

CHAPTER 158

A FIELD EXPERIMENT ON BREACH GROWTH IN SAND-DIKES

by

P.J. Visser * , J.K. Vrijling * and H.J. Verhagen **

ABSTRACT

The set-up and results of a field experiment on sand-dike breach erosion are described. It is found that the breaching process for the 2.2 m high sand-dike is similar to that in Visser's (1988) laboratory experiments with a 0.6 m high sand-dike.

Confrontation of Visser's (1988) breach erosion model with the field data shows reasonable agreement for the first stages of the breaching process. As yet the model is not applicable to the final phase of the sand-dike breach erosion. If applied then it would fairly overestimate the breach growth in this final stage.

1. INTRODUCTION

Since dikes have been constructed, in The Netherlands for more than 800 years now, the failure of these high-water defences has been the immediate cause of many inundations. The polder "Alblasserwaard", for instance, has been flooded 33 times since the year 1200. The consequences of a number of these inundations were disastrous, with great losses of human lives, livestock and properties. Curiously the knowledge of the breaching process in dikes is still very limited.

The Technical Advisory Committee on Sea Defences (TAW) in The Netherlands is completing a probabilistic design method for dikes.

* Department of Civil Engineering, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands.

** Road and Hydraulic Engineering Division, Ministry of Transport and Public Works (Rijkswaterstaat), P.O. Box 5044, 2600 GA Delft, The Netherlands.



Fig. 1 Map of The Netherlands showing the locations of the IJsselmeer Dam, the lake IJsselmeer and Cadzand (site of the field experiment). The dark area is land below Mean Sea Level.

This method determines the optimal dike-design as function of the construction costs and the expected damage costs (deaths, loss of property and revenues, repair costs, etc.) due to a failure of the dike.

In order to be able to determine the damage costs, it is necessary to predict the rate of inundation of the polder. This inundation rate is especially governed by the discharge rate through the breach in the dike, which largely depends on the process of breach erosion.

An example illustrating the benefit of a good breach erosion model is the IJsselmeer Dam in The Netherlands (see Fig. 1). This dam, which was completed in 1932, prevents the penetration of storm surges from the North Sea into the lake IJsselmeer and in this way flooding and collapsing of the dikes of the polders around the lake IJsselmeer. The IJsselmeer Dam is a primary dike, the dikes of the polders around the lake IJsselmeer are secondary dikes.

The height and stability of the IJsselmeer Dam do not meet the modern Dutch standards for sea defences. Expensive dike construction works are necessary to meet these requirements.

However, in case of failure of the IJsselmeer Dam it is possible that the dimensions of the breach(es) in the dike remain confined, consequently also the flow rate through the breach(es), such that the water level increase in the lake IJsselmeer remains relatively small and the dikes of the surrounding polders can withstand the higher water level. So it is possibly not necessary to reinforce the IJsselmeer Dam.

The present investigation is part of a project aimed at the development and verification of a mathematical model for breach erosion that describes the breach growth and the discharge rate through the breach in case of a dike-burst.

A first version of the breach erosion model, see Visser (1988), was especially developed for the huge (i.e. about 75 m high) sand-dike of a proposed pumped-storage plant along the Dutch coast.

The heart of the model is a modified Bagnold (1963, 1966) energetics-based sand transport conception combined with a simplified Galappatti and Vreugdenhil (1985) pick up mechanism for the suspended sediment. The model has been tested to three scale experiments in the laboratory giving a good agreement between model predictions and experimental results, see Visser (1988).

Additional experimental data of Dieteren and Pottinga (1988) have also shown good agreement with the model predictions. Dieteren and Pottinga (1988) have also found that the combination of Bagnold's sand transport theory and Galappatti and Vreugdenhil's sand pick up mechanism gives much better results than the erosion functions of Chee (1978) and Mastbergen and Winterwerp (1987) and the sand transport formulas of Engelund and Hansen (1967), Ackers and White (1973) and van Rijn (1984a, 1984b) combined with the Galappatti and Vreugdenhil (1985) sand entrainment formulation.

