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Backward Erosion Testing: Magnolia Levee

Axel M. Montalvo-Bartolomei, Bryant A. Robbins,
Erica Medley, and Benjamin Breland

September 2021

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Abstract

Using a confined flume device, an experimental study investigated the critical horizontal gradient of soils obtained from a site identified as potentially vulnerable to backward erosion piping (BEP). Tests were conducted on glacial outwash material obtained from a sand and gravel quarry in the vicinity of Magnolia Levee in the community of Magnolia, OH. The two bulk samples collected from the quarry had similar grain-size distributions, grain roundness, and depositional environments as the foundation materials beneath the levee. Samples were prepared at various densities and subjected to gradual increases of flow in a wooden flume with an acrylic top until BEP was observed. The critical average horizontal gradient ranged from 0.21 to 0.30 for a bulk sample with a coefficient of uniformity of 1.6, while tests conducted on a bulk sample with a coefficient of uniformity of 2.5 yielded critical average horizontal gradients of 0.31 to 0.36. The critical average gradients measured during these tests compared favorably to values in the literature after applying adjustments according to Schmertmann's method.

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Preface

This study was conducted for the U.S. Army Corps of Engineers Risk Management Center under Project A1070, "Investigation into Embankment Failure Mechanisms." The Funding Account Code was U4375173, and AMSCO Code was 031398.

The work was performed by the Geotechnical Engineering and Geosciences Branch (GSG) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Mr. Christopher G. Price was Chief, GSG; Mr. James L. Davis was Chief, GS; and Dr. Michael K. Sharp, GZT, was the Technical Director for Civil Works Infrastructure. The Deputy Director of ERDC-GSL was Mr. Charles W. Ertle II, and the Director was Mr. Bartley P. Durst.

COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

Backward erosion piping (BEP) is a mechanism by which soil particles are eroded beneath levees and dams (ICOLD 2015). This internal erosion mechanism initiates at an unfiltered exit and progresses in the upstream direction. BEP is a major concern for water-retaining structures because many failures have been attributed to this phenomenon (Foster et al. 2000).

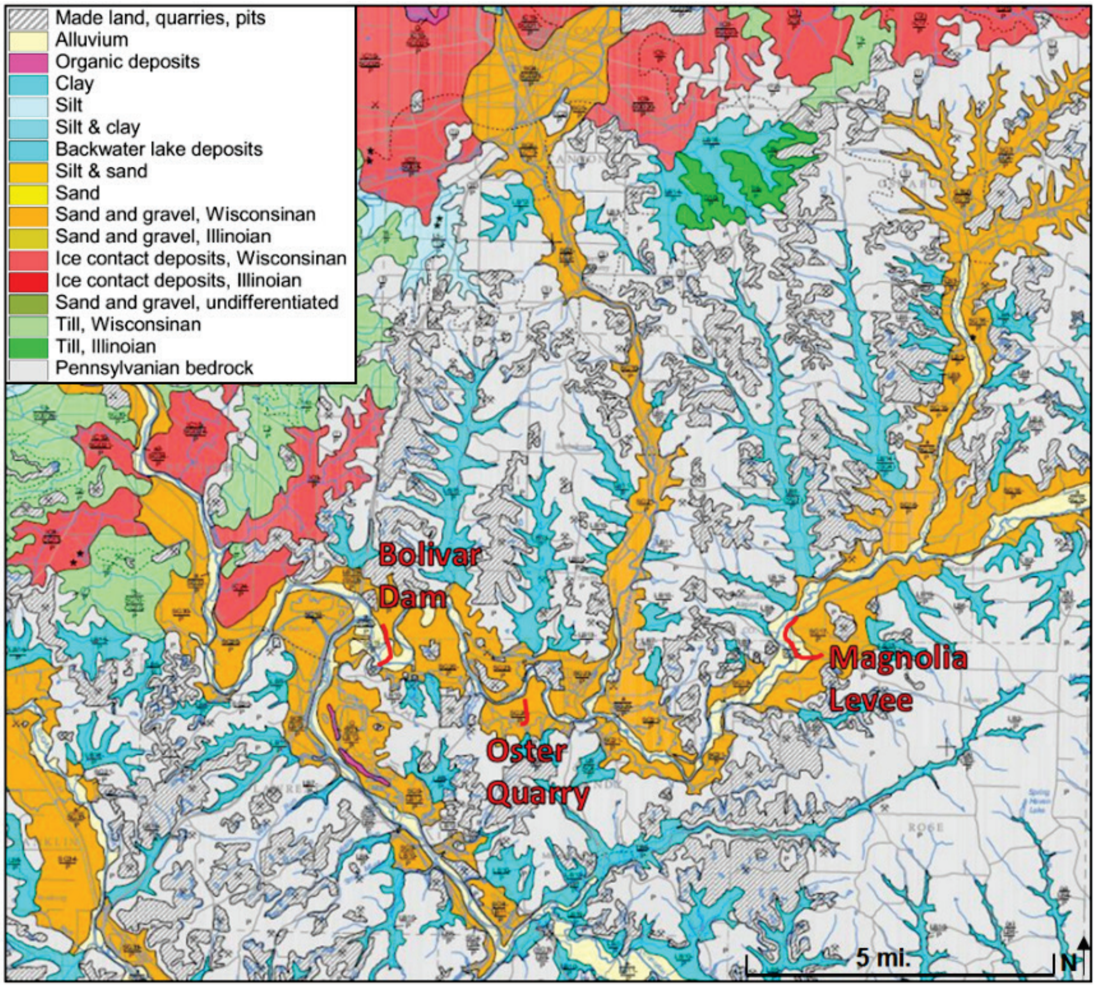
An experimental study on susceptibility of the foundation material to BEP was proposed as part of a larger project study. Previous laboratory tests investigating critical gradients have been conducted primarily on commercially available materials or on fabricated grain-size distributions. However, laboratory test data from naturally occurring soils of potentially vulnerable dams and levees to BEP are very limited. Therefore, this study sought to obtain measurements of critical gradient for naturally occurring soils from an earthen embankment owned by the U.S. Army Corps of Engineers to ensure consistency between fabricated soils data in the literature and the performance of natural soils in the field. The tests for this study were conducted at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS.

Magnolia Levee, a flood-risk-management embankment structure that protects the community of Magnolia, OH, was selected for this study. This levee is located along Sandy Creek and protects the community from high pools retained by Bolivar Dam. It was classified as high risk, mainly because of the potential for BEP. While samples from the levee were initially desired for testing, it was not feasible to recover foundation material without affecting the integrity of the levee. Therefore, samples were collected from a quarry in the vicinity of Magnolia Levee and found to be analogous to its foundation material according to grain size, roundness, and geological history. The samples were tested in a horizontal wooden flume to determine the critical gradient required for BEP. The wooden flume used for this study (Robbins et al. 2016) was designed and built according to the flume used by Townsend et al. (1981), Townsend and Shiau (1986), and Schmertmann (2000) at the University of Florida.

2 Magnolia Levee

Magnolia Levee is owned and operated by the U.S. Army Corps of Engineers (USACE)–Huntington District and is located 7 miles east of Bolivar, OH, along Sandy Creek of the Tuscarawas River. An area map showing Bolivar Dam and Magnolia Levee is shown in Figure 1. The levee is a 10-m[*] high, rolled-earth embankment, 1,336 m in length with a crest elevation of 297 m. The levee crest is ~12 m above the riverbed.

Figure 1. Surficial geology of the Magnolia Levee area, showing the locations of Oster Sand and Gravel Quarry and Bolivar Dam.



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[*]. For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

This levee was classified as a high-risk structure according to a semiquantitative risk assessment (SQRA) performed in 2015. The risk was primarily driven by BEP of the foundation, but I-wall instability and concentrated leak erosion along foundation corrugated metal pipes also contributed to the total project risk. The project entered an issue evaluation study (IES) in 2016 to reduce uncertainties and better quantify the project risks. As part of the IES, bulk samples of glacial outwash were collected from Oster Sand and Gravel Quarry. The quarry is located 5 river miles downstream of Magnolia Levee and 3 miles upstream from Bolivar Dam along Sandy Creek. As shown in Figure 1, the quarry is east of Bolivar and Magnolia. Figure 2 shows a view from the top of the crest of the levee.

Figure 2. Looking south on the Magnolia Levee crest.

The outwash materials in the present Sandy Creek valley are a product of glaciation and consist primarily of stratified sands and gravels with occasional loess deposits. The outwash deposits at Magnolia are characteristic of a distal proglacial zone, dominated by a single-channel fluvial system. Multiple episodes of erosion, deposition, and channel shifting can produce vertical stacking of bar deposits that represent thousands of years. The geomorphology and stratigraphy of glacial outwash deposits can best be understood with continuous lateral exposures and open excavations. The glacial outwash materials at Oster Sand and Gravel quarry (Figure 3) are within the same valley as Magnolia Levee and provide the best exposure of outwash materials analogous to the foundation materials beneath Magnolia Levee. As discussed in more detail later in this report, the quarry materials are similar to Magnolia foundation materials in geomorphology, gradation, grain roundness, and elevation.

