CHAPTER 120

Wave-Induced Uplift Characteristics on Concrete Block Slope Revetments

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Abstract

The paper deals with full-scale wave attack on concrete block slope revetments. The tests were carried out in the research facility LARGE WAVE CHANNEL, Germany. The blocks were placed on a filter layer (granular and/or geotextile) preventing the failure of the sandy sub-soil. Stability results are reported. Pressure measurements at special testblocks were used to investigate uplift characteristics of the blocks. Furthermore, the measurements were applied for verifying analytical design procedures.

Introduction

Permeable dyke revetments are preferably applied for coastal protection works at the German coast. An economical solution for the sloping cover layer on dykes with a sandy core can be realized by the use of prefabricated concrete blocks placed on a filter layer preventing failure of the sandy sub-soil. The filter layer can be constructed by a quasi three-dimensional granular filter, by a quasi two-dimensional geotextile filter or by a combination of both filter types. In the past, wave attack at storm surge conditions frequently caused failures of such dyke revetments. With the new full-scale laboratory LARGE WAVE CHANNEL a fundamental research project was started in order to investigate dyke revetments under prototype conditions. The main dimensions of this research facility are: depth 7.0 m, width 5.0 m and length 324 m. Regular waves and random seas are produced mechanically by a wave generator. The maximum wave height is 2.5 m. Details about the channel were published by Grüne and Führböter (1975); design criteria and technical works were reported by Grüne and Sparboom (1982).

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Test Set-Up

The core of the 1 to 4 sloping sea dyke was made by sand with a mean diameter of d_{50} = 250 µm. The area of the highest expected wave attack was subdivided into two testfields each of 10 m in length and 2.5 m in width. Both testfields were separated by a concrete wall of 1 m in depth. A cross-section of the revetment is given in Figure 1. The whole prototype revetment can be seen in Figure 2. The testfields are shown in Figure 3. The concrete blocks were placed in stretcher-bond equivalently to usual method in practice. The investigated structure types are drawn in Figure 4.

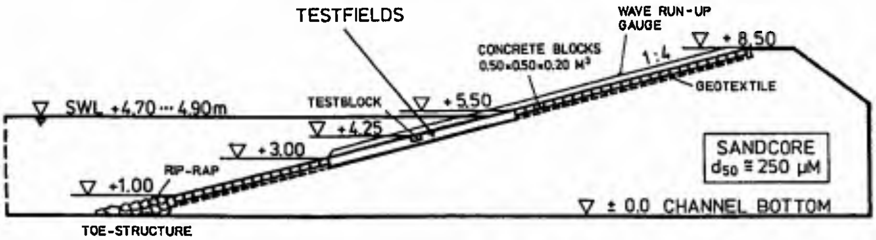

Figure 1. Cross-Section of the Prototype Dyke Revetment

Figure 2. 1 to 4 Sloping Dyke Revetment in the Large Wave Channal

Figure 3. Testfields of the Prototype Dyke Revetment

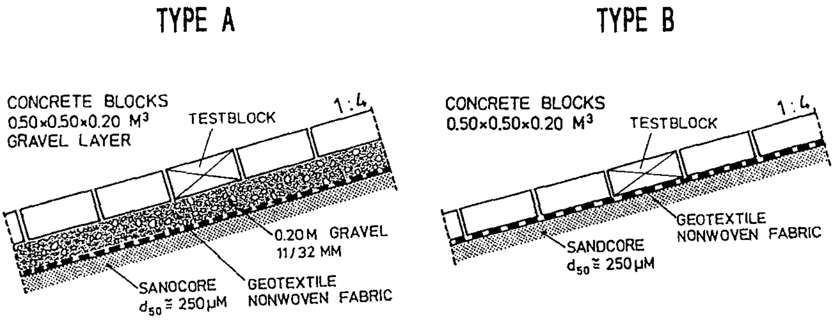

Figure 4. Investigated Structure Types of the Prototype Dyke Revetment

The testblocks which contained measuring devices were installed nearly 0.5 m below SWL in each teststructure or testfield. The measuring equipment was designed to registrate the following electrical signals synchronously:

- wave parameters (height and period) at the toe of the dyke revetment and
- wave pressures acting on the testblocks at the top and bottom side.

