CHAPTER 204

PROFILE DEVELOPMENT OF DUNES DUE TO OVERFLOW

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Abstract

The set-up and preliminary results of a series of model investigations on dune breaching is presented. Based on these 2DV-tests the insight into the processes related to the lowering of the crown of a sandy dam during overflow conditions has been enlarged significantly. Although dam erosion is mainly due to transport processes on the inner slope, the angle of the outer upstream slope showed to be very important also. Coarser sand results in larger erosion rates, whereas the effect of packing is only minor.

1. Introduction and background

The Technical Advisory Committee on Water Defences (TAW) in The Netherlands is completing a probabilistic design method for dunes and dikes, which determines its optimal cross section as a function of both construction and expected damage costs (deaths, loss of property, etc.) due to failure of the structure. In order to be able to determine the damage costs, it is necessary to predict the rate of inundation of the polder governed by the discharge rate through a breach.

The effect of a local dike breach in terms of costs, is mainly governed by the final level and speed of inundation. Apart from for example the dimensions of the low-lying polder behind the breach, this level will definitely be related to the flow rate through the breach and thus by its dimensions.

These dimensions, e.g. the breach width and depth, will not be constant. Moreover they increase in time, affecting the total discharge rate and thus the expected inundation level and damage costs.

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Detailed knowledge of the process of breach growth to predict the inflow rate is therefore indispensable.

2. Approach

2.1 Introduction

The process of breaching of dunes and dikes is a very complex phenomenon [Delft Hydraulics, 1988], as clearly confirmed by a field experiment described in [Visser et al., 1990]. As a first result, an useful theoretical model to describe the breaching process is presented by Visser [Visser and Steetzel, 1992].
The final objective of the long-term research program is to enlarge the insight in the obviously rather complicated three-dimensional processes which control the breach growth, this in order to assess the rate of water inflow through an eroding breach into a polder with a mathematical model. This study can be seen as a follow-up on dune erosion studies [Steetzel, 1993], in order to predict the profile development and consequences of a dune failure during a critical storm surge.

2.2 Successive research phases

The inflow rate through a breach will mainly be controlled by the decrease of the maximum crown level in the breach (say increase in breach depth) and the increase in the width of the breach along the axis of the defence structure.

Focusing in more detail on a specific cross-section, the development of the breach dimensions, say breach width and breach depth, will depend on:
- the outer hydraulic conditions (water level, intensity of wave attack),
- the dimensions of the structure (crown height, crown length and both the inner and outer slopes) and
- its composition (material present and kind of foundation) as well as
- the inner condition, namely the level of the polder.

Some physical model tests have been carried out to study the breaching process for a sandy structure. The results of these tests are used to develop, calibrate and (afterwards) verify a mathematical model. To study erosion processes in detail, initially a series of two-dimensional model tests were conducted in the Schelde flume of the Delft Hydraulics [Delft Hydraulics, 1991]. Simultaneously, a general applicable mathematical model is being developed in order to compute and predict profile developments and inflow rates for all kinds of hydraulic and geometric conditions.
In a following phase also some tests on three-dimensional breaching have been carried out in a basin, merely to study the processes which control the growth of the breach width.

2.3 Outline of present contribution

This paper focuses in more detail on the set-up and results of a series of first model investigations on 2DV-breach growth, which were carried out at the end of 1991. These tests provide the development of the breach along the breach axis. At the end of this paper some concluding remarks are made on both the results of these tests and the next phases of the research program. A related paper on this subject is presented by Visser and Steetzel [1992].

3. Model investigations

3.1 Model facility

The vertical development of a uniform structure due to overflowing water was investigated in the 50 meter long Schelde flume of the Delft Hydraulics, as shown schematically in Figure 1. The effective width of the flume at the dam location was 0.40 m.
A pumping system was installed in the flume to recirculate the overflowing water in order to maintain a more or less constant high outer water level for as long as possible.

3.2 Initial cross-section

At about 35 m from the wave board, a sandy dike-like structure was built having a 1.30 m long ($L_{c,0}$) and a 0.70 m high horizontal crown ($Z_{c,0}$). At the top of the crown a temporary defence structure was placed.
In these tests it is assumed that for some reason an initial, small breach is present at the beginning of a test (at $t = t_0$).
Consequently, in these 2DV-tests the initial outer water level was chosen to exceed the crown level by 0.05 m. After removal of the sandbag (in fact the start of a test denoted as $t=t_0$), water started flowing down the inner slope and the erosion of the dam occurred.

