Downstream Slope Protection with Open Stone Asphalt

A.BIEBERSTEIN, University of Karlsruhe, Karlsruhe, Germany.
N.LEGUIT, Bitumarin bv, Opijnen, The Netherlands.
J.QUEISSER, University of Karlsruhe, Karlsruhe, Germany.
R.SMITH, Hesselberg Hydro Ltd, Sheffield, UK.

SYNOPSIS
Recent investigations and results from tests on the performance of erosion protection systems in Open Stone Asphalt (OSA) on man-made embankments during overtopping conditions are presented. The paper also includes state of the art mix-designs / compositions, installation routines and experience generated from projects in Northern Europe. An analytical statical concept for revetments is presented, which was developed in a research project at University of Karlsruhe, Germany.

1. INTRODUCTION

A major problem during the construction of a dam that can be overtopped is the ability of the slopes covered with revetments to withstand hydraulic loads (e.g. Rathgeb 2001 and Dornack 2001). Therefore an engineering or geotechnical concept is necessary to ensure the stability (LfU 1997).

It is necessary to protect the downstream slope of such embankments against erosion. Four possible cases of overtopping of an embankment are considered:

<u>Overtopping arrangements</u>

1) Overflow of a man-made reservoir during / after rainstorms.
2) Overflow of flood storage reservoirs, whenever the collected rainfall of a catchment area exceeds the total drainage capacity of rivers plus the flood storage arrangements.
3) Overflow of river embankments, when the drainage capacity of the tidal basin (estuary) of a river has been reduced by a storm surge.
4) Overflow sections of river embankments, when the flood exceeds the design level.

Long-term benefits and performance of dams. Thomas Telford, London, 2004

2. CONSTRUCTION REQUIREMENTS

These overtopping cases are all emergency situations. Since the managed flood control system is only used during an overtopping event, which occurs with a low frequency, the construction can often be hidden in the landscape. The requirement to choose a long lasting and permeable construction material with plastic properties to compensate underground settlements is often combined with the request to restore the existing appearance of the embankment and to support the establishment of vegetation. Excellent hydraulic performance under extreme conditions, together with low or no maintenance cost to the materials are desirable for the erosion protection in stand-by mode.

Open Stone Asphalt

To fulfil the function of a durable, maintenance-free erosion resistant material together with a green appearance, Open Stone Asphalt is often selected. Based on experience gained from seafronts, river and canal revetments and reservoir erosion protection on the upstream faces of dams the material is now being used on the downstream slope of embankments. The bituminous mix consists of single sized crushed stone coated with sand mastic. The design of the mastic coating is based on a sand/filler mixture, overfilled with penetration grade bitumen and with or without added fibres (Smith 1998).

After installation and a light compaction sufficient voids remain for it to be permeable to water and air and to accommodate roots of the surface vegetation.

The porosity of Open Stone Asphalt is almost equal to the original used stone (without mastic coating), so a filter layer is required to avoid loss of subsoil particles when seepage occurs. A variety of filters can be applied: woven or non-woven geotextiles, lean sand asphalt or loose granular material.

Pioneers

After an exceptional storm surge along the Belgian coast, in early 1976, several controlled flood areas were constructed as overflows to the river Scheldt.

The hydraulic models were studied at Flanders Hydraulics in Belgium. Bitumar, the Belgian partner of Bitumarin, was contracted to install the Open Stone Asphalt and specific lab-investigations and studies were carried out at the facilities of Bitumarin in Opijnen, Holland (Leguit 1984).

Erosion resistance of Open Stone Asphalt

The properties of resistance to flowing water with high currents were available from test regimes used to design revetments under wave attack or propeller scour from navigation (TAW 1985).

The main conclusions were:

- (Lith, The Netherlands) - Stationary and quasi-stationary flow: limited, only surface, damage was observed after 34 hours with current velocities of 6m/s. (the maximum possible generated flow of the test facilities)
- (Main-Danube-Canal, Germany) - Turbulent flow: no damage occurred after direct attack by an 800HP cargo ship at full strength for 5 minutes (Kuhn 1971).
- (Opijnen, The Netherlands) - Duration flow by pump surcharge to test construction joints.

Performance of geotextile filters to support Open Stone Asphalt

Various woven and non-woven types of geotextile were tested on filter stability in combination with soil samples extracted from the planned location (Leguit 1984).

The main conclusions were:

- After duration testing, the permeability of most filters was reduced by trapped soil particles.
- A thin blanket of sand to catch silt particles would extend the life performance of the filter construction and would reduce the possibility of erosion under the revetment.