The waves were generated regularly applying an integrated absorption control system. The minimum wave number for each test was 200. After very first block failure which was observed by visual control the test was interrupted. A damaged teststructure was replaced by a more stable one being able to increase the wave parameters as far as the second teststructure was damaged. This is the reason why synchronous measurements at both structures (Type A and B) are only available for testserie 1. Testserie 2 was carried out with the structure of Type B only.

Stability Investigations

Designing blocks of sea dyke revetments it is very useful to consider the breaker parameter which contains the influence of the wave period (as part of the wave steepness) and the slope angle (Bruun,1985). The stability parameter proposed by Pilarczyk, 1987 is given with a non-dimensional quantity which is calculated by the ratio wave height to block thickness multiplied with the relative block density.

Breaker Parameter
$$\xi_0 = \frac{1}{n \cdot \sqrt{H_M / L_0}} \; ; \; L_0 = \frac{g \, T_M^2}{2 \, \pi} \tag{1}$$

ξ_0	(-)	breaker number in deep water
n	(-)	front slope 1 : n
L_0	(m)	wave length in deep water
T_M	(s)	wave period (regularly generated)
H_M	(m)	wave height (regularly generated)
g	(m/s^2)	acceleration due to gravity

Stability Parameter
$$\chi = \frac{H_M}{\Delta \; d_B} \; ; \; \Delta = \frac{\rho_b - \rho_w}{\rho_w} \tag{2}$$

χ	(-)	stability parameter
H_M	(m)	wave height (regularly generated)
Δ	(-)	relative block density
ρ_b	(kg / m^3)	density of concrete blocks
ρ_w	(kg / m^3)	density of water
d_B	(m)	block thickness

In Führböter and Sparboom, 1988 there can be found stability results for various types of block structures. In this paper tests with wave parameters very close to failure conditions are focussed. In testserie 1 the failure - very first block lifting out of the revetment - occurred at wave parameters H_M = 0.8 m and T_M = 6.0 s (Type A, Figure 5) whereas in testserie 2 the failure

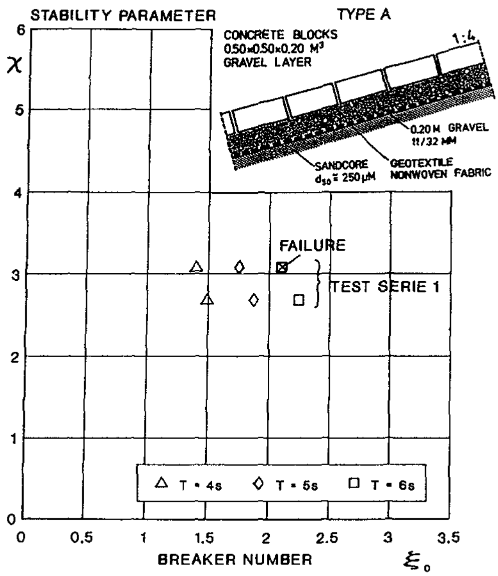

Figure 5. Stability Results Under Critical Wave Conditions - Granular Filter (Testserie 1)

occurred at wave parameters H_M = 1.2 m and T_M = 5.0 s (Type B, Figure 6). The structure of Type B remained stable under test conditions of testserie 1.

For both structure types the failure position was found nearly 0.5 H beneath SWL. The very first block lifting occurred just before wave breaking (foto Figure 7).

