Solutions for Various Obstacles Encountered with Laboratory Piping Tests

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ABSTRACT
Backward erosion piping, historically called piping, is a form of internal erosion that refers to a process by which seepage forces gradually erode soil particles from beneath a water-retaining structure creating an open pipe from the downstream to the upstream end of the structure, such as dams and levees. Piping may lead to the failure of a structure. Different approaches have been developed to estimate the critical hydraulic gradient necessary for the initiation and continuation of piping. Laboratory tests, physical models, and empirical equations are among the approaches that researchers have used to determine critical gradients. The Engineer Research and Development Center of the U.S. Army Corps of Engineers developed a small scale, laboratory flume to measure the critical gradient of nine uniform sands. Several obstacles were encountered during the initial testing phase. Examples of these complications include entrapped air in the system, ensuring that piping occurred in the center of the sample, and problems caused by head losses. The corrective actions that were implemented for the completion of a successful test program are discussed. The solutions used to overcome these obstacles led to repeatable tests with satisfactory results. The solutions are presented to ensure future efforts can make use of the lessons learned.

Keywords: piping, flume test, backward erosion, dams, levees

1 INTRODUCTION

Erosion is considered the most common cause of incidents and failures in dams and levees due to either overtopping or internal erosion (Bonelli, 2013). Internal erosion refers to any type of erosion that occurs within or beneath an embankment. According to Foster et al. (2000), internal erosion constitutes almost half (46.1%) of dam failures around the world. There are four different types of internal erosion: concentrated leaks, suffusion, contact erosion, and backward erosion piping (USACE & USBR, 2012; ICOLD, 2015). Backward erosion piping (BEP) occurs when particles are eroded away at an unfiltered exit, and a "pipe" is formed under a more cohesive material, progressing from the downstream to the upstream end of an embankment in the opposite direction of flow. The pipe is formed in the foundation material beneath the embankment.

Laboratory tests have been performed around the world as a way to study the phenomenon of BEP. The results of laboratory tests have been used to propose theoretical or empirical models that predict BEP. Small-scale and medium-scale tests have been typically performed in box-shaped flumes filled with soil samples. BEP research is currently being conducted at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, USA.