<u>Developments in OSA mix design</u>

Open Stone Asphalt is a gap-graded, underfilled mixture of mastic asphalt and aggregate. The mastic comprises sand, filler and bitumen, and coats the aggregate particles with a layer 1 to 1.2mm thick. The mastic film is resistant to weathering and fixes the open aggregate skeleton together to withstand hydraulic loading. Ongoing research and development has led to several improvements in the mix design procedure (TAW 2002).

Aggregate/bitumen adhesion

The adhesion between the aggregate and the bitumen is important for the durability of OSA as it is the integrity of this bond which gives the material its strength. In the past it was generally accepted that carboniferous limestone had good adhesion to bitumen and this stone was usually used. After problems with the durability of a coastal revetment, the adhesion of different aggregate was investigated, and it was concluded that the chemical composition and the surface texture of the aggregate should also be considered, and that other types of stone could be acceptable.

The current standard is to always check the adhesive properties of the stone with the Queensland stripping tests, using a known control stone.

Mastic Viscosity

The asphaltic mastic coats the aggregate to give the material strength. To coat the aggregate correctly the viscosity of the mastic is very important. At the mixing temperature (typically 140-160^{o}C) the mastic must be sufficiently fluid to coat the stones, but also sufficiently viscous not to drip off the stones causing segregation. The target viscosity for the mastic is 30-80 Pascal seconds (Pa.S) at 140^{o}C, which is tested in the Kerkoven apparatus.

Cellulose fibres

The viscosity of mastic is temperature dependent, so the effects of variations in the mixing temperatures are investigated for the designed mastic. Mastics with a relatively high bitumen content will be more temperature-sensitive than those with a lower amount of bitumen, and so the risk of segregation during mixing due to increased temperature will be greater.

A recent development in the UK is the addition of cellulose fibres to the more temperature-sensitive mastics. The fibres combine with the bitumen to decrease its viscosity and to make it more stable. Typically 0.4-0.5% fibres are added to the mastic, and the bitumen content is increased by 1-2%.

Coating thickness

The proportion of mastic in OSA is generally between 19% and 21% depending on the aggregate grading (40mm or 28mm).

The durability of the OSA depends on a sufficient layer of mastic coating each stone so it is therefore an advantage to calculate the coating thickness rather than rely on a 'rule of thumb'.

For current mix designs the aggregate grading and the flakiness index are used to calculate the surface area per unit weight for the stone. This is then used to calculate the amount of mastic required for each aggregate.

For standard OSA mixes a coating thickness of 1.0mm is used, but this can be increased to 1.2mm for mixes containing cellulose fibres, as the increased stability of the mastic means that a greater coating thickness is achievable without increasing the risk of segregation.

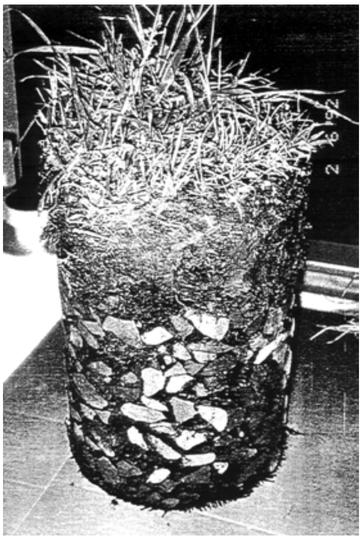


Figure 1: Drilling core extracted from a revetment of Open Stone Asphalt at the project Tielrode (B) with a layer of humus for planting vegetation (Source: ELSKENS 1995)

Performance of Open Stone Asphalt revetment, after overtopping.

Minor cracks were registered in the embankments after overtopping had occurred. A study was carried out to explain the mechanism of failure (Mulders 1983).

The main conclusions are:

Most of the embankments were built like a typical "Dutch Embankment": A sand core, capped with good quality clay. The sand is more permeable to air than the clay, so during a rapid rise in water level the overpressure of the trapped air in the sand core reduces the soil stability and even tries to lift the clay capping during overtopping.