A field experiment was performed to test the applicability of the model to (sand-)dikes with a height of order of magnitude of 10 m. This paper describes the set-up and results of this experiment, some further work on the model aimed at the present application and the confrontation of the model with the field data.

2. FIELD EXPERIMENT

2.1 Introduction

The field experiment took place on December 13, 1989 in the Zwin Gully near the village of Cadzand, in the south-western part of The Netherlands (see Fig. 1). The experiment was initiated and directed by study group TAW-C and financed by Rijkswaterstaat. De Looff (1990) has reported on the experiment.

2.2 The sand-dike

The Zwin Gully is a tidal inlet connecting the nature reserve "the Zwin" with the North Sea (see Fig. 2). The width of the inlet varies between 50 and 100 m. The bottom of the Zwin Gully is at about 0.3 m above Mean Sea Level.

The sand-dike was constructed, exclusively for the field experiment, with local sand ($D_{50} \approx 0.20$ mm) at low tide. The sand-dam temporarily closed the Zwin Gully, see Fig. 3.

The length of the dike was about 50 m, its cross-section is shown in Fig. 4: outer (seaward) slope is 1:1.25, inner (landward) slope is 1:3, height H_d above the Zwin Gully bottom is 2.2 m and width at the top is about 8 m. A small initial breach, about 0.2 m deep, about 0.5 m wide and about 8 m long was made in the crown of the dike to ensure breaching of the dike near the middle of the Zwin Gully (see Fig. 5).

2.3 Growth of breach width

The sand-dike was constructed at low tide, as described above,



Fig. 2 View of Zwin Gully and distantly natural reserve "the Zwin".



Fig. 3 Photo of sand-dike in Zwin Gully (seaside is to the right, landside is to the left).

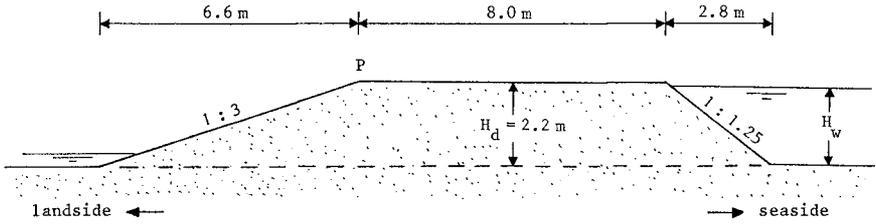


Fig. 4 Cross-section of sand-dike.

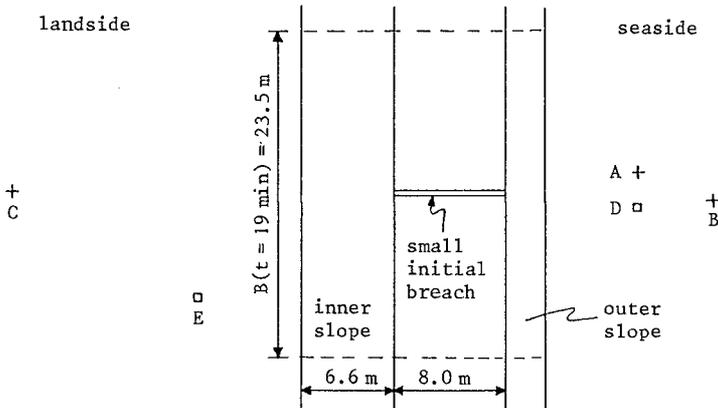


Fig. 5 Plan view of sand-dike and positions of measuring equipment (B = breach width at the top of the dike).

and was breached during (the final phase of) the next rising tide. The flow of water through the small initial breach at high water (at sea) started the breach erosion process. Let us define this point of time as $t = 0$.