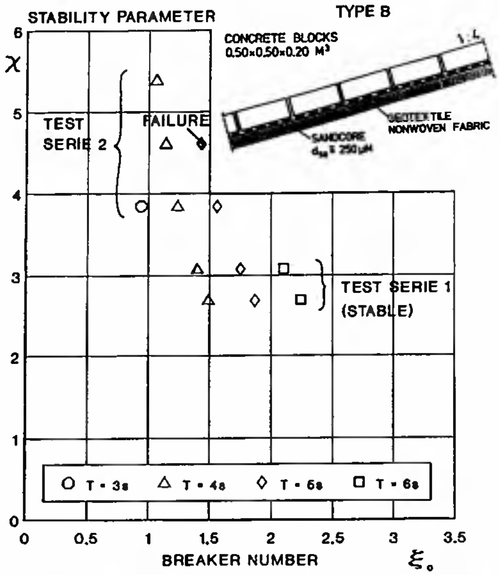

Figure 6. Stability Results Under Critical Wave Conditions - Geotextile Filter (Testseries 1 and 2)

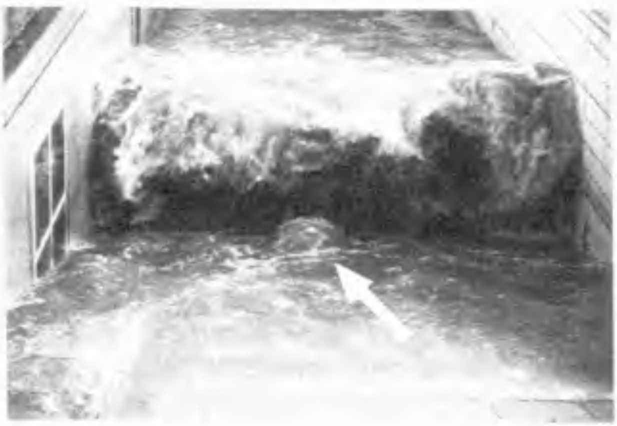

Figure 7. Very First Block Failure

Block Lift Forces

In order to investigate pressure variations causing block lifting special testblocks (see Figure 3) were supplied with pressure transducers at top and bottom side. An example of these measurements is plotted in Figure 8. The pressure differences Δp of top and bottom side just before wave breaking were evaluated. Additionally, the reaction times T_{pos} with uplift characteristic (from zero to maximum) were recorded.

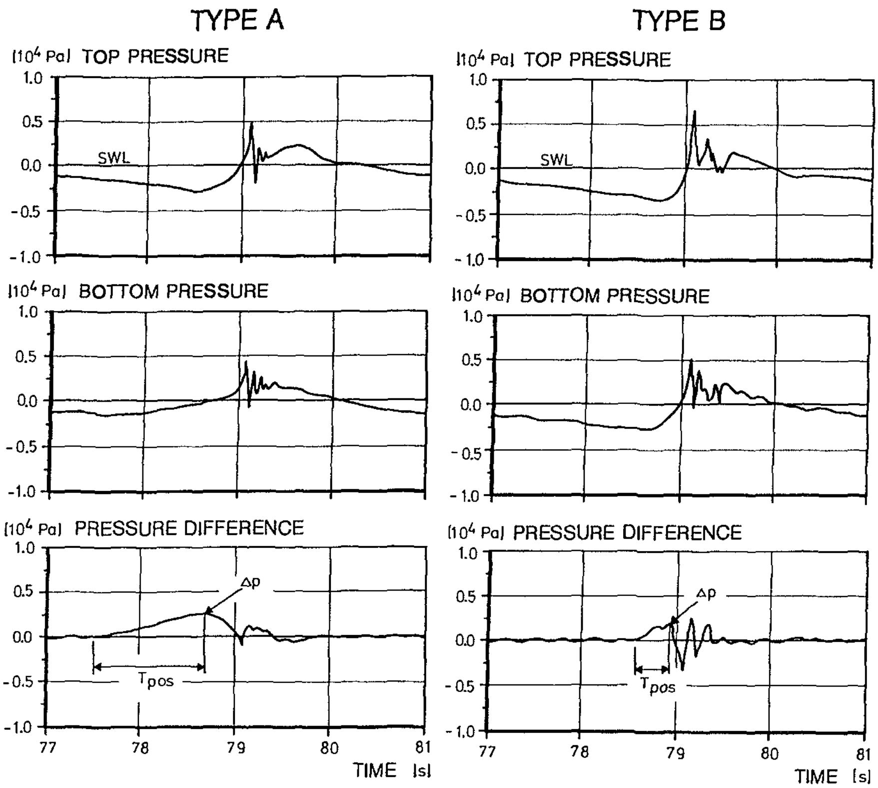

Figure 8. Example of Synchronous Pressures Acting on the Testblocks (Testserie 1)

Estimating the uplift forces (Sparboom and Debus, 1990) the uplift pressures were integrated over the plane of the testblock. For the critical damage tests the development of the uplift forces - evaluated for several waves in each test - can be seen in Figures 9 and 10. Both structure types were damaged in nearly 10 minutes. The maximum uplift force amplitudes are of nearly equal amount for both structure types.

