Computer Simulation of Levee Erosion and Overtopping

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Abstract

Improved computer models of erosion have been developed, considering soil hydraulic conductivity. The models deal with erosion of levees, dams and embankments due to overtopping. The simulations trace the formation of rills and gullies, beginning with initial overtopping and continuing to final breaching. Physical models performed at "1-*g*" and high "*g*" using a geotechnical centrifuge have been used to calibrate the models. Previous models did not consider soil hydraulic conductivity, and although results were quite good for the formation of rills and gullies and sediment quantities, breach times were underestimated. Essentially the water flow was treated as if passing over a solid surface, not entering the soil, and the total water flow was available for erosion. Thus, breach times were underestimated. Soil erodibility parameters had to be adjusted in order to achieve good agreement with breach times. The new models developed consider soil hydraulic conductivity, and produce good agreement with the performance of the physical modeling, including breach times and the use of proper soil erodibility parameters.

Introduction

Levee failures often occur due to overtopping and seepage, which creates erosive processes, portending the breaching of the levee and catastrophic damage on the adjacent flood plain. Planning for such emergencies for levee or dam breaches requires reliable predictions, especially on complex terrain. Griffis (2007) addressed the overall design of the engineering works, discussing the natural and engineered flood-protection structures and strategy for major hurricanes concerning New Orleans. His evaluation assessed the improvements necessary to protect from the damaging effects of water. After analyzing the failures of the natural system and of the levees, floodwalls, pumping stations, and the absence of flood gates on the canals, he concluded that the "design storm" specified by congressionally authorized projects deserved reconsideration, and that engineering design reviews should be reorganized and implemented. In order to make such improvements the properties of soil, especially the erodibility of it, had to be evaluated. Wan and Fell (2004) describe the development of two erosion rate tests, the Hole Erosion Test (HET) and Soil Erosion Test (SET), which measure soil erodibility. Using an Erosion Function Apparatus

(EFA), Briaud et al. (2008) investigated the erodibility of several different types of soil, classifying the soils by 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 effects erosion resistance, increasing with compaction effort, particularly with fine soils.

Post Hurricane Katrina field surveys showed that rolled, compacted clay filled levees performed well with minor erosion occurring when overtopped, whereas hydraulic filled levees with silt and sand performed poorly. Clayey material often required long haul distances that slowed construction progress, thus nearby granular material was often used Ginstead (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). Water also had another effect on soil in which rills formed and led to other important studies concerning the interactions between water and soil.

A major concern in advancing flood-protection is studying overtopping. Experience resulting from Hurricane Katrina has shown that land-side levee erosion due to wave overtopping can significantly limit levee performance and survival (USACE, 2000). 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 and the capability to withstand the induced erosion (Dean et al., 2010). Erosion, a time dependent process, requires a levee to withstand various overtopping magnitudes for different durations. Although the levee design should account for survival during a particular storm (e.g. a 100 year event), the erosional potential of storms causing greater overtopping creates additional interest. Dean et al. (2010), mentioned that present criteria for grass covered levee overtopping are based on average overtopping values and do not include the effect of overtopping duration. Therefore, their study applied to acceptable overtopping for intermittent wave overtopping. Using laboratory results of velocities and durations for land-side levee erosion from steady flows, they established the governing equations for flow, and concluded that the maximum velocity of water near the land-side levee toe would be supercritical.

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 a 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 surges of Hurricane Katrina. The time history of wave profiles and velocity magnitude fields in the vicinity of the levees were demonstrated and analyzed.

