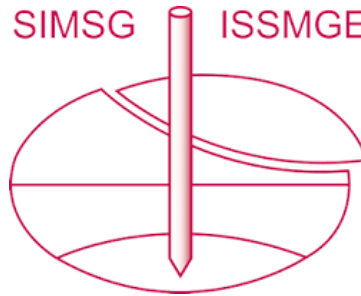


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Some Properties of Sandasphalt in Hydraulic Structures

Quelques Propriétés du Sable-Bitume Employé dans les Travaux Hydrauliques

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SYNOPSIS

Sandasphalt, or sand-bitumen, is a mixture of sand and 3 to 5 percents by weight of bitumen. Its resistance towards erosion and sand tightness renders sandasphalt a popular substitute for clay or minestone in dam constructions. Sandasphalt will probably be used in the outer shell of relatively steep abutments in the Eastern Scheldt storm surge barrier in the Netherlands. For this application restrictions on the allowed deformations are added to the usual stability requirements. In a recently started research programme it is investigated whether sandasphalt may meet these requirements. A visco-plastic stress-strain relation was developed and built into the well-known stability analysis according to Bishop to perform more reliable stability calculations. For the estimation of deformations a similar stress-strain relation was put into the originally visco-elastic finite element programme MARC. With these tools available now an assessment can be made of the applicability of sandasphalt in hydraulic structures where restrictions are imposed on the deformations.

INTRODUCTION

During the last half century a characteristic way of dam and dike building was developed in the Netherlands due to the absence of quarry stone, the abundant presence of sand and the availability of a well-equipped dredging industry.

The extension of dams is started by laying a bottom protection over the existing subsoil or over a dumped sand-gravel foundation. A kernel of hydraulically transported sand is deposited subsequently on the bottom protection between surrounding dikes which are made in advance of the sand core to protect it against eroding currents and wave attack. The protecting dikes will form part of the final dam structure and must for that reason satisfy minimum requirements as to sand tightness and stability especially in the zone of waves and tides.

Next to clay and minestone, both extensively used in the Netherlands, sandasphalt (or sand-bitumen) has been employed for considerable time as a relatively cheap material for protecting dikes as well as for dam cores. In not too severe conditions sandasphalt overlain by a surface dressing was also used at the dam surface. Figure 1 illustrates the application of sandasphalt in dikes around a hydraulic fill extending into the sea.

Sandasphalt is a mixture of dried (quartz) sand and bitumen hotly mixed in mass ratios (quartz) sand 95-97 per cent by weight, bitumen 5-3 per cent by weight. The mechanical stability of the mix is determined by the quantity and the "hardness" of the bitumen. In the Netherlands 4% B-100 bitumen was often used. The permeability of sandasphalt is in the order of that of the constituent sand. At maximum the coefficient of permeability of the mix is 10 times lower than that of the sand. Sandasphalt withstands erosion by

currents exceeding 3 m/s. The chemical stability of the mix surpasses at least the experience gained so far, which is 30 years (Van Asbeck, 1950, 1964).

The filter properties of sandasphalt and the resistance towards erosion render the material popular. Its permeability and pore size distributions are so similar to the properties of sandy core material that the core is not affected by suffosion. As a protecting filter sandasphalt surpasses rival gravelly materials. The resistance towards erosion enables the rapid construction of the sand core in the zone of the tides because the eventually needed stony surface layers can be constructed afterwards. The rapid construction of the sand core between surrounding dikes is also helped along by the easy bulk production of sandasphalt due to the combination of locally available sand and plant-mix production at any specified rate. A disadvantage may be the rising sandasphalt price due to rising oil prices. Recent large scale applications are a coffer dam in Hong Kong (Lehnert, 1979) and the outer harbour at Zeebrugge, Belgium (Schönian, 1979). In figure 2 the profiling of a subaqueous embankment at Zeebrugge is illustrated. Subsequent charges are dumped through a movable pipe underwater.

In the design of the abutments of the storm surge barrier in the Eastern Scheldt (Netherlands) the application of sandasphalt is one of the serious alternatives. A complication in the construction of these 17 m high and steep abutments is the nearness of the first piers (figure 3).



Figure 1. Sandasphalt protection dikes around a hydraulic fill for a wave breaker in the Northsea.