The breaching process was both video-taped and photographed. Levelling-staffs in the top of the dike (see one in Fig. 7) provided the proper length-scale for the readings from the video-images and photographs. The main result of these readings, i.e. the increase in time of the breach width at the downstream end of the crown of the dike (point P in Fig. 4) is shown in Fig. 13. Fig. 6 shows the breach at $t \approx 2$ min (minutes), Fig. 7 at $t \approx 10$ min.

2.4 Water level and current velocity measurements

Fig. 5 shows the positions of the points A, B and C where current velocity measurements were made (with Ott propeller current



Fig. 6 Photo of breach at $t \approx 2$ min.



Fig. 7 Photo of breach at $t \approx 10$ min.

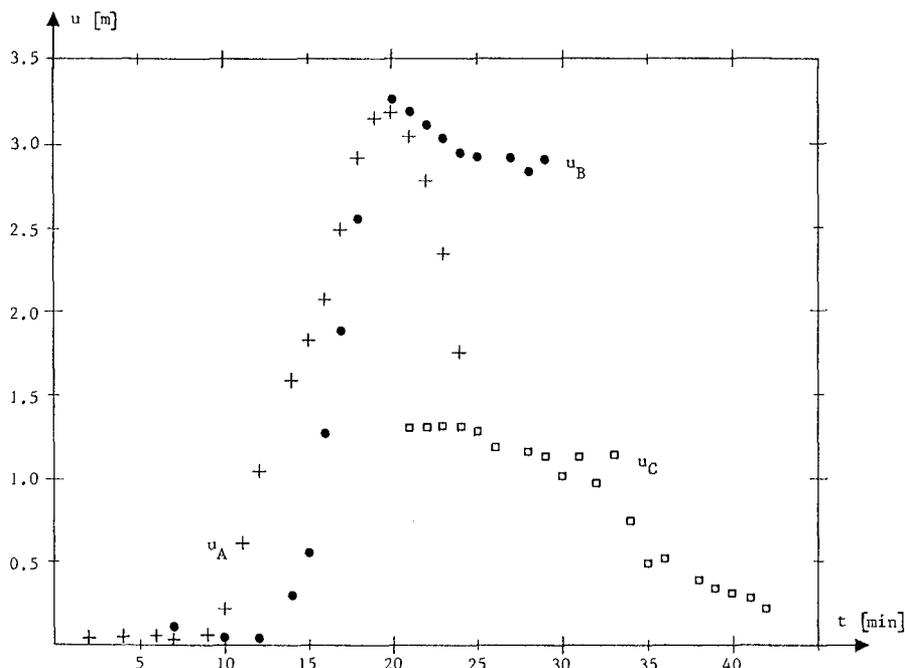


Fig. 8 Measured current velocities in points A, B and C.

meters, in A and C at a level of 0.60 m above the bottom of the Zwin Gully and in B 0.30 m above the bottom). Fig. 5 also gives the positions of the points D and E where water levels were measured (with tide-gauges). Fig. 2 shows the Ott propeller current meter in point C and the tide-gauge in point E. Fig. 3 shows the current velocity meters in the points A and B and the staff-gauge in point D.

The measured current velocities are given in Fig. 8, the observed water levels above MSL + 0.30 m are shown in Fig. 9.

3. BREACH EROSION PROCESS

Both the laboratory experiments, see Visser (1988) and Dieteren and Pottinga (1988), and the present field experiment have indicated that in case of sand-dike breaching, after a small initial gap in the dike top at $t=0$, the following four stages can be distinguished in the breach erosion process (see Fig. 10):

- I. Steepening of the inner slope angle β upto a critical value β_0 for $0 < t < t_0$.
- II. Continuing erosion of the inner slope for $t_0 \leq t \leq t_1$: the width of the top of the dike in the breach gets smaller while

