Computer simulation of overtopping of levees

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ABSTRACT
There have been many cases of earth embankment failures, for example, Hurricane Katrina in 2005, where breaching occurred and devastated the surrounding population. Levee failures are preventable by a better understanding of the ways in which these embankments are designed and fail. The objective of this research is to protect levees against future failures. This paper studies various overtopping quantities and durations to represent the same level of levee erosion hazard. This study is based on experimental results of steady flows on the land side of a levee. The effect of water flow has been investigated and a comparison has been done between rills formations and erosion time for various water flows. Results showed that the pictures of digital simulations and real photographs which have been taken during tests in the laboratory are in a good concordance.

RESUMEN
Ha habido muchos casos de fallos de terraplén, por ejemplo, el huracán Katrina en 2005, en el cual se produjo una ruptura, devastando la población de los alrededores. Las fallas de diques se pueden prevenir, y es un objetivo de esta investigación alcanzar una mejor comprensión de las maneras en que estos diques se diseñan y fallan, a fin de poder protegerlos contra futuros fallos. Este documento desarrolla y recomienda equivalencias preliminares de combinaciones acumulativas de varias cantidades de desbordamiento y las duraciones asociadas que representan el mismo nivel de riesgo de erosión del dique. Las metodologías se basan en los resultados experimentales de flujos constantes en el lado seco de un dique. El efecto del flujo de agua se ha estudiado específicamente en esta investigación, y se ha hecho una comparación entre las formaciones de surcos y el tiempo de erosión para distintos flujos de agua.

1 INTRODUCTION

Levee failures occur as a result of overtopping and, to a lesser extent, seepage during storm surges and flooding events. In both mechanisms, the erosive processes can eventually lead to breaching of the levee and catastrophic damage on the adjacent floodplain, possibly causing significant disaster. A reliable prediction of the flood process, especially in a complex terrain, is necessary for emergency plans for levee or dam breaches. Xiao et al., 2008 concluded that the failure of parts of the levee system was caused by erosion during wave overtopping.

The erosion processes described in this paper refer to hydraulic erosion. Small-scale erosion on earthen embankments is being studied, modeled and eventually simulated, with respect to the formation of rills and gullies. The erodibility of a soil relates the velocity of the water flowing over the soil to the corresponding erosion rate experienced by the soil. A soil's erodibility is a method of describing the behavior of a soil under erosion conditions. Erodibility which can be defined as the ratio of critical shear stress on the soil to velocity of the water required to erode, is one the main reasons that would cause a levee to fail. Therefore some aspects of it have been investigated in this research.

Many studies have been performed on the erodibility of soil and levees. Wan and Fell (2004) described the development of two erosion rate tests: the Hole Erosion Test (HET) and Soil Erosion Test (SET), which measure a soil's erodibility. Using an Erosion Function Apparatus (EFA), Briaud et al (2008) investigated the erodibility of several different types of soil. The soils were classified into different categories of erodibility based on degree of compaction, erosion rate, water velocity and hydraulic shear stress. Xu and Zhang (2009) found that in addition to soil type, the degree of compaction plays an important role in erodibility of embankments. The erosion resistance increases with compaction effort, particularly with fine soils. Bryan and Rockwell (1998) studied agricultural sites near Toronto, Canada and found that significant rill incision typically occurred in early spring, immediately following snowmelt. However, this relates to the study of levees or earth dams that are adjacent to water bodies and are saturated or can become saturated rapidly. Rills and gullies will form in areas of depression, or in areas where the soil does not have enough cohesion or shear strength to resist the hydraulic stresses from the flowing water. Factors affecting rill characteristics include the stress caused by the flow, roughness of the soil surface, slope gradient and soil erodibility (Mancilla, et al 2005). However, Govers, et al. 2007 presented that erodibility within a rill may vary with its depth, which can decrease the erosion process in granular soils, as a result of a reduced slope gradient. If a more erodible soil underlies the surface soil, however, the erosion rate in a rill or gully will actually be accelerated.