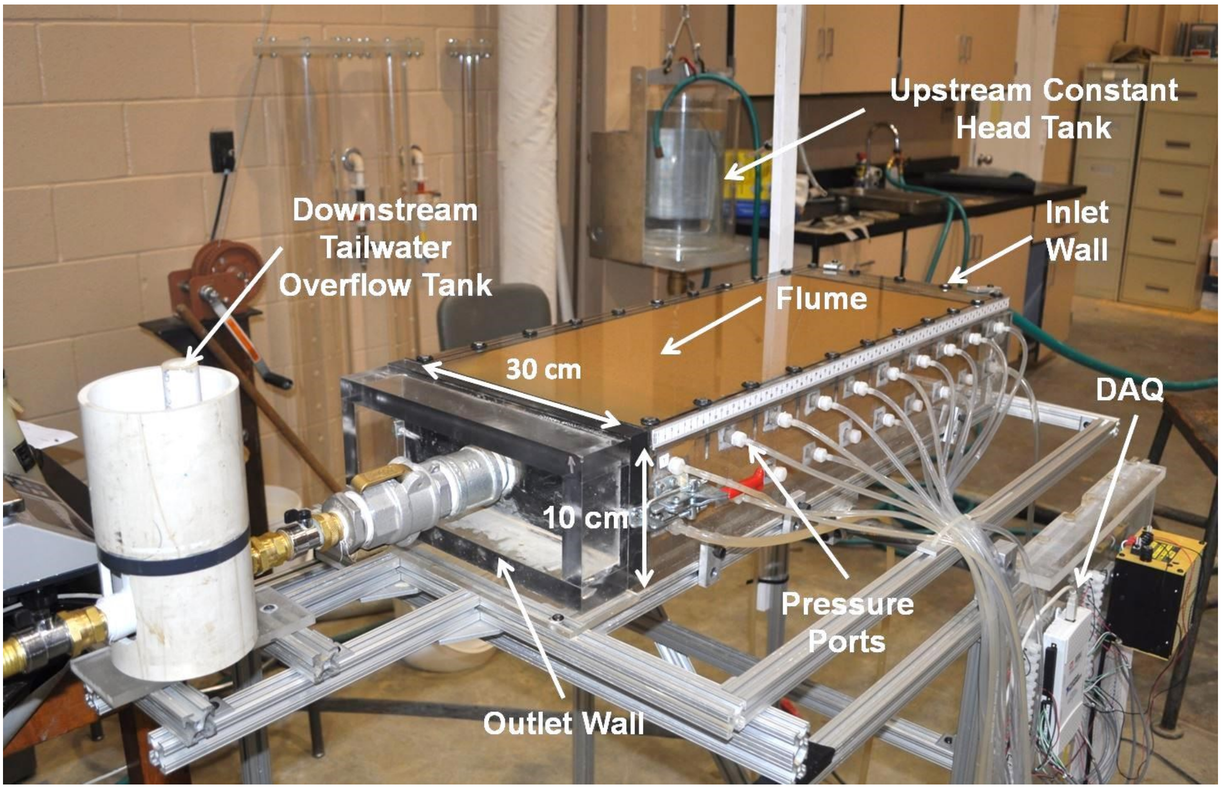

Figure 1. Overview of the small-scale flume and rest of equipment.

In the 1980s, laboratory tests to study BEP were performed by Townsend et al. (1981) and Townsend & Shiau (1986) at the University of Florida (UF) and by de Wit et al. (1981) and de Wit (1984) in the Netherlands. The research at the University of Florida was conducted by testing sands using a flume to determine the average hydraulic gradient at piping. Similarly, the studies at the Delft Soil Mechanics Laboratory in the Netherlands were performed using a flume and tested a range of sands with different particle sizes, exit conditions, and experiment scales. More recently, small-scale and medium-scale experiments have been performed by van Beek et al. (2010, 2011, 2014) at Deltares in the Netherlands. These laboratory tests were conducted to study the processes of initiation and progression of piping. These studies were performed in parallel with numerical analyses to study the local hydraulic conditions at the initiation of piping.

A similar experimental study to measure critical horizontal gradients in laboratory flumes was initiated in 2013 at ERDC. A small-scale flume was constructed to test a variety of uniform sands (Figure 1). The objective of these tests was to study the hydraulic conditions required for BEP by measuring the horizontal gradient at the moment of initiation. In these tests, flow through a soil sample would be gradually increased at discrete time intervals until BEP would initiate and progress through the entire sample. The results obtained from the tests performed in this apparatus were compared with the test results in the literature and the predicted values obtained from models such as those proposed by Sellmeijer (1988), Schmertmann (2000), and others.

The small-scale flume discussed in this paper was designed and built by taking into consideration the designs of the different laboratory flumes found in the literature. The testing program aimed at estimating the critical gradient required for BEP to initiate and progress through nine poorly-graded sands with similar coefficients of uniformity. The two principal variables of these tests were the soil grain size and density. The smallest and largest of these sands had a median grain size diameter (d_{50}) of 0.30 mm and 2.52 mm, respectively. Samples were tested either in a loose state or a dense state. To achieve a loose state, the soil was placed carefully without any compaction effort, while the dense state was achieved by compaction of the sand in lifts. The size of the flume made it possible to rapidly construct uniform, high quality samples such that a large number of tests could be completed. The goal of the testing program at ERDC was to perform more than one test per workday. However, some issues were found that needed to be corrected to be able to run the tests smoothly and to obtain the necessary results. This paper presents a brief description of the design of the small-scale flume device, the problems and issues encountered during the testing program, and the implemented solutions that resulted in repeatable tests.

