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HYDRODYNAMIC EROSION IN OVERTOPPING BREACH OF COHESIVE EMBANKMENTS

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ABSTRACT

Embankment breaching is a composite process coupled by hydraulic processes and sediment transport processes. Erosion is the link in the interaction between breach flow and embankment material. Surface erosion starts in the initial breach phase and triggers the initial damage of the embankment. As the surface erosion develops completely, the headcut erosion leads the breaching process by cutting the embankment slope and deepening the crest level finally. The helicoidal erosion undermines the side slopes of the breach and widens the breach in lateral direction by triggering the breach side slope to collapse. In order to reduce the scale impacts in the lab and defects from the prototype experiments in the field, there were 5 runs of large-scale sediment (sandy clay) models (2m high, 3m long) conducted in the flume (3m×3m×60m) to investigate the cohesive embankment breaching mechanism. The breach hydrodynamic processes (discharge, water level, velocity) were measured in the experiments and topography changes were recorded with 3D scanner every 5 minutes. The results for each runs of the breach experiments were good validations of the 3 types of erosion (surface erosion, headcut erosion and helicoidal erosion) in the cohesive embankment breach.

Keywords: Erosion; overtopping; breach; cohesive embankments.

1 INTRODUCTION

Breaching is the most frequent form of embankment failure, which has a composite process with uncertain initiation and formation. Due to overtopping and/or piping, an embankment starts to breach when part of the embankment actually breaks away, leaving a large opening for water to flood the land protected by the embankment. A breach can be a sudden or gradual failure that is caused by surface erosion, headcut erosion and lateral erosion in the embankment.

Erosion is the interaction link between breach flow and embankment material. Surface erosion starts in the initial breach phase and triggers the initial damage of the embankment. As the surface erosion develops completely, the headcut erosion leads the breaching process by cutting the embankment slope and deepening the crest level finally. The breach side slopes are undermined by the lateral erosion and their collapses widen the breach in lateral direction.

For cohesive embankments, the breaching process starts with surface erosion, but the breach takes place due to headcut erosion. After the surface erosion in the beginning phase, the headcut typically starts at the toe of the embankment and then advances upslope until the crest of the embankment is reached. In some cases, a series of stair-step headcut forms on the downslope face of the embankment. The action is similar to that described by Dodge (1988) for model testing of embankment overtopping, which is related with headcut initiation and headcut advance by hydrodynamic and geotechnical mass wasting.

According to Ralston (1987), Fread (1988) and Zhu et al. (2006), the headcut erosion plays a significant role in the breaching process in cohesive embankments. The mechanism of headcut erosion, however, still needs further understanding. A variety of breaching experiments have been conducted in the past (Zhu et al., 2004), most of which generally focused on the breaching process. As part of the breaching process, the mechanism of the headcut erosion is insufficiently understood to describe the breaching process and to simulate it with mathematical models.

The lateral erosion results in the embankment widening in transversal direction. Due to the undermining of the helicoidal flow, the breach slopes lose the balance and collapse in the form of blocks. The lateral erosion stimulates the breaching process by increasing the area of breach channel, which increases the breaching discharge dramatically. The lateral migration of breach determines the breach embankment development in transversal direction and the change of breaching discharge.

In this paper, the critical incipient shear stress and velocity are proposed to the undisturbed clay according to the moment equilibrium method. A moment equilibrium-based method is proposed to simulate the headcut development and migration in a cohesive embankment breach due to overtopping flow as well as the lateral migration development in the breaching process. The hypothesis is given that the particle and mass is removed in the minimum moment on the breach slope. The lateral migration model is developed based on the same approach with the headcut migration model. The proposed models would be important and valuable to predict and simulate the breaching erosion in cohesive embankments. A series of large scale embankment breach models in the flume are designed to reduce the scale impacts and defects of the prototype experiments. They are applied to investigate the embankment breaching process, including surface erosion, headcut erosion, and laterial erosion as well as the breaching hydraulics in different breaching stages. The breach hydrological process and topography changes were measured in the experiments. The large scale embankment breaching experiments can greatly contribute to the study of embankment breaching mechanism in theoretical levels, but also can be applied to verify and calibrate the current breach mathematical models (empirical models, semi-physically-based models and physically-based models).