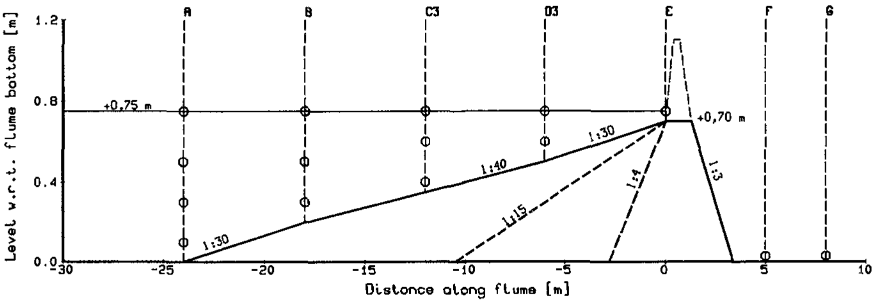

Figure 1 Model set-up, initial profiles (showing three slopes) and measuring positions of water levels and velocities (latter denoted by o-symbols)

In this test set-up three different outer slopes have been tested, ranging from 1 in 4 to 1 in about 35. Furthermore the grain size as well as the bed porosity of the dam have been varied.

3.3 Instrumentation

In order to allow a good recording of the erosion process, extensive instrumentation was installed in the flume.
In the upstream inflow section, four sets of two electromagnetic velocity meters were placed. Furthermore at 7 positions wave gauges were present to record the development of the local water level.

At the position of the sand dam itself, the glass wall of the flume was utilized with a square (0.10 m) grid. By recording each of the tests with three simultaneously operating video-cameras, the development of the dam profile has been determined by analyzing these recordings with great accuracy.

Model set-up, including initial profiles and position of measuring devices is presented in Figure 1. In this way the profile development due to initial overflow (video-recordings) and a range of seven instantaneous velocity profiles and water depths were monitored during the breaching process.

3.4 Test program

The relative, quantitative effect of next parameters has been investigated:

- the seaward bottom slope, ranging from a 1:4 (dike) to 1:15 and a 1:30/40 slope (schematized dune erosion profile);
- the effect of waves on the breaching process, by comparing profile development with and without the presence of wave attack;
- the effect of sediment diameter, by comparing results of D_{50} = 105 μm and D_{50} = 218 μm;
- the effect of porosity, by comparing results of two different porosities (with typical values of 38 and 45 % respectively).

An overview of the tests performed is presented in Table 1.

test number	brief description
T0	Essay experiment
T1, T2 and T3	Set of similar tests with mutually different angles of the outer slope
T4	Repetition of previous test (T3) with additional wave attack
T5 and T6	Repetition of both test T1 and T3 respectively using coarser sand for dam construction
T5A	Repetition of test T5 to check on the reproducibility of a test
T7	Repetition of test T5 for a more loosely packed dam

Table 1 Overview of test program

In total, the development of the sandy dam has been investigated in nine tests. In test T0 - T4 fine sand was utilized, while in the other tests (T5 - T7) coarse dune sand was used to construct the dam.

4. Direct test results

4.1 General

From each of the tests performed, two sets of data were obtained. The direct results, as discussed in this section, consist out of the observed profile development as well as the recordings of water level and water velocities during the erosion process.
After analyzing these data, detailed information on the discharge rates and the apparent transport rates have also been obtained. Some examples of latter dataset are presented in the next chapter.

4.2 Profile developments

The schematic development of the cross-section of a dam during the erosion process is shown in Figure 2.