Post Hurricane Katrina field surveys showed that in general, rolled compacted clay fill levees performed well

with minor erosion occurring when overtopped, whereas hydraulic filled levees with significant amounts of silt and sand performed poorly. Using good clayey material often required long haul distances that slowed construction progress, so nearby granular material was used instead to make the levees (Sills, et al. 2008). In cohesive embankments, breaching occurs as a result of head cutting, whereas in granular embankments, surface slips occur rapidly due to seepage on the downstream slope (Xu and Zhang 2009).

Experience resulting from Hurricane Katrina has shown that land side levee erosion due to wave overtopping can significantly limit levee performance and survival (USACE, 2008a). The options to ensuring levee integrity due to wave overtopping include: (1) a sufficiently high crest elevation such that overtopping does not occur, (2) armoring the levee land side such that the levee can withstand large amounts of overtopping, and (3) establishing a levee elevation that will allow an overtopping quantity that is within the capability of the levee to withstand the induced erosion (Dean et al., 2009). Erosion is a time dependent process such that a levee can withstand various overtopping magnitudes for different durations. Although the specific interest may be in designing the levee for survival during a particular storm (say a 100 year event), there is also interest in the erosional potential during storms that will cause greater overtopping. Flor et al. 2010, tested the relative importance of geologic, geomorphic, and other physical factors that have led to levee failures through the past century along the Mississippi River and presented some results that could potentially assist engineers and decision-makers in choosing appropriate locations and designs for levees. Dean et al. 2009, mentioned that present criteria for acceptable grass covered levee overtopping are based on average overtopping values and do not include the effect of overtopping duration. Therefore in their study, experimental steady-state results were applied for acceptable overtopping to the case of intermittent wave overtopping. Laboratory results consisting of velocities and durations for acceptable land side levee erosion due to steady flows were examined to determine the physical basis for the erosion. The governing equations for flow down the land side of a levee established that due to maximum velocity of water, the flows near the land side levee toe will be supercritical. Yu et al., 2009 carried out numerical simulations of levee or dam breach flow, often with constant flow parameters and in relatively simple channels rather than in natural rivers with complex boundaries using 2-D finite element model. The good performance of the model was demonstrated by comparisons of breaching with the theoretical solution of an idealized dam-break flow over a frictionless flat rectangular channel. The model was applied to simulate the flood propagation under complex boundary conditions. The unsteady flood process in a river and in the dry floodplain with a complex bed terrain was also simulated simultaneously. Benjamin, 1983 presented a brief practical review of the elements of statistical decision theory, decision making under probabilistic uncertainty, as applied to dams and levees. The methodology was developed through some examples and the concepts of risk analysis were presented. A general overview was also provided of the practical application of the methodology to problems with dams and levees. Xiao et al., 2008 applied a numerical wave model based on the incompressible Reynolds equations and k–e equations to estimate the impact of overtopping on levees during storm surge. The free surface locations were represented by volume of fluid function (VOF). The model was satisfactorily tested for an empirical equation of overflow discharge at a vertical seawall and experimental data of overtopping discharge at a sloping seawall. The validated model was used to simulate wave overtopping of the levee system during storm surge of Hurricane Katrina. The time history of wave profiles and velocity magnitude field in the vicinity of the levees were demonstrated and analyzed.

As computer capabilities progress in representing hurricane induced storm surges, there is a need to improve understanding of the overtopping erosion potential and to provide associated guidance for more rational design (Dean et al., 2009). Although much work has been done to simulate erosion in the field of computer graphics, very little has undergone any validation. A primary objective of this research is validation of our computer simulation by laboratory experimentation. Therefore in this paper, laboratory tests with different soils have been performed to improve the computer simulations of levee erosion. Laboratory tests provide real work parameters which help to make simulations more similar to reality. Results of simulations and special geometry of the model after erosion can also be validated by real lab tests results. Previous tests have been performed using different mixtures of the two soils and the effects of different percentages of clay have been investigated previously (Gross et al., 2010). The emphasis was to investigate the effect of water flow on the erosion. Therefore, all the tests were performed on one mixture of soil (25% clay, 75% sand) and water was added using various water flow rates.

