OVERTOPPING FLOW PARAMETERS ON THE INNER SLOPE OF SEADIKES

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Abstract: Wave overtopping was responsible for many dike failures in the past. It is not feasible to avoid wave overtopping completely in the future due to uncertainties in the prediction of the design water levels and the costs of uneconomical high dikes. Therefore, wave overtopping has to be taken into account for the design of seadikes. The overtopping flow velocities and related layer thicknesses are required which are responsible for infiltration and erosion of the dike crest and the landward side of a dike. The objective of this paper is to study the flow velocities and related layer thicknesses associated with wave run-up and wave overtopping based on theoretical and experimental investigations.

INTRODUCTION

Wave overtopping has been responsible for many severe dike failures in the past. For example, many sea dikes failed due to wave overtopping during the extreme storm surge disasters in 1953 (Netherlands), 1962 and 1976 (Germany and Denmark). In the meantime, the crest levels of sea dikes have been increased along the Dutch, German and Danish coasts. Nevertheless, wave overtopping cannot be avoided completely due to the remaining uncertainties in the design water levels and the design waves. This was actually confirmed by some broken dikes in southern Denmark in December 1999. If wave overtopping cannot be avoided, dikes have to be designed in such a way that overtopping water has no consequences on the stability of the dike crest and the landward slope. Therefore, wave overtopping must be described by the associated overtopping flow velocities and layer thicknesses which are responsible for erosion and infiltration and not by average

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overtopping rates which are not appropriate for the description of erosion and infiltration (Fig. 1).

Thus, a new way for the design of sea dikes on wave overtopping is required which is based on overtopping velocities and layer thicknesses instead of average overtopping rates. Much information on average overtopping rates is available in literature (e.g. Van der Meer and Janssen 1995), but no information concerning overtopping velocities and layer thicknesses was found. To fill this gap, a research project on the determination of the overtopping flow parameters was initiated and the main experimental and theoretical results of this project are described below.

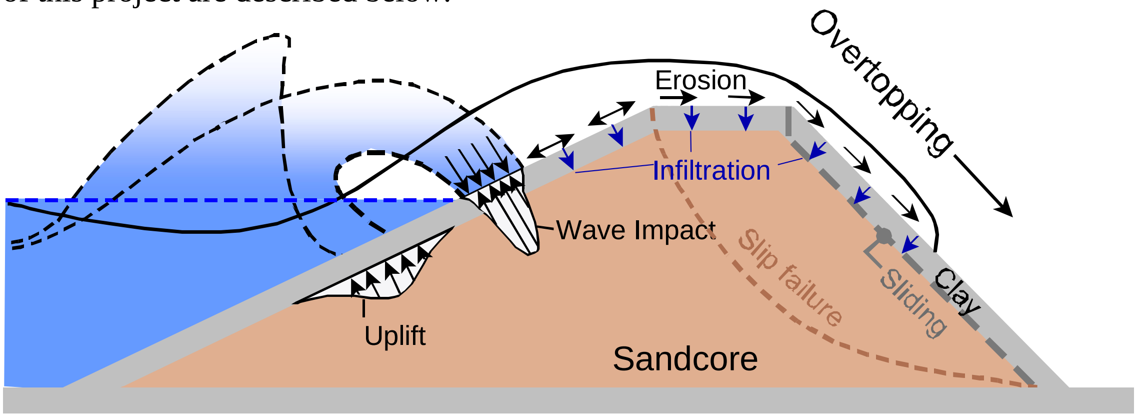


Fig. 1. Failure Mechanisms of a Sea Dike

MODEL SET-UP AND TEST PROGRAM

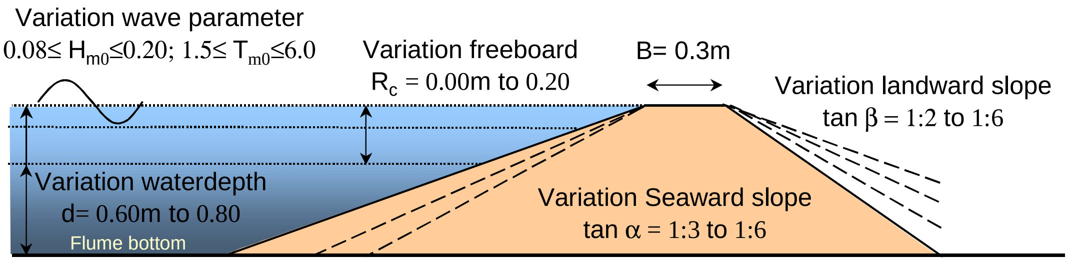
Model tests were performed in the small wave flume of the Leichtweiss-Institute for Hydraulics in Braunschweig and in the large wave flume of the Coastal Research Centre in Hannover.

