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# Breach Erosion in Dikes

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**A model for breach erosion in dikes is outlined. The model is based on the five-stage breach erosion process as described in [1] and [2]. For the final two stages three breach types are distinguished in the model, depending on the erodibility of the base of the dike, the presence (or absence) of a solid toe protection on the outer slope and the presence and erodibility of a high foreland. The model version for sand-dikes has been calibrated with the data of a field experiment and tested to the data of a 3D laboratory experiment, yielding good agreement. The confrontation of the model with the data of the failure of a prototype dike in the Netherlands yields results more or less in agreement with an eye-witness report. The model version for clay-dikes has been calibrated and tested with the data of a 2D laboratory experiment, the data of the laboratory experiment of the EC IMPACT Project and the data of a prototype dike-burst in China. The agreements between model predictions and the data are fairly good.**

## I. INTRODUCTION

The Netherlands has many kilometers of dikes to protect the land against flooding. Construction of dikes started some 1000 years ago and since then new dikes have been built and existing dikes have been strengthened to cope with the ongoing processes of land-subsidence and sea-level rise. Nevertheless, the Netherlands has a long history of flooding, with about 200 major floods reported, both along the rivers and in the coastal areas, some of these with many deaths (e.g. the St. Aagten Flood of 1287 with tens of thousands people drowned, the St. Elisabeth Flood of 1404 and the Storm Surge of 1953, both with thousands of deaths). Very surprisingly, until recently, the knowledge of the process of breaching of dikes was very poor, not only in the Netherlands but worldwide. Also prototype data of dike breaching are scarce and far from complete. Most information has been based on eye-witness reports of past dike-bursts.

Modeling of the dike breaching process, so also knowledge of this process, is of importance to both the design method of dikes based on a risk-norm and the development of evacuation plans for polders in case of a dike failure. In the Netherlands preparations are going on to substitute the present design method for dikes (based on an exceedance frequency of the water level) by an inundation risk approach. In this new method safety levels will be expressed in terms of risks (combinations of inundation chances with the consequences of flooding), see [3]. In order to determine the consequences of inundation, it is necessary to be able to predict the development of the breach. Evacuation plans have to be made in the Netherlands for all dike ring areas since the near flooding of polders along the river Rhine in 1995. The present evacuation plans were determined using a very simple description for the breach growth; a better breach erosion model is required to improve these evacuation plans.

The process of dike-breaching has similarities to breaching in earth dams and coastal sand-barriers. Earth dams (to make a distinction with dikes) are relatively high embankments, with relatively short lengths, having in general water on both sides, that are constructed with earth and rock to create reservoirs for water supply, hydro-electric power generation, flood control, etc. During the last forty years, and particularly since the 1980's, progress has been made in modeling of earth dam breaching and consequently also in flood forecasting. Many numerical models are available now for the simulation of breach erosion in earth dams (see the overview given in [4]). The calibration and validation of these models remains, however, problematic due to the lack of good empirical data.

Breaching of coastal barrier islands and spits is a common natural feature. Breaches in sand-barriers can be initiated in four ways: (1) inundation from the sea combined with wave action, (2) elevation of the water level in the lagoon, (3) narrowing of a barrier island by reduction of sediment supplied through longshore transport and (4) artificially for flood protection and to increase the water quality (see [5]). Breaching of some coastal barriers in the USA and Australia has been documented in [6], [7], [8], among others. For some years also some relatively simple models exists to simulate coastal barrier breaching, see [9] and [5].

Research on dike breaching has been initiated in the last few decades, see e.g. [10], [11], [12], [13], [14], [15], [1], [16]), [17], [18] and [2]. The results obtained so far are encouraging: good insight into the breaching process (see also Chapter III) has been obtained and some models are available for the simulation of breach growth in both sand-dikes and clay-dikes (see also Chapter IV). As for earth-dams, the calibration and validation of these models is still a major problem due to the lack of good empirical data. This applies especially to the models for clay-dikes (see Chapter V).