As computer capabilities progress in representing hurricane induced storm surges, a need to improve understanding of the overtopping erosion potential and to provide associated guidance for more rational design parallels. Dean et al. (2010) and Holmes et al. (2011) presented a three-dimensional smooth particle hydrodynamics (SPH) simulator for modeling grain scale fluid flow in porous media. The versatility of the SPH method has driven its use in increasingly complex areas of flow analysis, including the characterization of flow through permeable rock for both groundwater and petroleum reservoir research. SPH provides the means to model complex multi-phase flows through such media; however, acceptance of the methodology has been hampered by the apparent lack of actual verification within the literature, particularly in the three-dimensional case. The accuracy of results for low Reynolds number flows is highly dependent on the implementation of no-slip boundary conditions. They also presented a new, robust and numerically efficient, method for implementing such boundaries in SPH. Simulation results for friction coefficient and permeability were shown to agree well with the available benchmarks. Although much work has been done to simulate erosion, very little of the results have been validated.

A primary objective of this research was validation of the 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. Previous tests have been performed using different mixtures of two soils and the effects of different percentages of clay have been investigated previously. The emphasis of this paper 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. To better evaluate the effects of water flow on real levees, some centrifuge tests have also been performed which simulate full scale prototype levees and embankments.

Test Material

A mixture of two soils have been used in the tests represented herein, a clay soil (Kaolinite Clay) and a granular soil (Nevada 120 Sand). Tests were performed on mixtures of 25% clay and 75% sand. Maximum dry density and optimum water content of the sand and clay were 16.4kN/m^3 and 11% for the sand and 12.8kN/m^3 and 29% for the clay respectively. Table 1 lists the physical characteristics of the mixed soil, while Fig. 1 shows grain size distribution curves of the 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 15.4kN/m^3. Samples were prepared to achieve a relative density of 90% of the maximum dry density (13.9kN/m^3) and used the optimum water content (10%) which has been calculated according to AASHTO T99-70 / ASTM D698-70 (A-method).

Table 1. Soil Characteristics

Property	Mixed soil
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
Permeability	10e-5 cm/s
USCS symbol	SC

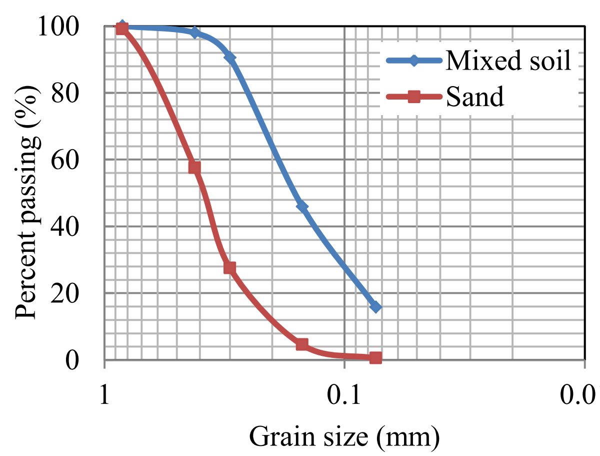


FIG. 1. Grain size distribution curves of soils

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 0.87m L x 0.39m W x 0.36m H. The geometry of the model levee was determined similar to conventional real levees before construction of the model began. 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(a)). Some tests were also performed in larger and smaller boxes to find the effect of dimensions of levee on the results (Fig. 2(b) and(c)). The compaction of soil was conducted manually by using a plastic hammer to strike the steel plate, which was placed on top of the soil until reaching the target unit weight.

(a) (b) (c)

FIG. 2. Aluminum model boxes (a). Big box, (b) Medium box, (c). Small box

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. 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. 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. To illustrate the dimensions of the levee, a schematic picture of the model is shown in Fig. 3.