2 EROSIONS IN EMBANKMENT BREACH

2.1 Surface Erosion

Surface erosion is the initial phrase of the breach in the cohesive embankment (Figure 1). The incipient motion of the clay particles can be calculated by the new Shields parameter formula (Zhao et al., 2011; Zhao et al., 2013) as

$$\frac{\tau_{Cc}}{(\rho_s-\rho)gD_b}=C\frac{\tau_f}{\rho v^2}\theta_c \qquad [1]$$

where θ_c is the critical Shields parameter of non-cohesive sediment, ρ_s is the density of clay, ρ is the density of water, τ_{Cc} is critical shear stress of the non-cohesive sediment particle's incipient with the same size, D_b is the diameter of the clay blocks, τ_f is the shear strength measured in the soil mechanics laboratory, v is the flow velocity over the embankment surface, and C is an empirical parameter. In the present study, the size of the clay blocks can be approximated as the multiples of the clay median diameter (e.g., $10D_{50}$, $20D_{50}$, $30D_{50}$, etc.), depending on the clay types. The clay is generally eroded as blocks or lumps not in the format of particle. The size of clay block or lump is equivalent to the size of the non-cohesive sand or gravel.

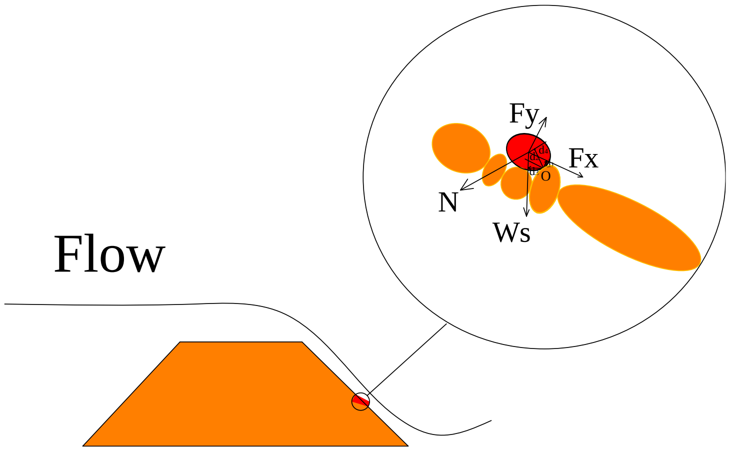

Figure 1. Sketch of forces on the clay particle in submerged flow (notation: F_y is the uplift force acting on the clay particle, N is the shear strength force among clay particles, W_s is the weight of a clay particle under water, τ_f is the shear strength)

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The erosion rate can be predicted by the maximum time-averaged hydraulic shear stresses in the vertical and horizontal direction. According to the dimensionless analysis, the erosion rate can be expressed with an excess stress equation (Hanson et al., 2001)

$$\varepsilon = \zeta(\tau_e - \tau_c)^m \quad [2]$$

where, ε is erosion rate, ζ is erodibility coefficient, τ_e is effective stress, m is an empirical parameter.

2.2 Head Erosion

Headcut Erosion is a hydrodynamic erosion process (Figure 2) in the breaching of cohesive embankment. It plays an important role of simulating the breaching in the longitudinal direction. The new headcut migration model (Zhao et al., 2012; Zhao et al, 2013; Zhao, 2016) is developed to predict the key procedure of the cohesive embankment breach as following

$$\frac{dx}{dt} = \frac{T}{f(T)}\varepsilon \quad [3]$$

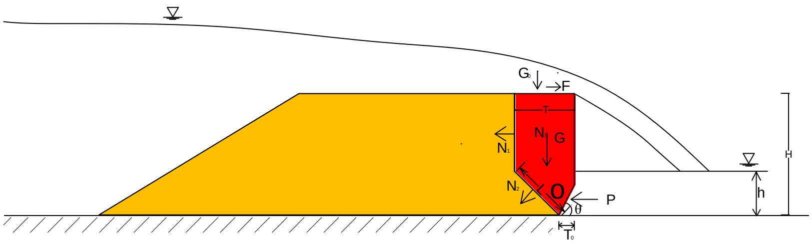

Figure 2. Sketch of Headcut Migration (notation: T is the headcut length, T_0 is the erosion required to cause the failure, L is the length of the failure plane, θ is the failure plane angle, H is the embankment height, h is the tail water height, G_0 is Water weight, F is Flow Stress, P is Tail water Pressure from water, G is the block weight G and N_1 and N_2 are embankment cohesion force from the embankment soil in the headcut migration process)

As the headcut develops, erosion occurs at the toe of the headcut. The embankment block fails and the headcut advances when the vertical erosion exceeds a certain amount and the base of the embankment cannot ensure the potential failure block. The time interval of failures is monitored by the erodiblity and strength of the embankment. It is based on the ero-sion on the vertical toe of the headcut face, which stimulates the headcut to become unstable.