This paper summarizes the results of the research work on breaching of sand-dikes (see [1]) and clay-dikes (see [2]) performed at Delft University of Technology (DUT) in the period 1986-2006.

## II. OBJECTIVE

The aim of the present investigation is a mathematical model that predicts the breach development and the discharge through the breach in case of a dike-burst as function of relevant parameters as the cross-section of the dike, the structure of the dike and the hydraulic conditions. The first version (see [1]) has been focused on the breach erosion process in sand-dikes. The present model has also a version for clay-dikes (see [2]).

It is assumed that the body of the dike is homogeneous and that it consists of sand, or clay, or a mixture of sand, silt and clay, and that, after the formation of an initial breach at the top of the dike the revetments on the slopes do not decelerate the erosion process. As yet possible effects of waves have not been included in the model.

## III. Breach Erosion Process

It is assumed that the breach erosion starts (at time $t = t_0$) with the flow of water through a small initial breach at the top of the dike with a trapezoidal cross-section. In general five stages (see Fig. 1) can be distinguished in the process of breach erosion, both for sand-dikes (as described in [1]) and clay-dikes (see [2]). In Stages I and II ($t_0 < t \leq t_2$), the breach eats its way into the dike, decreasing gradually the width and the height of the dike in the breach. In Stage III ($t_2 < t \leq t_3$) the breach growth accelerates, and consequently also the discharge through the breach. After the wash-out of the dike in the breach at the end of Stage III, the breach grows further in Stage IV ($t_3 < t \leq t_4$), mainly laterally. In Stage V ($t_4 < t \leq t_5$) backwater in the polder decelerates the flow in the breach, and consequently also the increase of the breach width. Raising backwater ultimately stops the flow of water through the breach.

In Stage I ($t_0 < t \leq t_1$), erosion occurs along the inner slope of the dike and, depending on the flow velocity, possibly also along the dike crest. The flow along the inner slopes accelerates, consequently the erosion along this slope increases, steepening the slope until a critical slope angle is achieved at $t = t_1$. This critical gradient is held later on by the inner slope throughout Stages II and III. In sand-dikes the breach erosion process in Stages I, II and III is dominated by shear erosion (see [1]), which leads to a gradual and relatively uniform retreat of the inner slope. However, in clay-dikes, when the inner slope of the dike has been steepened to the critical gradient, the steep slope acts as a headcut. Headcut erosion, including flow shear erosion, fluidization of the headcut slope surface, impinging jet scour of the dike foundation and discrete soil mechanical slope mass failure from the headcut dominates the breach development (see [19], [20] and [2]). In principle, in Stages I, II and III the breach develops mainly vertically with only ignorable widening, for both sand-dikes and clay-dikes.