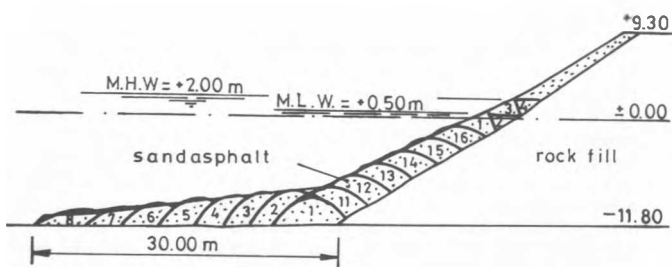


Figure 2. Subaqueous deposition of sandasphalt.

Therefore maximum allowable deformations of the abutment were specified in addition to the usual requirements of stability. The viscous nature of bitumen renders sandasphalt to be essentially a visco-plastic material. It was qualitatively well-known that it reacts stiff and strong to transient loadings like waves and ductile to slowly growing deformations like settlements. The imposition of a deformation requirement called however for stability calculations which included the contribution of internal viscous

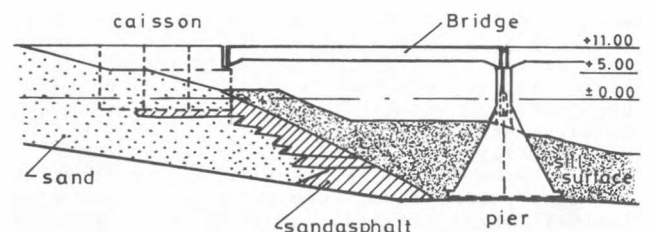


Figure 3. Cross section of abutment, caisson and first pier (storm surge barrier design Eastern Scheldt).

deformations to the shear strength of sandasphalt and for visco-plastic computations of the deformations of the abutments. The Netherlands Department of Public Works asked Bitumarin BV (maritime applications of bituminous materials) to provide representative samples of sandasphalt from dumped trial charges and asked the Delft Soil Mechanics Laboratory to determine a realistic stress-strain relation for

the material and to perform stability and deformation computations. The first results of this joint effort are reported in this paper.

STRESS-STRAIN RELATIONS FOR SANDASPHALT

As mentioned in the introduction sandasphalt consists of sand particles glued together by bitumen. In fact, the bitumen is present as a thin coating (thickness 10 μm) of all or nearly all sand particles.

To get some grip on the response of this sand-bitumen mixture to applied loads or deformations a number of tests were run in a Dutch cell apparatus (De Beer, 1950). The instrument is illustrated in figure 4. It has low-friction top and bottom platens, a bottom drain (determination of volume change) and a double membrane enclosing hydrophobic fluid to separate the saturated sand-asphalt sample from the cell-fluid.

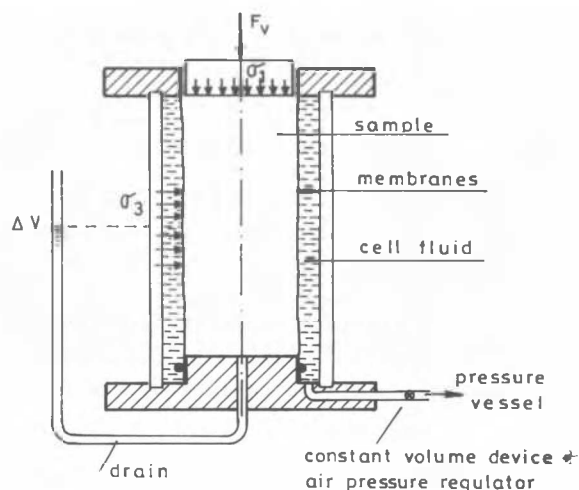


Figure 4. Cross-section of Dutch cell apparatus.

In the cell test horizontal and vertical stresses are applied. The stress paths consisted of isotropic consolidation $\sigma_0 = \sigma_1 = \sigma_2 = \sigma_3$ followed by pure distortion $3\sigma_0 = \sigma_1 + \sigma_2 + \sigma_3 = \text{constant}$. Since $\sigma_2 = \sigma_3$ pure distortion means $\Delta\sigma_1 = -2\Delta\sigma_3$. The coefficient of permeability of usual sandasphalt mixes is in the order of $5-10 \times 10^{-5}$ m/s; permeable enough to prevent pore pressure generation during drained tests under expected rates of loading. Hence the applied stresses are effective stresses.