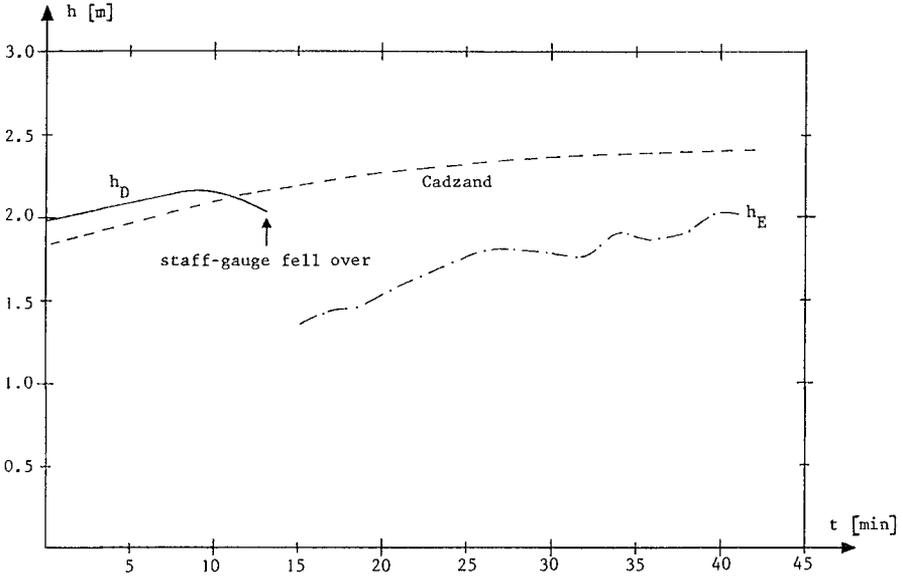


Fig. 9 Measured water levels h above MSL + 0.30 m in points D and E.

β remains equal to β_0 .

- III. Lowering of the dike top in the breach and a subsequent increase of the breach width.
- IV. Continuation of the breach growth horizontally and in vertical direction (scour hole) after the complete wash-out of the dike in the breach.

Essential for this process of breach erosion is that suspended sediment transport dominates bottom transport, see Visser (1988).

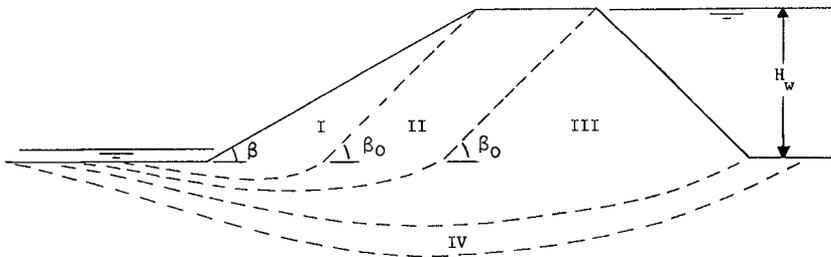


Fig. 10 Four stages in process of breach erosion.

4. MATHEMATICAL MODEL

4.1 Entrainment and transport of sand

The entrainment and subsequent transport of sand in suspension along the inner slope is described by (see Visser, 1988):

$$s(x') = \frac{x'}{L_a} s_s \quad \text{for } 0 \leq x' \leq L_a \quad (1)$$

in which

$$L_a = \frac{q}{w \cos \beta} \quad (2)$$

$$s_s = \frac{0.01 C_f u^4}{(1-p) \Delta g w \cos^2 \beta} \quad (3)$$

where $s(x')$ is the suspended sand transport per unit width along the inner slope (bulk volume transport), s_s is the transport capacity for the suspended sand, x' is the coordinate along the inner slope ($x'=0$ at the top of the dike, see Fig. 11), L_a is the adaptation length, w is the fall velocity of sand in water, C_f is the friction coefficient for the bed (about 0.01), u is the depth-averaged current velocity of the flow on the inner slope with discharge rate q per unit width, p is the bed porosity, $\Delta = (\rho_s - \rho)/\rho$, ρ_s is the sand mass density, ρ is the water mass density, g is the acceleration of gravity and β is the angle of inclination of the inner slope.

