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Computer Simulation of Levee's Erosion and Overtopping

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ABSTRACT

The overall intent of this research is to develop numerical models of erosion of levees, dams and embankments, validated by physical models. The physical model tests were performed at 1-g and at high g's using a geotechnical centrifuge facility. The erosion was modeled in detail, from beginning to end, that is from the time the levee was overtopped until the levee was breached. Typical quantities measured as a function of time included the depth, width and volume of rills, number of junction points, rills shape (straight or meandering), sediment transport quantities, and time to breach. This data can be obtained from the numerical modeling, but is difficult to obtain from the physical tests, except at the beginning and end of tests. Video images indicate that the physical modeling results which have been tested in this research agree with the numerical modeling results. Results show that at small water flows, seepage plays a significant role in controlling erosion. Although long-term seepage may eventually cause failure, in the short term low flows tend to reduce erosion by reducing the amount of overtopping.

Key words

Erosion, Levees, Computer Simulations, Physical Modeling

I INTRODUCTION

Flood disasters are commonly caused by levee breaches due to high river flows. This generally results in damage inside the protected zone of the levees. Levee failures commonly occur due to overtopping of the levees. However other major levee failure mechanisms are initiated due to

seepage, for example internal erosion and piping. A reliable prediction of the erosion process, especially in a complex terrain, is necessary for emergency plans for levee or dam breaches. [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. 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.

Present criteria for acceptable grass covered levee overtopping are based on average overtopping values but do not include the effect of overtopping duration. [Dean et al. \(2010\)](#) applied experimental steady state results 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. Three bases were examined: (1) velocity above a threshold value, (2) shear stress above a threshold value, and (3) work above a threshold value. The governing equations for flow down the land side of a levee established that the flows near the land side levee toe will be supercritical. Wave run-up was considered to be Rayleigh distributed with the run-up above the levee crest serving as a surrogate for overtopping.

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, 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 ([Gross et al., 2010](#)). 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.

II MATERIALS AND TEST PROCEDURES

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, which is a typical mixture found in many levees. 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. 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 . Models 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	D ₁₀ (mm)	D ₃₀ (mm)	D ₆₀ (mm)	CU*	CC*	Liquid limit	Plastic limit	Permeability (cm/s)	USCS symbol
Mixed soil	0.074	0.11	0.19	2.57	0.86	17	11	10e-5	SC

*CU: Coefficient of uniformity; CC: Coefficient of curvature

The models used in this research were constructed in an aluminum box having 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. Some other tests were also performed in smaller and larger boxes to determine the effect of levee dimensions on the results.

Small-scale erosion on earthen embankments is being studied, modeled and simulated, with respect to the formation of rills and gullies. Validation of the simulations was one of the primary goals of this research. Therefore 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. The erosion processes described in this paper refer to hydraulic erosion. 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. In order to simulate large scale prototype levees centrifuge tests were performed at 20g's (Fig. 1).



Fig. 1. RPI 150 g-ton geotechnical centrifuge

In high g tests water will become heavier and erosion will occur much faster than 1-g. Therefore a high speed camera was used to take pictures and record videos during the centrifuge

tests. Two other cameras were also recording videos from different angles. These videos and pictures were used to evaluate the results of digital simulations and computer predictions.

The erosion simulation system utilized the theories of Smoothed Particle Hydrodynamics (SPH) (Monaghan 1992). Both the water and the levee are discretized by particles, and the behavior 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:

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

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 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. 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. Fig. 2 shows a visualization of the average times-to-breach for each experimental flow rate, levee slope, and soil erodibility, with each axis representing one parameter. The figure shows the same data with three different components as the main focus. For instance, in the left-most image, flow rate is the primary focus, and so each data point with the same flow rate is highlighted by the same color (red, green, or blue). The average of these data points' times to breach is expressed on the flow rate axis as a bar and numerical value. The other two images visualize the averaged data for levee slope and soil erodibility, respectively.