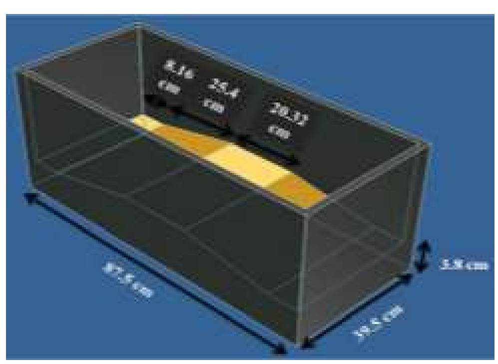


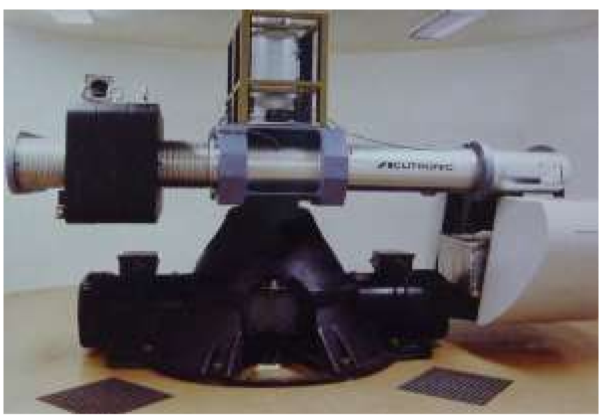
FIG. 3. Dimensions of the modeled levee in the medium box

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 (t_{breach}) was measured during the tests. Photographs and videos were taken before, during and after each test. The width and depth of the rills were also measured after failure of the levee.

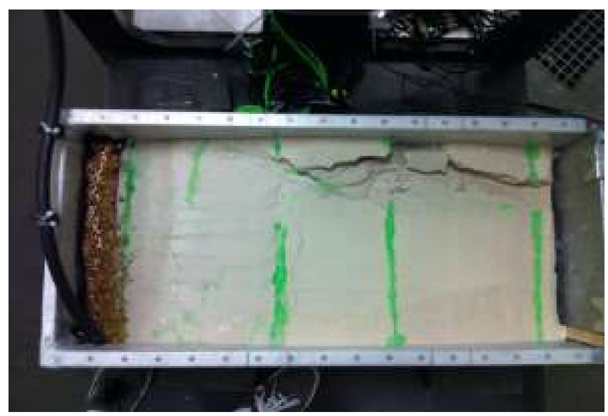
In order to simulate some large scale measurements centrifuge tests were performed at 25g's (Fig. 4(a)). Since in high "*g*" tests water will be heavier, erosion will occur much faster than "1-*g*". A high speed camera was used to take pictures and record videos during the tests in centrifuge. The camera is a V5 High Speed CMOS Camera with full image resolution 1024x1024 pixel array capability at 60,000 pps.Three other cameras were also recording videos from different angles. These videos and pictures were being used to evaluate the results of digital simulations and computer predictions.

Fig. 4(b) shows a levee after a centrifuge test. The green lines are colored sand that was used for the purpose of better viewing in the crest of the levee. Since the water is 25 times heavier in this centrifuge test, pebble size sands overlaying a piece of geotextile were used in the left side of the box, where water was added to the levee from a hose, to prevent erosion. To collect the overtopped water, an empty space was left underneath the levee. The overtopped water passed through a small gap in the right side of the levee and was collected underneath the levee.

The erosion time was about 5 minutes for a water flow equal to 0.56 lit/min. However in the centrifuge time and dimensions will scale by "*g*", and this would be equal to 100 minutes in full scale prototype time. The tested levee would also simulate a 17.50m long prototype levee with 1.78m height and 7.90m width.



(a)



(b)

FIG. 4. (a). RPI 150 *g*-ton geotechnical centrifuge, (b). The eroded levee after the centrifuge test

Computer Simulation

To model the system the high resolution particle-based Lagrangian methods based on Smooth Particle Hydrodynamics (SPH) was used, which was first presented by Gingold et al. (1977). This method is based on the Navier-Stokes equations and discretized into a set of particles. The solution is based on momentum and mass conservation equations:

$$\frac{d\rho}{dt} + \nabla(pv) = 0 \qquad (1)$$

$$p\left(\frac{dv}{dt} + v.\nabla v\right) = -\nabla\rho + pg + \mu\nabla^2 v \qquad (2)$$

where $\boldsymbol{v}$ is the velocity field, p is the density field, ρ is the pressure field, "g" is gravity, and μ is the viscosity of the fluid. Fluid implementation in this research is primarily based on Muller et al. (2003) and to model the soil a set of statically placed erodible particles was used as introduced by Kristof et al. (2009) and Muller et al. (2003). Three types of particles were used in this simulation; soil particles, boundary particles (soil particles near a water particle), and water particles. The method introduced by Briaud et al. (2008) was used to model the transfer of mass from boundary particles into water particles based on the shear stress between the water and soil.