Several samples of a continuous, poorly graded sand deposit were collected across the quarry site for comparison with Magnolia Levee foundation materials from explorations carried out in May 2016. The poorly graded sand deposits were generally horizontal but varied in elevation and thickness (exposed thickness greater than 1.5 m in some areas) across the open excavation. The sand stratum was continuous across the exposure for a minimum of 300 m laterally. The elevation of the top of the cut was approximately 290 m, which correlates to the top of ground elevation at Magnolia Levee. The sand deposit is shown in Figures 4, 5, and 6 (October 2016) after removal of the overlying gravelly sand deposit. Weathering and erosion of the exposed sands revealed planar-bedded and well-sorted, fluvially deposited sands.

The collection of samples was coordinated with the USACE–Huntington District. Grain-size distribution and grain-roundness analysis of the collected quarry samples (Figure 7) were carried out at ERDC. Select samples from the May 2016 subsurface explorations at Magnolia Levee were also tested for grain-size distribution and grain roundness. The results of the gradation analyses and the rest of the laboratory tests are included in section 5.0 of this report. All the samples classified as poorly graded sand (SP) and had a coefficient of uniformity (C_u) <3.

Figure 3. Plan view showing Oster Sand and Gravel Quarry with the approximate bulk sample location. The *red dashed line* represents the approximate limits of the cut on 19 October 2016.

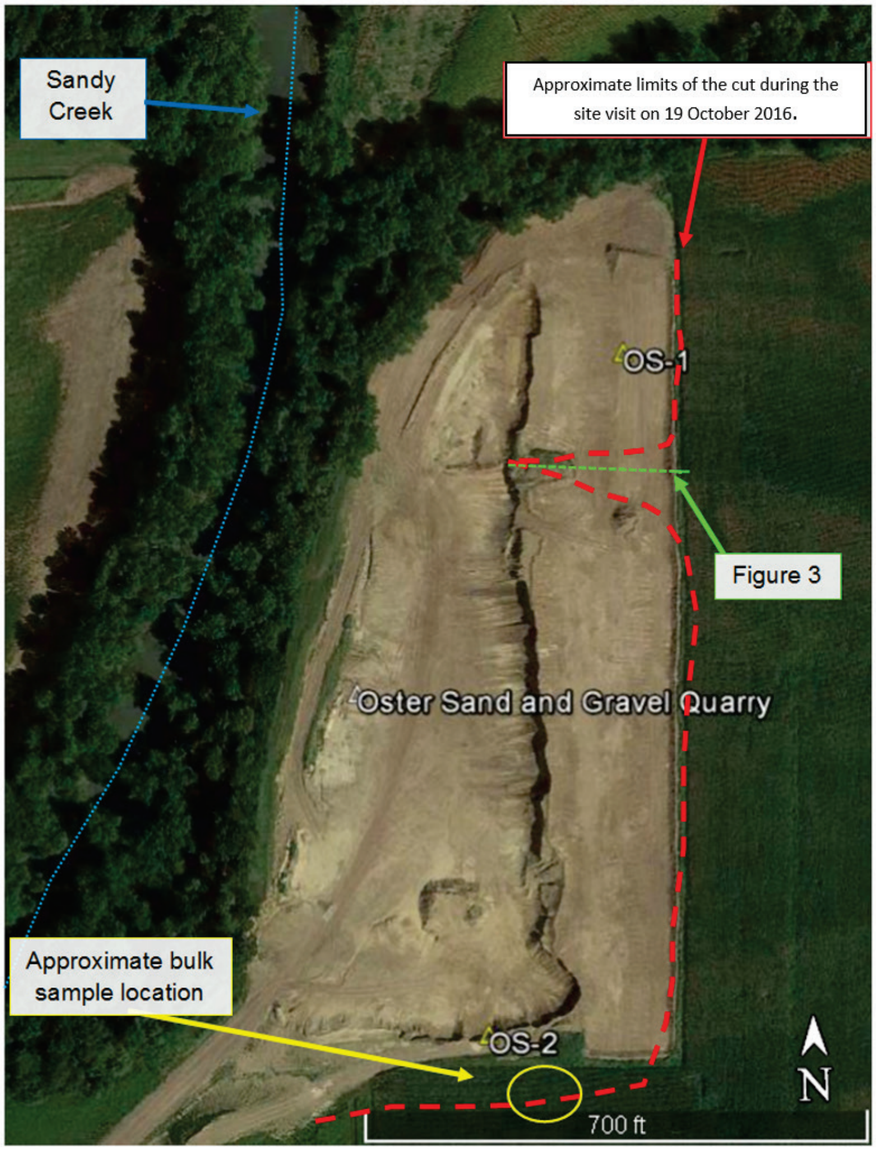


Figure 4. The lateral exposures of continuous poorly graded sand (SP) where small samples were collected on 30 June 2016 (*top*) and bulk samples on 19 October 2016 (*middle*, *bottom*).

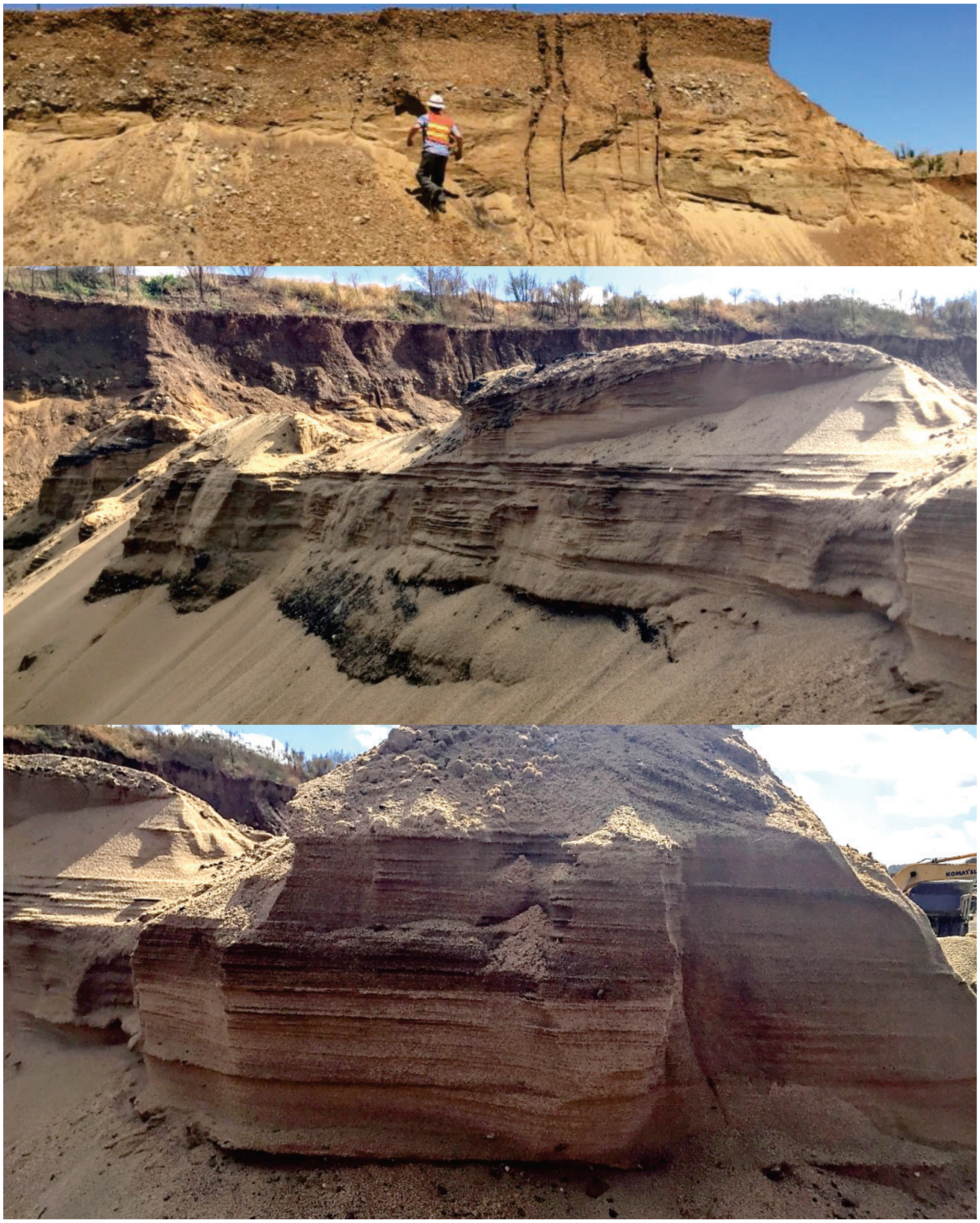


Figure 5. Photos of the bulk sample location prior to any excavation along the cut, with the *bottom* photo showing the stratigraphy (planar-bedded sands and cross-bedded sands separated by erosional boundaries) and the paleoflow direction to the east.