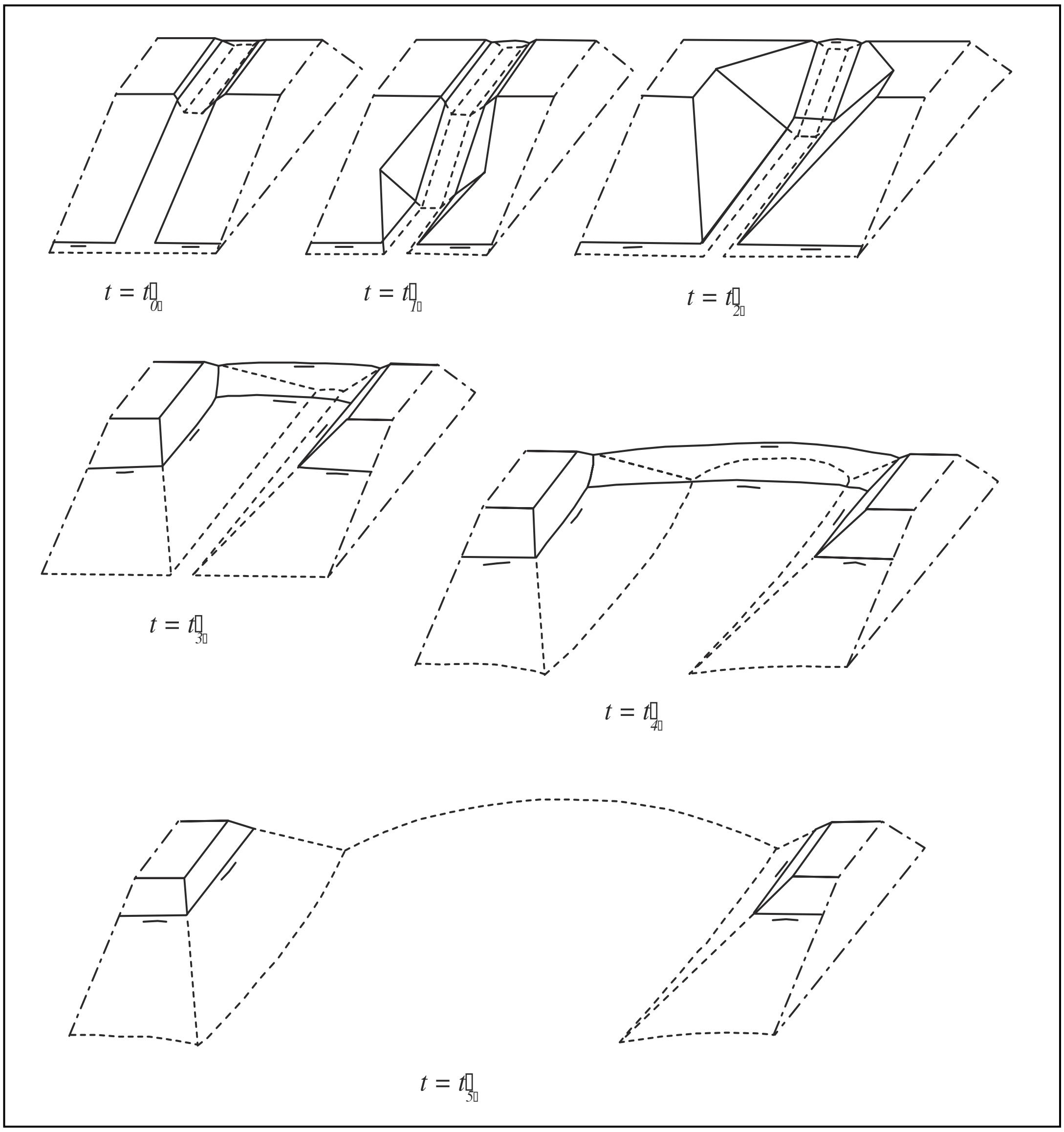


Figure 1. Schematic illustration of breach development in a sand-dike.

The breach erosion process in Stages IV and V depends on the erodibility of the foundation of the dike, and on the stability of the toe protection on the outer slope of the dike (if any) or the height and erodibility of the foreland in cases where the dike foundation has low resistance against erosion. Hence, three types of breaches (Types A, B, and C) can be distinguished in Stages IV and V, depending on these geometrical and material conditions (see [1], [2] and [20]). Generally, the dominating mechanisms of breach erosion in Stages IV and V are the flow shear erosion along the side-slopes of the breach and the resultant discrete soil mechanical breach side-slope instability. Fig. 2 shows the breach development in Stages IV and V with a toe protection on the outer slope of the dike.

## IV. Mathematical Model

The model is based on the five-step breach erosion process shortly outlined above.