Small Scale Model Tests

The small scale model tests were used (i) to verify the theoretical model and (ii) to get model data for a wide range of different geometries and wave conditions. Therefore, three different seaward slopes (1:3; 1:4 and 1:6) and five different landward slopes (1:2, 1:3, 1:4, 1:5 and 1:6) were tested. The test program was set-up in such a way that typical ratios (e.g. relative freeboard R_C/H_S, wave steepness H_S/L_0) in nature were used for the model tests (Fig. 2). In total about 270 model tests were performed in small scale with regular waves and wave spectra (JONSWAP-spectrum; 50 waves). Different instruments were installed to measure the various parameters. The wave field in front of the dike was measured by typical resistance type wave gauges, the layer thickness of the up-rushing and overtopping water by small sensitive wave gauges, the overtopping velocities by micro propellers and the overtopping volume by an overtopping tank situated on three weighing cells. A detailed description of the model set-up and the test program is given by Schüttrumpf (2001).

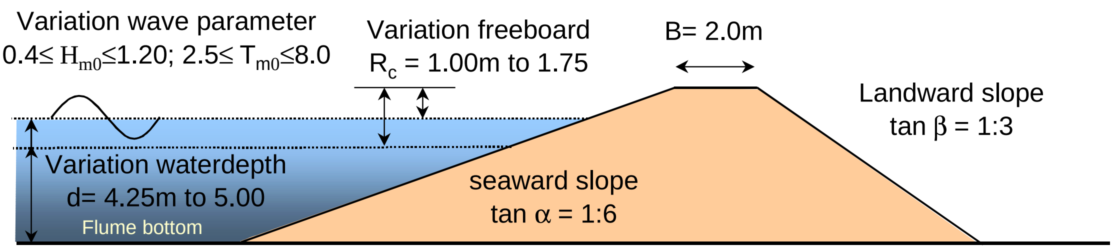
Large Scale Model Tests

The large scale model tests were used to (i) validate the results from the small scale model tests without scale effects (1st phase) and (ii) to get model data on erosion and infiltration (2nd phase, Möller et al. 2002). All model tests in the large wave flume were performed for a 1:6 seaward slope and a 1:3 landward slope (Fig. 3). The crest was 2m wide and 6m above flume bottom. The test program of the small scale model tests was adapted for the large scale model tests (model scale 1:5 for small scale tests). Thus, model tests in small and large scale can be compared directly and scale effects can be determined. In total about 250 model tests were performed in large scale with a few regular waves and wave spectra (JONSWAP-spectra, TMA-spectra, natural wave spectra, about 200 waves). The incoming wave field was measured by typical resistance type wave gauges, wave run-up velocities and wave overtopping velocities by micro-propellers, layer thicknesses in wave run-up and wave overtopping by digital wave gauges, pressures on the dike surface by very sensitive pressure cells and the overtopping volume by a discharge meter and by an overtopping tank installed on four weighing cells. A detailed description of the test program and the model set-up is given by Oumeraci et al. (2001).



ratio	Nature	Model
tan α	1:3 ÷ 1:8	1:3; 1:4; 1:6
tan β	1:3 ÷ 1:5	1:2; 1:3; 1:4; 1:6
R_c/H_S	1.0 ÷ 2.5	0.0 ÷ 2.5
H_S/d	0.2 ÷ 0.5	0.10 ÷ 0.30
H_S/L_0	0.02 ÷ 0.03	0.001 ÷ 0.06
d/L	0.10 ÷ 0.18	0.01 ÷ 0.26
ξ_d	0.75 ÷ 1.50	0.66 ÷ 9.43

Fig. 2. Model Set-up and Test Program for Small Scale Model Tests



ratio	Nature	Model
tan α	1:3 ÷ 1:6	1:6
tan β	1:3 ÷ 1:5	1:3
R_c/H_S	1.0 ÷ 2.5	0.20 ÷ 0.40
H_S/d	0.2 ÷ 0.5	0.8 ÷ 4.4
H_S/L_0	0.02 ÷ 0.03	0.08 ÷ 0.3
d/L	0.10 ÷ 0.18	0.008 ÷ 0.50
ξ_d	0.75 ÷ 1.50	0.5 ÷ 2.6

Fig. 3. Model Set-up and Test Program for Large Scale Model Tests

KEY RESULTS

The overtopping flow parameters were defined for the three sections of the dike (i) seaward slope of the dike, (ii) the dike crest and (iii) landward slope of the dike. The parameters at the end of one section are always the input parameters for the beginning of the next section.

Seaward Slope

Wave run-up velocities and related layer thicknesses are required to calculate the initial conditions at the transition line between the seaward slope and the dike crest.