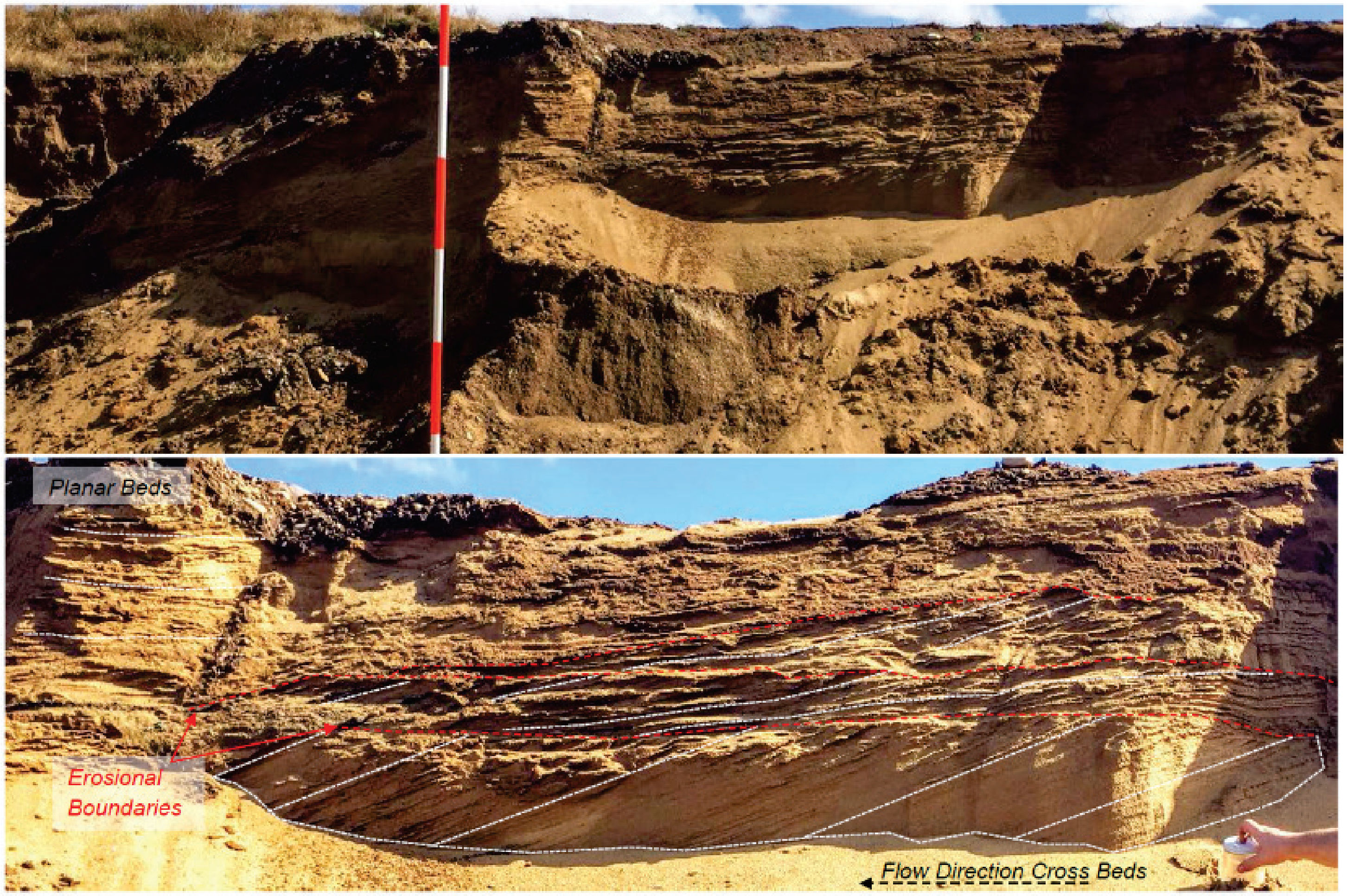


Figure 6. View from the top of the cut shown in Figure 5 showing the excavated trench and sample collection location.

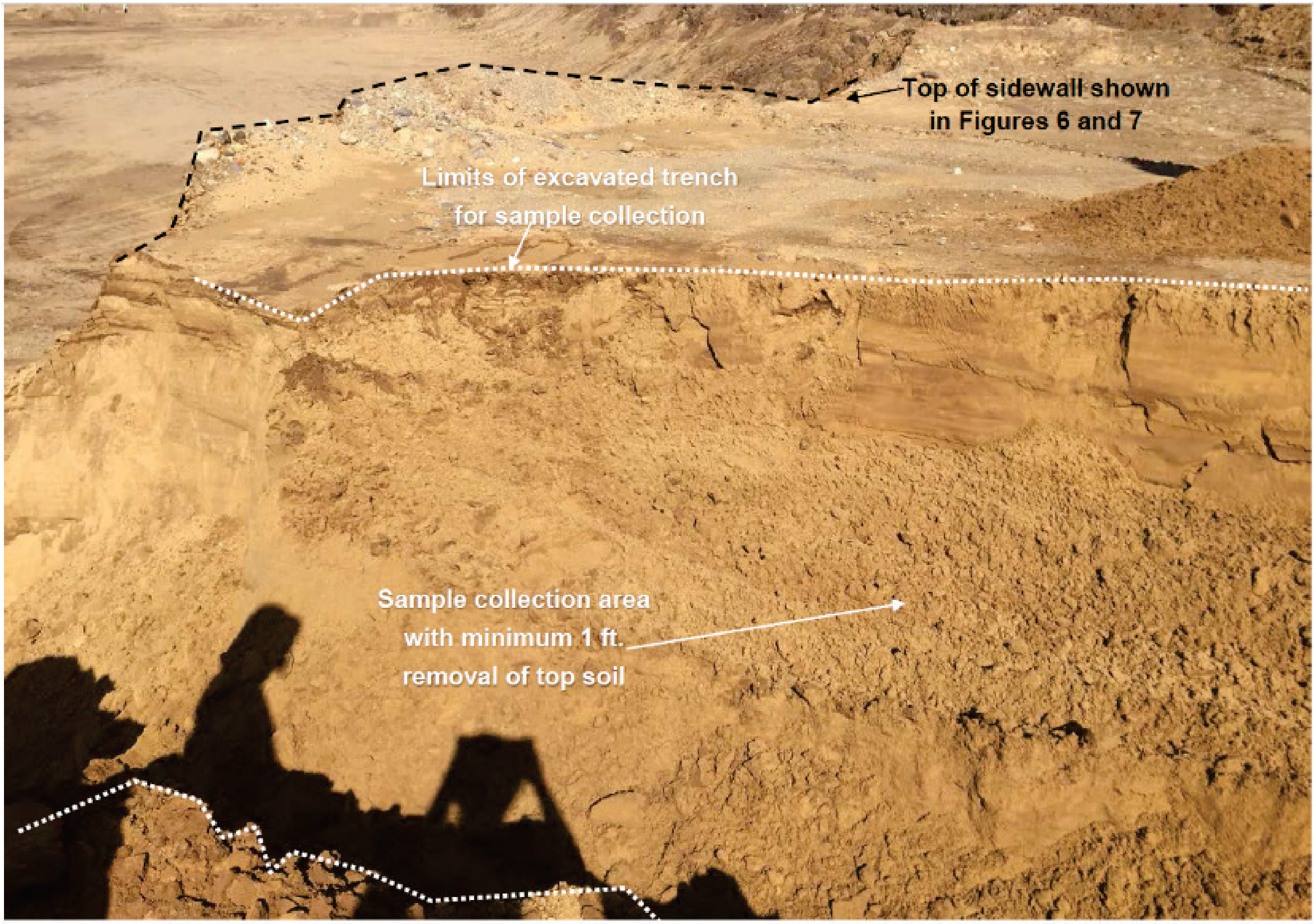


Figure 7. Soil collected was placed in plastic bags to transport from the quarry to the laboratory facilities.

3 Subsurface Characterization Approach

Data from approximately 70 boring logs previously drilled in 1986, 1993, 2009, 2013, and 2016 on Magnolia Levee were compiled into RockWorks software (RockWare, Golden, CO) to characterize subsurface features possibly susceptible to BEP and supplement the laboratory investigations. The borehole data used in this subsurface characterization consisted of percent-fine content (%), C_u, and lithologic classifications according to the Unified Soil Classification System (USCS). Some samples from these boreholes were sent to the ERDC laboratory and compared with the samples collected from the quarry. The subsurface characterization was performed using available exploration data based on a 3-D grid using the kriging interpolation method. Node spacing was 3.0 m in the horizontal (x and y) direction and 0.05 m in the vertical (z) direction between 275–290 m in elevation, with the base of the confining layer (Figure 8) defined as an upper boundary for the domain of interest (sandy soils) in the kriging analyses. The confining layer was designated using soils containing 10% or more fines. This cutoff was selected as a delineation between the sand foundation and overlying confining layer because it was assumed that 10% fines would be sufficient for the material to provide roof support over an advancing pipe.