2 TEST MATERIAL

The tests represented herein used two soils, a clay soil (Kaolin Clay) and a granular soil (Nevada 120 Sand). They were performed on mixtures of 25% clay and 75% sand. This mixture is a good representation of materials generally used to build levees. Table 1 lists the physical characteristics of the mixed soil, while Fig. 1 shows grain size distribution curves of pure sand and the mixed soil. The mixed soil is classified as SC according to the Unified Soil Classification System (USCS). The maximum dry unit weight for the soil sample was 15.4 kN/m^3. Samples were prepared to achieve relative density of 90% of the maximum dry density (13.9 kN/m^3) and used the optimum water content (8%) which has been calculated according to AASHTO T180 (B-method).

Table 1. Soil Characteristics

Property	25% clay- 75% Sand
D_{10} (mm)	0.074
D_{30} (mm)	0.11
D_{60} (mm)	0.19
Coefficient of uniformity	2.57
Coefficient of curvature	0.86
Liquid limit	17
Plastic limit	11
USCS symbol	SC

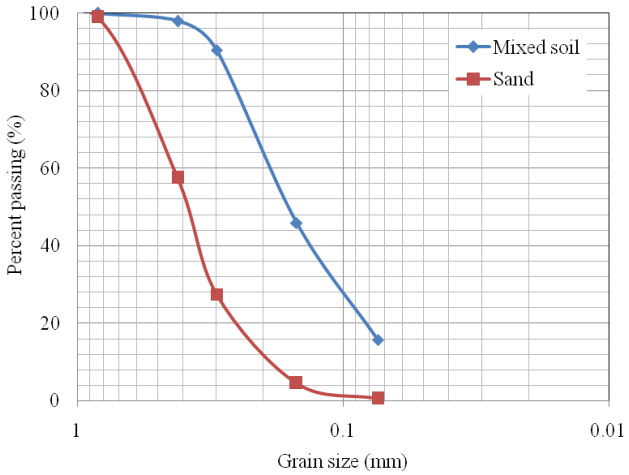


Fig. 1. Grain size distribution curves of soils

3 TEST PROCEDURES

The models used in this research were constructed in an aluminum box having a wall thickness of 0.0254m and interior dimensions of 0.91m L x 0.61m W x 0.36m H. The geometry of the model levee was designed to be similar to conventional levee designs. The dimensions were marked on the sides of the model box at the proper angles to ensure that the model levee was constructed to the desired specified geometry (Fig. 2). The compaction of soil is conducted by using a manual plastic hammer to hit the steel plate, which was placed on top of the soil until reaching the target unit weight.

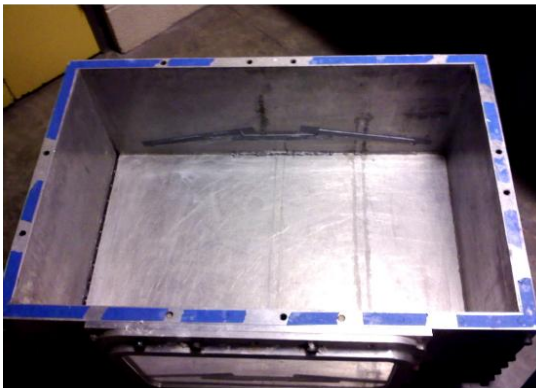


Fig. 2. Aluminum model box

Validation of the simulation is a primary focus in this research, so scaled-down model levees are used to perform erosion experiments at 1 *g* and at higher levels of *g* in a geotechnical centrifuge. The results of experiments to date are presented in the following sections. Tests reported herein have been performed at 1 *g* using the homogeneous laboratory Nevada sand – kaolin clay mixes. Different water flows were used and complex geometries and boundary conditions utilized to quantitatively assess the effects of differing conditions. The physical models serve as the basis for developing accurate, digital simulations of the embankment erosion processes