The flow through the breach and the flow velocities in the breach are calculated with broad-crested weir formulae (see (1) and (2)), i.e. for critical discharge in Stages I through IV and for subcritical discharge in Stage V.

$$Q = m\left(\frac{2}{3}\right)^{3/2}\sqrt{g}B\left(H_w - Z_{br}\right)^{3/2} \quad \text{for } t_0 < t \le t_4 \quad (1)$$

$$Q = m\sqrt{2g}B\left(H_w - H_p\right)^{1/2}\left(H_p - Z_{br}\right) \quad \text{for } t_4 < t \le t_5 \quad (2)$$

in which $Q$ is the discharge through the breach ($m^3$/s), $m$ is the discharge coefficient (non-dimensional), $g$ is the gravity acceleration (m/$s^2$), $B$ is the breach width averaged over the water depth (m), $H_w$ is the outer water level (m), $Z_{br}$ is the height of the breach bottom (m), and $H_p$ is the level of the backwater in the polder (m). The discharge coefficient $m$ is about 1 for Types A and C breaches and about 1.5 for a Type B breach. In a Type B breach the erosion of the relatively high foreland creates a circular or elliptical spillway with a length that is a factor $m$ larger than the breach width.

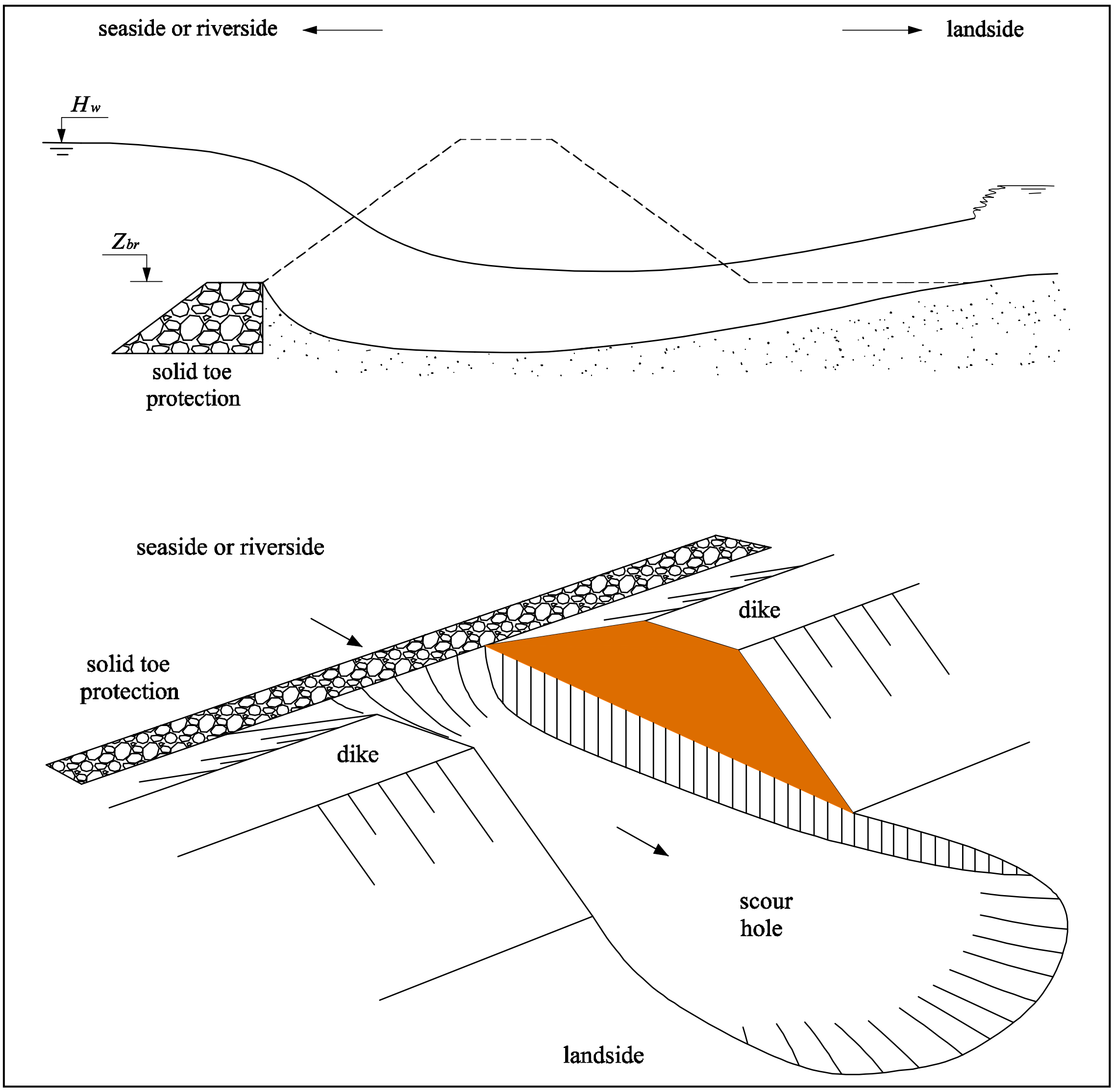


Figure 2. Breach development in Stages IV and V when vertical erosion at the breach inflow is obstructed by a toe protection on the outer slope of the dike (Type A breach).

An essential part of a breach erosion model is the description of the entrainment of sediment, both for sand-dikes and clay-dikes. For each stage separate descriptions for the erosion rate can be implemented. However, up-to-date best results have been obtained:

- for sand-dikes with Galappatti's (see [21] and [22]) description for the pick-up of sediment combined with the sediment transport formulae of Bagnold-Visser ([12], see also [1]) or Van Rijn (see [23] and [24]) in Stages I, II and III, and Van Rijn ([23], [24]) in Stages IV and V (see [1]);