Based on the moment balanced method, the headcut migration model can be expressed by Eq. [3] which is different from the stress balanced model (Hanson et al., 2001) in form. Eq. [3] can be iterated and gets a deterministic T and f(T). The headcut migration process will stop when the toe erosion rate, i.e., the headcut cannot be infinitely tall if there is no erosion in the model, which well fits the headcut development in prototype.

Headcut migration is a hydrodynamic progress in the cohesive embankment breach. The model based on the moment equilibrium principle and clay incipient formula (Eq. [1] and Eq. [3]) as well as the erosion rate with excess stress method (Eq. [2]). The new headcut migration model is developed to predict the key progress of the cohesive embankment breach.

2.3 Helicoidal Erosion

The embankment blocks collapse due to the undermining erosion at the toe of the breach side slope. And the peak breach outflow can occur during the lateral erosion phase (Figure 3), as the breach opening continues to enlarge under a relatively constant reservoir head. So the lateral erosion can be simulated as

$$\frac{dy}{dt} = \frac{W}{f(W)}\varepsilon \qquad [4]$$

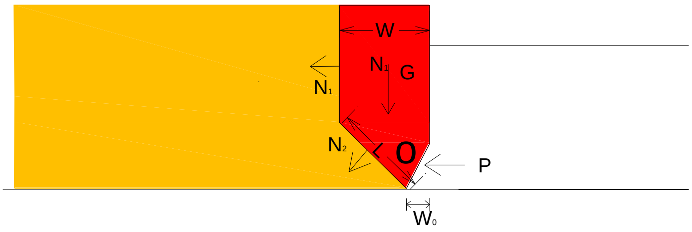

Figure 3. Sketch of Lateral Migration of Embankment Breach (Notation: W is the lateral erosion width, W_0 is the breach slope toe erosion required to cause the failure, L is the length of the failure plane, θ is the failure plane angle, H is the embankment height, h is the breach channel water depth, P is tail water pressure from water, G is the block weight, N_1 and N_2 is embankment cohesion force, θ is the failure plane angle,)

As the lateral migration develops, erosion occurs at the toe of the breach slope. The embankment block fails when the vertical erosion exceeds a certain amount and the base of the embankment cannot ensure the potential failure block. The time interval of failures is monitored by the erodiblity and strength of the embankment. It is based on the erosion on the vertical toe of the breach slope, which stimulates the breach slope to collapse.

3 EMBANKMENT BREACH IN LARGE SCALE

3.1 Experiment setup

There are 5 runs of embankment breach experiments in the flume (3m×3m×60m) to investigate the cohesive embankment breaching mechanism (Zhao et al., 2014). The embankments were built on erodible flume bed, 0.8 m thick of clay with the same characteristics as the dike (see Table 1). There are four embankments designed of 1.20 m high and one embankment designed of 0.6 m high to study the scale influence. All the riverside slopes are the same in 5 models, i.e., 1:1. The landside slopes are designed of 1:3 and 1:2 to study the influence from the landside slope. And the crest width is designed into 0.6 m. The initial trench is set to 0.5 m wide and 0.2 m deep, with a slope of 1:1. In this paper, Model 4 was taken as an example to describe the breaching morphological developing processes.