The viscous character of sandasphalt is fairly well described by a slightly modified version of the rheological model of Burgers for bitumen, which consists of a linear spring E and a Kelvin model A (Suklje, 1969). In figure 5 the adopted model is shown.

The relation between shear stress τ and shear strain γ , primitively illustrated in a state of simple shear, is described by three simple coupled elements:

E, the instantaneous and reversible component, A, the visco-elastic component and P, the visco-plastic component. This last ele-

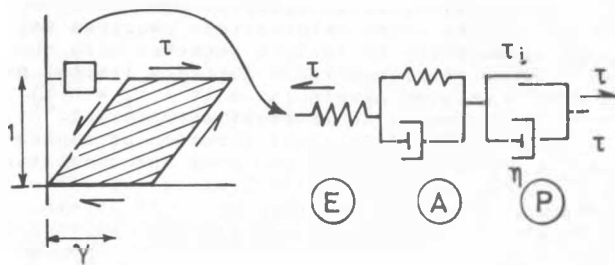


Figure 5. Adopted rheological model for sandasphalt.

ment P is added to the Burgers-model. It consists of a dashpot with apparent coefficient of viscosity η and a shear element modeling internal shear resistance τ_i . τ_i is a function of isotropic stress σ_0 and total shear strain γ . In symbols:

$$\tau = \tau_i(\sigma_0, \gamma) + \eta \frac{d\gamma}{dt}, \quad t: \text{time} \quad (1)$$

For larger shear strains, more than 4%, the contribution of the elements E and A to the stress-strain relation of sandasphalt, especially in monotonic loading, is vanishing small. In the simple discussion presented in this paper these elements are therefore disregarded. The effect of temperature T is not considered either; it can be easily included into $\eta(T)$. A typical test result of a cell test on sandasphalt is given in figure 6.

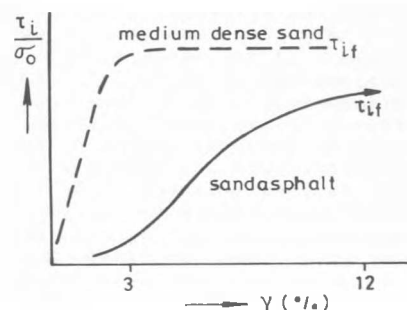


Figure 6. Stress-strain relation of sand and sandasphalt.

In medium dense sand the maximum mobilized shear resistance τ_{if} (failure limit) is reached at shear strains γ of 2-4%.

In sandasphalt the initial grain skeleton does not exist in fact while the bitumen coating prevents particle-to-particle contact. Due to isotropic consolidation the coating will be squeezed out from between adjacent particles whereas deviatoric loading (distortion) causes the bitumen coating to shear between particles and eventually to be squeezed out. Shear deformation results in a gradual built up of internal resistance of the medium due to the increasing number of sand particles getting into direct contact. In figure 6 this behaviour is illustrated by an initially horizontal segment, representing the ideal case of no particle-to-particle contact at all, followed by a curved segment which approaches the internal resistance

curve for sand at large shear strains (9-16%). The relatively large deformations required to bring sandasphalt to failure together with the capacity to carry overloads during a limited period by increased strain rates ($\tau - \tau_i = \eta \frac{d\gamma}{dt}$) render sandasphalt an interesting material. The lower angle of internal friction of sandasphalt as compared to the angle of the constituent sand (figure 6) is deceptive, since any virtual onset of failure would increase local strain rates and mobilize increased viscous resistance. The effect of strain rate $\dot{\gamma}$ ($\frac{d\gamma}{dt}$) is not represented in figure 6. Had it been, it would have demonstrated that failure at small strains and at low shear stress levels is nearly impossible.

At constant temperature (to get reproducible results it should vary less than 0.2°K) and at constant shear stress level τ/σ_0 , $\dot{\gamma}$ is a function of time (figure 7).