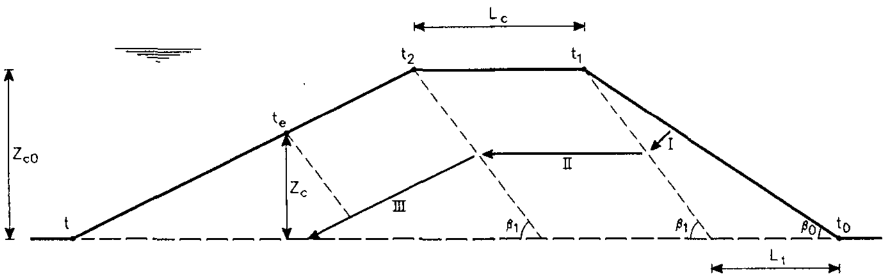

Figure 2 Schematic three-phase development of cross-section: I - increasing steepness of inner slope, II - decreasing crown length, III - decreasing crown level

In these tests, three subsequent stages (I, II and III respectively) can be distinguished. Initially the increasing transport rate on the inner slope results in a steepening of this slope up to a critical value. In phase II, the erosion of this slope remains nearly constant in time, resulting in a decrease of the length of the crown (L_c). After erosion of the complete crown (at $t = t_2$), the maximum crown level (Z_c) starts to reduce. During this third phase, the discharge rate starts to increase strongly.

The grid on the glass wall allowed a direct assessment of both the instantaneous dam profile as well as the water depth contour. Figure 3 shows the observed development of the cross-shore profile (based on the analyses of the video-recordings) in test T5A. The numbers indicate the time in seconds with respect to the actual start of the test. Contours are presented at 20 seconds intervals.

Lowering of the crown started after about 140 s (= t_2 - t_0). The average speed of reduction of the crown length amounts about 0.01 m/s. As can be observed, the total duration of such a test lasted only 5 to 6 minutes. At the end the total dam was washed out and, for the most part, in suspension circulating in the flume.

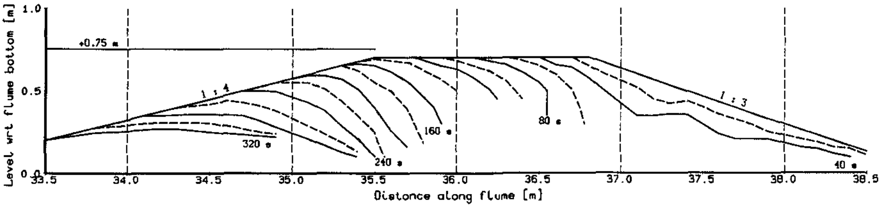

Figure 3 Measured development of cross-section during erosion process (for test T5A)

4.3 Water levels and velocities

The recordings of both water level and flow velocities are very important, since the water motion over the inner slope dominates the process under investigation. The observed velocities on the inner slope range from 0.5 to 3.0 m/s. Moreover the data at the begin of the inflow section will be used as a boundary condition for the mathematical model.

4.4 Additional measurements

During the test program additional measurements were carried out to assess water temperature, grain size distribution and actual volumetric porosity.

5. Interpretation of results

5.1 Introduction

A thorough analysis of the results has provided valuable information on the water motion as well as on the sediment transports during the breaching process. The outcomes will also be used in order to check and improve the computational model. As can be seen readily from the former figure, the erosion is taking place at the inner slope of the dam.

5.2 Crown development

The development of the maximum crown elevation for all tests is shown in Figure 4.
In the first stage of decreasing crown length, the crown level remains constant. Next, say from about 140 s, the level decreases. The actual rate of decrease differs for some tests due to the different test conditions. Most clear is the effect of the outer slope,

showing a relative decrease of this rate for the more gentle slopes (as present in tests T2, T3 and T6).