During 1-g tests different times were measured and recorded. Table 2 shows the symbol and definition of measured times. Although photographs and videos were taken before, during and after each test, the initial and final surface geometries of the model levee were also recorded using a 3-Dimensional Laser Range Scanner (LIDAR). The Laser Range Scanner rotated through a user specified angle and, using a single laser beam, conducted a scan of the surface at each incremental rotation within the range of rotation. Each incremental movement was characterized by a new pulse of the laser beam that collected data based on features in surface elevation or geometry of the object of interest at that specific position being scanned. The result of the scan was a point cloud of 3D points representing the surface of the levee. The Laser Range Scanner used in this research was a Leica 30 HDS 3000, by Leica Geosystems HDS, LLC. The Laser Range Scanner is shown in Fig. 3 (a), while the scan of a specific slice of the model using the laser beam is shown by the green line in Fig. 3 (b).

The erosion simulation is based on the method of Smoothed Particle Hydrodynamics (SPH) (Monaghan 1992). Both the water and the levee are discretized by particles, and the behaviour of fluid is modeled by the Navier-Stokes equations. In each of the simulations, approximately 450,000 and 2,500,000 particles are used to represent the water and the soil, respectively (Chen et al. 2011).

In simulations, the erosion rate, “z”, (mm/hr) is modeled

by using Eq. 1:

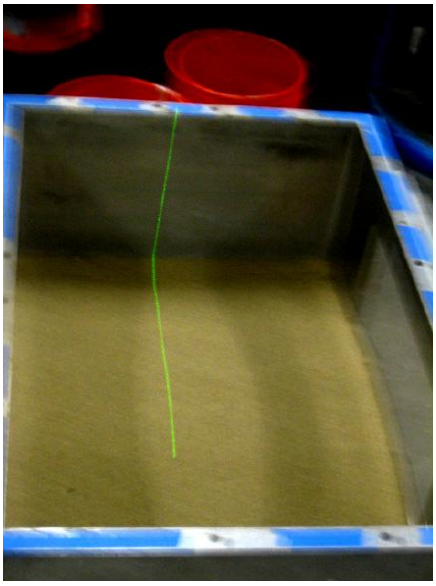
$$z = \begin{cases} 0 & when\ \tau \le \tau_c \\ a \times \tau + 0.1 & when\ \tau > \tau_c \end{cases} \quad (1)$$

where τ is the hydraulic shear stress (Pa) and τ_c is the critical shear stress. Since the values of a and τ_c are different for different materials, their values have to be determined for each material used in physical experiments. In the authors' previous experiments, pure sand and sand-clay mixtures (85% sand and 15% clay) have been used. In previous simulations, the value for a was estimated to be 187 and 93 for pure sand and sand-clay mixtures respectively, and the value for τ_c was estimated to be 2.0 and 3.0. A series of simulations on those two materials have been run, as well as some imaginary materials whose erodibility lies between the erodibility of those two materials (Chen et al. 2010). In order to determine the values of the parameters for the material of current experiments, a comparison between the results of previous simulations and the results of current physical experiments have been done. The comparison was done by observing the duration of the four different erosion phases mentioned in Table 2. Since water permeability is not yet simulated in the system, it is not accurate to compare $t_{elevation}$, $t_{cross\ crown}$ or t_{rill}. By comparing t_{breach}, the value of the parameters have been determined to be a = 187 and τ_c = 3.0 for the current material that is being used. A series of 5 simulations have been started with different inflow rates. To date, three of the simulations have been finished and the t_{breach} for these simulations have been plotted in Fig. 8. Since it seems reasonable to fit the values of these three t_{breach} to a linear function, a prediction for the value of t_{breach} has been used in the two simulations which still are being run. As can be seen, there is a good concordance between the results of real tests and digital simulations. However the predictions of results for Q= 0.20 and 0.35 are not so precise.