2 DESCRIPTION OF SMALL SCALE FLUME FOR BEP TESTS

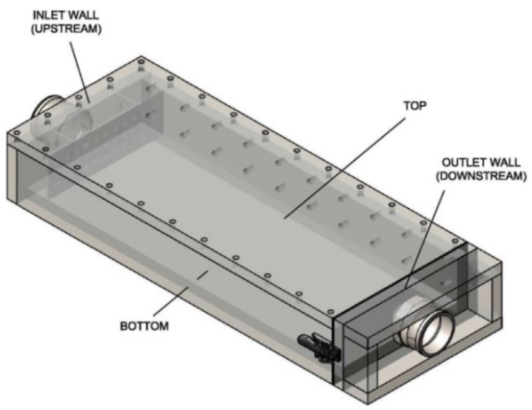

Figure 2. Schematic of small-scale flume.

The small-scale flume was designed and built as a rectangular-shaped box (Figure 2). The flume was built with 2.54-cm-thick acrylic (top, bottom, and all of its walls). The acrylic design permitted a clear view of the whole sample before, during, and after a test. Seeing through the flume would be effective not just for monitoring the initiation of piping, but also during sample preparation for visual inspection of air bubbles trapped in the system.

The top of the flume was attached along the edges of three walls by 25 bolts. The outlet wall of the box was designed to be removable and was attached to the side walls using two latches, one on each side of the flume. The leak-proof seal was obtained by O-ring gaskets and vacuum grease in shallow grooves between the removable faces and the body of the flume. Also, a closed-cell foam rubber sheet was adhered to the outlet wall, allowing a better sealing contact.

To ensure integral contact between the soil and acrylic, the flume was designed to be rotated 90° from an upright vertical position for filling (Figure 3) to a horizontal position for testing (Figure 4). This is similar to the tests performed by van Beek et al. (2011), whereas the flume used by Townsend et al. (1981) used a rubber bladder to apply pressure and ensure contact between the sand and the acrylic top. After testing, the flume could then be rotated an additional 90° to empty the flume by gravity. The flume was mounted to a custom frame designed for its rotation. This frame was built with aluminum t-slotted framing (80/20). The design of the frame took into consideration its capacity to sustain the weight of the flume, hoses, soil, water, and instrumentation. A rod and bearings made it possible to rotate the flume smoothly a full 180°.

Figure 3. Small-scale flume in vertical position after sample preparation.

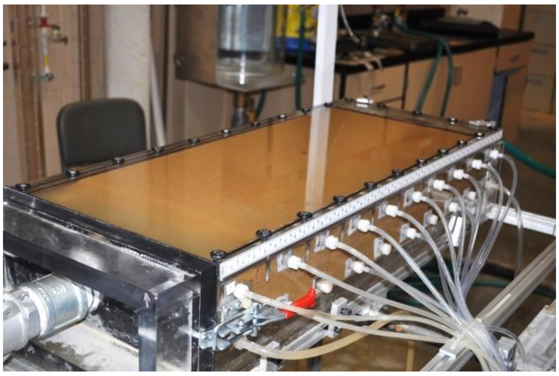

Figure 4. Small-scale flume in horizontal position for testing.

At the beginning of sample preparation, the outlet wall (downstream side of flume) was removed and the flume was rotated to the vertical position. Full saturation of samples was obtained by first filling the flume with water and pluviating (or "raining") the air-dry sand into the flume (Figure 5). This method was used to prevent trapped air in the soil sample. Typically, about half of the flume was filled from the inlet with water before placing sand, and this was sufficient for full saturation of the sample. For the majority of the tests, a constant head water tank was used for supplying constant flow. This tank supplied water through a hose attached to the inlet wall of the flume with a 3.81-mm NPT (National Pipe Thread) stainless steel male-female coupling connector.

Figure 5. Pluviating sand for the preparation of test sample.

The pore pressures during the test were monitored continuously to study the hydraulic conditions during the test. The flume had twenty 0.635-cm threaded holes on one side wall that were used for obtaining pore pressure data inside the sample. From the available ports, sixteen were used for testing, and the rest were plugged. Fourteen pressure transducers (Honeywall 26PC – ranges from 0.0-34.5 kPa) were connected to fittings in each hole by using clear PVC 0.3175-cm tubes. The remaining two ports were used for manometers that allowed for real-time visual readings upstream and downstream and that could be compared to the pore pressure readings. Clear PVC tubes with a diameter of 0.635 cm were used for these manometers. The average global gradient of the sample was estimated quickly by using the difference in head readings and dividing it by the shortest flow path, measured at the top of the soil sample. It was important to ensure that all of these tubes were fully saturated and that no air bubbles were present during the tests, as they could cause erroneous pressure readings. As the flume was being saturated, water was allowed to enter the PVC clear tubes, thus releasing the air from them. After all the air exited these tubes, they were connected to the pore pressure transducers, ensuring accurate readings.

