuations
- stabilisation of the upper layer against ground-waterflow
- fairly good wave resistance
- complete flow resistance in most cases.

So in one layer already an almost complete filter-construction can be achieved, only lacking enough wave-resistance and durability in the water- and windzone. In this area an extra protective layer is needed, for instance a layer of rubble or porous light stone-asphalt.

As to the excellent filter-properties of a sand-asphalt-layer, it could be added that no clogging up will occur, for soil particles lying under this layer will hardly move, unless they are transported by groundwaterflow. In this case however, they will reach a region where the flow gradient is steeper, so the chance of settling down in that region is much lower than the chance of being transported further on and out of the slope.

2.2.3. Stability of revetment.

In most cases the angle of the protected slope will be such that the weight-component of the revetment along the designed slope is counterbalanced by the shear of the revetment on the subsoil, so that no tensile stresses will occur in the revetment itself.

In the case of an impermeable revetment however, uplift pressures can develop as a result of downdrag, which will readily exceed the weight component normal to the slope over a considerable length (see fig.1). The shear stresses between revetment and subsoil thus having decreased or even disappeared totally, the weight component of the revetment in the direction of the slope has to be counterbalanced by tensile and/or pressure stresses in the revetment itself.
This means that a proper reinforcement is needed, capable of resisting loads while a relatively small elongation is achieved (for else the bituminous revetment would still be elongated beyond the breaking point).

So in the case of uplift pressures under an impermeable revetment, either the weight of the revetment should be increased, or a high quality reinforcement is needed, both tending to an expensive solution. Here the big advantage of a permeable revetment becomes obvious, in the way that no uplift pressures can develop. Another possible reason for the development of tensile stresses in the revetment is the occurrence of erosion at the toe of the revetment. Both permeable and impermeable revetments are endangered by this phenomenon, though an impermeable revetment is more apt to undergo erosion at the toe, because of the concentrated emerging of groundwater-flowlines at the toe. In any case either erosion should be made impossible or a proper reinforcement should be used to prevent rupture of the revetment. In some cases use can be made of a steady artificial support at the toe.

2.3. Methods of execution.

After regrading the bank the primary filter layer can be placed in situ by means of a grab using an appropriate plotting system. Immediately after this a simple compacting roll should be applied to allow for even spreading, superficially smoothing and close contact with the subsoil. It is clear that this method requires an easily workable material, even under water, i.e. still workable at relatively low temperatures. Now "wet-sand", consisting of approximately 94 1/2 % sand, 1 1/2 % lime and 4 % Special Road Oil, is a very suitable material in this respect. It can be considered as an artificial permeable clay. For many years Bitumarin uses a floating unit with which the wet sand is produced, put in place and rolled all together in one course.

For the protective layer rubble could be used, or, if more strength is required, a layer of permeable light stone-asphalt.

Direct application of this material on the bank would be attractive, but up till now spreading this material in relatively thin layers is still impossible as a result of the fast cooling under water and the poor workability of the cooled down mix. Efforts are being made to design a durable porous mixture which is still workable at low temperatures, but for the moment use has to be made of prefabricated mattresses. Of course these mattresses have to be provided with some kind
of reinforcement for transport and handling purposes which could be useful also if erosion at the toe is likely to occur.

The prefabricated mattresses could be picked up at one side hanging longitudinally in a crane, but a more accurate positioning is possible by picking up the mattress at supporting devices, evenly distributed over its surface.

So Bitumarln has come to the concept of a prefabricated mattress reinforced by an underlying mat consisting of strong and longitudinally stiff wires or strips, woven with relatively fine meshes to ensure adhesion and equal distribution of strain forces.

3. ACTUAL DESIGN OF BITUMINOUS REVETMENTS - EXAMPLES.

In the past many kinds of bituminous bank revetments of rivers and navigation canals have been applied with more or less success. In order to achieve a durable construction only impermeable mixtures were used, which brought along some disadvantages concerning the stability of revetment and subsoil.

Coping with uplift pressures tends to heavy or artificially reinforced slabs, which are still subject to erosion at the toe by groundwaterflow.

Application of a cohesive filter such as lean sandasphalt could be considered as a stabilisation of the upper layer of the slope, so that only the stability problem of the protective layer itself is left. Moreover in many cases further protection of the sandasphalt is only necessary in the "water-and-wind" zone.

For the protective layer an impermeable slab could still be used, but this slab should be either heavy enough or provided with a high-quality reinforcement to ensure its stability on the slope.

In order to avoid water pressures and therefore stability problems for the protective layer, either rip-rap or light porous stone-asphalt could be used. The latter will be durable and resistant to wave-action already in a relatively thin layer (approx. 0.1 m) which could make this solution economically the most feasible one.

The advantages of a bituminous filter construction - reducing the number of filter-layers to one or two relatively thin layers - of course are only relevant if accompanied by easy workability, even under water.

Now for the primary filter-layer S.R.O.-sand is a very suitable material, which can be applied under water simply by grabs and superficially smoothed by a simple compaction-roll.

Though research is in progress to develop porous stone-asphalt-mixtures which are durable and still
applicable in situ in thin layers under water, for the moment porous stone-asphalt layers have still to be applied using prefabricated mattresses.

An example of the prefab porous stone-asphalt mattresses can be found in a test-section at the River Ussel (Neth.) which has been carried out in the Spring of 1968. A typical section is given in fig 3.