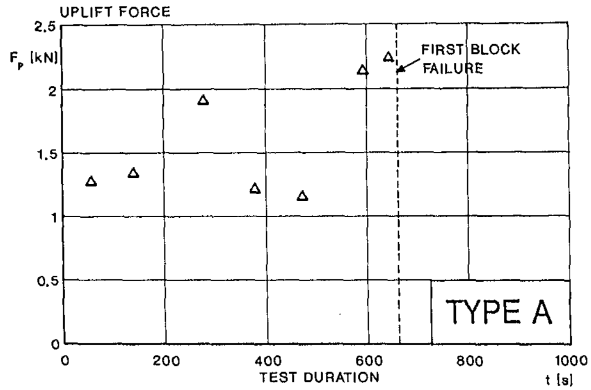

Figure 9. Block Failure Testserie 1; Waves: H_M = 0.8 m, T_M = 6.0 s

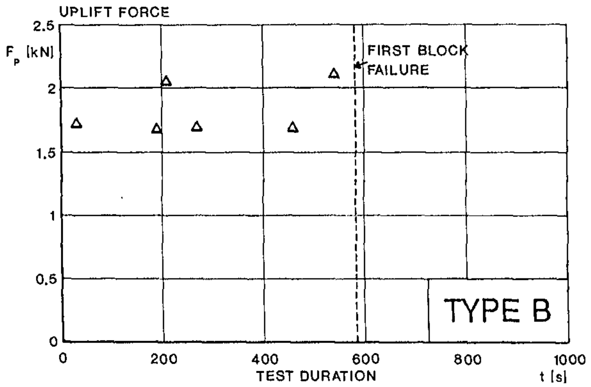

Figure 10. Block Failure Testserie 2; Waves: H_M = 1.2 m, T_M = 5.0 s

For the testseries 1 and 2 a representative set of parameters defined in Figure 8 were evaluated. The uplift forces F_p were found by integrating the pressure differences over the testblock. These force values F_p were related to the block weight under water F_w (weight force minus buoyant force). The reaction times T_{pos} were related to the wave period T_M of the corresponding test. In the case of a granular filter the uplift force works in the range 0.10 to 0.45 of the period ratio (Figure 11). For comparison in the case of a geotextile filter the main range lies between 0 and 0.15 (Figure 12). But there are also period ratios in the range 0.3 to 0.4. It can be assumed that uplift forces acting under such conditions cause block failures.