$$\frac{dM_b}{dt} = \sum_j L_b^2 K_e (K\frac{v_{rel}^n}{l} - \tau_c) \qquad (3)$$

where K is the shear stress constant, n is the flow behavior index, v_{rel} is the velocity relative to the solid surface, l is the distance between the fluid and boundary particle, K_e is the erosion strength, τ_c is the critical shear stress, M_b is the mass of a boundary particle, and j is a particle within the smoothing radius.

The model presented by Toon et al. (2008) was used in the next step of simulation, after modeling water that permeates into the soil. To do this, the properties porosity and permeability were added to all of the soil particles in the system. These were used to model the capillary pressure gradient (Eq. 4), which gives rise to the Darcy flux (Eq. 5). The fluid mass is then integrated using explicit Euler integration.

$$\nabla P_i^c = \sum_j V_i P_j^c \nabla W(x_i - x_i, h_j), P_i^c = K^c(1 - \frac{m_{pj}}{p^{fluid}\varphi_j V_j})^\alpha \qquad (4)$$

$$\frac{dm_{pi}}{dt} = \sum_j v_{pj}.\frac{x_j - x_i}{\|x_j - x_i\|} S_j^\beta m_{pj} \nabla^2 W(x_j - x_i, h_j) \qquad (5)$$

Where k^c and $0<\alpha<1$ control the strength of the potential, m_{pj} is the fluid mass of s dirt particle, K is the permeability, and $\beta>0$ controls flow.

To determine the proper α and β, a physical permeability test was performed using a soil mixture whose permeability and porosity properties are used in the computer simulation (Fig. 5).

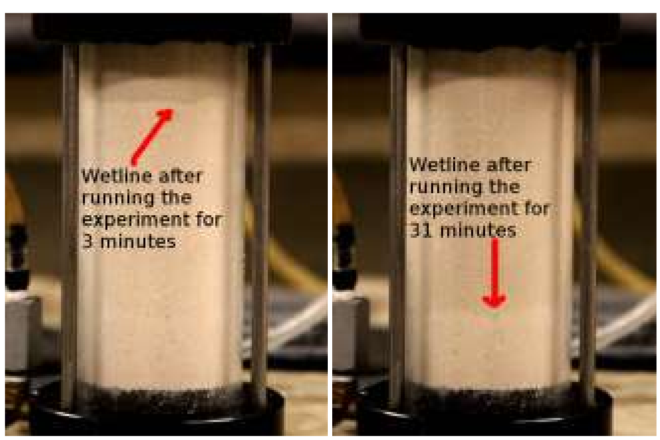


FIG. 5. Physical saturation tests using soil and clay mixture

After the physical test, 3 soil samples were taken from the top, middle and bottom of the oil cylinder to gather saturation statistics. Then 103 computer simulations were executed using different alpha and beta values to do a statistical analysis of the impact of each variable on the saturation simulation result at the given sampling heights. The alpha and beta values acquired from the analysis above produced the following result (Fig. 6) in which the time that the wet line took to reach the bottom and the saturation values at all sampling heights agreed with what the physical test demonstrated.