In a river generally there is much variation in waterlevels, so a considerable length of the slope can be subject to wave-action. The waterlevels mentioned in fig 3 only indicate mean levels. Thus in this example the total length of the slope is covered with prefab mattresses 88 ft x 25 ft, 4" thick, the toe of the revetment being excavated in order to cope with possible variations in depth of the river.

The porous stone asphalt of this example is prefabricated on an aluminium undermatting of interwoven strips, which acts as a transport and handling reinforcement, but also as a filter cloth, if lying on the sandy slope.

In fig 4 an alternative design for bank protection is given, which seems to be contradictory to what has been stated in the foregoing chapter. In this design the bank is covered with 2 ft of gravel, of which the upper part is penetrated with sandmast. The gravel cannot be considered as a filter layer, for the minimum particle size is 1", whereas the filter laws would require much smaller particles.

In fact the layer of open gravel under the penetrated gravel acts as a drainage layer so that uplift pressures are avoided. Of course this implicates that this gravel layer should remain clean, i.e. without sand. Whereas the sand of the subsoil is not anymore subject to rapid pressure-fluctuations from wave-action, only groundwater flow could transport the sand in the drainage layer. The relatively flat slope of 1 on 3,5 (\(\alpha = 16^\circ\)), consisting of riversand, however, is already stable at \(\phi = 32^\circ\) under the influence of the emerging groundwater, so that no movement of sand-particles will occur.

The success of this solution, being cheap as a result of the low cost of materials, for the greater part depends on the ease and precision of the depositing of relatively thin layers uniformly spread under water. Departing from its experience in bank revetments BITUMARIN designed a special gravel-laying barge for this purpose to achieve both high precision and capacity.

The example of fig 5 refers to the "Hartelkanaal", the inland navigation canal of Europoort, Rotterdam's newly built harbour.

Here indeed, because of the stable canal level, the primary filter layer has only to be protected locally against wave-action. The canal bottom being deeper, the toe of the primary filter layer has been provided with a firm support consisting of polypropene-fabric
filled with S.R.O.-sand and anchored to the piles at canal level by a large-meshed net (protection against erosion at the toe). Afterwards the S.R.O.-sand-layer is applied by means of a grab and rolled superficially. The rip-rap in the wave zone is placed in the end.
APPENDIX. INFLUENCE OF EMERGING GROUNDWATERFLOW ON LOCAL SLOPE-STABILITY.

If the watertable in the bank is higher than in the river or canal, which can be the result of a stationary hydrological situation or of a sudden down-drag on the passage of ships, or of a combination of both, the phreatic line can touch the slope above the waterlevel in the river or canal, and coincide with this slope down to the canal-level. Thus in the region between the tangential point and the canal-level the flowlines emerge essentially in a horizontal direction while the equipotential lines 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. The revetment is considered to be permeable.

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

The equipotential lines being vertical, the water pressure varies hydrostatically with the depth under the slope, so the force $P$ normal to the slip path of the length $c \cos \alpha$ due to water pressure can be written:

$$P = \frac{6}{c \cos \alpha} \cdot \gamma_w \cdot d_s$$
which can be considered as the resultant force of the vertically directed water-displacement 

\[ \vec{F}_w \cdot d_S \]

and the horizontally directed "seepage force"

\[ \vec{F}_w \cdot d_S \cdot \tan \alpha \]

Now for the plane considered it can be written:

Shear force = \( T = \vec{F}_w \cdot \sin \alpha \left( d_S \gamma_S + d_r \gamma_r \right) \)

Normal force = \( N = \vec{F}_w \cdot \cos \alpha \left( d_S \gamma_S + d_r \gamma_r \right) - \frac{1}{\cos \alpha} d_S \gamma_w \)

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 shear forces can be calculated and represented in a diagram.

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:

\[ T = C + N \tan \gamma \]
the stability in the planes under consideration can be judged. Major results are:
- without cohesion and surface weight taking into account \( \alpha < \frac{1}{4} \) \( \varphi \) holds.
- for steeper slopes \( \frac{1}{4} \varphi < \alpha < \varphi \) surface weight can force the critical slippage down into a region where overall stability considerations are valid.
- For \( \alpha > \varphi \) local stability could only be achieved by cohesion. Surface-weight is unfavourable in this case.
GROUNDWATER FLOW - IMPERMEABLE REVETMENT

FIG. 1
GROUNDWATER FLOW - PERMEABLE REVETMENT

FIG 2
PREFAB MATTRESSES 88ft x 25ft, thick 4"

MLW = P-2

P = 0

MHW = P + 2'8"

P + 6'

P-10'

4" porous stone asphalt

sandmastic penetrated hardcore

aluminium undermatting

BANK REVETMENT RIVER USSEL

FIG. 3
8" layer of gravel 3"-8" penetrated with sandmastic

MLW = P - 2'

P = 0

3.5

1' layer of gravel 1"-8"

2' layer of gravel 1"-8"

MHW = P + 2' 8"

10

clay

FIG. 4

BANK REVETMENT RIVER IJSSEL
BANK REVETMENT ROTTERDAM INLAND NAVIGATION CANAL

FIG. 5
nv maatschappij tot ontwikkeling en toepassing van bitumineuze constructies onder water
company for the development and application of bitumen in hydraulic engineering
zonder schriftelijke toestemming van:
NV maatschappij tot ontwikkeling en toepassing van bitumineuze
constructies onder water bitumarin
mag de inhoud van dit document geheel noch gedeeltelijk worden
vermengvuldigd of aan derden ter inzage worden gegeven.

without the consent in writing of
bitumarin, company for the
development and application of bitumen
in hydraulic engineering,
nothing of the contents of this document may be reproduced,
published or imparted to others.