3. INVESTIGATIONS AT UNIVERSITY OF KARLSRUHE

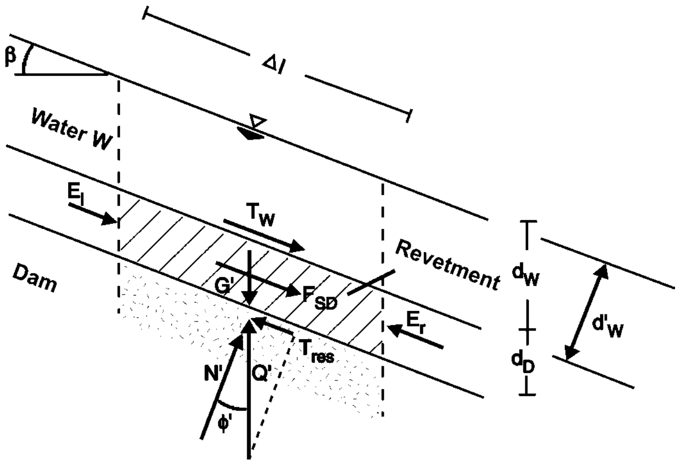
A collaborative research project “dams and embankments (levees) designed for overtopping” was carried out by the Institute of Soil Mechanics and Rock Mechanics and the Institute of Water Resources Management, Hydraulics and Rural Engineering of the University of Karlsruhe. The main question was how to build dams and embankments of a few metres in height in order to withstand intentional overtopping during a flood. In order to do this~~,~~ the downstream slope must be adequately protected against erosion. Up to now there have been no design rules, which made it possible to carry out the necessary stability checks in order to obtain technical solutions which are both economical and easy to build. During this project a statical approach was developed to determine the dimensions of a coherent, self-supporting revetment made of Open Stone Asphalt.

Suitability of a coherent revetment

Various steps were examined to prove the suitability of the selected revetment concept:

- Geotechnical aspects: Dimensions of the revetment, determination of the shear parameters as well as proof of the load capacity of the revetment in a tilting flume.
- Hydraulics: Numerical investigations to determine the dimensions and optimisation of the discharge conditions, in particular to guarantee a reliable dissipation of energy at the toe of the embankment.
- Verification of the results by means of investigations on a half dam model on a technical scale.

The proof of the stability of an overtopped revetment can take place on an embankment element for the given conditions (cf. Larsen et al. 1986). Here the stability can be analysed by comparing all relevant forces and resistances (see Fig. 2).



N', T_{res}, Q'	resulting forces in the shear plane		
Φ'	Angle of friction between the subsoil and the revetment	T_W	Shear stress resulting when overtopped
G'	Weight of revetment under uplift	d_W	Average thickness of the water layer
$E_l \cong E_r$	Earth pressure	d_D	Thickness of the revetment
F_{SD}	Strength of flow	β	Slope angle

Figure 2: Individual element of an embankment which is overtopped and percolated (Larsen et al. 1986)

An evaluation of the analytical correlation is shown in Fig. 3. In this case the slope is covered with a 12 cm thick revetment layer, and the maximum permitted load for an Open Stone Asphalt revetment is given; the results are shown for different angles of friction in the shear plane.

For practical application, the following becomes clear from the correlations shown, as was to be expected:

- The angle of friction in the shear plane has a significant influence on the permitted load capacity of the embankment.
- On flat embankments (small slope angle) higher hydraulic loads are always permissible.
- On the other hand, steep slopes (e.g. β > 15°) permit only a very low hydraulic load – almost regardless of the size of the angle of friction.
- The correlation shown applies for the limiting state ($F_S = \eta = 1.0$).

The friction conditions in the shear planes are fundamental for the design and the static proof of the self-supporting revetment system. Thus the shear parameters for the system were quantified without any hydraulic load – an angle of friction of approx. 31° was determined.