Table 1. Breach scale model parameters

Parameters	Model 1	Model 2	Model 3	Model 4	Model 5
Experiment Date	01/02/2013	27/02/2013	07/03/2013	14/03/2013	22/03/2013
Initial Trench Location	Side	Side	Side	Side	Middle
Dam Length (m)	3	3	3	3	3
Dam Height (m)	0.6	1.2	1.2	1.2	1.2
Dam Crest Width (m)	0.6	0.6	0.6	0.6	0.6
Waterside slope	1V:1H	1V:1H	1V:1H	1V:1H	1V:1H
Landside slope	1V:2H	1V:2H	1V:3H	1V:3H	1V:3H
Bottom Width (m)	3.6	4.2	5.4	5.4	5.4
Flume bed Length (m)	20	20	20	20	20
Flume bed Thickness (m)	0.5	0.5	0.5	0.5	0.5
Volume(m^3)	33.78	38.64	40.8	40.8	40.8

In the breaching process of cohesive embankments, the morphological changes depend on the hydraulic parameters; conversely, the morphology influences the hydraulic parameters. Therefore the hydraulic and morphological parameters both play an important role in the breaching process. In the present flume tests, the water levels were measured with water level meters, and flow velocities with electromagnetic velocity meter. ADV was also used in the tests. The topography was measured with a 3D laser scanner and with video cameras.

Eight water level meters were setup along the flume from the inlet of the channel to the tailgate. Four meters were fixed to measure the water level changes upstream of the embankment. Two meters were used to measure the water levels just above the crest of the embankment and in the initial channel of the embankment. Downstream of the embankment, one meter was used to measure the water level and one meter to control the tailgate water level.

Three electromagnetic velocity meters were fixed upstream of the breach, in the breach channel and downstream of the breach to measure the flow velocities. Particle tracing was used to indicate the velocity distribution at the flow surface, while the three high-speed video camera systems recorded the breaching process. According to the video records, the surface velocity could be measured and calculated using the traced particle movements.

A 3D laser scanner was used to measure the breach geometry variation, every 5 minutes. The scour hole and the breach channel development were measured and recorded with topography survey instruments and video cameras through the glass wall of the flume.

3.2 Surface Erosion

Before the experiment started, the total topography of the flume model was scanned (Figure 4 and Figure 5). In the 5 runs of the experiments, Model 4 had a side initial breach channel and when the flow came from the upstream and went through the initial channel, the breaching process started via erosion. The surface erosion (Figure 5) happened due to the flow generated by the high water pressure in the reservoir. The flow firstly broke the embankment surface and washed away the model material by blocks, not by particles.

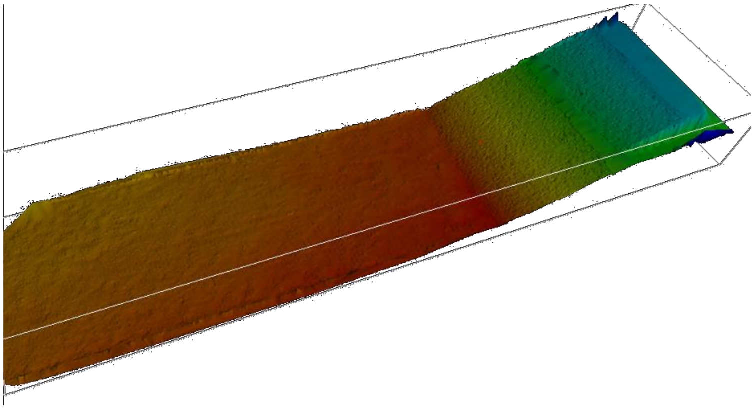

Figure 4. Topography of the model before the test (Model 4)

Figure 5. Topography of the model before the test (Model 4)

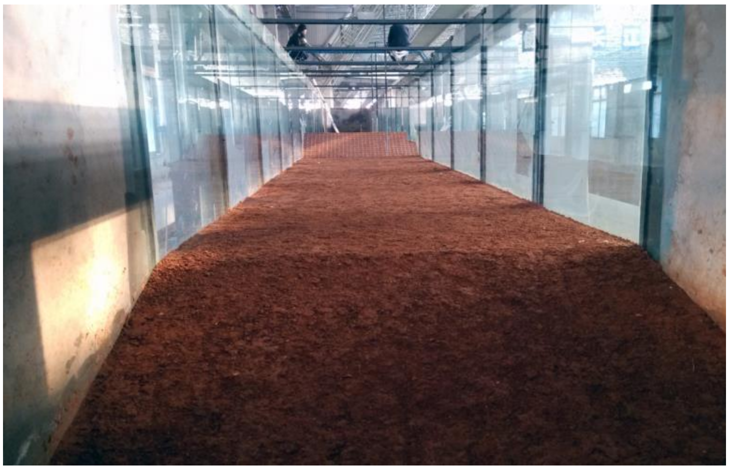

Figure 6. Flume Overview from Tailgate (Model 1)