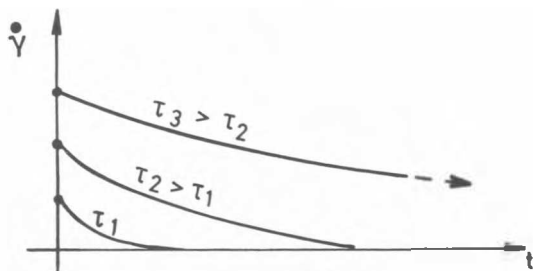


Figure 7. $\dot{\gamma}(t)$ as a function of shear stress τ .

To arrive at finite strains $\dot{\gamma}$ must decrease to zero. It is very time-consuming to obtain the maximum value of τ for which $\dot{\gamma}$ still becomes zero. The easiest way to arrive at this limiting τ_{if} value appeared to be to apply small, increasing deviatoric stress steps until the strain rate is found not to decrease (after a specified time of observation). Then the cell-valve was closed which made the cell pressure σ_3 to rise until the sample stopped deforming. By this procedure the deviatoric stress $\tau_0 = \sigma_1 - \sigma_3$ dropped whereas the isotropic stress σ_0 rises. A comparison with the more correct procedure illustrated in figure 7 learned that the obtained values of τ_{if} were practically similar. The cell tests were used to obtain numerical values for τ_{if} and τ_i and $\eta(T)$ from (1).

COMPUTATION OF DEFORMATIONS AND STABILITY OF SANDASPHALT MASSIVES

Computation of deformations

The abutments of the Eastern Scheldt storm surge barrier are made of sand, sandasphalt, gravel and rockfill. Sand, gravel and rockfill may be described by a non-linear stress-strain relation independent from time whereas sandasphalt behaves non-linearly and time-dependent. The finite element programme MARC (Marcal, 1971) appears sufficiently flexible to include all these stress-strain relations.

The granular media are described by an angle of internal friction (Mohr-Coulomb behaviour) combined with the Von Mises yield condition in

$\sigma_0 = \text{constant}$ planes in the stress space. The programme employs an associated flow rule. The stress-strain relation was checked against plane strain test results upon Eastern Scheldt-sand and was found to predict the test results with a fair similarity regarding τ - γ -relation and τ - ϵ (volume strain)-relation.

As to the sandasphalt behaviour a specific subroutine was set up based on the following constitutive model:

- By laboratory tests a relationship between ultimate shear-strain and shear-stress divided by the isotropic stress was determined (see figure 8).

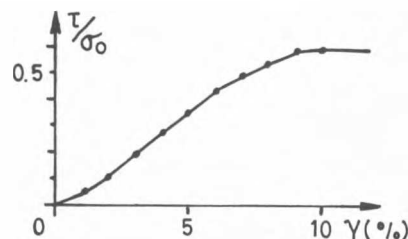


Figure 8. Computer simulation of τ - γ -relation of sandasphalt.

The curve runs through $\tau=\gamma=0$ in contradiction with most of the test results. This is done for ease of calculation and also because a number of test results show this behaviour due to the existence of particle-to-particle contacts in sandasphalt from the start of the test.

- Creep then could be defined by the formula

$$\Delta\gamma = \frac{\tau - \tau_i}{\eta} \cdot \Delta t, \quad (2)$$

η is the apparent viscosity determined by laboratory tests (at 293°K).

Computer calculations led to the time dependent shear-strain development shown in figure 9, which is conform to the time dependent behaviour of sandasphalt (progressive deformations at high shear levels, stabilisation at low shear levels)

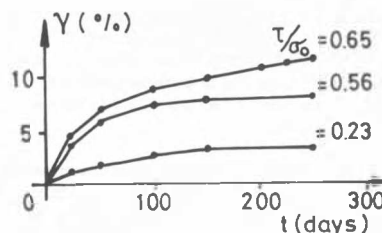


Figure 9. Computer simulation of γ - t relations at different shear-stress levels.

When all boundary conditions (geometry, loads, material parameters) were determined they were input for some final runs to calculate the long

term deformations of the abutments.