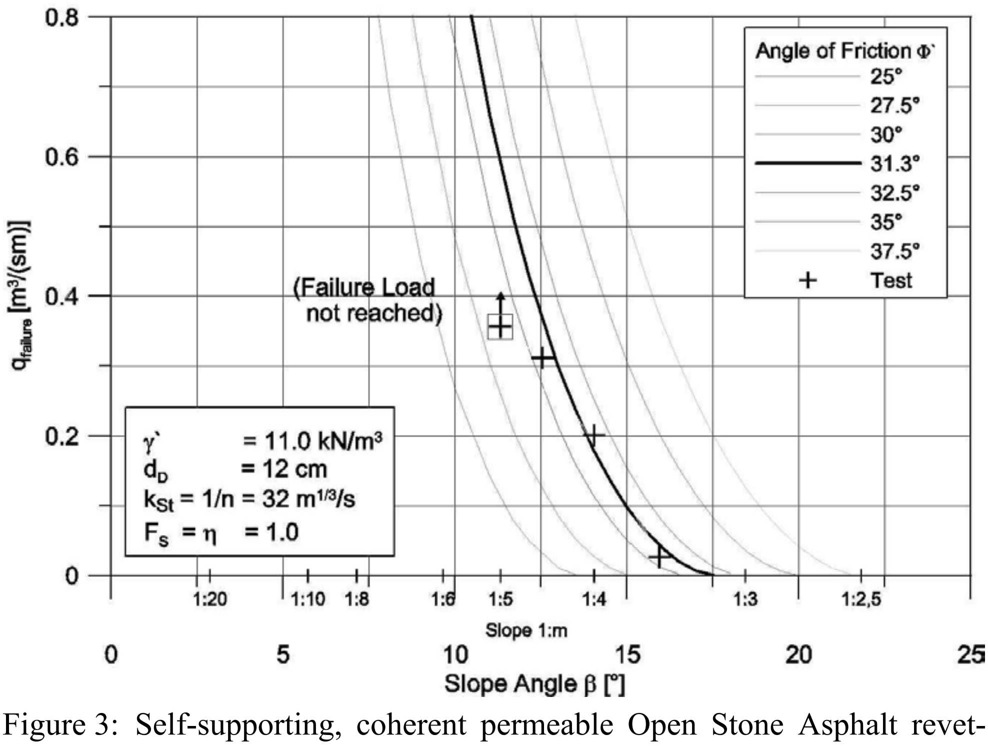


Figure 3: Self-supporting, coherent permeable Open Stone Asphalt revetment – theoretical maximum loads $q_{failure}$ depending on the slope angle β and the angle of friction Φ' (lines) as well as results of experiments from the tilting flume at Φ' = 31°(crosses)

In order to ascertain the maximum hydraulic load of the selected revetment, investigations were carried out on a slope element in a tilting flume, which was infinitely adjustable between an angle of 0° to 35° (length: 4 m, width: 1.31 m). The results confirmed the analytical calculation approach in the investigated load range; the maximum loads for varying slope angles are entered as crosses in Fig. 3. In the future, the dimensions of revetments can be calculated on this basis for the relevant discharge.

From a hydraulic point of view, it was important to look more closely at the three runoff regimes which arise when a dam is overtopped. These differ from one another characteristically with regard to the development of the flow speeds and the water levels as well as the Froude numbers. Here the dam crest with the transition from a subcritical to a supercritical flow was examined and the slope was evaluated with a supercritical steady flow. Above all, the toe of the slope, where at the transition from a supercritical to a subcritical flow a significant portion of the energy dissipation takes place, was the centre of attention. In preparation for the tests on the physical model one-dimensional numerical calculations were carried out. With the help of these calculations, estimates could be made of the position of the hydraulic jump to be expected and on the quality of the energy dissipation.

Finally all the results were used to design and build a half dam model on a technical scale (see Fig. 5), in which the indeed load situation could be realistically reconstructed. This was done up to a hydraulic load of q = 300 l/(sm), in addition the flow conditions in the dambody (sand) were observed and analysed.

An important aspect of the investigations was to optimise the intended energy dissipation at the transition from the slope to the horizontal area, in order to protect the downstream area from erosion. This was achieved by creating a hollow secured with Open Stone Asphalt acting as a scour protection in the transition area between the slope and downstream the toe. The forces and loads arising during energy dissipation are absorbed by the safety element and discharged to the subsoil. Due to the form of the hollow the hydraulic jump cannot move into the unsecured tailwater (see Fig. 6).

Fig 4: Tilting flume – Self supporting Open Stone Asphalt revetment under a load of q = 360 l/(sm) at a slope of 1: 5

Fig 5: Half dam model for overtopping tests at a slope of 1 : 6 during operation

Figure 6: Energy dissipation at the toe of the slope – View from upstream (cf. Bieberstein et al. 2002)

Suggestion for practical application

Based on the statical concept, it is possible to calculate the dimensions of overtopping stretches up to a specific discharge of approx q = 500 l/(sm). As a result of the investigations, an alternative design suggestion for the flood retention basin at Mönchzell, as shown in fig. 7, could be constructively derived: The downstream slope of the dam with an angle of 1 : 8 is covered with a layer of geotextile, on which the revetment of Open Stone Asphalt with a thickness of 20 cm is placed hot.