(a) Layer Thickness

The layer thickness on the seaward slope is a function of the horizontal projection x_Z of the wave run-up height R_u, the position on the dike x_A and a dimensionless coefficient c_2 (Fig. 4). The layer thickness on the seaward slope can be calculated by assuming a linear decrease of the layer thickness h_A from SWL to the highest point of wave run-up:

$$h_A(x_*) = c_2(x_Z - x_A) = c_2 \cdot x_* \tag{1}$$

where x_* is defined as a remaining run-up length ($x_* = x_Z - x_A$) and $x_z = R_u/\tan\alpha$. Eq. 1 has been verified by small and large scale model tests (Fig. 5) and the following conclusions were drawn:

- The layer thickness $h_A(x_A)$ increases linearly with increasing remaining run-up length x_*.
- The coefficient c_2 is identical for plunging and surging breakers because the influence of wave breaking is included in the wave run-up height R_u.
- The coefficient c_2 is a function of the dike slope n ($c_2^* = c_2 \cdot n$=const.).
- No significant differences in the layer thickness were found for model tests with and without wave overtopping.
- Characteristic values for the coefficient c_2 are given in Table 1.

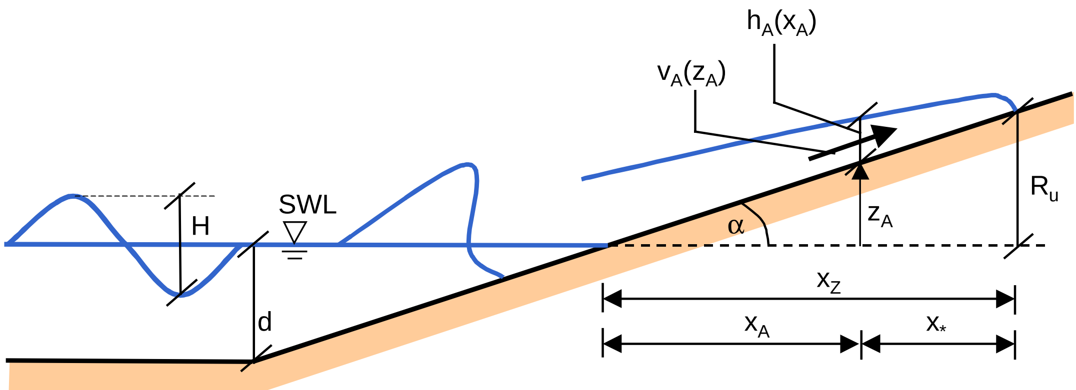


Fig. 4. Definition Sketch for Layer Thicknesses and Wave Run-up Velocities on the Seaward Slope

Table 1. Characteristic Values for Parameter c_2 (TMA-spectra)

Parameter	c_2	Comment
$h_{A,50\%}$	0,028	Large scale
$h_{A,50\%}$	0,028	Small scale
$h_{A,10\%}$	0,042	Large Scale
$h_{A,2\%}$	0,055	Large Scale

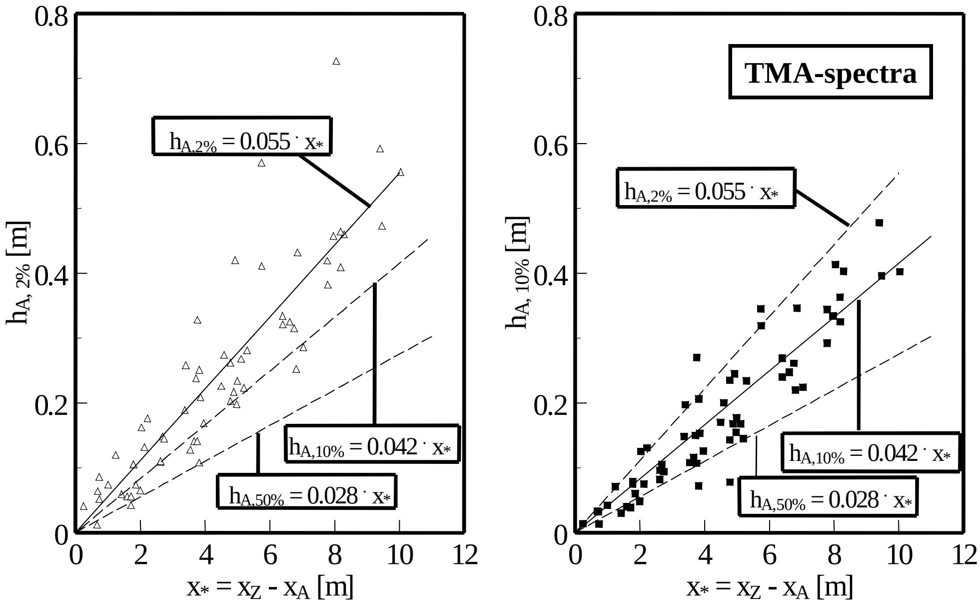


Fig. 5. Layer Thickness for 2% (left) and 10% (right) Exceedance Probability (Large Scale Model Results)

(b) Wave Run-up Velocities

The wave run-up velocity is defined as the maximum velocity that occurs during wave run-up at any position on the seaward slope. Therefore, this velocity is equal to the front velocity of the run-up tongue. The wave run-up velocity can be derived from a simplified energy equation and is given by:

$$v_A = k^* \cdot \sqrt{2g(R_u - z_A)}$$

where v_A is the run-up velocity at a point z_A above SWL, R_u is the wave run-up height, g is the acceleration of gravity and k^* is a dimensionless coefficient.