Several cross sections of the Magnolia Levee foundation were investigated as part of this subsurface investigation, but section C-C’ was chosen as an example for this report. Cross section C-C′ (Figure 8 and Figure 9) spans from Sandy Creek, across the levee, through a low-lying ditch on the land side of the levee. The C-C′ cross section (Figure 9) shows the foundation sand daylighting in the ditch at the land side of the levee. Borings D-15-21, D-5, and D-93-23 also show the presence of SP, with relatively low C_u values and low fines content near the bottom of the confining layer. Specifically, the grain-size distribution of the SP from D-15-21 compared favorably with materials obtained from the quarries, as demonstrated in section 5.0 of this report. The presence of SP soil along the base of the confining layer as well as the exposed sand in the ditch bottom suggests that BEP may be likely at this location.

Figure 8. Lidar elevation map of Magnolia Levee (data downloaded from Ohio Geographically Referenced Information Program, OGRIP), with *colored elevation contours* representing the base of the clay layer. Cross section C-C′ shown by *red line*.

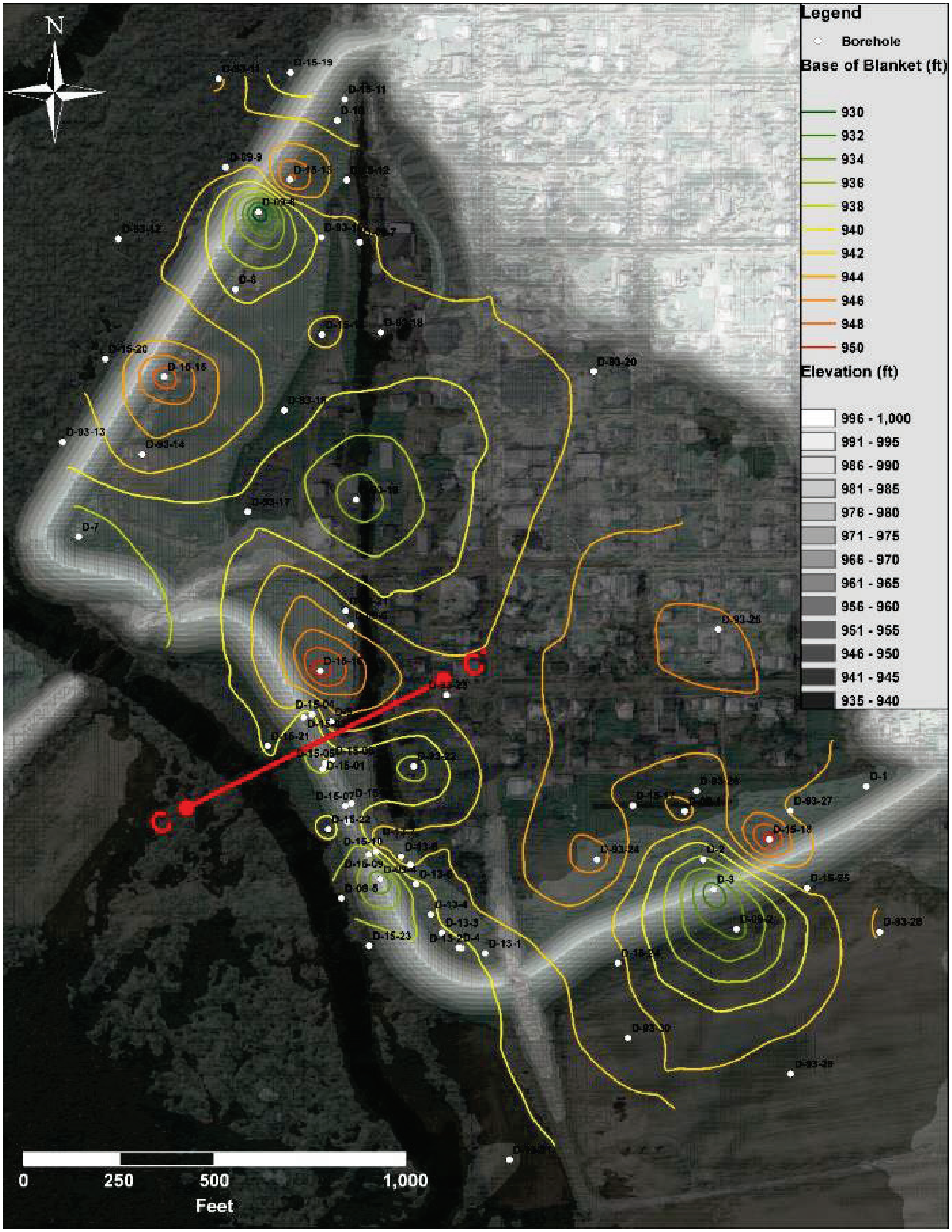
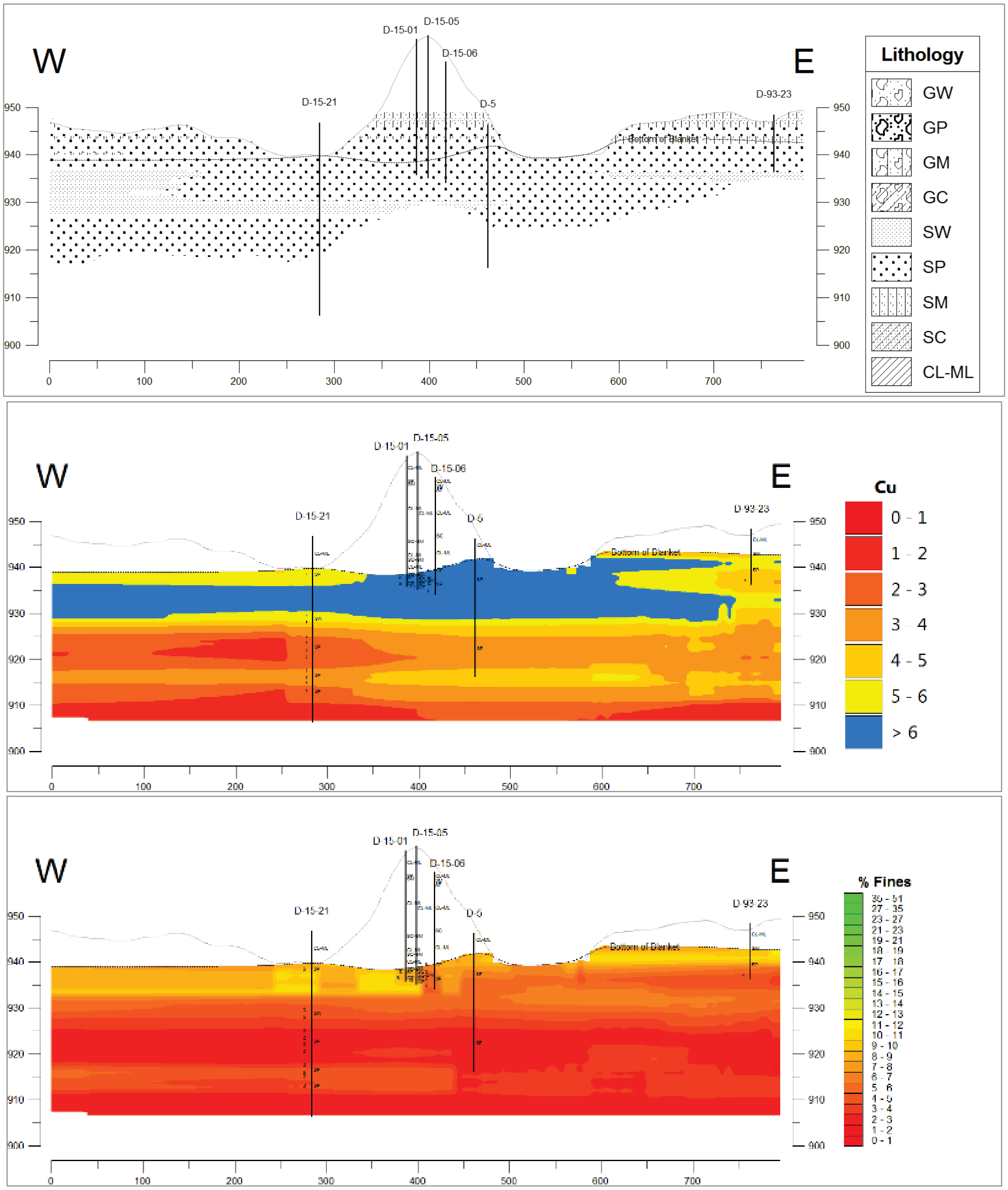


Figure 9. Cross section C-C′ characterization results of lithology (*top*), C_u (*middle*), and percent fines (*bottom*).