The Open Stone Asphalt revetment is finally completely covered with topsoil and seeded with grass. However, the grass is not included in the statical considerations. In the case of flooding, the fact cannot be ignored that it could become damaged – and in fact could be lost completely, since the topsoil is not necessarily secure. The revetment underneath takes over the securing of the dam or levee as planned during the period of overtopping.

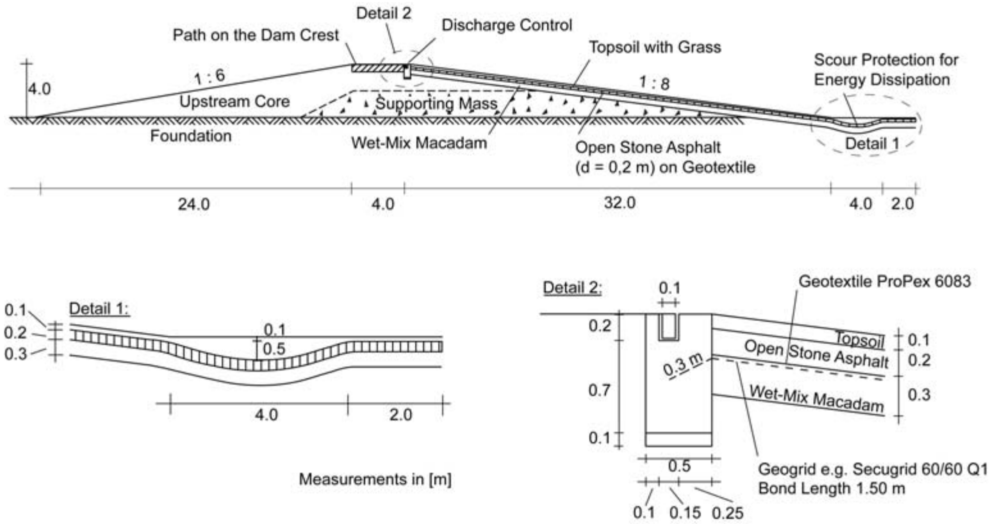


Figure 7: Design for the flood retention basin at Mönchzell with a revetment of Open Stone Asphalt (spec. hydr. load q = 405 l/(sm))

4. DOWNSTREAM SLOPE PROTECTION IN THE UK

Scheme

The Bodmin town leat flood alleviation scheme was designed by Halcrow for the Environment Agency and the main contractor was TJ Brent. The scheme involved the construction of a storage pond above the Cornish town.

The storage pond was created by the construction of a 4 metre high earth embankment with a culvert beneath it to take normal flows. A control structure at the intake limited the flow through the culvert and into the leat through the town, so during flood conditions water would back up and be stored behind the embankment.

In the event of a flood exceeding the design criteria, the embankment was designed to be overtopped over a lowered 60 metre section of the crest, with the water flowing over the downstream slope onto sports pitches below.

The erosion protection required to protect the downstream slope was specified as Dycel 100 blocks placed as pre-fabricated mattresses and secured with in-situ reinforce concrete edge beams.

Open Stone Asphalt (OSA) erosion protection

Hesselberg Hydro proposed an alternative to the concrete blocks comprising a 125mm thick layer of OSA, 250 kg/m^2, placed on a geotextile filter layer.

The OSA layer was thickened by 100mm around the outer edge to increase stability during high flows and at the crest the geotextile was placed in a soil-filled trench to give additional support to the revetment (see Fig. 8).

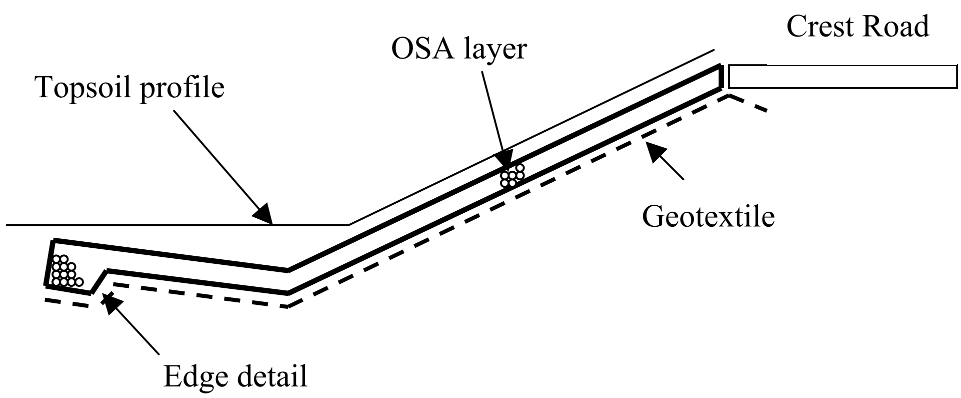


Figure 8: Scheme of the OSA erosion protection

Once the OSA was installed, a layer of topsoil was placed over it and seeded to give the revetment an acceptable appearance.

