Paper presented at the 1999 International Symposium on Flood Control ('99 ISFC)
Beijing, China, Nov 10-13, 1999.

COMPARISON AND VALIDATION OF TWO DUTCH MODELS OF BREACH GROWTH IN SANDY DIKES

S.Q.YE[1], and H.J.VERHAGEN[2]

ABSTRACT

The Netherlands are waterlands. In order to develop a new philosophy of flood safety in terms of probability of a certain level, two mathematical models of breach growth in sandy dikes have become available to determine the flood discharge in case of a dike failure.

BREACHES 1.0, developed at Alkyon/Delft Hydraulics and BRES 1.0 at Delft University of Technology are different in principle. The comparison of these two models with the previous dam breach models was carried out. The validation of the two models using Dutch field sandy-dike experimental data was conducted, the non-homogeneous fuse plug dam tests in China were also used as validation data. A suggestion to improve the capability of BRES model had been done. Further work on the dike breach models was recommended.

INTRODUCTION

Because of the fact that most of the land in the Netherlands is located below the flood level of the sea or the major rivers, the land is protected by dikes. Dikes are designed in the Netherlands with a probability of failure between 1/1250 and 1/10000 per year, depending on several factors (like economic activities, warning time, salt/fresh water). This means that there is always a small probability of failure. In case of a failure, the area protected by the dike will be inundated. It is important to know how fast this area will be inundated, and what will be the extend of the inundation. This is relevant for planning of evacuation measures, but also for the assessment of potential damage.

The hydraulic calculations for the determination of the speed of the rise of the water and of the extend of the flood are quite simple, provided the size of the breach in the dike is known as a function of time. Unfortunately until a few years ago no information at all was available on breach growth in dikes. Because of that, the Technical Advisory Committee on Water Defense (TAW) in the Netherlands has commissioned a long-term research project to determine breach growth. Parts of this program were analysis of breaches in the past (unfortunately historical dike breaches were not very well documented), to do some large-

[1] Ph.D. candidate, Department of Civil Engineering, University of Manitoba, Winnipeg, Canada, R3T 2N2.
Senior Engineer, Design institute of Yellow River Conservancy Commission, Zhengzhou, 450003, China.
[2] Associate Professor, International Institute for Infrustructural, Hydraulics & Environmental Engineering (IHE), Delft. The Netherlands.

scale field experiments (Visser et al, 1991) and laboratory experiments. Based on the results of the experiments, two mathematical models have been made. The BREACH model is mainly based on the data from the laboratory investigations, while the BRES model is largely based on a fundamental approach to sediment transport under high-speed conditions.

In this study the two mathematical models are compared and conclusions are drawn for further work to improve the practicability of breach growth.

DESCRIPTION OF MODELS

BREACH model (Steetzel, 1998)

With the assignment of TAW, Alkyon/ Delft Hydraulics (Steetzel, 1996, 1998) developed a model, called BREACH model, to simulate the sandy-dike erosion growth, the new version BREACH 1.0 was completed in February 1998.

The rectangular breach is always assumed. The discharge through the breach according to the broad weir is produced. Water depth of flow in the breach is determined by the Belanger Equation (also valid for a horizontal bottom).

Steetzel employed the Bagnold's suspended load formula for sediment transport in the BREACH model:

$$S = \frac{C_s}{(\rho_s - \rho) g w_s (\cos\beta)^2} \tau_b u^2 \tag{1}$$

where C_s *is a* constant for sediment transport (suggested value is 1.0) and w_s is fall velocity of a particle. τ_b is the bed shear stress. Bottom changes in the breach are computed using the conservation equation of sediment mass.

The new bottom profile at time t + Δt is computed using a modified numerical LAX-scheme.

BRES model (Visser, 1998)

The **BRES** (**Br**each **E**rosion in **S**and-dikes) model has been developed at Delft University of Technology. It is based on the five-step breach erosion process.

I. Steepening of the inclination angle β of the (channel in the inner) slope from an initial value β_0 at $t=t_0$ up to a critical value β_1 at $t = t_1$.