Figure 7. Surface Erosion at the initial phrase of breach (Model 4)

3.3 Headuct Erosion

As the development of the breach, the cascade headcut erosion (Figure 8) started to develop from the toe of the embankment after the fully completion of the surface erosion on the model surface. The blocks of the clay were washed out by the high velocity breaching flow. The initial breach channel (Figure 9) increased to 1.020 m stimulated by the breaching flow and the embankment toe was fully eroded by the headcut erosion.

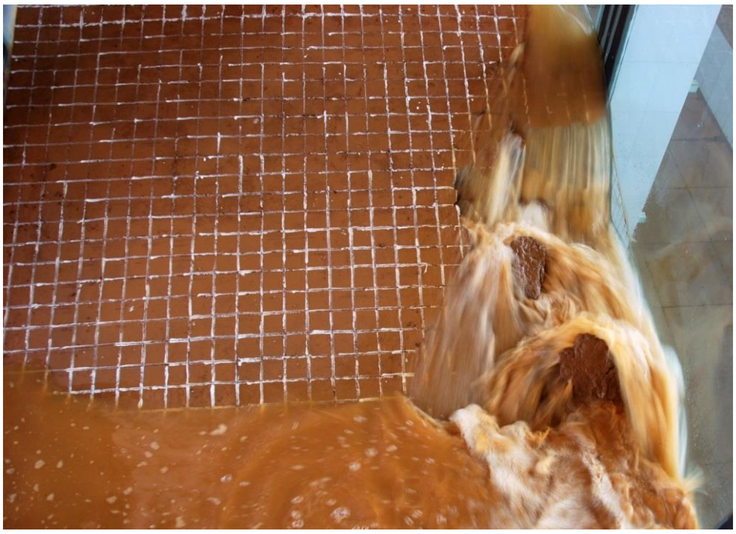

Figure 8. Photo of Headcut Erosion in Model 4

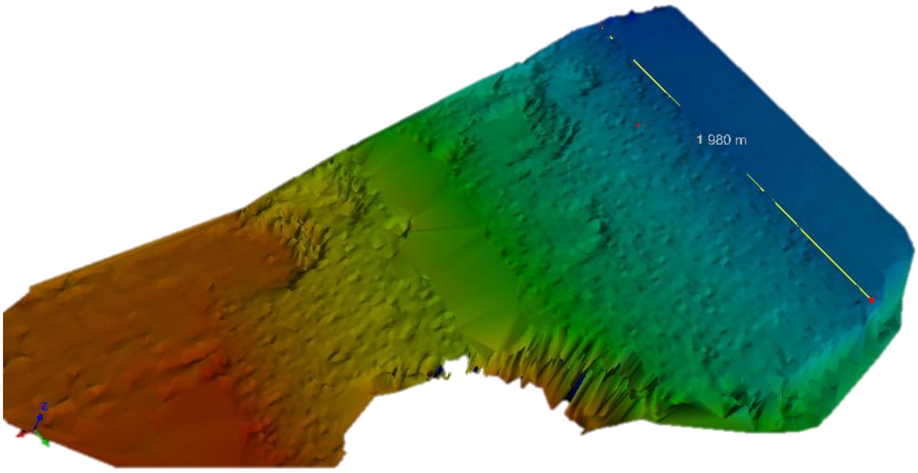

Figure 9. Topography Change during the test of Model 4

3.4 Helicoidal Erosion

The lateral erosion started to play an important role in the breaching process when the development of the headcut erosion processed. Due to the helicoidal flow (secondary flow) in the breach channel (Figure 10), the under mining process triggered the erosion at the side toe of the embankment. The helicoidal erosion at the side toe broke the balance of the embankment and the material blocks collapsed due to the unbalanced situation of the embankment. The lateral erosion stimulated the lateral development of the breach channel and made the breach width increase directly. Due to the cohesion of the material, the lateral breach slope (Figure11) was generated very steep by the breach flow. The undermining process at the side toe of breach channel usually made the breach slope into negative one.