In dimensionless form, the wave run-up velocity is:

$$\frac{v_A}{\left(\frac{\pi H_S}{T_m}\right)} = a_0^* \cdot n \cdot \xi_d \cdot \sqrt{\frac{R_u - z_A}{H_S}} \quad \text{with: } \xi_d = \frac{\tan\alpha}{\sqrt{H_S / L_0}} \tag{2}$$

Eq. (2) has been calibrated by small and large scale model data. Fig. 6 shows a comparison of Eq. (2) to model results from the large scale model tests with 2%, 10% and 50% exceedance probability.

Table 2. Characteristic Values for Parameter a_0^* (TMA-spectra)

Parameter	a_0^*	Comment
$v_{A,50\%}$	0,82	Large scale
$v_{A,50\%}$	0,75	Small scale
$v_{A,10\%}$	1,09	Large Scale
$v_{A,2\%}$	1,24	Large Scale

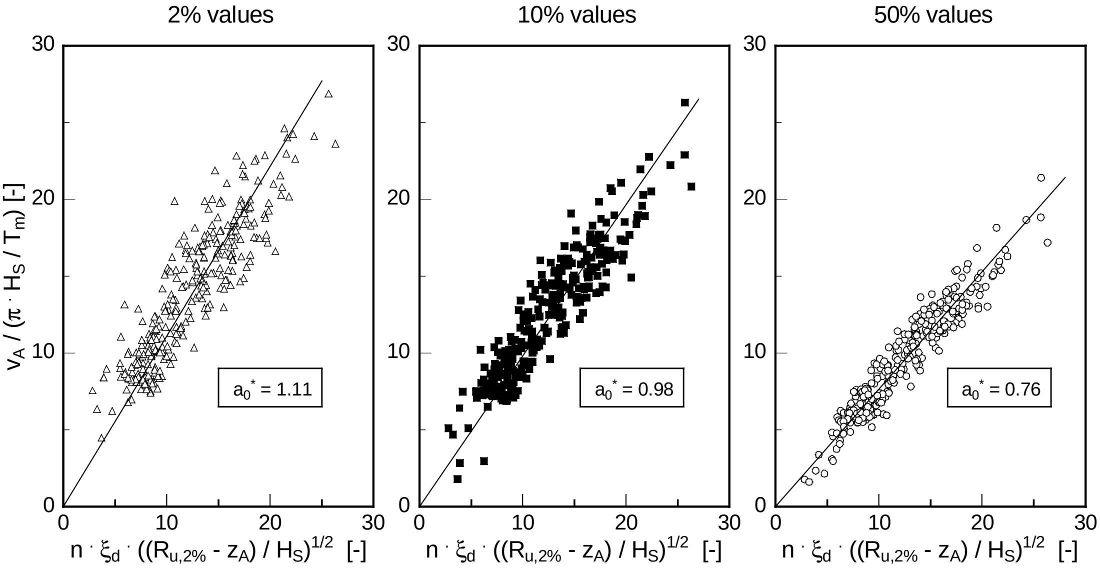


Fig. 6. Wave Run-up Velocities with 2%, 10% and 50% Exceedance Probability (Large Scale Model Results)

Dike Crest

The flow parameters at the transition line between seaward slope and dike crest are the initial conditions for the overtopping flow. Layer thickness and run-up velocity at the transition line can be determined from Eq. (1) and Eq. (2) with $z_A = R_C$, respectively.

(a) Layer Thickness

The layer thickness on the dike crest depends on the width of the crest B and the co-ordinate on the crest x_C (Fig. 7). The layer thickness on the dike crest decreases due to the fact that the overtopping water is deformed. Thus, the decrease of layer thickness over the dike crest can be described by an exponential function:

$$\frac{h_C(x_C)}{h_C(x_C = 0)} = \frac{c_2(x_C)}{c_2(x_C = 0)} = \exp\left(-c_3 \frac{x_C}{B}\right) \tag{3}$$

where h_C is the layer thickness on the dike crest, x_C is the horizontal co-ordinate on the dike crest, c_3 is a dimensional coefficient and B is the width of the dike crest.

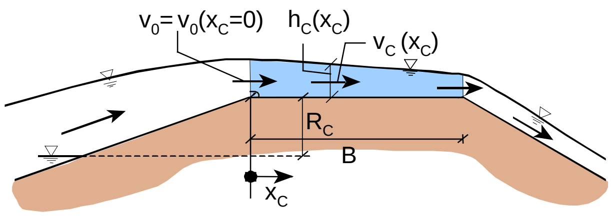


Fig. 7. Definition Sketch for Overtopping Flow Parameters on the Dike Crest

The coefficient c_3 has to be determined experimentally. A comparison of Eq. (3) to the experimental data is given in Fig. 8.