- for clay-dikes with the frequently used excess shear stress equation representing the detachment process of cohesive sediment: $E = M\left(\tau_b - \tau_c\right)$, in which $E$ is the erosion rate (m/s), $M$ is a material-dependent coefficient describing the soil erodibility (s-m$^2$/kg), $\tau_b$ is the bed shear stress (N/m$^2$), and $\tau_c$ is the critical shear stress for erosion of the soil (N/m$^2$), see [2] and [20].

The erosion at a headcut during the breach erosion process of clay-dikes, including the impinging jet scour of the dike foundation (if any), headcut undermining and discrete slope mass failure, etc, is simulated through the mathematical model developed in [19] (see also [2] and [20]).

The breach growth and the breach discharge in Stages IV and V are computed by the model depending on the geometrical and material conditions of the foundation and the foreland of the dike. Fig. 3 shows the breach growth of a Type A breach in sand-dikes. In this situation, the vertical erosion at the breach inflow is prevented by a solid dike foundation, or by a solid toe protection on the outer slope of the dike, or by a solid, relatively high foreland (solid here means: with relatively high resistance against erosion).

The increase in time of the breach width at the top of the dike in Stages IV and V in a sand-dike is described by (see [1])

$$\frac{\mathrm{d}B_t}{\mathrm{d}t} = \frac{2}{\tan\gamma_1} E_{sl} \tag{3}$$

in which $B_t$ is the breach width at the dike top (m), $\gamma_1$ is the critical value of the angle of the breach side-slopes ($^{\mathrm{o}}$), and $E_{sl}$ is the erosion rate in vertical direction at the toe of the side-slopes (m/s).

For clay-dikes, the breach width increase in Stages IV and V is given by (see [2])

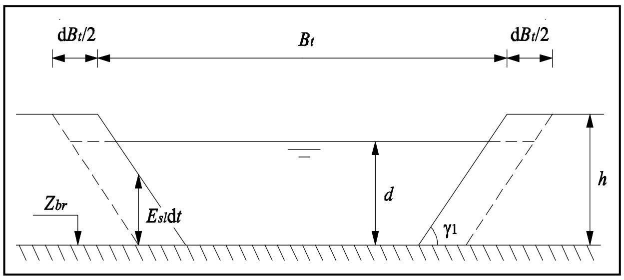


Figure 3. Growth of breach width in a Type A breach in sand-dikes in stages IV and V.

$$\frac{\mathrm{d}B_t}{\mathrm{d}t} = \frac{2}{\sin\gamma_1} E_{sl} \tag{4}$$

in which $E_{sl}$ is defined as the erosion rate at the toe of the side-slopes perpendicular to the slope (m/s).