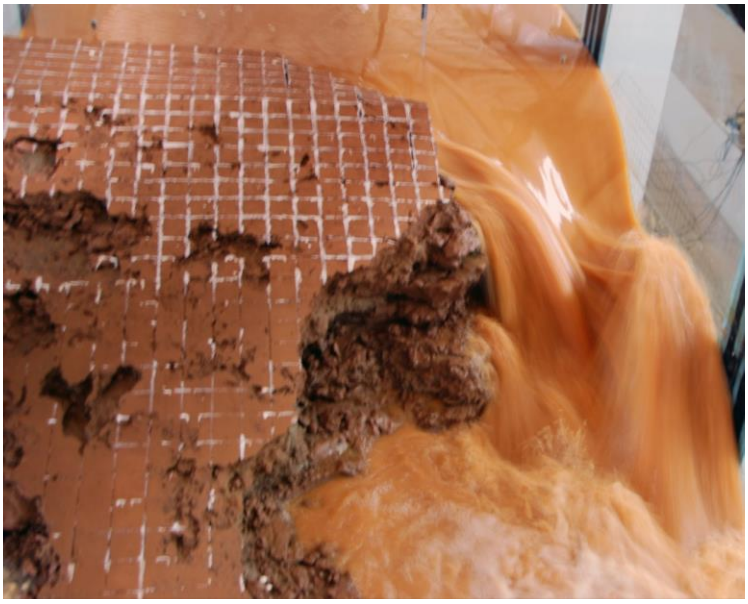

Figure 10. Lateral erosion of the breach in Model 4

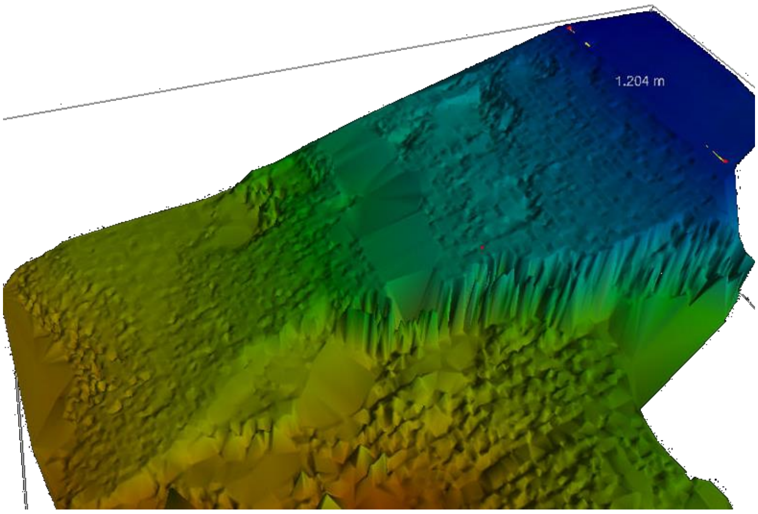

Figure 11. Steep Breach Side Slope of Model 4

4 MATHEMATICAL SIMULATION

4.1 Headcut Migration

According to headcut migration model, the migration rate *dx*/*dt* was calculated as 4.9 m/h. When the headcut migration was supposed as a linear process, the headcut migration (Figure 12) can be calculated as the embankment breach develops. In the beginning phase of the breach, the headcut migration is higher than the measure result since the surface erosion postponed the headcut migration process. However measured data is larger than the calculated ones as the breach fully develops.