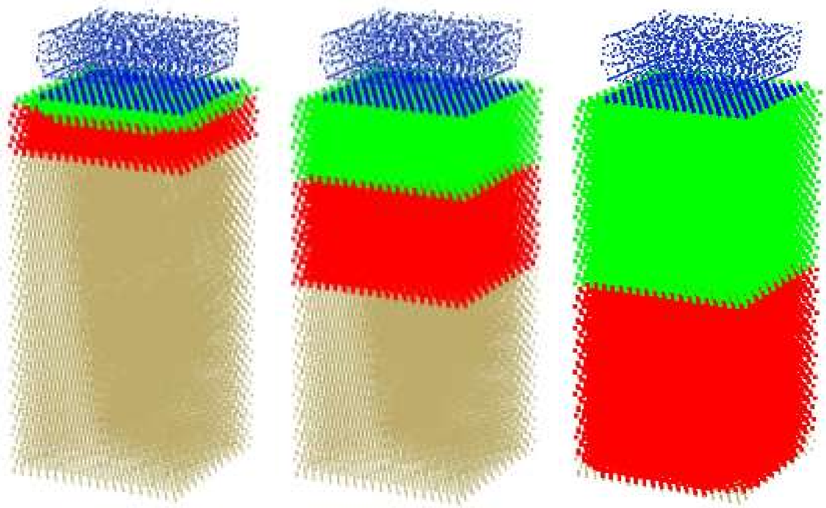


FIG. 6. Permeability simulation result produced using proper α and β values matched physical test result: particles were marked blue if above 78% saturated (top soil sample saturation), green if above62% saturated (middle soil sample saturation)and red if above 32% saturated(bottom soil sample saturation)

Levee erosion was simulated, taking permeability into account. For each of the simulations approximately 450,000 water and 2,500,000 soil particles were introduced (Chen et al., 2011). The erosion rate in the simulation, "Z", (mm/hr) is modeled by using Eq. 6:

$$Z=\begin{cases}0 & when\ \tau \le \tau_c \\ a \times \tau + 0.1 & when\ \tau > \tau_c\end{cases} \quad (6)$$

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 used in the current experiments, a comparison between the results of previous simulations and the results of current physical experiments have been done.

Water flow rate, geometry of the levee surface, and erodibility of the soil were identified as three major components in the formation of channels during erosion simulation. A total of 27 computer simulations have been run, one for each possible combination of three different flow rates, levee down-slope angles, and erodibility values. For flow rates, values of 8, 11, and 14 mL/s, were chosen. For erodibility values, 137, 159, and 187 alpha-values, representing the range from sand-clay mixture made up of approximately 10% clay to pure sand were chosen. Finally, for levee slope, dry-side slopes of 4:1, 5:1, and 6:1, typical ranges found in real levee design were chosen. For each simulation result, the time to breach was visually determined, and has been identified by the Dam-Break Flood Forecasting Model (Fread, 1984).

Results and Discussions

Times to breach statistics were observed to be based primarily on the flow rate of the water rushing over the levee. This appears logical, as a higher velocity implies more shear stress, and more opportunity to surpass the soil's critical shear stress and cause erosion. Secondarily, soil erodibility impacted the level of erosion as well. Within a single flow rate's time set, highly erodible soil failed first. The slope of the levee geometry had minimal impact on times to breach, an observation that is somewhat surprising considering how important levee slope is in the design of levees, as it has an impact on levee seepage and levee stability. However, at present our simulation does not model seepage or piping, nor does it consider large deformations of the levee due to mudslides or surface fracture. If these phenomena were modeled, the results may indicate levee slope as a more important factor during overtopping conditions.

Fig. 7 shows a visualization of the average times to breach of each experimental flow rate, levee slope, and soil erodibility.