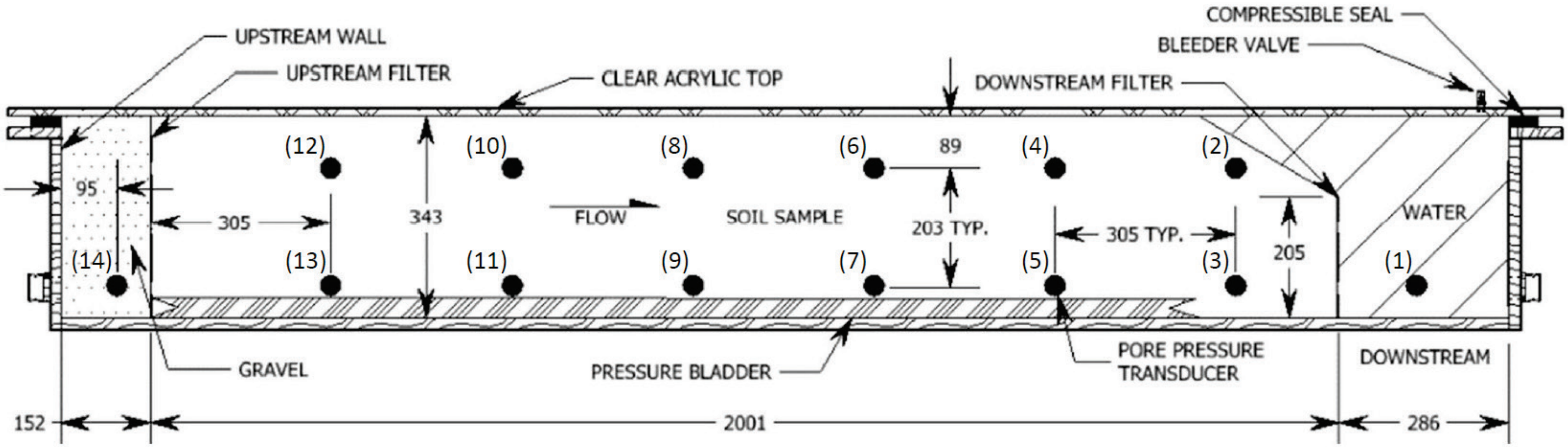
4 Experimental Approach

On 19 October 2016, two bulk samples (herein S1 and S2) were collected from the Oster Sand and Gravel Quarry. The collected samples were comparable to the foundation material of Magnolia Levee according to grain-size distributions, grain roundness, and depositional environments. shows a sketch of the dimensions and sensor locations of the flume that was used for testing the collected samples at ERDC. Fourteen ports with pressure transducers on one of the side walls were used to continually monitor pore pressures during the tests and are identified with numbers in Figure 10. The piping process was observed through a clear acrylic top that acted as the impermeable layer. Inflow was supplied by an adjustable-height head tank connected to the upstream wall of the flume.

4.1 Test setup

The soils tested were dried overnight in an oven prior to sample construction. A bladder was placed on the bottom of the flume. This bladder was pressurized after sample preparation to obtain a nominal confining stress at the sand-acrylic interface. Water was let into the flume from a tailwater tank by opening the downstream valve, and the water level was slowly raised to approximately a quarter of the height of the flume. Clear PVC tubes with a 0.32 cm internal diameter were installed to connect the 14 ports on the side wall of the flume to pressure transducers. These tubes were flushed and saturated as the water level was raised to ensure no air entrapment and accurate pressure response during testing. The water level was adjusted during preparation to avoid overflowing from the top of the flume.

Figure 10. Cross section of the flume used for the testing program (dimensions in millimeters).



Using a scoop, the soil was carefully wet pluviated (rained) into the flume. Wet pluviation was used to obtain nearly isotropic permeability of the soil samples (Chapuis et al. 1989). In addition, dry gravel was placed behind the upstream filter wall to diffuse the inflow, resulting in a uniform flow distribution and a uniform boundary condition at the upstream side. The samples were prepared either loose or dense. Loose samples were prepared by avoiding any vibrations when pluviating the sand in the flume. Dense samples were obtained by tamping the soil with a rod and using a rubber mallet with a flat piece of wood. The downstream slope of the sample was carefully prepared with a flat piece of wood (Figure 11). Any soil particles that rolled down the slope during preparation were caught using a trap downstream and not considered for sample density calculations. A screed was used to level the top of the sample when finalizing the preparation. Finally, the dry weight of the sample and measurements for volume were used to calculate the unit weight and relative density. Sample volumes were adjusted for volume change because of the bladder pressurization.

Figure 11. Sample preparation (Test S1-1).

After initial sample inspection, additional small layers of the same material with a width of ~2–2.54 cm were placed along the edges of the long walls of the flume (Figure 12). These small layers were added to ensure uniform contact of the sample when the bladder was inflated. Additionally, a thin layer of the material was placed in front of the upstream wall. This layer covered the whole width of the sample and was

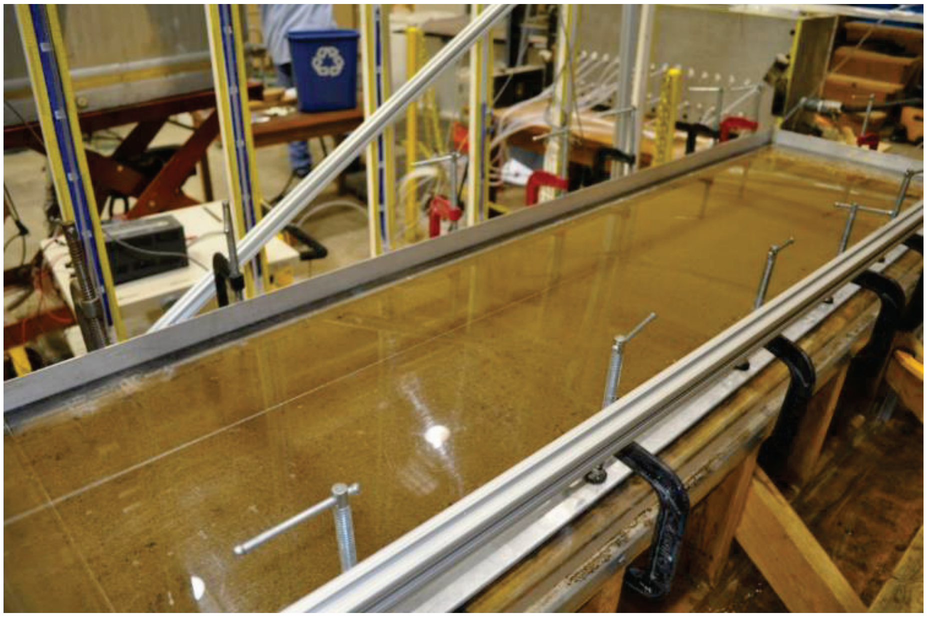
30 cm long. This layer was added after observing poor contact between the soil and the acrylic near the upstream wall during trial tests.

Figure 12. Additional layers along the side walls of flume and in front of the upstream wall (Test 1).

After sample preparation, the water level was gradually raised, and the acrylic top was carefully placed and clamped down starting from the upstream side. Trapped air between the acrylic top and soil sample was avoided by having the water level close to overflowing and by raising the downstream side of the flume 1 cm from the floor. Elevating the downstream side of the flume allowed the air-water interface to gradually move downstream as air escaped through two bleed valves located in the acrylic top. Clamps were tightened to compress the neoprene compressible seal to obtain a watertight seal. Once the flume was sealed, the tailwater tank was slowly raised again until its water level was slightly higher than the flume.

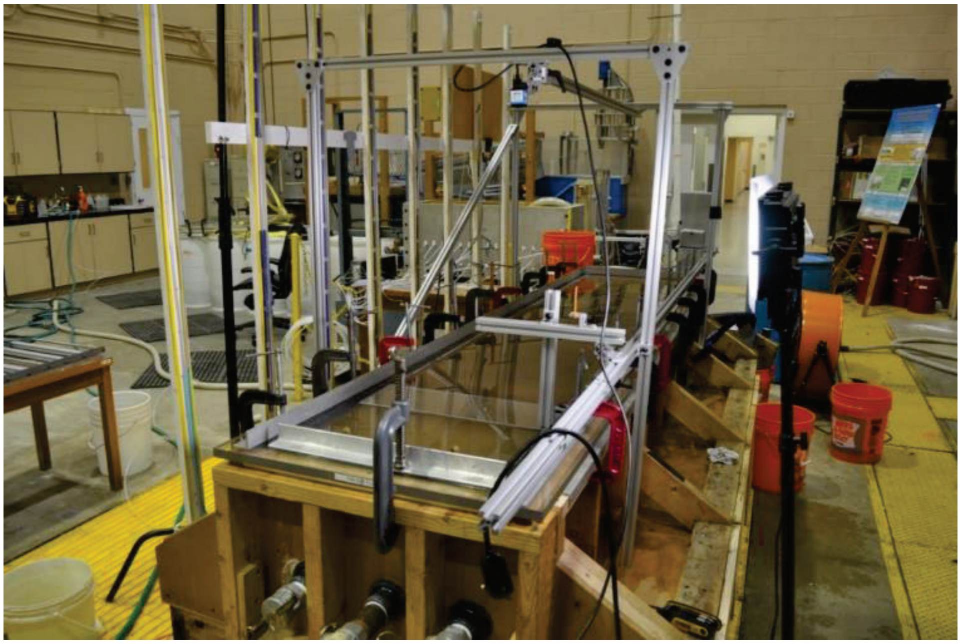
At this moment, the sample was ready to be loaded with the bladder. Using a modified triaxial apparatus as a source of pressurized de-aired water, the bladder was pressurized in increments of 6.9 kPa (1 psi) until the top of the sample was in contact with the acrylic top. This process could take hours, and the maximum pressure of the bladder was between 41.4 kPa (6 psi) to 55.2 kPa (8 psi). After obtaining a good contact between the sample and the acrylic top (Figure 13), the seating pressure was decreased to 19.0 kPa (2.75 psi) for testing. The water level of the pressurized triaxial apparatus was recorded, and the bladder valve was closed once the water level was in equilibrium at this constant pressure. The final top length of the sample was measured after the bladder valve was closed.