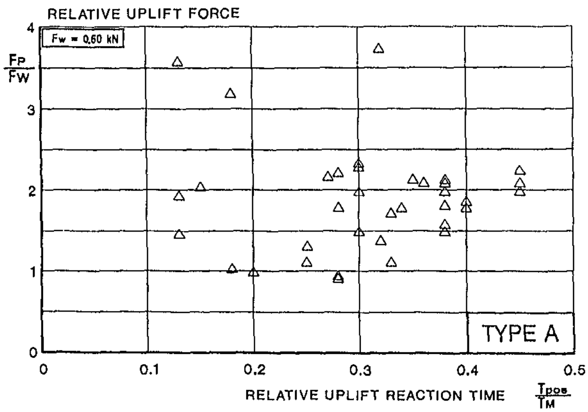

Figure 11. Uplift Forces vs. Reaction Time for Testserie 1 - Granular Filter

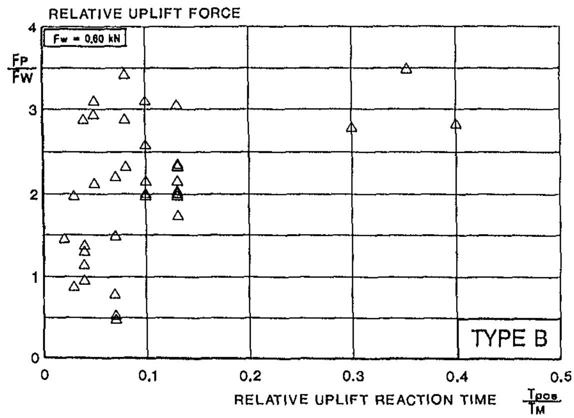

Figure 12. Uplift Forces vs. Reaction Time for Testserie 2 - Geotextile Filter

From Figures 11 and 12 it may be assumed that block failures occur if the uplift forces are acting in a time interval with a duration of at least 1/3 of the wave period (Führböter and Sparboom, 1988). Uplift forces causing block movements roughly amount 2 to 4 times of the block weight force under water.

Verification Analysis

Experimental full-scale data on block revetments are especially helpful verifying theoretical evaluations. Burger et al., 1990, Bezuijen et al. 1990 and Klein Breteler and Bezuijen, 1991 published analytical procedures for the design of block revetments placed on a granular filter layer. In Figure 13 a definition sketch of the used parameters is given.

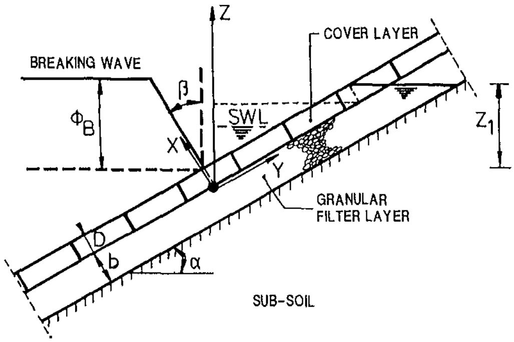

Figure 13. Definition Sketch of the Analytical Solutions on Waves Acting on Block Revetments

It was assumed that - with respect to full-scale failure mechanism - the maximum pressure over the revetment occurs just before wave breaking. The following equations were used (see also Figure 13):

BURGER et al., 1990 and BEZUIJEN et al., 1990

$$\Phi_W = \left[\frac{\lambda}{2 \tan\alpha \tan\beta} * \left(1 - e^{-\tan\alpha \tan\beta \, \Phi_B / \lambda}\right) + \frac{\lambda}{2} \right] * \left[1 - e^{-2 Z_1 / \lambda} \right] \quad (3)$$

Φ_W (m) maximum uplift pressure over the revetment
λ (m) vertical leakage factor
α (^{o}) slope angle
β (^{o}) angle of the wave front
Z_1 (m) height of the phreatic surface in the filter layer
Φ_B (m) height of the wave pressure front

$$\lambda = \sin\alpha * \sqrt{\frac{k * b * D}{k'}} \quad (4)$$

k (m/s) permeability of the filter layer
k' (m/s) permeability of the cover layer
b (m) thickness of the filter layer
D (m) thickness of the cover layer

BURGER et al., 1990

$$\Phi_B = H * (0.17 * \cot\alpha + 0.07) * \xi^{(-0.125 * \cot\alpha + 1.22)} \quad (5)$$

H (m) incoming wave height (regularly generated)
ξ (-) breaker number

$$\beta = (26.6 + 2.45 \cot\alpha) * \xi^{(-0.215 * \cot\alpha + 0.73)} * \left(\frac{d}{H}\right)^{(0.05 * \cot\alpha + 0.06)} \quad (6)$$

d (m) water depth

BEZUIJEN et al., 1990

$$\Phi_B = 0.36 \; H \left(\frac{\tan \alpha}{H / L_0} \right)^{0.5} ; \quad \frac{\tan \alpha}{H / L_0} \leq 37 \tag{7}$$

H	(m)	incoming wave height (regularly generated)
L_0	(m)	wave length in deep water ($g * T^2 / 2\pi$)
g	(m/s^2)	acceleration due to gravity
T	(s)	wave period (regularly generated)

$$\tan \beta = \frac{0.17}{\sqrt{H / L_0}} \tag{8}$$

KLEIN BRETELER, BEZUIJEN, 1991

$$\Phi_W = \Lambda * [\; 0.43 * (H / \Lambda)^{0.6} * (H / L_0)^{-0.2} * (\tan \alpha)^{0.5} \;] \tag{9}$$