II. Continuation of the erosion of the inner slope, yielding a decrease in the width of the crest of the dike in the breach for $t_1<t\leq t_2$; the slope angle of the inner slope remains at its critical value β_1.

III. Lowering of top of the dike in the breach, with constant angle of the side slopes (β_1), resulting in an increase of the breach width for $t_2<t<t_3$.

IV. Continuation of the breach growth in both vertical (scour hole) and horizontal directions for $t_3\leq t<t_4$. At t_4 the flow through the breach is critical, i.e. changes from supercritical (Fr>1 for $t<t_4$) to subcritical (Fr<1 for $t> t_4$). The effect of tail water starts at t_4.

V. Continuation of the increase of the breach width for $t_4<t<t_5$. At t_5, the flow velocities in the breach become so small (incipient motion) that the breach erosion stops.

Several sediment transport formulae can be selected for each stage: Engelund-Hansen (1967), Van Rijn (1984), Wilson (1987) and Bagnold-Visser (1989). The default is Bagnold-Visser for Stage I, II, III and Van Rijn for stage IV and V.

It is assumed that the breach has a trapezoidal cross-section with a breach depth h; side slope angles β_1. The discharge through breach is computed with the broad-weir formula.

The flow on the inner slope accelerates up to $x=l_n$, beyond which the flow is uniform with depth-averaged flow velocity U_n and water depth d_n (the subscript n refers to the word normal). For $0 < x < l_n$, the general differential equation for a gradually varied flow (Belanger equation) can be applied. The definition of l_n is as follows:

$$l_n = 2.5\frac{Fr_n^2 - 1}{\tan\beta} d_n \tag{2}$$

It is assumed that the pick up of sediment and the resulting transport S(x) starts at x=0 at the top of the inner slope: S(0)= 0. It is also assumed that the adaptation length of the bed-load transport is relatively small and that at x= l_n the bed-load transport is equal to its equilibrium value (or transport capacity). At a distance l_a (adaptation length of the suspended load transport) from x=0, the suspended load transport reaches its equilibrium value S_s. l_a can be approximated by (Galappatti, 1983):

$$l_a = \frac{Ud}{w_s \cos\beta} = \frac{q}{w_s \cos\beta} \tag{3}$$

An improvement made to the model (Ye, 1998): at $0<x<l_n$, although the flow velocity is less than the normal velocity, the capacity of the suspended load is accordingly less than that at $x> l_n$, thus at the interval $0 < x < l_n$ the bed-load transport occurs mainly; $l_n<x<l_a$, the suspended load is dominant. During stages I, II, and III, the erosion rate is approximately related to the capacity of total sediment transport capacity (suspended load plus bed load, approximately only suspended load in some cases) when the flow is a uniform flow. As a result, there is the following mathematical model for breach growth in sandy-dikes.

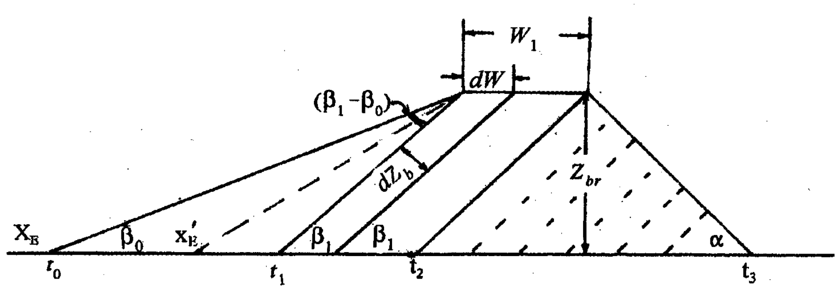

Figure 1 Erosion of inner slope in Stage I, II, III

Stage I and II

Due to this erosion process, the angle β of the inner slope increases from an initial value

β_0 to the critical value β_1 at t_1 in stage I, t_1 is computed by:

$$t_1 = t_0 + \frac{B_w}{B_t} X_E(\beta_1 - \beta_0)(1-p)\frac{l_a}{S_t} \tag{4}$$

where x_E is the length of the inner slope, S_t is total capacity of sedimentation (Bed-load plus Suspended load), p is soil porosity of filled material.