Figure 13. Sample with acrylic top and bladder pressurized for contact (Test S1-4).



The rest of the equipment was tested before beginning a test (Figure 14). A 16-bit USB data acquisition device (USB 6218, National Instruments, Austin, TX) continuously recorded the pore pressures, flow measurements, and pipe position during the tests. The measurements were logged at ~1 Hz by using a data acquisition script developed in MATLAB (MathWorks, Natick, MA). The pore-pressure transducers (Honeywell 26PC—range of 34.5 kPa, Honeywell, Golden Valley, MN) were connected to a power supply that provided a constant 10 V excitation voltage. Flow was measured by two means—that is, either with a flowmeter or a load cell. A 1.91 cm Omega FMG-84 (Omega Engineering, Norwalk, CT) flowmeter was used to measure the inflow of the first two tests. For the rest of the testing program, the outflow was measured by constantly weighing a bucket that captured the outflow from the flume. The bucket was hanging from a load cell (Omegadyne LCM703-25—resolution of 1 g, Omega Engineering) and was emptied every time it filled. The flow was calculated constantly from the weight of the water in the bucket, and these flow measurements were accurate to the nearest milliliter per second. A high-definition video camera (DFK AFU130 L53, The Imaging Source, Charlotte, NC) was attached to an aluminum frame on top of the flume to record the downstream slope area of the sample. A string potentiometer (string pot) was also installed to this frame to accurately track the pipe position. After pipe initiation, the video camera and string pot could be manually adjusted to follow the pipe-tip position as it progressed upstream. Photos were taken before, during, and after each test for documentation.

Figure 14. Complete equipment with instrumentation (Test S1-1).



4.2 Test procedures

After verifying that the equipment worked correctly, tests were performed by following the next steps:

1. A MATLAB code for data acquisition was initiated. The pore-pressure transducers and flowmeter (or load cell) were zeroed at hydrostatic conditions. The string-pot position was set at the top of the downstream slope to indicate the seepage length in contact with the acrylic prior to any erosion.
2. The constant head tank that supplied water was elevated slightly higher than the tailwater. After making the adjustment, the valves were opened to let water flow through the sample. The hydraulic average gradient was calculated using a linear, least-squares fit of the pressure measurements (in centimeters of water) versus distance. The head tank was raised until an average gradient of ~0.05 was observed. This gradient was sufficiently low so as to not cause any movement at the exit slope downstream. The gradient and flow measurements were manually verified. For verification purposes, the gradient was also calculated by manual readings of the

upstream and the downstream manometers, while flow was measured manually by filling a cup with the outflow and using a stopwatch.

3. After the flow was in equilibrium, the head tank was slowly raised again. The gradient was gradually changed in increments of approximately 0.02 to 0.04. After each increment, the flow was set constant under equilibrium conditions for at least 3 min before the next increment. The exit slope downstream was observed for any particle movement. If soil sloughing at the downstream slope or grain movement occurred, the flow rate was held constant until no further movement was observed. Some grain movement was typical early in the test before the initiation of BEP.
4. Flow was gradually increased until observing the initiation of BEP. The approximate time, flow, and gradient were manually recorded. Photos were taken, and the video camera and string pot were moved to follow the pipe tip as it progressed. The pipe was allowed to progress through the whole sample, or at least 90% of the sample length (Figure 15). Once it reached the upstream end of the sample, all the valves were closed, and the acquisition of data was stopped.
5. The flume was slowly drained as the clamps were loosened. The acrylic top was removed, the bladder was depressurized, and photos of the pipe were taken. Soil was removed from the flume and dried overnight for testing again. The flume and bladder were cleaned.
6. The data were processed, and the calculated average critical gradient was obtained at the time of continuous pipe progression. The exact time was obtained during postprocessing by observing the video recorded during the test.

Figure 15. Developed pipes meandering from downstream (*left*) to upstream (*right*) in Test S1-5.

5 Results

Five tests were conducted with bulk sample S1 and six tests with bulk sample S2 in this testing program. Only four tests of S2 are included in this report, because two other tests had issues with getting a good contact with the acrylic top and so were not included. Before conducting the BEP tests, the soil was characterized to ensure it was similar to samples from the Magnolia levee foundation. Roundness (or circularity) of grains was compared between samples from Oster Quarry and samples from Magnolia Levee by using microscopic images and processing them with the program ImageJ (https://imagej.net/; Figure 16). Roundness values range from 0 to 1, with 1 indicating a perfect circle. Roundness was compared to determine whether the bulk samples were suitable substitutes for the backward erosion piping tests. The average roundness of samples obtained from the Oster Quarry was 0.75, while the roundness from samples from the Magnolia Levee was also 0.75.

Particle-size analyses (Figure 17 and Figure 18, Table 1) and minimum and maximum density tests (Table 2) were performed in accordance with the procedures of ASTM Standards D422 (2007), D4254 (2016a), and D4253 (2016b), respectively, to also assess the suitability of the Oster Quarry sand as a substitute.

Figure 16. Typical optical images of glacial outwash from Oster Quarry (*top*) and Magnolia Levee boring D-15-20 sample S-13A, depth 5.5 m (*bottom*).

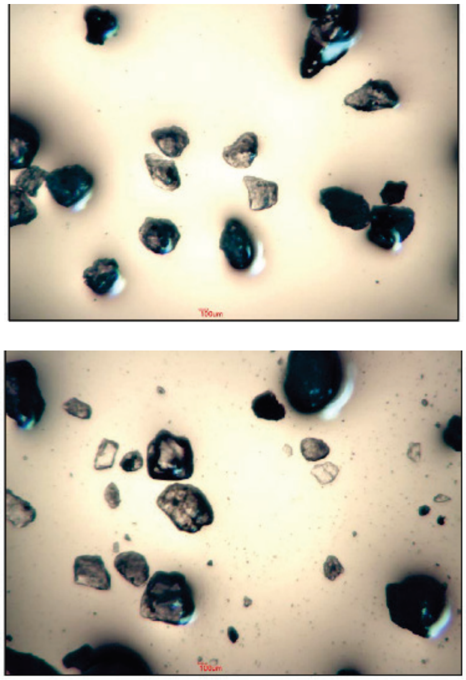


Table 1. Sieve analysis test results. (C_u: uniformity coefficient)

Opening (mm)	Bulk S1–S1	Bulk S1–S2	Bulk S1–S3	Bulk S2–S1	Bulk S1–S2
25.4	–	–	–	100	–
19.1	–	–	–	94.5	100
12.7	–	–	–	94.5	98.1
9.525	–	–	–	92	96
4.75	100	100	100	88	90
2	99.6	99.6	99.1	78.0	82.9
0.71	97.5	97.6	96.1	60.9	66.6
0.425	86.7	87.3	84.9	35.3	35.9
0.25	55.9	61.9	42.1	8.2	7.2
0.15	7.5	8.9	5.2	1.5	1.4
0.106	1.7	1.9	1.2	0.7	0.6
0.075	0.6	0.7	0.5	0.4	0.4
0.035	0.0	0.0	0.0	0.0	0
C_u	1.7	1.6	1.8	2.6	2.3

Table 2. Average minimum and maximum densities of S1 and S2.

Bulk sample number	ρ_{min} (kg/m^3)	ρ_{max} (kg/m^3)
S1	1398.6	1704.0
S2	1584.4	1852.2

Figure 17. Gradations of samples from Magnolia Levee 2016 foundation explorations (D-15-XX) and from a continuous SP deposit from Oster Quarry (OS-1, OS-2, and OS Bulk 1—S-1, S-2, and S-3).