Samples tested in the small-scale flume were prepared in two states: loose or dense. The flume holds approximately 30 to 40 kg of sand, and the desired density conditions were obtained through compaction during preparation. This allowed studying the effect that density had on the hydraulic critical gradient for piping. To prepare the samples in a loose state, the sand was pluviated into the water continuously while avoiding any vibrations. Dense samples were prepared by compacting with a steel rod and tapping the acrylic with a rubber mallet. Typically, the sample would be densified in lifts 10 cm thick. The highest density possible, using this densification method, was always desired when preparing dense samples. If a desired density had to be achieved, the required weight for obtaining it was calculated, and the sand would be densified accordingly.

The soil sample formed a slope between the acrylic top and a downstream filter wall. This wall, a perforated acrylic plate covered with filter fabric, held the sample in place while letting water flow through. After the samples were prepared, this plate was placed on top of the sand. Six steel springs were fixed to the plate, and they pushed against the outlet wall as the flume was closed with the latches. When rotating the flume to the horizontal position, particles roll down over this half wall and a slope is naturally formed on the sample exit. During testing, eroded soil particles fall to the bottom of the flume without interrupting the erosion process, while some others were washed away during the test.

After attaching the outlet wall and conducting a final visual inspection to ensure there was no air trapped in the flume or in the tubes, the water was raised until water came out of the downstream overflow tailwater tank attached to a 3.81-mm NPT stainless steel male-female coupling connector. The flume was then rotated to a horizontal position, the pore pressures transducers were zeroed with the tailwater head, and the test was initiated. The test procedure consisted of slowly increasing the flow at discrete time intervals until it was observed that BEP initiated at the downstream slope and progressed through the whole sample. The time of BEP initiation was recorded, and the critical gradient was obtained after processing the data.

3 PROBLEMS AND SOLUTIONS FOR SMALL-SCALE BEP TESTS

The following sections discuss the problems that occurred during the testing program of uniform sands with the small-scale flume and how these problems were effectively solved.

3.1 Head loss due to area reductions

The first problem was related to head losses due to the reductions of cross-sectional area from the water supply to the flume. The setup of the test had small modifications as the testing program progressed. The initial tests were conducted with mason sand, which had a d_{50} of 0.33 mm. The average size of the sand particles increased until finishing the testing program with a d_{50} of 2.52 mm. The larger particles required higher flow to initiate piping due to the higher sample permeability. The requirement of providing sufficient head (energy) to initiate BEP became a limiting factor to the initial soil testing procedure for coarse sands. It was found that the fittings, valves, and hoses that were used to connect the constant head tank to the flume had to be replaced because their cross-sectional area caused considerable head losses in the system. Originally, the constant head tank was connected to the flume through garden hoses, and a 1.90-cm-diameter threaded valve was connected to the inlet, which had an internal diameter of approximately 0.8 cm. Another source of head loss occurred inside a small turbine flow meter that was used for several tests. The flow meter, installed to measure the inflow just before it entered the flume, allowed continuous flow measurements. Inside this flow meter, significant head loss was caused by a drastic reduction in diameter. Also, this flow meter required the use of 0.635-cm hoses that added to the losses in the system. To solve the problems with head losses associated with the water supply, several solutions were implemented:

- The garden hose valves were replaced with 1.90-cm-diameter valves that had no significant area reduction through them.
- The turbine flow meter was replaced with an electromagnetic flow meter (FMG82 with a flow range of 0.113-11.3 L/min). This flow meter had minimal head losses through it and used 1.90-cm hoses.
- After replacing the valves, all of the hoses were replaced as well with 1.90–cm hoses. No hoses of a smaller diameter to supply water were used afterward.
- For most tests, water was inserted into the flume and controlled with a constant head water tank that could be raised or lowered with a hand winch. For a few samples with a high permeability, the flow rate necessary

to induce BEP was higher than the flow supplied by the municipal water supply, and thus, the constant head tank could not be used. For these tests, a pump capable of 300 L/min (Gould Model 316 S.S.) was used to pump water from a 1,900 L reservoir. This pump used 3.80-cm hoses and valves that allowed recirculation control.