Φ_W	(m)	maximum uplift pressure over the revetment
Λ	(m)	leakage factor

$$\Lambda = \sqrt{\frac{k * b * D}{k'}} \tag{10}$$

The relative uplift pressures evaluated for waves of testserie 1 are plotted in Figure 14. Since these measured uplift pressures belong to the structure type with a granular filter layer they are comparable to calculated uplift pressures using the formulae (3) to (10).

As also remarked by Bezuijen et al., 1990 it was very difficult to estimate real cover layer permeabilities. The joint width between the blocks of the investigated revetment differed from close contact to 10 mm wide gaps (mean 5 mm). For comparison, three various cover layer permeabilities were

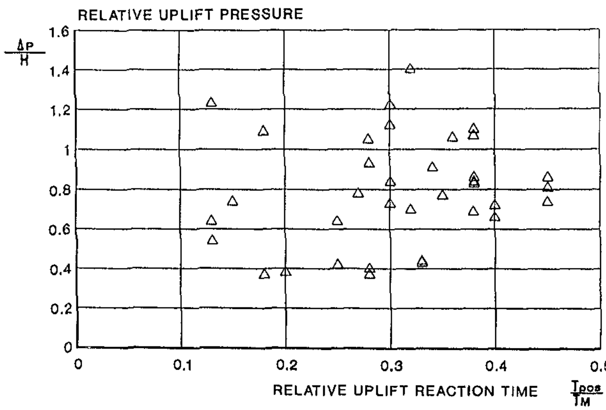

Figure 14. Measured Uplift Pressures With Wave Parameters of Testserie 1; Structure Type A With a Granular Filter Layer

estimated. It was assumed that the relative reaction time of the calculated uplift pressures would have been as long as in the experiments. Results of the calculations are shown in Figure 15.

Comparing the results of Figures 14 and 15 it can be seen that theoretically calculated uplift pressures are much smaller than the highest pressures measured in full-scale. In the case of 5 mm joint width the maximum measured pressure is nearly 75 % underestimated. On the one hand the analytical approach seems to be affected by semi-empirical assumptions based on small-scale modelling, especially the description of the pressure due to the breaker process and the description of the permeabilities of the cover layer as well as of the filter layer. On the other hand real uplift pressures are larger due to friction or clamping forces between single blocks. It is very difficult to estimate these resistant forces theoretically. It is proposed to combine the theoretical design for loose block revetments with results of full-scale experiments with naturally placed blocks using transfer factors from theoretical to prototype conditions. In Figure 16 theoretically calculated uplift pressures of the different procedures are compared with measured uplift pressures. For the special structure considered here such transfer factors could be expected in the range between 2 (small gaps) and 4 (wide gaps). This means that theoretically calculated maximum uplift pressures for a loose block should be increased at least 2 to 4 times being able to estimate the total uplift pressure causing block failure.

Concluding Remarks

According to earlier results reported by Führböter and Sparboom, 1988 it is expected that placed concrete blocks (relative density $\Delta = 1.3$) protecting a slope 1 to 4 remain stable under the following assumptions:

$d_B \geq 1/3\ H$ case of granular filter on sandy sub-soil,

$d_B \geq 1/5\ H$ case of geotextile filter on sandy sub-soil.

Failure occurrence of such structures is expected at breaker numbers ξ_0 ranging from 1 to 2. The failure location was found nearly 0.5 H below SWL.

From time history records of pressure measurements at top and bottom side of testblocks it was found that block movements occur if uplift forces are acting at least 1/3 of the wave period. Uplift forces may cause block movements if the amplitude is 2 to 4 times higher than the block weight force under water.