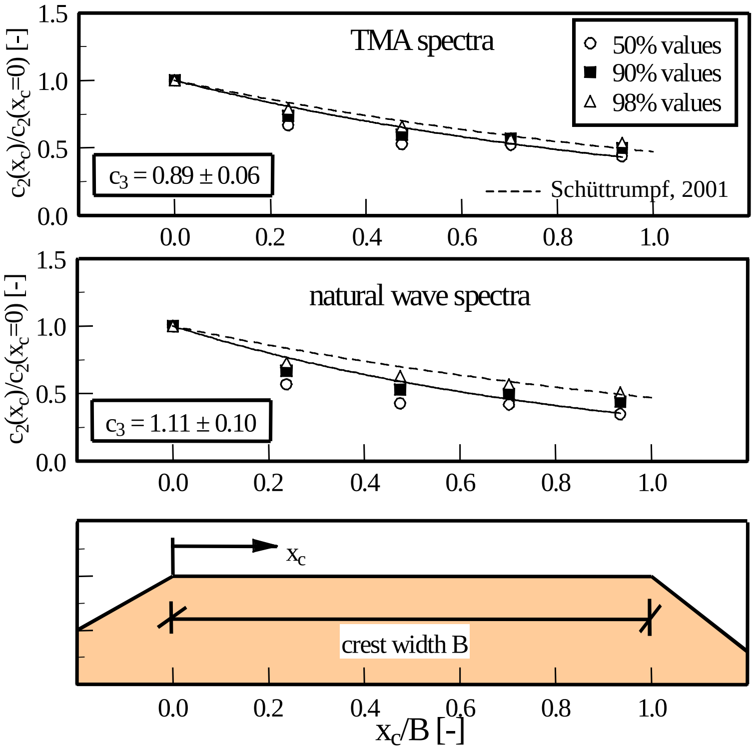


Fig. 8. Comparison of model data to layer thickness formula (Eq.3) for dike crest (Large Scale Model Results)

(b) Overtopping Velocity

The overtopping velocity on the dike crest is only influenced by surface friction. A theoretical function for overtopping velocities can be derived from the simplified Navier-Stokes-equation by the following assumptions:

- the dike crest is horizontal
- velocities vertical to the dike slope can be neglected
- the pressure term is almost constant over the dike crest
- viscous effects in flow direction are small

The following formula was derived and verified by small and large scale model tests:

$$v_c = v_0 \exp\left(- \frac{x_c\, f}{2\, h_c} \right) \tag{4}$$

where v_C is the velocity on the dike crest, v_0 the velocity at the beginning of the dike crest (x_C=0), x_C the co-ordinate along the dike crest, f the friction coefficient and h_C the layer thickness at x_C.

The velocity decreases from the beginning of the dike crest to the end of the dike crest due to bottom friction (Fig. 9).

Details of the derivation of Eq. (4), its calibration and comparisons with the experimental data are given by Schüttrumpf (2001).

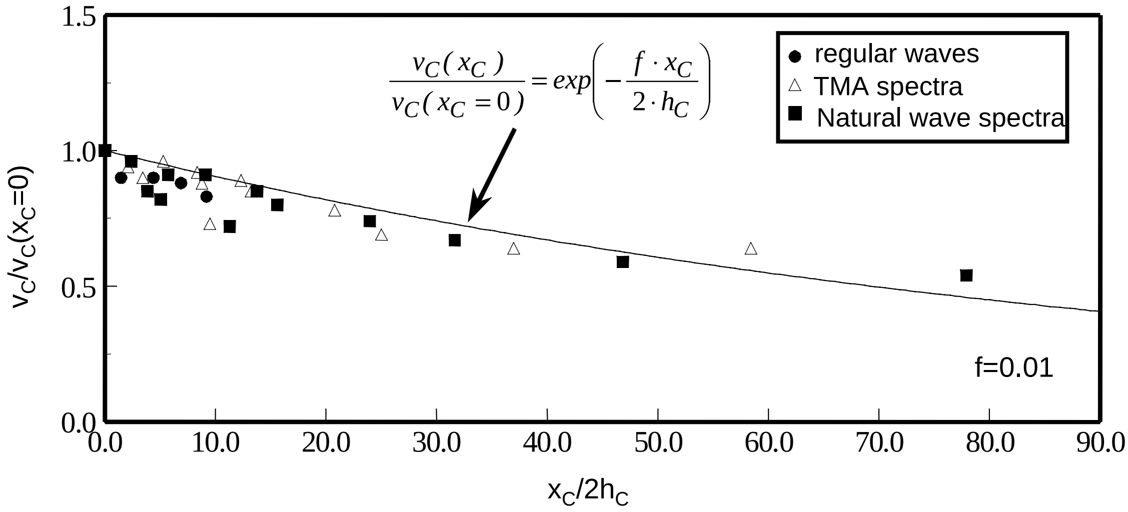


Fig. 9. Determination of the Friction Coefficient f for the Dike Crest
(Large Scale Model Results)

In Fig. 10 the influence of layer thickness $h_C(x_C=0)$ and bottom friction on the overtopping velocities on the dike crest is shown. The left panel shows, that the overtopping velocity decreases with decreasing layer thickness, due to the fact that the surface roughness becomes more important for smaller layer thicknesses than for higher layer thicknesses. On the other hand, the overtopping velocity decreases with increasing surface roughness. The right panel of Fig. 10 shows the influence of the friction coefficient on overtopping velocities for constant layer thickness $h_C(x_C=0)$.