Overall, 1,000 m^2 was installed complete with crest and edge detail in less than 3 days.

Advantages of OSA

- The in-situ material follows all contours of the stilling basin and is easily placed around manholes and other structures. No cutting of blocks is required.
- A flexible revetment will follow the settlements associated with new earthworks.
- The material is durable and resistant to vandalism and unexpected impacts. In the event of damage to the revetment, the bound nature of the material ensures that damage is not progressive as with a revetment consisting of individual elements.
- The irregular surface voids can support a wider variety of plants than the regular voids in blockwork. The uniformly sized 'pots' in the blocks may suit particular plants which then become dominant.
- A layer of OSA will retain moisture more efficiently than a layer of open concrete blocks where moisture can escape through the holes through the whole block.
- OSA is quick to install and competitive on cost.

Fig 9: OSA erosion protection as installed

Fig 10: Downstream slope after topsoil/seeding

5. CONCLUSIONS

Overflow sections of dams and also of levees are used for flood prevention purposes all over Europe. Open Stone Asphalt has been used in hydraulic engineering for more than 35 years in many countries. In this paper examples of overflowable dam embankments protected by Open Stone Asphalt have been described. The first such attempts were performed in 1976 in Belgium. The experiences have been presented in short form as well as optimized mix design procedures existing at the present time.

In a research project the University of Karlsruhe, Germany, an analytical statical concept was developed for such coherent, self-supporting and permeable revetments. The results were verified in models on a technical scale and are being transferred into practice right now.

LITERATURE

Bieberstein, A., Brauns, J., Queisser, J., Bernhart, H. (2002): *Überströmbare Dämme – Landschaftsverträgliche Ausführungsvarianten für den dezentralen Hochwasserschutz.* Zwischenbericht: BW Plus

CUR, VBW Asfalt, Benelux Bitume (1995): *Toepassing van asfalt bij. Binnenwateren,* (No.1791995) (Dutch).

Dornack, S. (2001): *Überströmbare Dämme – Beitrag zur Bemessung von Deckwerken aus Bruchsteinen.* Dissertation, Institut für Wasserbau und Technische Hydromechanik, Universität Dresden.

Elskens, F. (1995): *Protecting Overflow Dikes for Controlled Flood Areas in Belgium.* PIANC Conference on Inland Waterways and Flood Control, Brussels, Belgium.

Kuhn, R. (1971): *Erprobung von Deckwerken durch Schiffahrtsversuche.* Wasserwirtschaft 3.

Larsen, P., Blinde, A., Brauns, J. (1986): *Überströmbare Dämme - Hochwasserentlastung über Dammscharten.* Versuchsbericht der Versuchsanstalt für Wasserbau und Kulturtechnik und der Abteilung Erddammbau und Deponiebau am Institut für Bodenmechanik und Felsmechanik, Universität Karlsruhe, unveröffentlicht.

Leguit, N. (1984): *Filter Investigations for Paardewijde, Berlare-Wichelen (B).* Report Bitumarin division R&D.

LfU - *Landesanstalt für Umweltschutz Baden-Württemberg (1997): Dammscharten in Lockerbauweise bei Hochwasserrückhaltebecken.* Handbuch Wasser 2.

Mulders, G. (1983): *Technical Report Failmachanism of Overflow Embankments.* Tielrode - Bovenzande, Bitumarin division R&D.

Rathgeb, A. (2001): *Hydrodynamische Bemessungsgrundlagen für Lockerdeckwerke an überströmbaren Erddämmen.* Dissertation, Institut für Wasserbau, Universität Stuttgart.

Schönian, E. (1999): *The Shell Bitumen Hydraulic Engineering Handbook.* ISBN 0953588505.

Smith, R. (1998): *The use of asphalt in dam maintenance work.* Dams & Reservoirs Vol. 8 No. 3, Dec. 1998.

TAW - Technical Advisory committee on Waterdefences (1985): *The use of asphalt in hydraulic engineering,* (No.37/1985).

TAW - Technical Advisory committee on Waterdefences (2002): *"Technisch Rapport Asfalt voor Waterkeringen"* (Dutch).