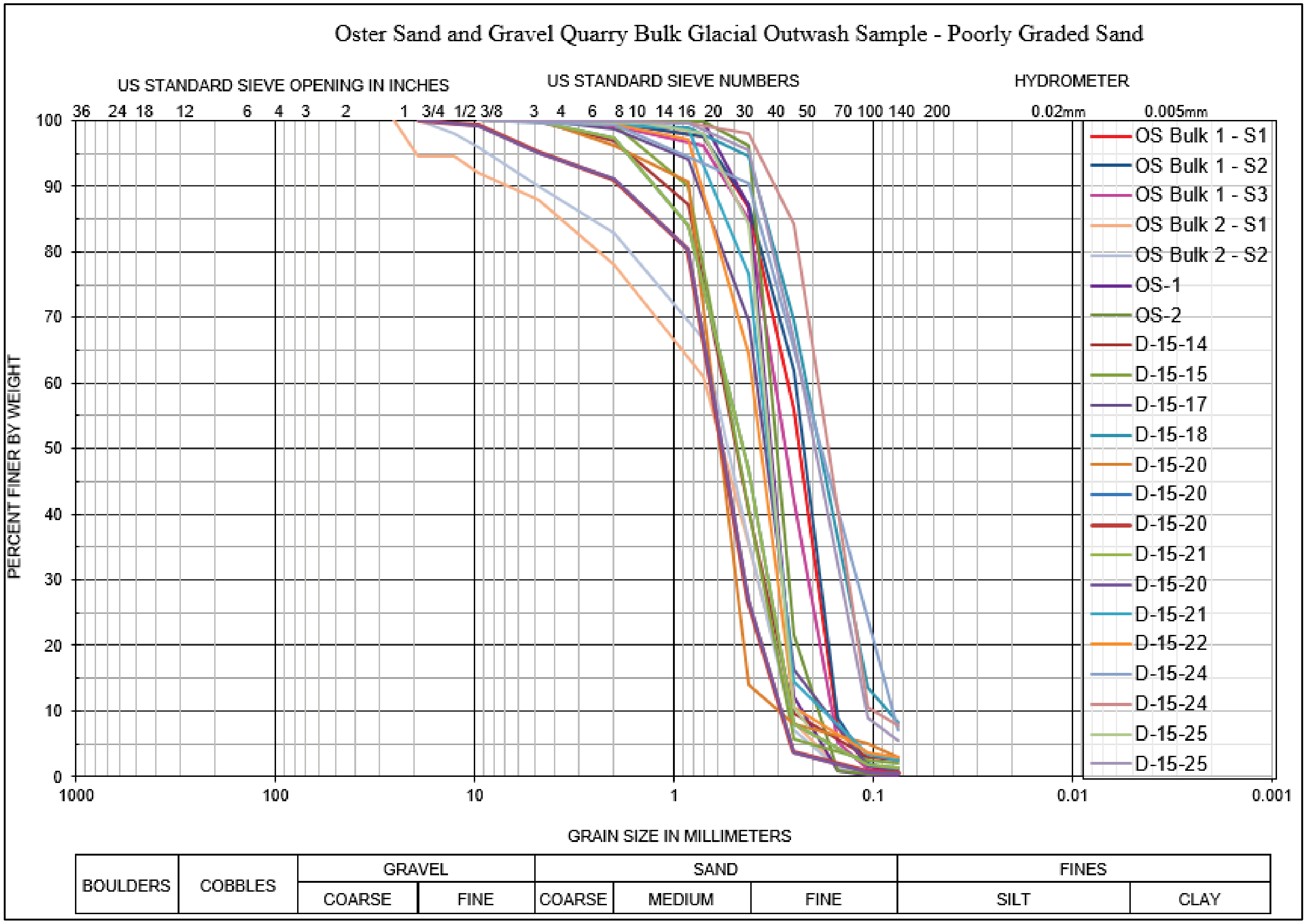
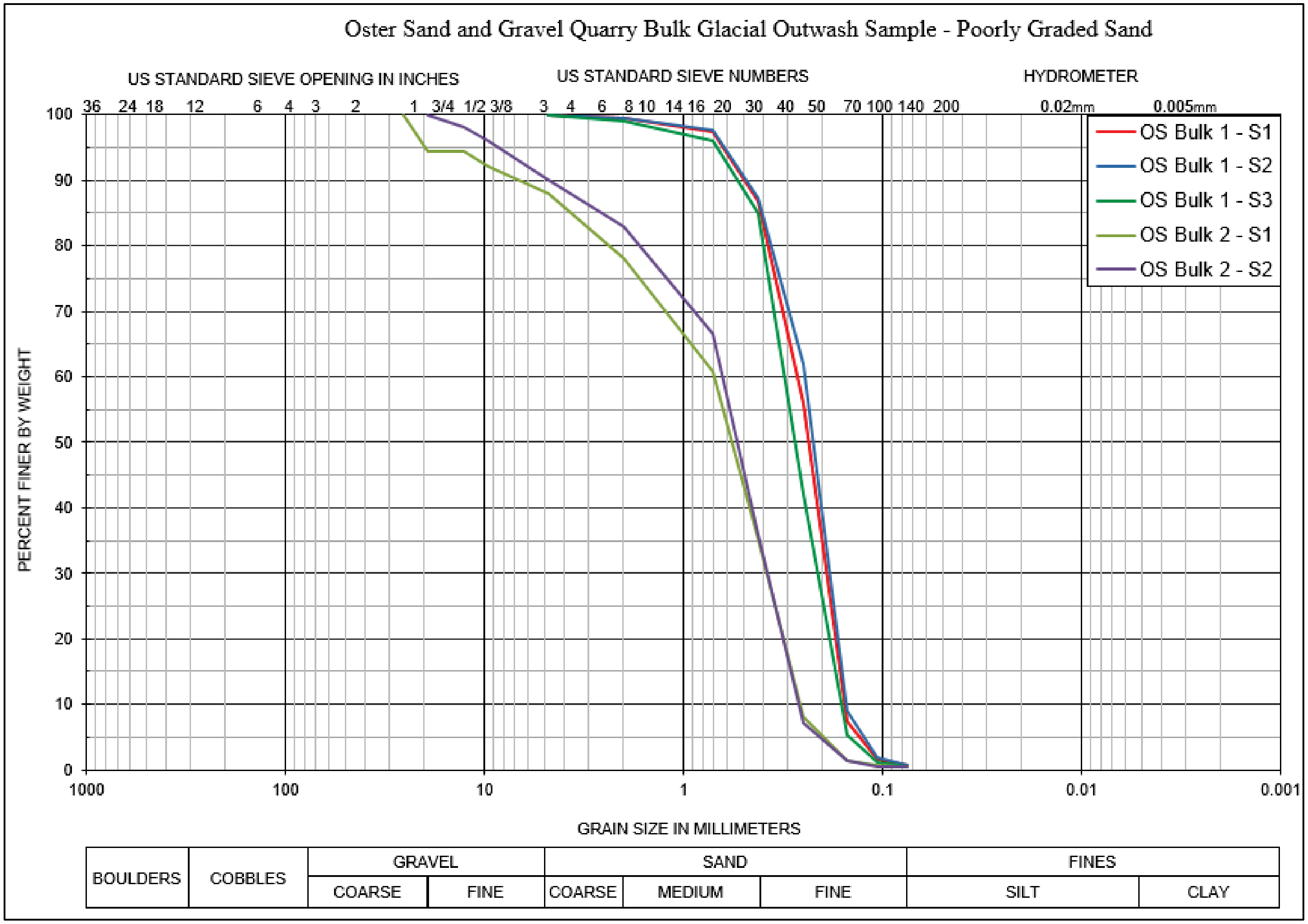


Figure 18. Gradation curves of the two bulk samples.



The estimate for relative density (D_r) for the actual foundation material of Magnolia Levee was 40%. This estimate of the foundation material was at a depth where BEP was possible in this levee. The experimental study, therefore, sought to obtain samples with D_r close to 40%. Densities of S1 samples that were prepared in loose condition (no tamping involved) ranged from 43% D_r to 50% D_r, approximately. However, the densities obtained of the S2 loose samples ranged from 16% to 22%. The average C_u of S1 samples was 1.6, while the average C_u of S2 was 2.5. In general, the critical gradient required for BEP was found to be higher at lower void ratios. Table 3 and Table 4 provide a summary of the sample properties of each test along with their critical gradient for piping. Figure 19 and Figure 20 show the plotted results of critical gradient at piping versus relative density and void ratio of each test. A summary sheet for each test is presented in Appendix A.

Table 3. Summary of tests of bulk sample S1.

S1 Tests	S1-1	S1-2	S1-3	S1-4	S1-5
Top sample length (m)	177.0	179.0	176.8	177.0	177.0
Soil weight (kg)	421.30	393.02	396.31	395.14	396.02
Soil volume (m^3)	0.260482	0.259037	0.257452	0.257830	0.260199
Dry unit weight (kN/m^3)	15.87	14.88	15.10	15.03	14.93
Relative density (%)	74.41%	43.02%	50.30%	48.09%	44.60%
Void ratio	0.638	0.746	0.721	0.728	0.740
Density (kg/m^3)	1617.4	1517.2	1539.4	1532.6	1522.0
Flow (L/min)	0.71	0.57	0.66	0.65	0.63
Hydraulic conductivity (cm/s)	2.832E−02	2.842E−02	2.70E−02	3.72E−02	3.59E−02
Average velocity (cm/s)	8.49E−03	6.83E−03	7.92E−03	7.81E−03	7.60E−03
Average critical gradient	0.30	0.24	0.29	0.21	0.21

Table 4. Summary of tests of bulk sample S2.