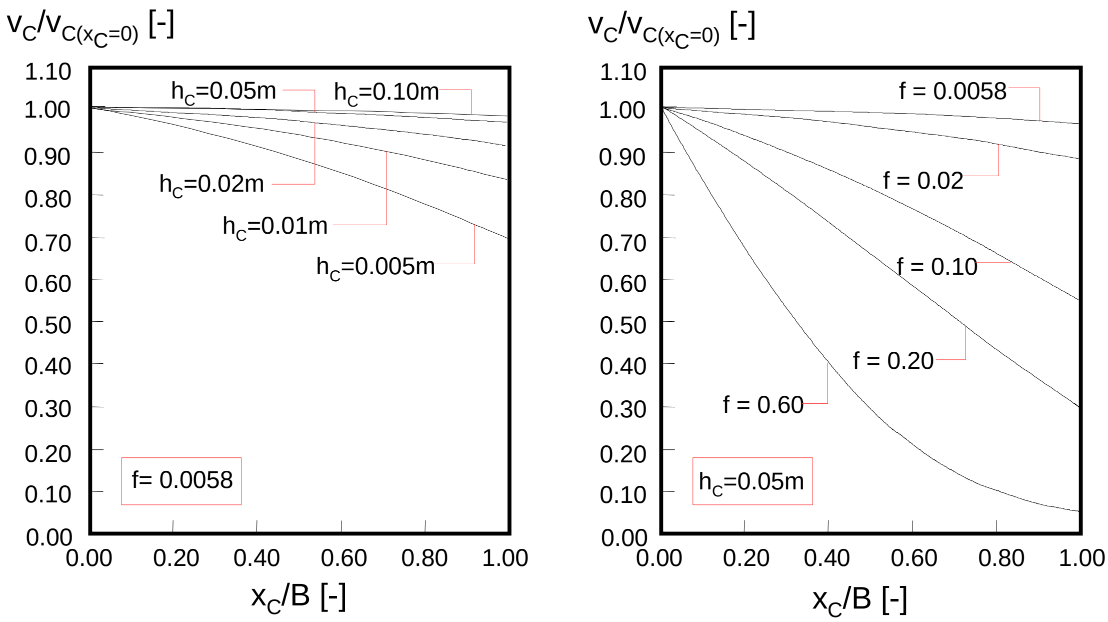


Fig. 10. Sensitivity Analysis for the Dike Crest
(left side: influence of layer thickness on overtopping velocity;
right side: influence of bottom friction on overtopping velocity)

Landward Slope

The overtopping water flows from the dike crest to the landward slope of the dike. The description of the overtopping process on the landward slope is very important with respect to dike failures which often occurred on the landward slope in the past. Therefore, an analytical function was developed which describes overtopping velocities and layer thicknesses on the landward slope as a function of the overtopping velocity at the end of the dike crest ($v_0 = v_C(x_C=B)$), the slope angle β of the landward side and the position s_B on the landward side with $s_B=0$ at the intersection between dike crest and landward slope. A definition sketch is given in Fig. 11. The following assumptions were made to derive an analytical function from the Navier-Stokes-equation:

- velocities vertical to the dike slope can be neglected
- the pressure term is almost constant over the dike crest
- viscous effects in flow direction are small

This results in the following formula:

$$v = \frac{v_0 + \frac{k_1 h}{f}\tanh\left(\frac{k_1\, t}{2}\right)}{1 + \frac{f\, v_0}{h\, k_1}\tanh\left(\frac{k_1\, t}{2}\right)} \tag{5}$$

with:

$$t \approx -\frac{v_0}{g\sin\beta} + \sqrt{\frac{v^2}{g^2\sin^2\beta} + \frac{2\,s}{g\sin\beta}} \quad \text{and} \quad k_1 = \sqrt{\frac{2\,f\,g\sin\beta}{h}}$$

The layer thickness h and the overtopping velocity v on the landward slope are unknown in Eq.(5). The layer thickness can be replaced in a first step by:

$$h = \frac{v_0 \cdot h_0}{v}$$

where v_0 and h_0 represent the overtopping velocity and the layer thickness at the beginning of the landward slope ($v_0=v_B(s_B=0)$, $h_0=h_B(s_B=0)$).