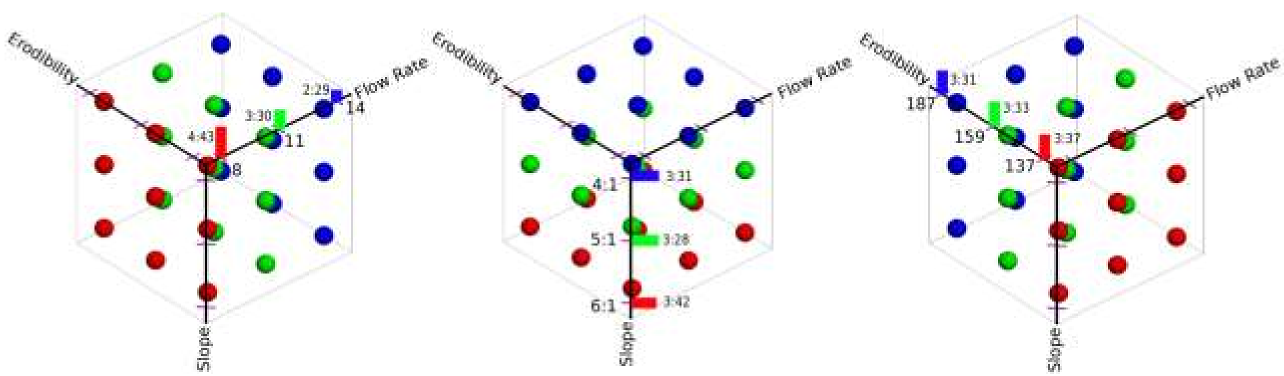


FIG. 7 A visualization of the average times to breach of each experimental flow rate, levee slope, and soil erodibility. Each data point represents a single erosion simulation, and planes are colored to represent the points that were used to determine a single characteristic's average time to breach. For instance, in the left image, all data sets with a flow rate of 8 mL/s are represented by red, 11 mL/s by green, and 14 mL/s by blue data points. The bars on each axis represent the average time to breach of all data points of the corresponding color, and each image compares averages across a single characteristic. We can see that levee slope and erodibility have little effect on the times to breach, whereas flow rate has a major impact

An interesting outlier in our data was the fastest flow rate (14 mL/s) and the highest erodibility value (187). All levee slopes in this category failed within 20 seconds of each other, and it was not the fastest time to breach, as would be expected. This result may indicate that there is a critical flow rate past which any flow is too destructive to adhere to any general trends.

However, it is more likely that this anomaly is a result of the number of channels witnessed, an additional observation made of the test results.

The number of channels that formed under each testing condition was also observed. We designated the number of channels by two numbers, *n*/*m*, where *n* is the number of channels visible on the down slope side of the levee, and *m* is the number of channels that reached full breach during the test. The majority of tests presented a 1/1 channel result, meaning exactly one primary channel formed and it reached breach condition. The majority of tests in which a 2/2 channel formation was observed had flow rates of 14 mL/s, whereas the majority of the tests with flow rate of 8 mL/s had a 1/1 channel condition. The tests with flow rate of 11 mL/s provided both 2/1 and 1/1 channel conditions, but no 2/2.

The large number of tests with fast flow rates and multiple channel formations could account for the slower breach times for faster flow rates, as more soil is being eroded from two different locations along the levee, instead of a single channel. Since the total eroded volume is higher with faster flow rates, this appears logical.

Conclusion and Future Works

An investigation of various overtopping quantities dealing with levee erosion has been performed. Digital simulations have been presented to predict the time that it would take the levee to breach under different water flows. Additional centrifuge tests are planned. Since the breaching in centrifuge tests happens rapidly, some modification may be needed for the centrifuge tests; e.g. using cameras with higher quality to capture better images and videos during and after the tests. It will help to observe and measure the exact breaching time during centrifuge tests; because even a few seconds in high "*g*" tests represents a significant amount of prototype time. The following specific conclusions can be drawn from the study:

1. Higher water flow will lead to smaller t_{breach}. That is, in similar levees with different water flows, breaching would happen faster in the one which undergoes a higher water flow.
2. At higher water flows, most of the water will overtop the levee and the amount of water that seeps through the levee is negligible compared to overtopped water.
3. At smaller water flows (smaller than 0.4 lit/min), the amount of water that seeps through the soil is significant compared to the amount of water that overtops.
4. At small water flows, seepage plays a significant role on controlling the erosion. That is, long term seepage may eventually cause failure, but for short times it tends to reduce erosion.

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