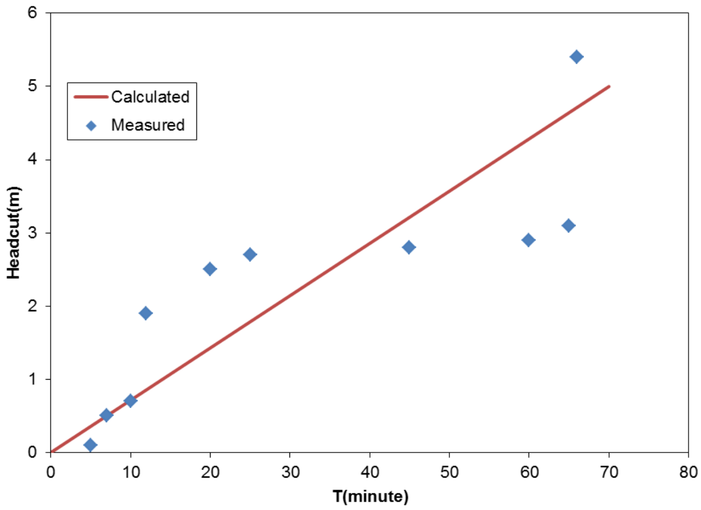

Figure 12. Calculated and measured Headcut Migration for Run 4

4.2 Lateral Migration

If the breach lateral migration *dy*/*dt* was supposed as a linear process, it can be model calculated as 2.5 m/h (Figure 13). However, the lateral migration process developed with the embankment failure and collapse of the soil materials in Run 1. It started at the initial breach channel of 0.3 m wide, and developed due to the helicoidal flow and lateral erosion. In the beginning phase, the calculated results were greater than the measured, however, it is less than the measured ones as the lateral migration developed fully.

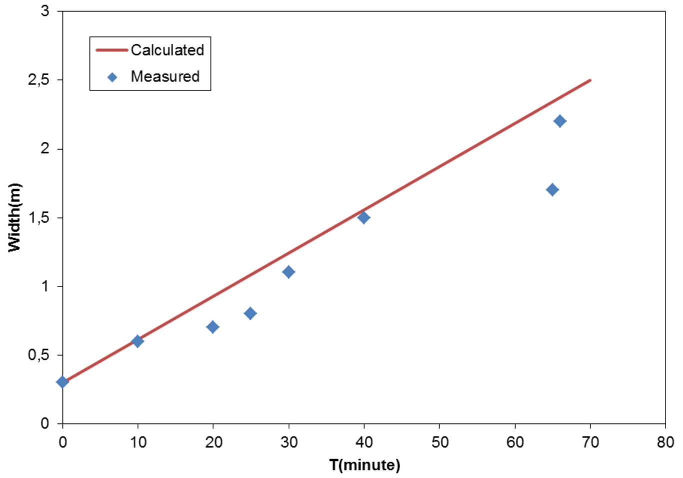

Figure 13. Calculated and measured Lateral Migration for Run 4

5 Conclusions

Since the breaching in cohesive embankment is a hydrodynamic process coupled by soil mechanics, the mathematical model has been developed by coupling compound weir flow and erosion (surface erosion, headcut erosion and lateral erosion). The breaching process is simplified into initial motion, deepening motion and widening motion, which corresponds to the surface erosion, headcut erosion and lateral erosion, respectively.

The experimental results strongly support the hypothesis that cohesive embankment breaching is a hydrodynamic process coupled with soil mechanics. The breaching starts with the initial erosion of the embankment surface and, then wash away the embankment surface. Due to the surface erosion at the toe of the embankment, the headcut erosion is stimulated on the embankment slope. The headcut erosion can also develop into cascade headcut migration, due to the non-homogenous characteristics of the embankment material (Hanson, et al., 2001). While headcut migration stimulates the breach to develop in longitudinal direction, the lateral erosion triggers the breach to widen in lateral direction. Three types of erosion (surface erosion, headcut erosion and lateral erosion) contribute to the erosion process of the breaching in the embankment, however, the breach flow is the driving force for the erosion. Sediment deposition in the breaching process can be of importance, but is generally ignored in the embankment breaching studies. Due to scale effects, the small-scale breach model cost more breaching time than the larger ones.

The simulated headcut and lateral migration results have reasonably good agreements with the experimental data. The headcut migration model has also been applied to simulate Test 2 of the breach tests of Delft University of Technology (Zhu, 2006), and the calculated results have a good agreement with the measured data.

The application of the lateral migration model to the prototype breach also fits well with the measured data, especially for the final breach width, even though the water level has been assumed constant in the lateral migration model. The proposed breach model overcomes the shortcoming of Bres-Visser (Visser, 1998), which just focuses on the sand dike breaching. The previous breach models for cohesive embankments (e.g. Zhu, 2006) used individual sediment particle erosion formulae, however, the breach model in the present study proposes that the clay erosion is in the form of clay blocks instead of individual particles, which can provide more realistic simulation results. But the headcut migration model and the lateral migration model still require more validations of laboratory tests, field tests and prototype measurements to improve the accuracy of the models.

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