Detailed information on the derivation of Eq. (5) and a comparison to experimental data is given by Schüttrumpf (2001).

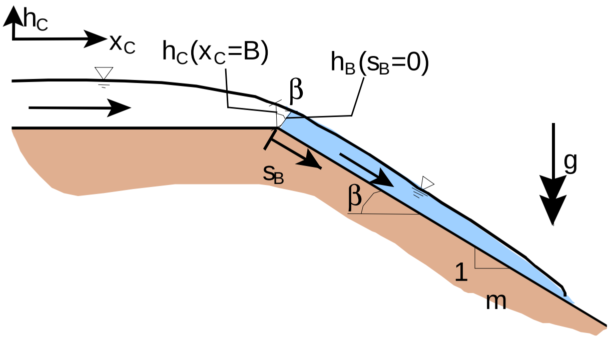


Fig. 11. Definition of Overtopping Flow Parameters on the landward Slope

In Fig. 12, the influence of the landward slope on overtopping velocities and layer thicknesses is shown. The landward slope was varied between 1:m=1:2 and 1:m=1:6. It is obvious that overtopping velocities increase for steeper slopes and related layer thicknesses decrease with increasing slope steepness. Therefore, the effect of erosion is reduced for smoother slopes while the effect of infiltration increases for smoother slopes. Nevertheless, erosion is more important for the initiation of dike failures and has to be considered first.

This is confirmed by results from large scale model tests with clay dikes (Möller et al., 2002).

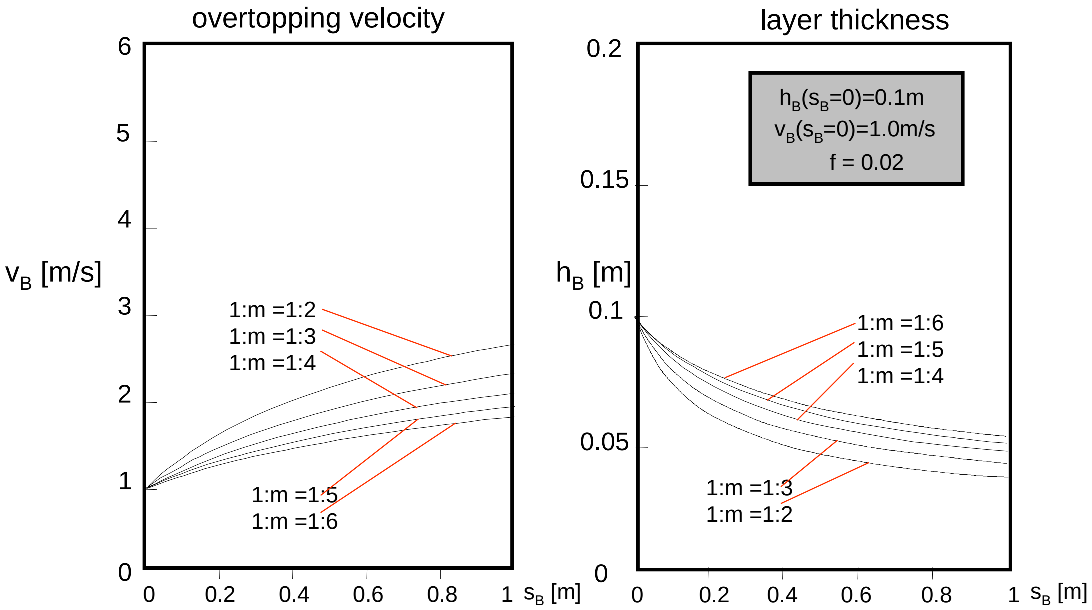


Fig. 12. Sensitivity Analysis for Overtopping Velocities and related Layer Thicknesses – Influence of the landward slope -

The bottom friction coefficient f has to be determined experimentally. Some references for the friction coefficient on wave run-up are given in literature (e.g. Van Gent, 1995; Cornett and Mansard, 1994, Schulz, 1992). Here, the bottom friction coefficient was determined by comparison of the experimental data to Eq. (5). Based on this comparison, the bottom friction coefficient was found to be f=0.0058 for the small scale model tests and f= 0.02 for the large scale tests. These values are comparable to references in literature. Van Gent (1995) recommends a friction coefficient f=0.02 for smooth slopes and Schulz (1992) determined friction coefficients between 0.017 and 0.022. Both authors worked with slopes built of concrete which are comparable to the slope in the Large Wave Flume. The wooden slope in small scale was smoother and therefore the friction coefficient is lower.