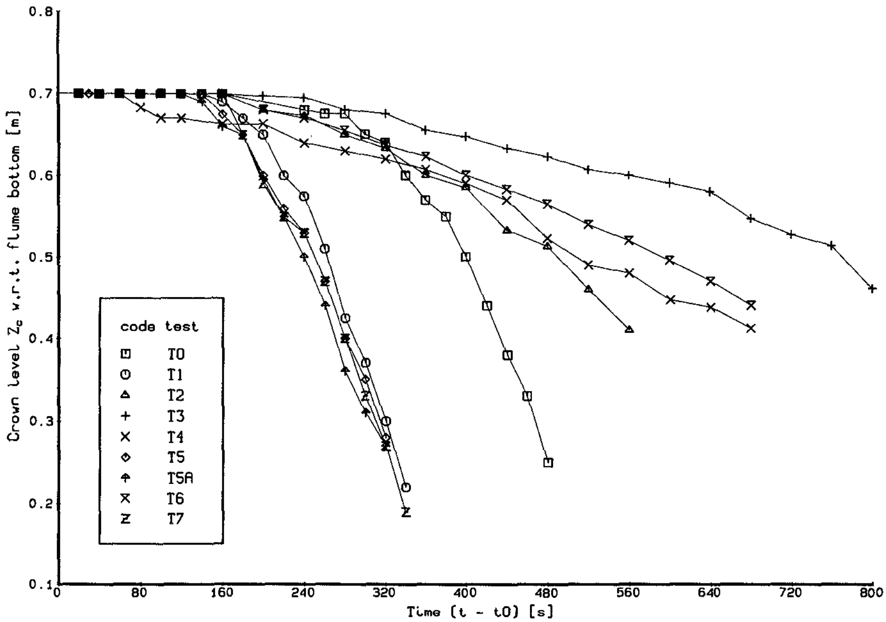

Figure 4 Overview of development of maximum crown level Z_c for all nine tests performed

5.3 Crown discharge rates

From the simultaneously measured velocities and water levels the magnitude of the rate of crown discharge has been estimated. An example of the computed development (for the same test T5A) is shown in Figure 5. In this figure both the instantaneous estimate at a frequency of 25 Hz (denoted by the small dots) as the filtered signal are presented. Furthermore the actual start of the test (denoted by t_0) and the start of lowering of the crown level (denoted by t_2) can be observed. At $t = t_2$ the discharge starts to increase dramatically up to a more or less constant magnitude which is related to the installed pump capacity.

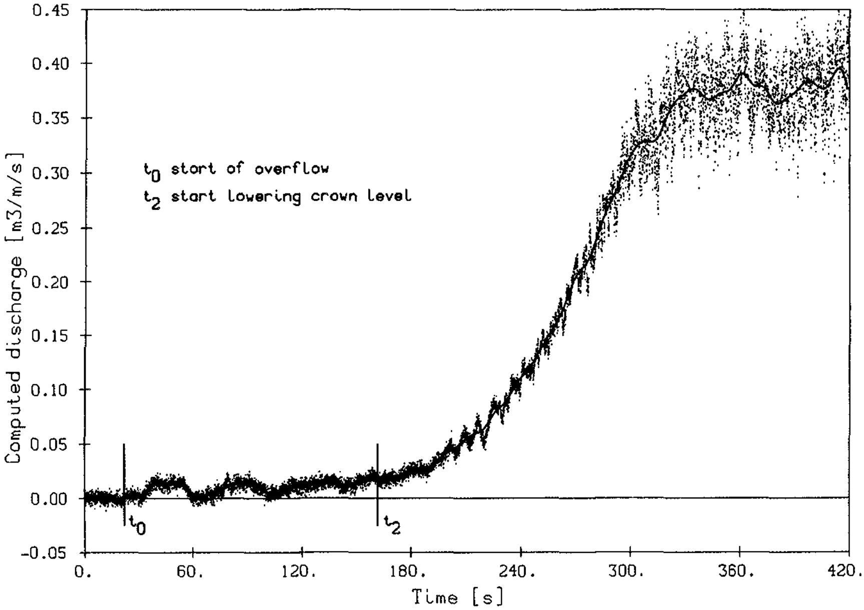

Figure 5 Development of computed (crown) discharge Q_c (for test T5A); both instantaneous estimate and smoothed signal (denoted by dots and line respectively) are shown

5.4 Transport rates

As a result of the observed and recorded profile development, the apparent transport rate S was computed from the sediment balance equation at several moments and positions for each test. Figure 6 shows in the down-left corner a detail of the inner slope of the dam in test T5A at $(t - t_0) = 100$ s.
The calculated transport distribution on a horizontal grid is shown at the top of the figure. The same distribution on a vertical grid is presented on the right, showing a near-linear downward increase of the transport and thus indicating a more or less equilibrium shape of the inner slope for this particular case. From visual observations of the transport process it has been concluded that this increasing transport rate is related to an increase in the thickness of the near-bottom suspension layer (sheetflow layer). The mean concentration within this layer has been estimated to be about 40 to 50% by volume.