Equations (1) and (2) describe the pick up of sediment in suspension for large values of u_*/w (u_* is the bed shear velocity) according to Galappatti and Vreugdenhil (1985). Equation (3) rests on a modified Bagnold (1963, 1966) energetics-based sand transport conception for the suspended sediment load (which dominates bottom load here), see Visser (1988). The factor 0.01 in (3) is also according to Bagnold (1963, 1966). It is assumed that the transport of sand over the top of the dike in the breach is negligible.

4.2 Discharge rate through the breach

The discharge rate q per unit breach width is described by

$$q = m_0 \frac{2}{3} \left(\frac{2}{3} g \right)^{1/2} (H_w - \hat{z})^{3/2} \quad (4)$$

where m_0 is the discharge coefficient (≈ 1.0), H_w is the water level at sea in front of the dike, \hat{z} is the height of the dike top in the breach, both H_w and \hat{z} are measured above $z=0$ (i.e. above the Zwin Gully bottom), see Fig. 11.

It can be concluded from Fig. 9 that for $0 < t < 20$ min: $H_w \approx h_D$ at $t = 10$ min, so $H_w \approx 2.2$ m. For $t > 20$ min: $h_E > (2/3)H_w \approx 1.5$ m, see Fig. 9, so for $t > 20$ min the downstream water dammed up the flow of

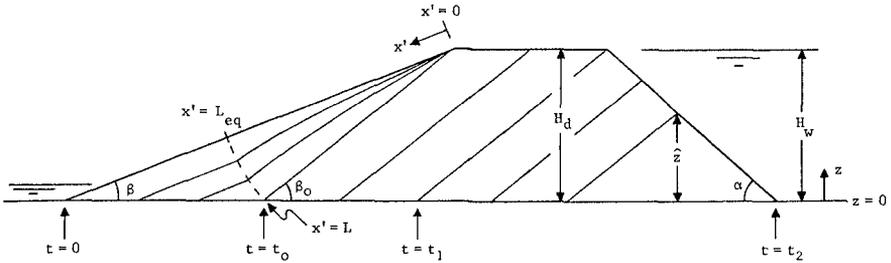


Fig. 11 Erosion of inner slope.

water through the breach. Consequently, equation (4) can be applied for the present field experiment only for $0 < t < 20$ min.

4.3 Breach growth

Fig. 11 shows the process of erosion as discussed by Visser (1988) using theoretical arguments; this process is in agreement with that of Fig. 10 as observed in both the laboratory experiments and the field experiment.

Visser (1988) argues that for $t_0 \leq t < t_2$ the erosion of the inner slope is determined by the erosion at $x' = L_{eq}$ (where the depth-averaged current velocity reaches the equilibrium value for uniform flows), which comes down to the same as the erosion at the toe of the slope (at $x' = L$, L is the length of the inner slope):

$$-L \frac{dz'_b}{dt} = s_L \quad \text{for } t_0 \leq t < t_2 \quad (5)$$

where $z'_b = z'_b(x', t)$ is the position of the sloping bottom in z' -direction and s_L is the sand transport at the toe of the slope.

The current velocity for $x' = L$ can be written as

$$u_L = \left(\frac{g q \sin \beta_0}{C_f} \right)^{1/3} \quad (6)$$

The relation between the decrease dx_c of the width of the crown of the dike and dz'_b , and that between the fall $d\hat{z}$ of the top of the dike and dz'_b , follow both from simple geometrical considerations, see Fig. 12:

$$\frac{dx_c}{dt} = \frac{1}{\sin \beta_0} \frac{dz'_b}{dt} \quad (7)$$

$$\frac{d\hat{z}}{dt} = \frac{\sin \alpha}{\sin(\alpha + \beta_0)} \frac{dz'_b}{dt} \quad (8)$$