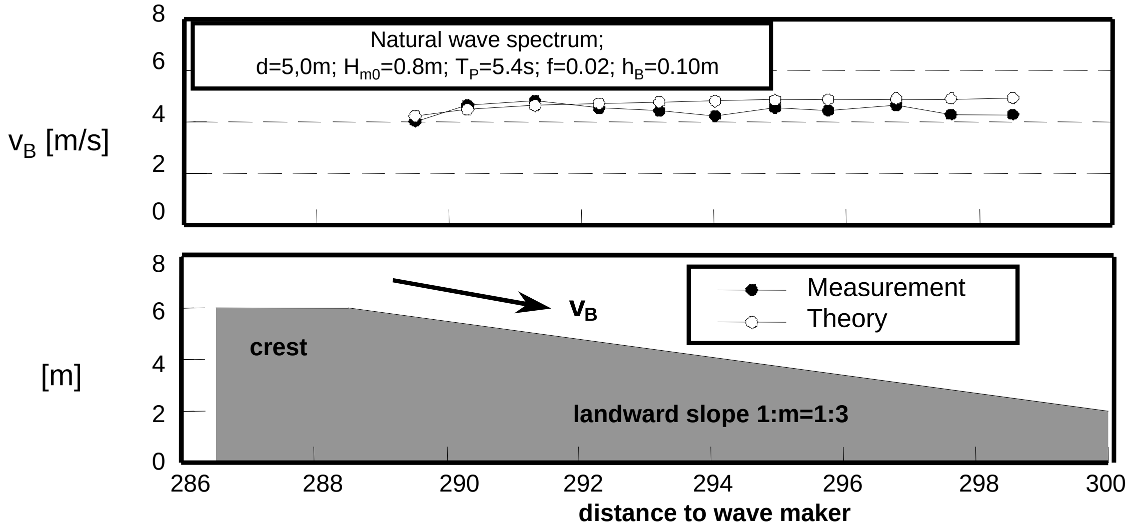


Fig. 13. Comparison of experimental Data and analytical Function (Example from Large Scale Model Tests)

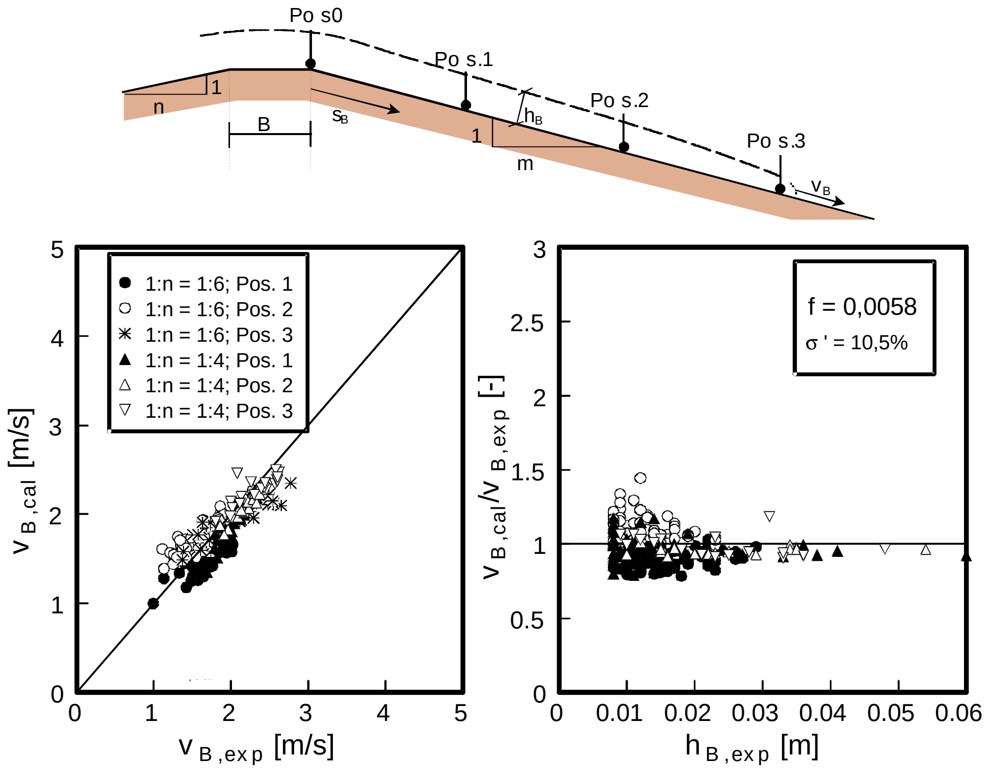


Fig. 14. Comparison of experimental Data and analytical Function
(Example from Small Scale Model Tests)

CONCLUSIONS

Average overtopping rates are not appropriate to describe the interaction between the overtopping flow and the failure mechanisms (infiltration and erosion) of a clay dike. Therefore, small and large scale model tests have been carried out to measure the overtopping velocities and related layer thicknesses on the seaward slope, the dike crest and the landward slope. Empirical and theoretical functions have been derived and verified by experimental data. Thus, a prediction method has been developed to describe the overtopping flow parameters which are responsible for the infiltration and erosion of a clay dike. The main task for future research consists in the determination and description of the infiltration and erosion processes of the clay.

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Hydraulic model tests
Layer thickness