3.2 Head loss due to low permeability of filter

Another source of head loss was identified when pressure transducer data were processed. During a test, the gradient was obtained with manual readings of manometers and was calculated as the difference in upstream and downstream heads versus the sample length. One manometer was installed upstream (behind the sample and end plate) and the other one downstream (outside the sample). Measurements were taken from the manometers while the pore pressure transducers readings were logged to a computer at one second intervals using a program coded in LabVIEW. A comparison of the two measurements revealed the drastic head loss due to the upstream filter.

Reviewing the piezometric data showed a disproportionate head loss between the pressure transducer upstream (behind the sample and the plate) of the filter and the next transducer when compared with the head loss occurring generally in the sample. This loss increased proportionally with flow. This indicated that the filter fabric and plate geometry used was much less permeable than the material tested, as it was getting clogged with fines from the tested sands and from the water supply. This considerable head loss caused an inaccurate value for the average global gradient calculated from the upstream and downstream manometer measurements. Replacing the filter fabric periodically was not enough, therefore, the solution to this problem was to determine the hydraulic gradient by a linear fit of the hydraulic heads (converted from the measured pressure from each transducer) along the sample. The slope of this plot (Figure 6 and Figure 7) determined the hydraulic gradient across the sample. The time at piping initiation was recorded, and the critical hydraulic gradient was calculated using this method. Figure 6 shows the significant head loss due to the upstream wall between pressure transducers 9 and 10. Figure 7 shows the linear fit of piezometric data points without the total head obtained from pressure transducer 10 for the calculation of a precise value of hydraulic gradient.

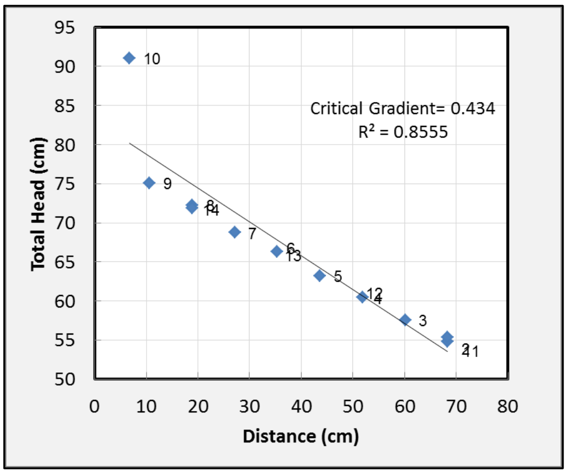

Figure 6. Piezometric data points showing head loss due to filter wall.

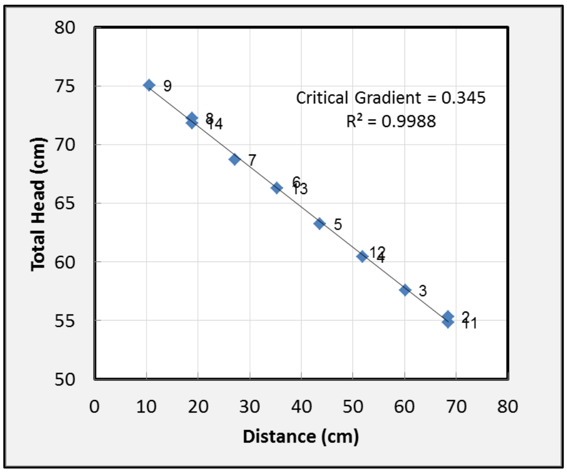

Figure 7. Piezometric data points showing linear-fit for estimating critical hydraulic gradient.