## V. Experiments

For the calibration and validation of the model the following experiments were executed:

### A. *The Zwin'94 field experiment*

The Zwin'94 experiment was performed in October 1994 in the Zwin Channel, a tidal inlet at the Dutch-Belgian border connecting the nature-reserve the Zwin with the North Sea (see [1]). The Zwin area measures about 1.5 km$^2$; the mean tidal prism is about 350000 m$^3$. The experiment was done in quiet autumn weather, with negligible wave heights against the sand-dike.

A sand-dike closing of the Zwin Channel was built with a height of 2.6 m above the channel bottom, a width at the crest of 8 m and a total length of about 250 m. The inclination of the outer slope was 1 : 1.6, that of the inner slope 1 : 3. A small trapezoidal pilot channel, 0.8 m deep and with a width of about 1 m at the breach bottom and about 3.6 m at the dike crest was made in the upper part of the dam to ensure breaching near the middle of the Zwin Channel.

The experiment started at $t = t_0 = 0$, about 20 minutes before high water, with the flow of water through the pilot channel. At three locations upstream and three locations downstream from the breach, current velocity meters (Ott propeller type) and pressure probes measured continuously horizontal flow velocities and water elevations, respectively. The breach development was both video-taped and photographed (marks put in the dike-top allowed the observation of the dimensions of the breach at different times from the video-images, slides and photos). A total number of 40 vibration probes, buried in the sandy bottom of the Zwin Channel, detected the development of the breach under water in Stages IV and V. Each probe acted as a burglar-alarm: by measuring its own rate of vibration it could detect when the erosion process had exposed it to the flowing water. The signals of all vibration probes were recorded on the hard disks of personal computers. At $t = t_5 \approx 60$ min the flow velocities in the breach had become so small that the erosion process stopped.

The Zwin'94 field experiment has clearly confirmed the five-step breach erosion mechanism as described in Chapter III. The development of the breach width in time is shown in Fig. 4.

The data set of the Zwin'94 experiment is very useful for the validation of mathematical breach erosion models. Reference is made to [1] and [14] for details about the data set resulting from this experiment.

### B. *3D laboratory experiment in basin of DUT*

The 3D laboratory experiment was performed in 1996 in the 34.0 m long, 16.6 m wide and 0.7 m deep (wave) basin of the Laboratory of Fluid Mechanics of Delft University of Technology. The experiment was prepared by C.P. Caan as part of his MSc thesis project at the Delft University of Technology, see [25]. In the Zwin'94 experiment the scour hole could only be measured in a limited number of points. Hence, the laboratory experiment was especially aimed at an accurate observation of the development of the scour hole and its upstream spillway in Stages IV and V.

The small-scale sand-dike was built normal to a 9.0 m long and 0.75 m high glass-wall on a 0.50 m thick sand-bed. The $D_{10}$, $D_{50}$ and $D_{90}$ of the sand of both the dike and the bed are $D_{10}$ = 0.070 mm, $D_{50}$ = 0.088 mm and $D_{90}$ = 0.120 mm, respectively. The laboratory dike had a height of 15 cm and a width at the crest of 20 cm. The inclination of the outer slope was 1 : 2 and that of the inner slope 1 : 4. A small pilot channel was made in the upper part of the dike at the glass-wall to ensure breaching started near the glass-wall.

Water was pumped into the inflow section of the basin through two pipes at a maximum capacity of 0.66 $m^3$/s. The water level against the dike in the upstream section was kept constant as good and long as possible by increasing the rate of inflow to the basin.

Water level measurements were done with wave height probes in three positions in the upstream part of the basin and in one position in the downstream section. Flow velocity measurements were done using electromagnetic flow velocity meters in two positions upstream of the breach and one in the breach. The data of these instruments were recorded on a personal computer. The breach development was both video-taped (through the glass-wall) and photographed (from above). The increase of the breach width in time is shown in Fig. 5.