In Stage II, the erosion of the inner slope of the dike in the breach continues, resulting in a decrease of the width of the dike-crest in the breach for $t_1 < t \leq t_2$; the inner slope angle remains at its critical value β_1. Stage II ends when the width of the dike-crest has become zero. t_2 can be given by:

$$t_2 = t_1 + \frac{B_t}{B_w}\frac{W_1 l_a(1-p)\sin\beta_1}{S_t} \tag{5}$$

Stage III

At $t=t_2$, the top of the dike in the breach starts to drop. It is assumed that in this stage the angle of the inner slope remains at the critical value β_1. The relation between the fall dZ_{br} of the inner slope follows from a simple formula:

$$\frac{dZ_{br}}{dt} = -\frac{B_w}{B_t}\frac{\sin\alpha}{\sin(\alpha+\beta_1)}\frac{S_t}{(1-p)l_a} \tag{6}$$

The fall dZ_{br} of the height of the crest of the dike in the breach causes an increase of the flow through the breach. Consequently, both the suspended load transport capacity S_s and the adaptation l_a increase. This means that right-hand side of the above formula is in general not constant and may be calculated numerically.

With the drop of the top of the dike, the width of the breach at the upstream side of the crown also starts to grow. With the assumption of constant bottom width and the constant side slope γ_1, the width at water line B_w is determined:

$$B_w = b_0 + \frac{2d}{\tan\gamma_1} \tag{7}$$

Stage IV and V

After the complete wash-out of the dike in the breach at t_3, the breach continues to grow laterally in stage IV ($t_3 < t \leq t_4$) and stage V, depending on the subsoil of the dike.

$$\frac{dB}{dt} = \frac{d}{h}\frac{2S_t}{(1-p)l_a\tan\gamma_1} \tag{8}$$

When the H_p-$Z_p < d_c = 0.7(H_w - Z_p)$ at the $t=t_4$, the effect of tail water starts and the flow becomes subcritical and the flow velocity in the breach decreases, resulting in a deceleration of the breach growth for $t_4 < t < t_5$. At t_5, the flow velocity in the breach becomes so small (incipient motion) that the breach erosion stops.

VALIDATION DATA

Tidal polder test, The Netherlands

Three tests (D_{50} =0.22 mm) on prototype scale have been carried out at "Het Zwin" located in Zeeuwsch-Vlaanderen, at the bounder between The Netherlands and Belgium. The first test was carried out on 13 December 1989, and the second and third tests on 6 and 7 October 1994, respectively. The third test (3.3 m high), Zwin'94, is the most successful and used to validate the models.

Fuse plug dam test, China

Three tests were selected as validation data in the "Chinese-Finnish Co-operative Research Work on Dam break Dynamics" (Pan Shuibo and Erkki et al, 1993), and also this validation. They are Dahoufang (3.0 m high) in Liaoning, Nanshan (2.4 m) in Zhejiang, and Yahekou (5.6m) in Henan province respectively. All of them have a core of silt, fine sand or loam.

VALIDATION OF MODELS

Figure 2 shows a fair agreement between the observed of Zwin'94 and predicted of BREACH 0.1 when using Cs=100 instead of 1.0 in Equation (1). From Figure 3, it may be summarized for BRES modelling of Zwin'94 test that Bagnold-Visser (1989), Wilson (1987) may be applied for stage I, II, III, the Van Rijn (1984) and Engelund-Hansen (1967) can be used for stage IV and V.