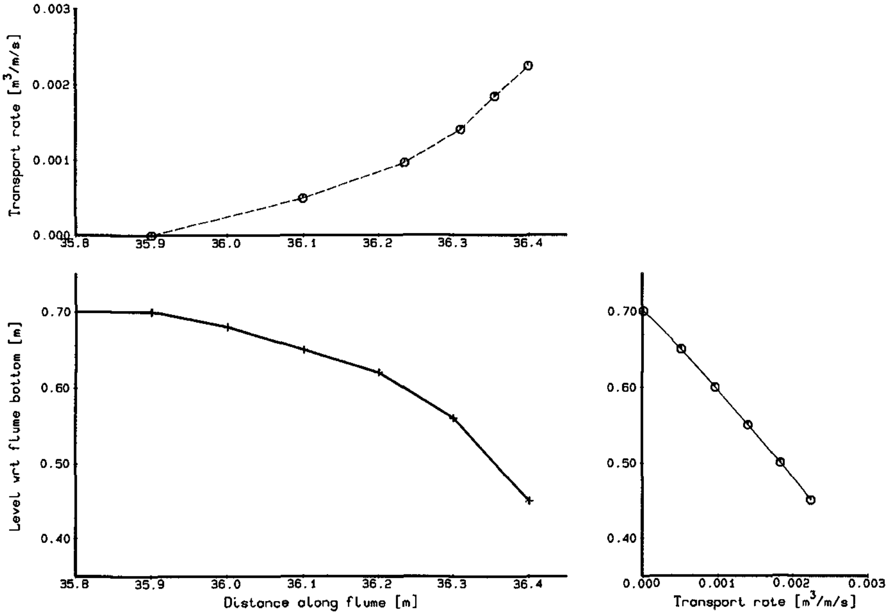

Figure 6 Computed transport distribution (S) at inner slope of test T5A after $(t - t_0) = 100$ s; both S = F(x) (upper figure) and S = F(z) (right-hand figure) are presented

6. Conclusions

6.1 General

Studying breaching processes in a model facility is difficult because of the speed of the processes involved, although in the present tests very accurate data on the breaching process have been obtained. Moreover the repetition of an identical test (test T5 and T5A) showed an almost perfect reproduction of the principal results. Some of the main conclusions are summarized hereafter.

6.2 Effect of seaward bottom slope

The influence of the seaward bottom slope is very important and primarily related due to volumetric effects. A relatively steeper outer slope results in a larger erosion rate.

6.3 Presence of wave attack

The presence of wave attack leads to accelerated erosion and speeds up the erosion process significantly.

6.4 Sand diameter

Coarser sand increases the erosion rate by 15 to 25 %. This seems mainly due to the effects of hindered erosion present in case of finer material.

6.5 Sand porosity

Effects of sand porosity are relatively small, although a loosely packed dam shows an about 5 % increased transport rate (for coarse sand).

7. Next research items

7.1 Introduction

Although very interesting and useful findings have already been obtained, a continuing further analyses of the large amount of available data will enlarge the insight in the processes responsible for the breaching phenomena further.

7.2 Computational model

In the development of the numerical mathematical model, one of the major problems to be dealt with is the formulation of the transport rates.
The sediment transport at high velocities is not yet well understood. Literature review, e.g. [Voogt et al, 1991], indicated that standard formulae tend to overestimate the transport rate. The transport on the inner slope seems to be affected by at least non-local effects and hindered erosion.
The dynamical, computational model will be based on the water motion according to the quasi-steady 'long wave' equations. Crown discharges will be iteratively derived using 'backward fitting', after which the super critical downward flow along the inner slope is computed. The sediment transports will initially be based on an adapted energetics-based Bagnold-formula (see [Visser, 1988]), although ongoing analyses of all the available test results may lead to other formulas.

7.3 Further testing

Some additional tests on three-dimensional breaching in a basin have been carried out also. Next phases of the research program will have to enlarge the insight into the effect of clay and the presence of partial revetments on the breaching process.

Both the results of the computational model as the outcomes of the 2DH/3D-model investigations will be discussed in a forthcoming paper.

8. Acknowledgements

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