Table 2. Definition of different times

Symbol	Definition
$t_{elevation}$	The time duration for water (at a specific flow rate) to fill the upstream and reach the elevation of the crown
$t_{cross\ crown}$	The time duration for water to cross the crown of the levee
t_{rill}	The time elapsed from initial rill formation at the crest of the landside slope to the time the rill reached the toe of the slope
t_{breach}	The time elapsed from initiation of initial rill erosion began at the crest of the landside slope to the time the eroded channel reached the crest on the waterside slope

(a)



(b)

Fig. 3. (a). Leica HDS 3000 Laser Range Scanner, (b). Scan of model levee

However, to illustrate the dimensions of the levee, a schematic picture of model is shown in Fig. 4.

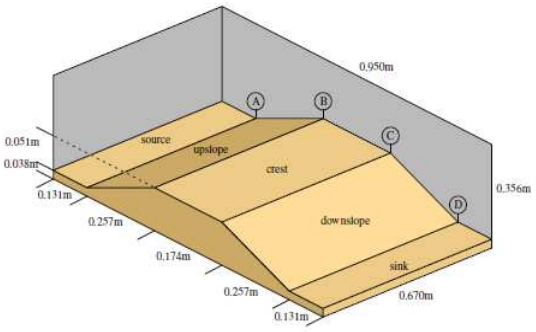


Fig. 4. Dimensions of the modeled levee (Chen et al., 2010)

4 RESULTS AND DISCUSSIONS

Five different water flows (0.2, 0.35, 0.65, 0.75 and 0.88 lit/min) were used and different time durations (Table 2) measured to evaluate the effects of water flow on the erosion and overtopping. Fig. 5 shows the variation of different times related to water flow. The vertical axis in Fig. 5 is cumulative time which shows that the time have been measured from the beginning of the tests.

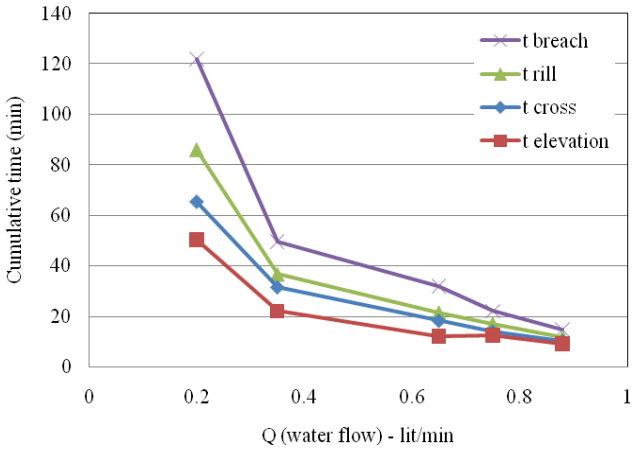


Fig. 5. Variation of different times versus water flow according to lab tests

As expected, increasing water flow will decrease the time needed for each stage of overtopping. However, the number of rills due to overtopping and their depth and formation were quite different depending on the flow rate.

Fig. 6 shows digital simulation of erosion for these tests. It should be noted that simulations for tests with Q= 0.88, 0.75 and 0.65 has been done, but for Q= 0.20 and 0.35, the results have been predicted and simulations are currently (to date) not finished.