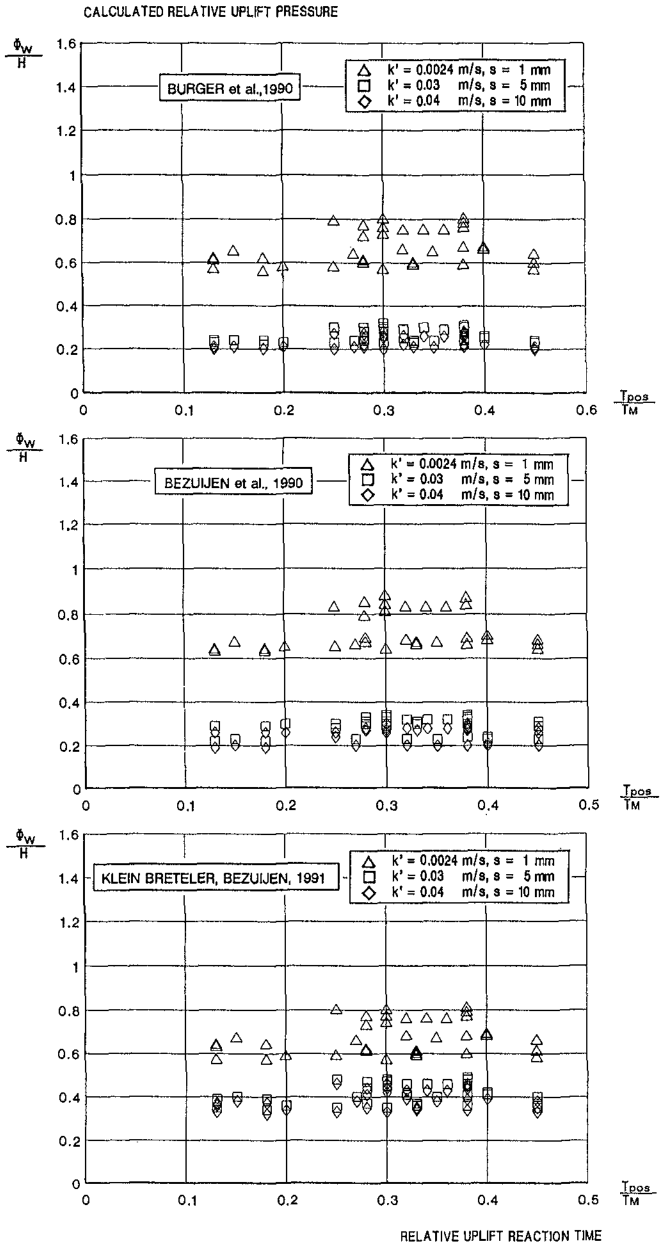

Figure 15. Calculated Uplift Pressures for Various Cover Layer Permeabilities Related to Wave Parameters of Testserie 1, Structure Type A With a Granular Filter Layer