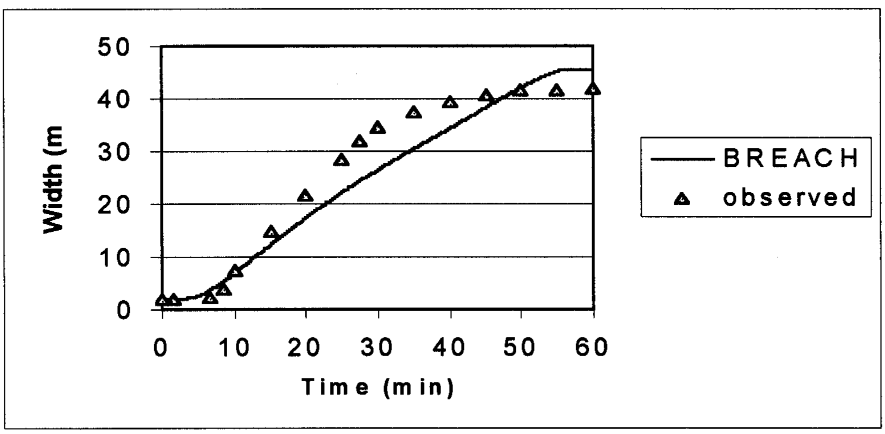

Figure 2 Breach development of Zwin'94 by BREACH model

The present version of both models is particularly developed for sandy-dikes, especially Dutch coastal sand with D_{50} ranging from 0.1mm to1.0 mm. According to the geotechnical and hydraulic points of view, the coarse soil (for instance the gravel) play a relatively minor role to resist the erosion of dikes compared with fine soil. Therefore, in simulations of Chinese tests, the assumption of a homogeneous dam consisting of fine particles is taken.

Both models may be used in a simulation of the Dahefang test, assuming a homogeous dam (D_{50} = 0.028 mm), in spite of underestimations or overestimations. Applications of the BREACH model to the Nanshan test (sands, D_{50} = 1.0 mm or 0.4 mm) give reasonable tendency with the real test, but the BRES model has some difficulties simulating this test because of the irregularities of a non-erodible bottom.The simulation of the Yahekou test (D_{50} = 0.4 mm) by the BRES model applying the Van Rijn Formula to all five stages is very good with the observed. However, the Yahekou (D_{50} = 0.01mm) simulation by the BREACH model considerably underestimates the vertical erosion capability of water flow. As a conclusion, with selected combinations of sediment transport formulae, the BRES model has a wide scope of application for dikes(different height and particle diameters), but the BREACH model seems to have a limitation of only dikes around 3.0 m high.

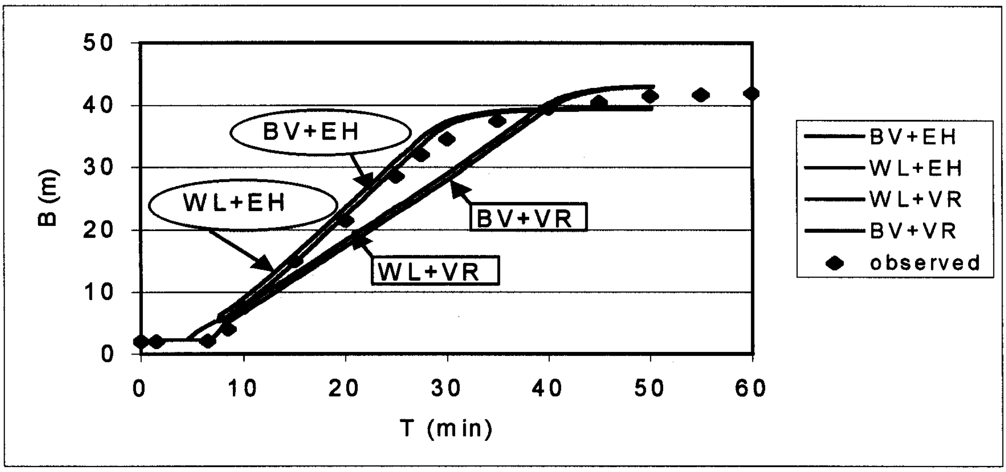

Figure 3 Comparison of Zwin'94 simulations by BRES model

COMPARISON OF BREACH MODELS

This paragraph compares these two models with previous models, mainly in relation to vertical erosion and lateral erosion. It also attempts to explain the reasons of above-mentioned simulations, in principle. Table 1 numerically summarizes the comparison of these models.