Modified Bishop stability analysis

Conventional methods for stability analysis of slopes cannot take into account the viscous properties of the sandasphalt mixture, which however play an essential role in the philosophy of design of temporary dams. Viscosity of the mix has a restraining influence on the sliding velocity in case of actual failure. Small sliding rates may be very well accepted for short term earthworks. To take advantage of the viscous properties a slight modification of the conventional stability analysis is needed. Mobilized shear strength is defined as

$$\tau_s = f_s(\gamma) \sigma \tan(\phi_s) \quad (3)$$

for sand, where s stands for sand, and

$$\tau_a = f_a(\gamma) \sigma \tan(\phi_a) + \eta \frac{d\gamma}{dt} \quad (4)$$

for sandasphalt, where a stands for sandasphalt. Here, γ stands for (uniform) shear strain along the failure surface, f_s and f_a are mobilization factors (figure 10), σ is stress normal to failure surface, $\tan(\phi_s)$ and $\tan(\phi_a)$ are friction parameters.

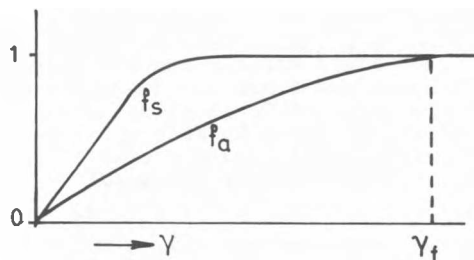


Figure 10. f_s and f_a as functions of shear strain γ .

Equation (4) is essentially similar to (1). These definitions are used in the equilibrium analysis in the Bishop method of slices (Craig, 1974) and thus obtaining an ordinary first order differential equation for γ (figure 11).

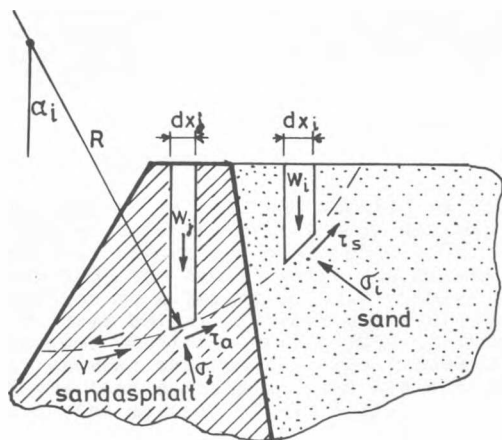


Figure 11. Input parameters for sandasphalt and sand into Bishop's stability analysis based on the equilibrium of slices.

Two different types of solutions of γ are possible:

1. $\frac{d\gamma}{dt} \rightarrow 0$, $f_s(\gamma) \leq 1$ and $f_a(\gamma) < 1$ as $t \rightarrow \infty$
(t = timeparameter).
2. $\frac{d\gamma}{dt} > 1$, $f_s(\gamma) = 1$ and $f_a(\gamma) = 1$ as $t \rightarrow \infty$

In the first case deformations will be bounded and equilibrium needs no draw on viscosity. In the second case deformation goes on, but viscosity prevents sudden failure.

The procedure of finding the critical sliding circle is as follows:

1. For each potential centre of rotation and radius of the sliding circle coefficients of the differential equation are determined, based on the test results of par. 2.
2. The differential equation is analysed to determine the limiting value of the associated shear strain γ , or the strain rate in case of actual failure. The critical sliding circle is defined as the potential failure circle with highest value of associated shear strain, or highest strain rate.

CONCLUSIONS

Sandasphalt, a mixture of sand and bitumen, has been found for many years to be a completely acceptable substitute for clay and minestone in the construction of protection dikes and temporary dikes for maritime dam building. The knowledge of sandasphalt performance was based on field tests and practice of coastal and river engineering.

Recently, for example for the Eastern Scheldt storm surge barrier in the Netherlands, new requirements for the use of sandasphalt were made putting restrictions to the allowable total deformations of embankments and abutments. The new demands necessitated experimental research into the viscous and visco-plastic character of sandasphalt and the introduction of obtained stress-strain relations into computational procedures for stability and deformations of embankments.

The first results of this research are presented here. It appeared acceptable to describe sandasphalt behaviour at somewhat larger strains by a simple visco-plastic model. The model could be introduced into both the MARC finite element programme for deformations and the Bishop method of stability analysis.

The calculations performed now for the abutments in the storm surge barrier show that sandasphalt may be used as core protection.

The research will be continued to check the reliability of the first results and to obtain more fundamental knowledge of sandasphalt behaviour, the favourable effects of preshearing during the deposition of the hot mix and of hardening of the mix in the course of time. In the computation of deformations three-dimensional geometry will be investigated.

ACKNOWLEDGEMENTS

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