3.3 Trapped air

BEP tests were performed in fully saturated samples. It was very important to avoid any air bubbles from getting into the sample. Bubbles that were present during a test moved between the acrylic top and the sample, and they could cause movement of particles that could trigger erosion prematurely. There were four possible ways that air bubbles could get into the sample:

- Air could get trapped behind the plate on the upstream side of the flume. Before pouring sand for preparing a sample, the flume was usually filled halfway with water. If the water level was raised slowly, the chance of air getting trapped on the filter fabric of the plate was high. To avoid this problem, the flume was filled with pressurized water rapidly while tapping with a rubber mallet. After filling with the necessary volume of water, the filter fabric was vigorously tapped to ensure air released from the filter fabric.
- It was noted that bubbles became trapped if the sand was deposited quickly, principally in loose samples. Dense samples did not usually exhibit this problem as the compaction helped to get rid of any bubbles. To avoid air bubbles in the sample, the sand was poured from the scoops slowly and evenly. Samples that were prepared carefully did not have problems of air trapped within.
- Even when the flume was completely saturated, it was found that air could still be trapped in the hoses leading to the flume. As a precautionary measure to avoid air during testing, all of the 1.90-cm garden hoses were replaced with clear 1.90-cm PVC tubing. These hoses could be saturated easily before a test by letting the water run and observing carefully that all the bubbles escape. Usually, once the clear hoses were saturated, the water supply system would be kept saturated for a series of tests by closing a series of strategically placed valves. Adding clear hoses such that air bubbles could be visually observed was a critical aspect of ensuring saturation of the water supply system and obtaining a successful testing program.
- As a last measure to avoid trapped air, three bleed valves were installed: one upstream (behind the sample, next to the inlet) and two downstream (in front of the sample, close to the outlet). Air was let out from these valves if bubbles were present prior to the test.

3.4 Piping through the center

The most important part of the procedure of these tests is being able to increase the flow carefully until erosion initiated. Piping usually starts on the weakest flow path, which most of the time is the shortest path. A problem that was observed during the first trials was that the location of erosion initiation was not consistent. For some of the small-scale experiments at Deltares (van Beek et al., 2010), an arc-shaped exit was manually formed in the sample to force piping to occur at the center of the sample.

To correct this issue and ensure the pipe developed through the center of the sample in every test (or close to the center), a shallow 1:12 v-notch was cut into the half wall where the slope is formed (Figure 8). This shape caused a natural arc to form in the exit slope due to the sand coming to equilibrium at the angle of repose (Figure 9). The deepest portion of the notch was at the sample center, which forced the shortest path length to be in the center as well. When setting the flume from the vertical to the horizontal position, the newly formed exit slope of the sample was arc-shaped with the shortest flow path in the center. The shortest path distance was measured at the beginning of every test.

Figure 8. Filter wall plate with v-notch.

Figure 9. Arc-shaped slope formed by v-notch.

4 CONCLUSIONS

The design and operation of laboratory equipment used for measuring the critical gradient of nine different uniform sands was discussed. Multiple issues were encountered during the initial testing phase and as the tests progressed. These issues and the corresponding solutions were presented to ensure future efforts can make use of the lessons learned. The three main problems encountered in these tests were: trapped air, head losses, and piping not initiating at the center of a sample. Trapped air bubbles in the sample could trigger erosion earlier than expected when they pushed soil particles. Bubbles were avoided by: pushing the air through a filter with pressurized water, pluviating the sand slowly into the water, using clear PVC hoses to connect the flume to the water supply, and adding bleed valves to the flume. The head losses due to reduction in area through fittings, hoses, and flow meters caused a significant reduction of the maximum head that could be obtained from the constant head tank that supplied the water during the tests. They were all replaced with equivalents of larger inner diameter when higher flows were required for piping initiation and progression. Also, head loss through a filter fabric resulted in inaccurate readings of gradients and therefore, the readings from behind the filter were not used in the final estimates of critical hydraulic gradient, which was obtained from the slope of a linear-fit of pressure within the sample. Finally, a v-notch was added to the downstream filter wall to naturally form an arc-shaped slope, ensuring the piping erosion would begin close to the sample center in every test. The solutions to the problems involved using all the available tools, knowledge, and some creativity to progress in the testing program and obtain satisfactory results.

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