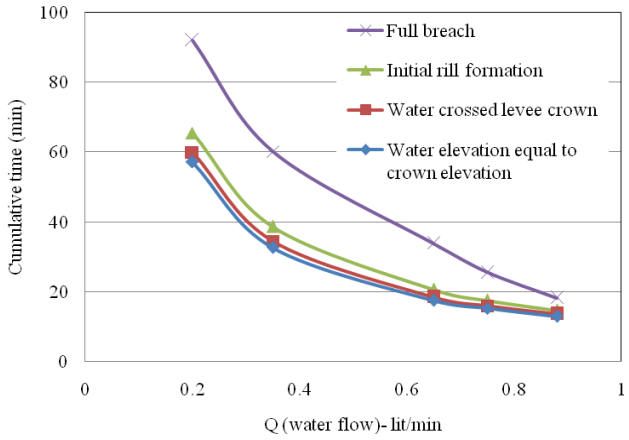


Fig. 6. Variation of different times versus water flow according to digital simulations

The full breach condition for the models with flows equal to 0.88 lit/min and 0.2 lit/min are shown in Figs. 7(a) and (b) respectively. As shown in Fig. 7, at higher flow rates, the levee can fail even when most of the body of the levee is still dry.

(a). water flow = 0.88 lit/min

(b). water flow = 0.2 lit/min

Fig. 7. Full breach condition, (a). Water flow equal to 0.88 lit/min, (b). Water flow equal to 0.2 lit/min

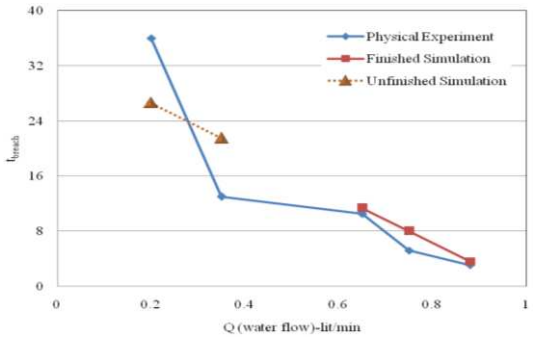
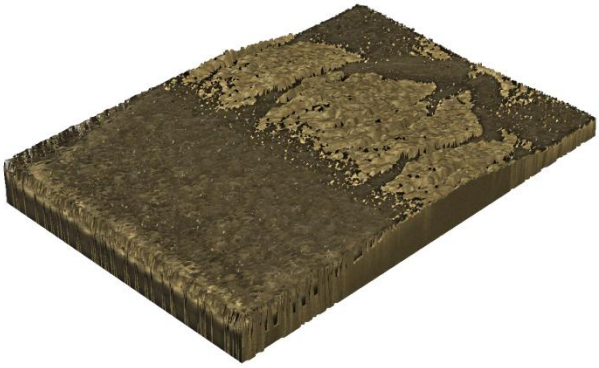


Fig. 8. Values of t_{breach} determined by physical experiments and simulations

Fig. 9 shows the pictures of digital simulations for test with Q= 0.65 lit/min. Different stages of overtopping of the levee can be seen in this figure. Comparing these pictures with real photographs which have been taken during tests in the laboratory, good concordance can be observed between them.

(a). Before overtopping

(b). Overtopping and formation of rills



(c). Full breach

Fig. 9. Digital simulations for different stages of overtopping, (a). Before overtopping, (b). During overtopping, (c). Full breach

To better evaluate the effects of water flow on real levees. Centrifuge tests will be performed, simulating full scale prototype levees and embankments.

5 CONCLUSION

An investigation on various overtopping quantities of levee and erosion hazard has been performed. Digital simulations have been presented to predict the time that would take the levee to breach under different water flow. The following specific conclusions can be drawn from the study:

1. Higher water flow will lead to smaller t_{breach}. In other words, in similar levees with different water flow, breaching would happen faster in the one which has higher water flow.
2. At higher water flow, most of the water will over top and the amount of water that seep through the levee is negligible comparing to overtopped water.
3. At smaller water flow (smaller that 0.4 lit/min), the amount of water that seep through soil is significant comparing to the amount of water that seep.
4. At small water flow, seepage plays a significant roll on controlling the erosion. On the other words, although long seepage may eventually cause failure but it will prevent erosion.
5. Digital simulations for high water flow that the seepage is negligible are consistent with the results of physical tests.

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