*C. 2D laboratory experiment in flume of DUT*

The 2D laboratory experiment was performed in 2005 in a 35.5 m long, 0.80 m wide and 0.85 m deep flume of the Laboratory of Fluid Mechanics of Delft University of Technology. The aim of this experiment has been to observe the breach erosion process in clay-dikes in Stages I, II and III. The small-scale dike had a height of 75 cm, a width of 40 cm and a length of the crest of 60 cm. The inclination of both slopes was 1 : 2.

Water level measurements were done with wave height probes in four locations (three upstream and one downstream from the dike). Flow velocity measurements were done using electromagnetic flow velocity meters in two locations upstream of the breach and in one downstream from the breach. The breach development was both video-taped (through the glass-wall) and photographed (from above and through the glass-wall).

In this experiment five tests were done, one with a small-scale sand-dike, four with clay-dikes constructed with different mixtures of fine sand, silt and clay. Much attention was paid to get a proper sand-silt-clay mixture. For details of this experiment readers are referred to [2].

## VI. MODEL VALIDATION

The model version for sand-dikes has been calibrated with the data of the Zwin'94 field experiment and validated against the data of the laboratory experiment (see [1]). The agreement of the model predictions with the data of these two experiments is good (see e.g. Fig. 4 and Fig. 5). Fig. 4 shows the model prediction for the breach width increase in the Zwin'94 experiment by applying Bagnold-Visser ([12]) in Stages I, II and III and Van Rijn (1984, see [1]) in Stages IV and V. Fig. 5 shows the model prediction for the growth of the breach width in the 3D laboratory experiment by applying Bagnold-Visser ([12]) in Stages I, II and III and Van Rijn (1984) in Stages IV and V. The confrontation of the model with the failure of the Noord Dike in Papendrecht (a sand-dike) in the Netherlands during the 1953 Storm Surge indicates that the final breach width $B_t \approx 110$ m was present after about 2.5 hr, which is more or less in agreement with a rough eye-witness report (see [1]).

The model version for clay-dikes has been calibrated with the data of two 2D DUT laboratory experiments and two 3D EC IMPACT (Investigation of Extreme Flood Processes and Uncertainty) Project laboratory experiments on clay-dike breaching (see [2]). The model predictions are in good agreement with the experimental data (see e.g. Fig. 6). Validation of the model with the data of other two 2D DUT laboratory experiments yields reasonable agreement between the model predictions and the measurements (see e.g. Fig. 7, see also [2]). Finally, the model has been confronted with a prototype dike failure in China in 1998 (see [2]). The predicted final breach width 274 m is about 39.7% smaller than the observed 390 m. The predicted 5.6 $\times 10^8$ $m^3$ of diverted floodwater volume is close to the investigation-based estimation of $5.2 \times 10^8$ $m^3$.

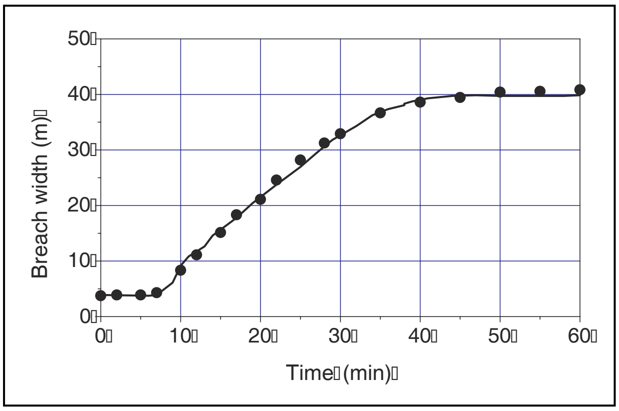


Figure 4. Comparison of predicted (solid line) and observed (dots) breach width at the dike crest for the Zwin'94 sand-dike experiment.