Vertical erosion

The different way used by the BREACH model for vertical erosion is very obvious. $\partial S/\partial x$ is related to $\partial u/\partial x$. This means that the erodibility of flowing water is a function of the derivative of water velocity. Just this approach allow the BREACH model to simulate the arbitrary shape of a dike, and it is also just this approach that makes BREACH multiplied a big modified coefficient (100, instead of 1.0) in order to achieve a reasonable prediction. 10,000 times of original constant (0.01) in the Bagnold-Visser (1989) suspended load formula is too big and unacceptable. It is also found that C_s is numerically instable, and related to cases, different C_s is for different soil and height of dikes. It may be concluded that the vertical erosion formula used in the current version of the BREACH model need improvement.

Table 1. Brief comparison of breaching models

	BREACH model	BRES model	Dam breach models
Vertical erosion	$\frac{\partial Z}{\partial t}+\frac{1}{(1-p)}\frac{\partial S}{\partial x}=0$	$\frac{\partial Z}{\partial t}+\frac{S_t}{(1-p)l_a}=0$ l_a : adaptation length	$\frac{\partial Z}{\partial t}+\frac{S}{(1-p)l_b}=0$ l_b : channel length
Lateral erosion	$\frac{dB}{dt}=C_b\frac{q_b d_b}{A_d}$ $C_b = 0.06 \sim 0.08$	$\frac{dB}{dt}=2\frac{S_t}{(1-p)l_a}$	Constant bottom breach width with constant side slope; or Instability of side slope;
Sediment formula	Bagnold 1.0 instead of 1.0 (0.01)	Bagnold_Visser Van Rijn Engelund-Hansen Wilson	Cristofano Meyer-Peter & Muller Einstein and others

The BRES model uses a similar approach as the previous model, with the adaptation length instead of a channel length. The concept of adaptation length is first used in such models. In the computation of adaptation, the normal velocity must always be used in stages I to III. The previous models usually use the average velocity in the channel length to sediment formula.

The BRES model, perhaps the first in the history of breaching modelling, divides the vertical erosion into three stages which is significant from a hydraulic point of view.

Lateral erosion

In the hydraulic point of view, particularly for the damage zoning in case of dike breaching, the lateral erosion plays a more important role than the vertical, since it determines the maximum discharge and final size of a breach. In this respect, there is a big difference between dam breaching and dike breaching.

The BREACH model employs an experimental relationship with the flow velocity and the area of the cross-section of a breach. The relationship is from a laboratory flume experiment of a dike consisting of medium sands. The approach limits the relationship and is only used effectively in a dike around 3m high. This approach determines that the BREACH model is less sensitive to the diameter of particles than the BRES model. This is why in the simulation of the Yahekou test (silty sand core), the final width of breach meets the prototype experiment, but the final cross-section shows only part of the dike is eroded (about 3.3 depth eroded), as if only a 3.3 m high dike was completely eroded.

Another limitation is that the BREACH model does not consider tailwater effect downstream, i.e. doesn't distinguish stages IV and V. The BRES model extends the concept of adaptation length to stages IV and V, with the depth-averaged velocity, instead of the normal velocity. This modification of velocity seems to explain why the sediment transport formulae should have a modified coefficient in order to simulate successfully.

All the sediment transport formulae are related to the properties of soil (D_{50} and fall velocity). Thus, the BRES model is very sensitive to the filled materials. It is the selectable sediment transport formulae used in stages IV and V that allow the BRES model to simulate various dikes of different height and soils. Further study is necessary to determine how to select the most suitable formula for certain cases.

ACKNOWLEGMENTS

First of all we would like to express my sincere thanks to Ir. De Looff, Road and Hydraulic Engineering Division, Government of the Netherlands for sponsoring this study. We are also indebted to Prof. Pan Shuibo, Chinese Institute of water Conservancy and Hydroelectric Power Research (IWHR) for his kind supply of additional data to Chinese-Finnish Cooperative Research on Dam Break Hydrodynamics. Our special thanks are due to Dr. ir. P.J. Visser for his explanation and discussion on the BRES model, and the same thanks to Dr. H.J. Steezel and Ir. H. de Vroeg of Delft Hydraulics. A great thank to Prof. J. C. Doering, University of Manitoba, for his technical review of this paper.

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