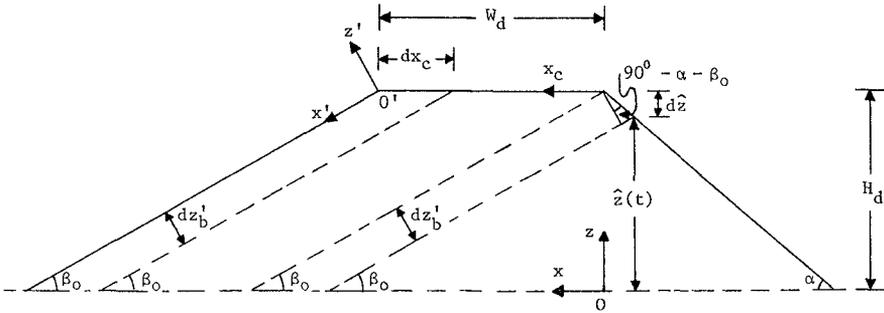


Fig. 12 Decline dx_c of the crown width x_c of the dike and fall $d\hat{z}$ of the top height \hat{z} of the dike, both as function of an erosion dz'_b of the inner slope.

where α is the angle of inclination of the outer slope.

Figures 11 and 12 show the erosion of the inner slope and the breach growth in vertical direction in a 2D-situation. For the 3D-situation Visser (1988) argues that the breach width B at the crown of the dike can be coupled with the breach depth $H_d - \hat{z}$:

$$B = r (H_d - \hat{z}) \quad \text{for } t_0 \leq t < t_2 \quad (9)$$

where H_d is the height of the dike and r is a coefficient with a value of about 3.8 (for sand-dikes).

The effect of the breaching process in horizontal direction on the breach growth in vertical direction is that the latter slows down with a factor f compared with the 2D-situation:

$$f = \frac{b + 2q/u}{2b} \quad (10)$$

where b is the depth-averaged breach width, see Visser (1988).

Substitution of (5), (1) with (2) and (3), (6) and (4) successively into (7) and (8) and taking into account the factor f gives:

$$\frac{dx_c}{dt} = - f k_1 (H_w - \hat{z}_0)^{1/2} \quad \text{for } t_0 \leq t \leq t_1 \quad (11)$$

$$\frac{d\hat{z}}{dt} = - f k_2 (H_w - \hat{z})^{1/2} \quad \text{for } t_1 \leq t < t_2 \quad (12)$$

in which \hat{z}_0 is \hat{z} at $t = t_0$ and where

$$k_1 = \frac{0.0082}{(1-p)\Delta} \left(\frac{m_0}{C_f}\right)^{1/3} (g)^{1/2} \frac{(\sin\beta_0)^{1/3}}{\cos\beta_0} \quad (13)$$

$$k_2 = k_1 \frac{\sin\alpha \sin\beta_0}{\sin(\alpha + \beta_0)} \quad (14)$$

Equations (9), (11) and (12) with (10), (13) and (14) describe the breach erosion for $t_0 \leq t < t_2$. The model is not (yet) valid for $t \geq t_2$, after the complete wash-out of the dike in the breach, since it rests on the erosion process of a (relatively) steep slope.

In principle it is also possible to describe the steepening of the inner slope for $t < t_0$ with the present approach. However, in practise the time period t_0 is very sensitive for the dimensions of the small initial breach.

5. CONFRONTATION OF MODEL WITH FIELD DATA

If $H_w = \text{constant}$, as can be assumed in the present field experiment for $0 < t < 20$ min (see section 4.2), simple analytical solutions for (11) and (9) with (12) result.