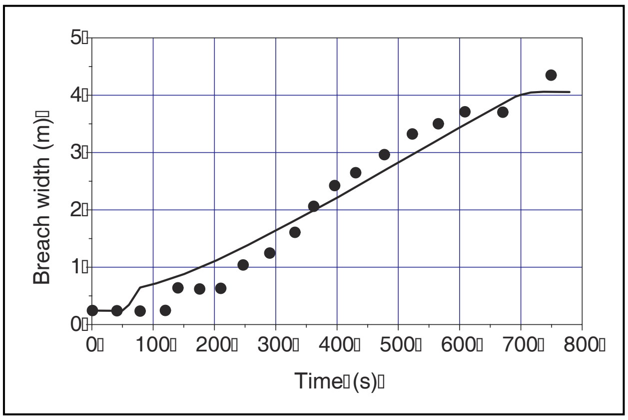


Figure 5. Comparison of predicted (solid line) and observed (dots) breach width at the dike crest for the laboratory sand-dike experiment.

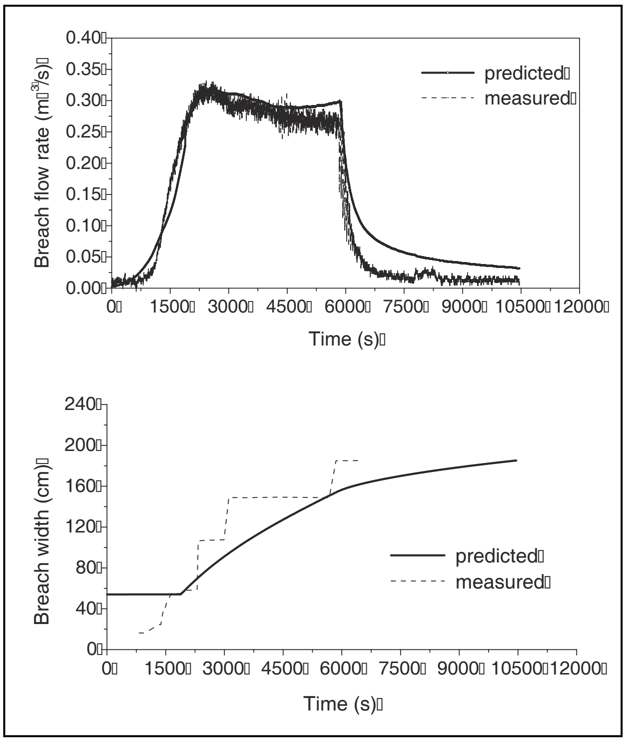


Figure 6. Comparison of predicted and measured breach flow rate (upper panel) and breach width increase (lower panel) for test no.10 of the EC IMPACT Project laboratory clay-dike experiment.

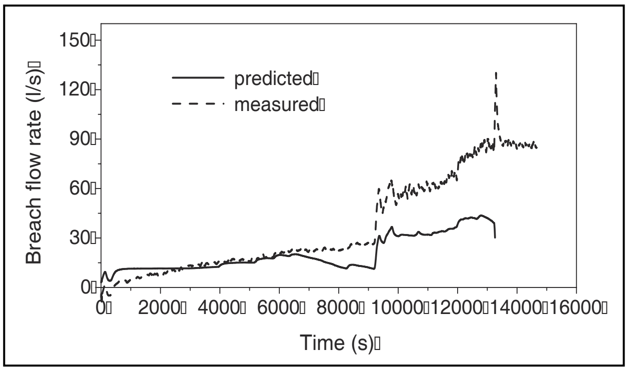


Figure 7. Comparison of predicted and measured breach flow rate for test $T_3$ of the DUT laboratory clay-dike experiment.

## VII. DISCUSSION

After suitable calibrations, the agreement of the model predictions for sand-dikes with the data of both the Zwin'94 experiment and the 3D laboratory experiment is good. Also the confrontation of the model with a rough eye-witness observation of the breaching of the Noord Dike in Papendrecht yields reasonable agreement.

The model version for clay-dikes has been calibrated with the data of four laboratory tests and validated against other two laboratory tests and one prototype dike failure in China. The agreements between the model predictions and the data are fairly good. More reliable data, from both laboratory and/or field experiments as well as prototype dike failures are needed for the further calibration and validation of the model.

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