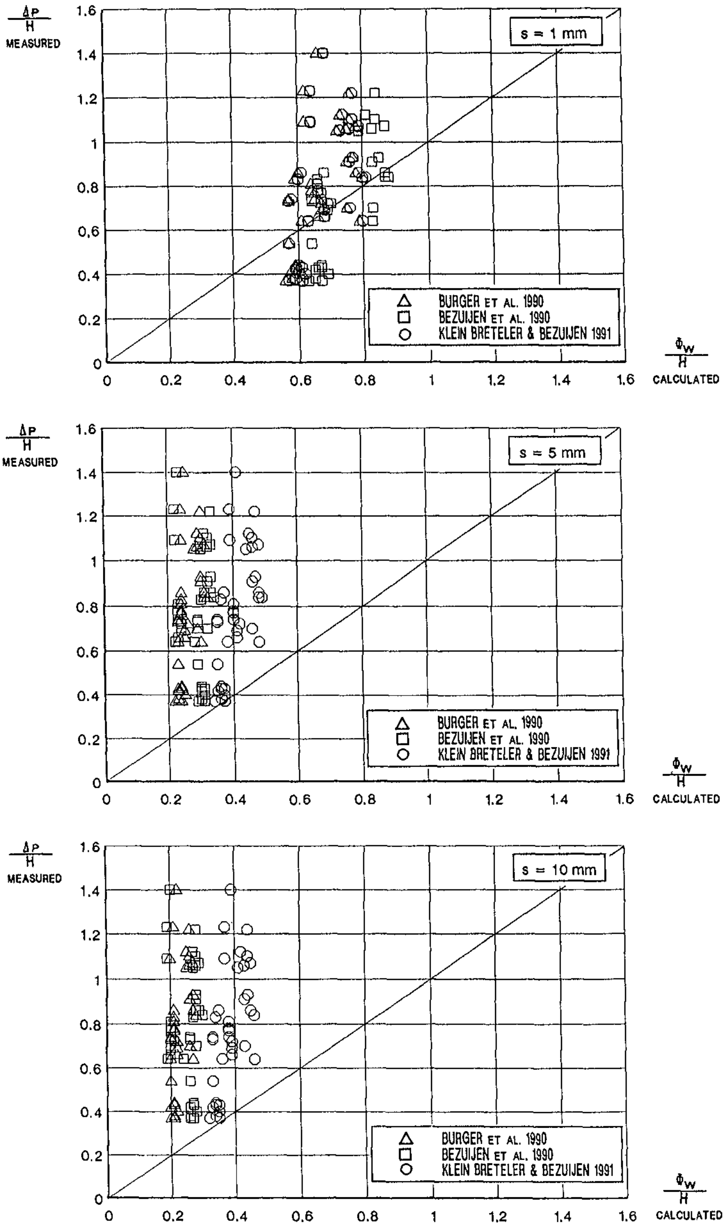

Figure 16. Measured Versus Calculated Relative Uplift Pressures for Joints With a Width of 1, 5 and 10 mm

For an economical design on placed block revetments it is recommended to select structural permeabilities increasing from sub-soil to filter layer and from filter layer to cover layer.

Verifying analytical approaches on placed block revetments it was found that calculated uplift pressures in the case of loose blocks are definitely smaller than measured uplift pressures in the naturally placed revetment. The physical mechanism of wave breaking together with the response of a more or less permeable and flexible block revetment is a very complex domain. In the opinion of the authors full-scale laboratory experiments as well as field investigations are inevitably necessary to study breaking wave attack of sea dykes and revetments. Results of such experiments are especially useful to verify theoretical solutions or to calibrate numerical models.

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References

Grüne,J. and Führböter,A.: Large Wave Channel for "Full Scale Modelling" of Wave Dynamics in Surf Zones.Proc. Symp. on Modelling Techniques, San Francisco, 1975

Grüne,J. and Sparboom,U.: Großer Wellenkanal - Problemstellung und Lösung aus versuchstechnischer und konstruktiver Sicht. Techn. Bericht,SFB 79, Universität Hannover, 1982 (in German)

Bruun,P.: Design and Construction of Mounds for Breakwaters and Coastal Protection. Elsevier, Amsterdam, 1985

Pilarczyk,K.W.: Sea Defences-Dutch Guidelines on Dike Protection. Report WB-NO-87110,Rijkswaterstaat, Delft, 1987

Führböter,A. and Sparboom,U.: Full-Scale Wave Attack of Uniformly Sloping Sea Dykes. Proc.21st Int. Conf. on Coastal Eng.,ASCE, Malaga, 1988

Sparboom,U. and Debus,W.: Wellenbelastung von Deichdeckwerken mit gesetzten Betonblöcken - Versuche im Großen Wellenkanal. Techn. Bericht,SFB 205, Universität Hannover, 1990 (in German)

Burger,A.M.,Klein Breteler,M.,Banach,L.,Bezuijen,A. and Pilarczyk,K.W.: Analytical Design Formulas for Relatively Closed Block Revetments. Journal of Waterway, Port, Coastal and Ocean Eng., ASCE, Vol. 116, 1990

Bezuijen,A., Klein Breteler,M. and Burger,A.M.: Placed Block Revetments. Coastal Protection, Ed. K.W. Pilarczyk, Balkema, Rotterdam, 1990

Klein Breteler,M. and Bezuijen,A.: Simplified Design Method for Block Revetments. Proc. Conf. on Coastal Structures and Breakwaters, Institution of Civil Engineers, London, 1991