Integration of (11) gives with $x_c = 0$ for $t = t_1$:

$$x_c = f k_1 (H_w - \hat{z}_0)(t_1 - t) \quad \text{for } t_0 \leq t \leq t_1 \quad (15)$$

Hence, with $x_c = W_d$ for $t = t_0$, where W_d is the width of the crown of the dike (see Fig. 12):

$$t_1 = t_0 + \frac{W_d}{f k_1 (H_w - \hat{z}_0)} \quad (16)$$

Substitution of the result of the integration of (12), with $\hat{z} = 0$ for $t = t_2$ and $H_d = H_w$, into (9) gives

$$B = r \left[\frac{1}{4} f^2 k_2^2 (t - t_2)^2 + f k_2 (t - t_2) H_w^{1/2} + H_w \right] \quad \text{for } t_1 \leq t < t_2 \quad (17)$$

where

$$t_2 = t_1 + \frac{2}{f k_2} [H_w^{1/2} - (H_w - \hat{z}_0)^{1/2}] \quad (17)$$

The photos and video-images of the breach growth in the field experiment show that: $t_0 \approx 3$ min. The results of the computations of t_1 , t_2 and B with $t_0 = 3$ min, $H_w - \hat{z}_0 = 0.2$ m, $p = 0.4$, $\Delta = 1.65$, $m_0 = 1.0$, $C_f = 0.015$ (see Visser, 1988), $\beta_0 = 32^\circ$ and $\alpha = 39^\circ$ are shown in Fig. 13. Fig. 13 also gives the measured values for B (field experiment). The agreement for $t < t_2$ is good.

The extrapolation in Fig. 13 for $t > t_2$ was done with a constant value for dB/dt , i.e. the value at $t = t_2$.

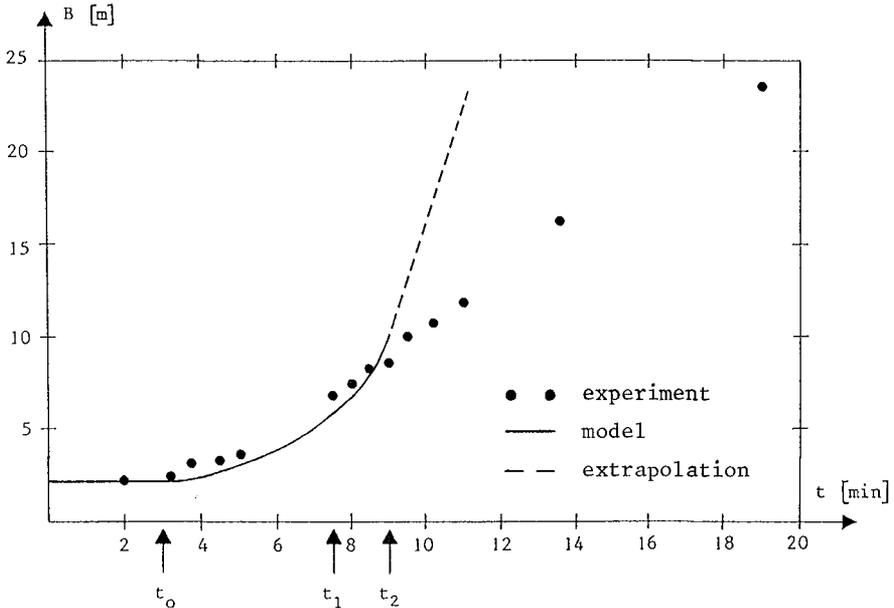


Fig. 13 Comparison of measured and computed development of breach width B at the crown of the dike.

6. DISCUSSION

The agreement between the process of breach erosion in the 0.6 m high laboratory sand-dikes, see Visser (1988), and that in the present 2.2 m high prototype sand-dike gives satisfaction. It means that much of the experimental work on sand-dike breach erosion can be done in the laboratory. This also applies to the comparable process of breach erosion in dunes.

As yet the model is only valid for the breach growth for $t < t_2$, since the model rests on the erosion process of a (relatively) steep slope. The agreement between the model predictions and both the laboratory experiments of Visser (1988) and the present field experiment is quite satisfactory.

The present investigation indicates that extrapolation of the model for $t > t_2$ (in stage IV) gives a significant overestimation of the breach growth. Hence it is meaningless to apply the model in its present state for $t > t_2$. Therefore it can be concluded that further study is necessary to include the process of breach erosion in stage IV in the model.

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