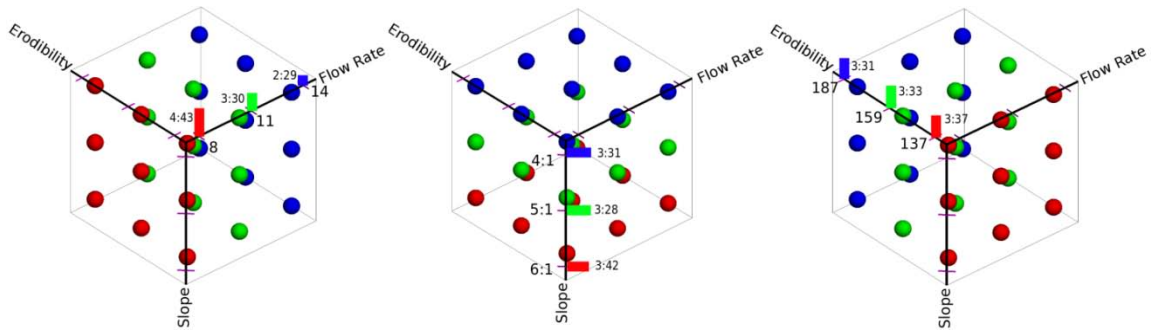


Fig. 2. A visualization of the average times to breach of each experimental flow rate, levee slope, and soil erodibility. Each data point represents a single erosion simulation, and planes are colored to represent the points that were used to determine a single characteristic's average time to breach. 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. It can be seen that levee slope and erodibility have little effect on the times to breach, whereas flow rate has a major impact

Several levees were built in an aluminum box and the effect of overtopping on the levee failure was investigated. It appears intuitive that larger levee models would yield more accurate and reliable results. However practical considerations indicate it would be difficult and time consuming to build large model levees. Therefore to find the most efficient size of model levee that leads to optimum results, a number of tests were performed in three different boxes with different dimensions: a small box (38.0cm×37.5cm), medium box (87.5cm×39.5cm) and a large box (91.0cm×61.0cm). The shapes of the rills and the time for levee failure were compared utilizing the different boxes. It was found that the medium sized box had the most efficient size so that models could be built in a reasonable time and lead to accurate results. Fig. 3 sketches the dimensions of the medium box and the levee built inside of the box.

Several 1-g tests using different water flows were conducted and different characteristics of the rills such as their shape and depth were recorded. This information was used to calibrate the computer simulations. For a better validation, four different times were defined and measured during the tests: $t_{\text{elevation}}$, the time duration for water (at a specific flow rate) to fill the upstream and reach the elevation of the crown, $t_{\text{cross crown}}$, 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, and 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.

However to study the effects of overtopping on larger levees, centrifuge tests were conducted. In the centrifuge, time and dimensions scale by g , for these experiments. Therefore the experiment using the medium size box (Fig. 3) with water flow equal to 0.56 lit/min that took 5 minutes to fail, simulates a 17.50m long levee with 1.78m height and 7.90m width that fails in 100 minutes in prototype time. Fig. 4 shows the levee after failure in the centrifuge test.

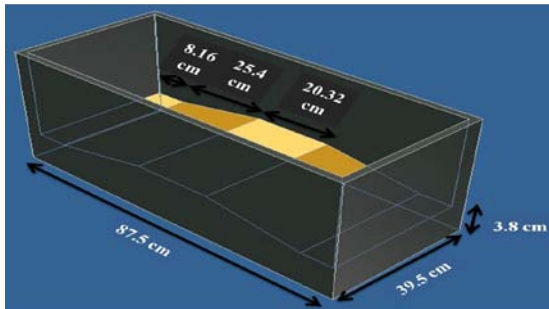


Fig. 3. Dimensions of the modeled levee in the medium box



Fig. 4. Failure in centrifuge test; water flow = 0.56 lit/min, $g = 20$

III SUMMARY

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. Secondly, 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. The computer model results presented here agree reasonably with the observed model behavior. 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.

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