S2 Tests	S2-1	S2-3	S2-4	S2-6
Top sample length (cm)	175.5	176.0	176.0	177.5
Soil weight (kg)	421.40	437.36	425.84	423.90
Soil volume (m^3)	0.257139	0.251102	0.261330	0.260694
Dry unit weight (kN/m^3)	16.08	17.09	15.99	15.95
Relative density (%)	21.56%	61.17%	17.73%	16.30%
Void ratio	0.620	0.524	0.629	0.632
Density (kg/m^3)	1638.8	1741.8	1629.5	1626.0
Flow (L/min)	1.951	1.560	2.817	2.529
Hydraulic conductivity (cm/s)	7.37E−02	5.50E−02	9.31E−02	9.87E−02

S2 Tests	S2-1	S2-3	S2-4	S2-6
Average velocity (cm/s)	2.33E−02	1.87E−02	3.37E−02	3.03E−02
Average critical gradient	0.31	0.34	0.36	0.31

Figure 19. Horizontal critical gradients at piping versus relative density.

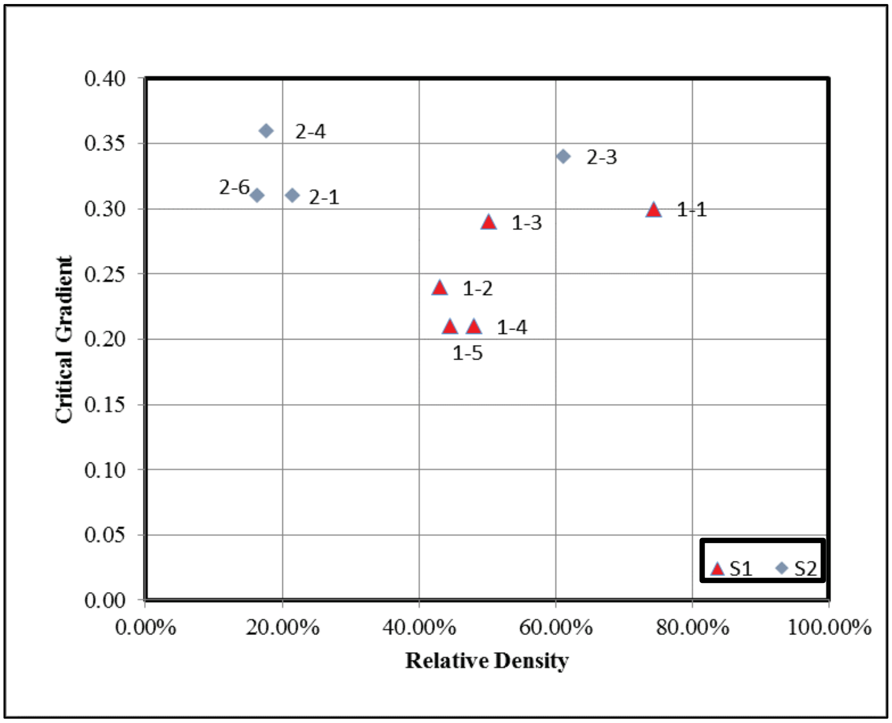
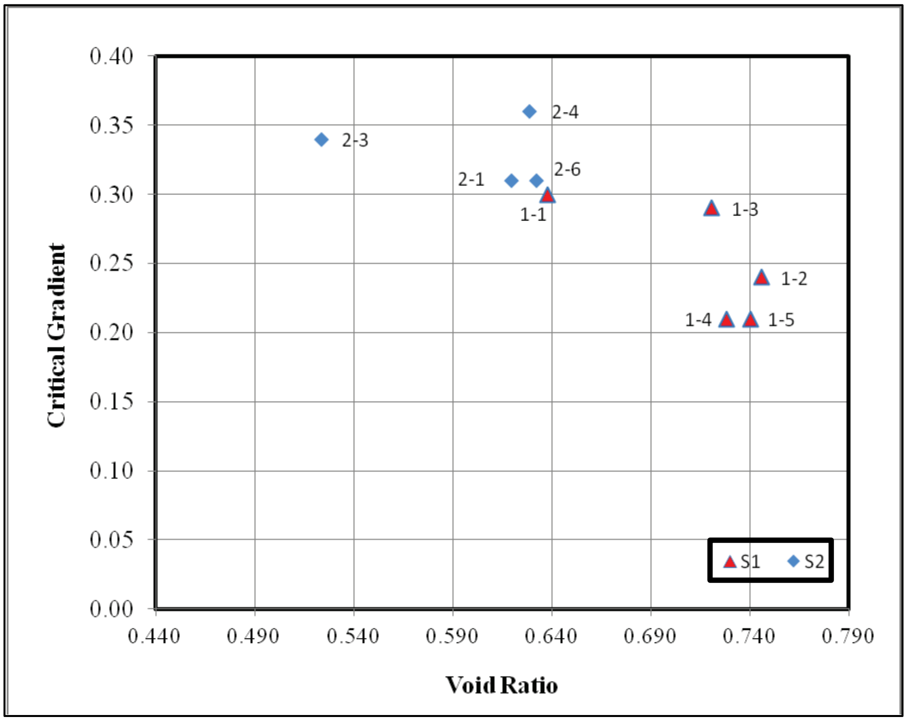


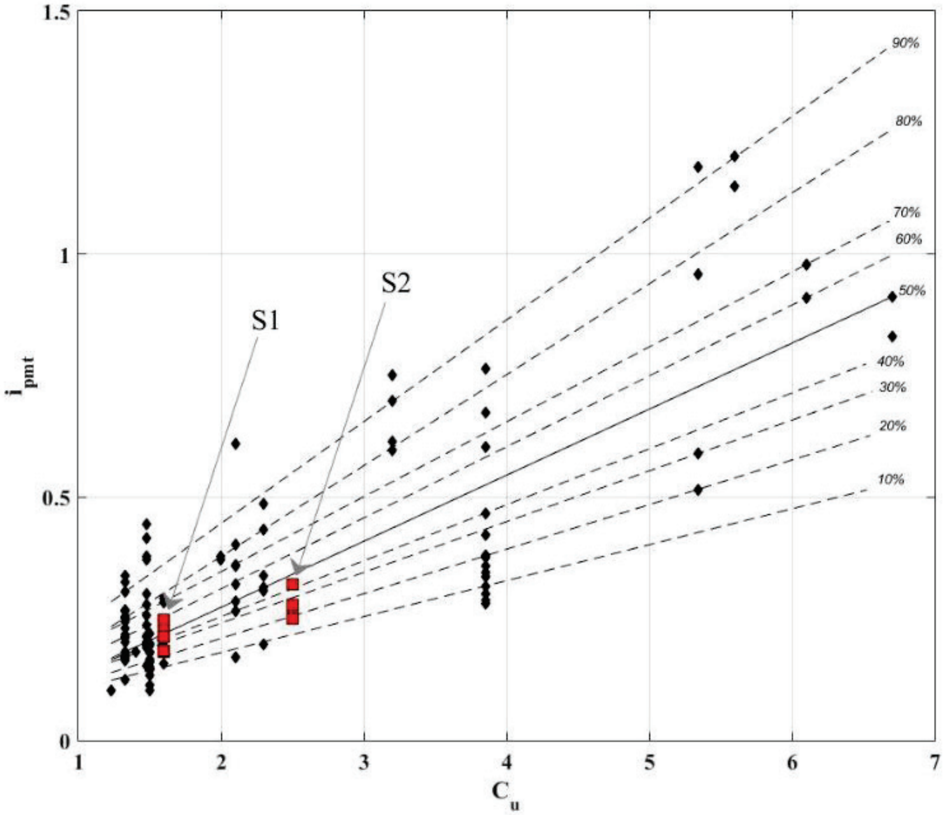
Figure 20. Horizontal critical gradients at piping versus void ratio.



The measured critical gradients were compared to values from the literature by comparing the measurements to the probabilistic distribution of critical point gradients proposed by Robbins and Sharp (2016), which is an extension of the method developed by Schmertmann (2000). To compare the measurements to the data, the measured gradients must first be corrected using the correction factors proposed by Schmertmann, which adjust for variables such as grain size, relative density, and sample dimensions. The adjusted values of critical gradient (i_{pmt}) from this study were compared to the data from the literature in Figure 21. The measured values compare favorably to previous measurements, albeit this study appears to be slightly low relative to the median of the data for sample S2.

Observation of values of C_u in Figure 9 indicates that a continuous path under the levee encounters $C_u = 3$ material. While the tested materials did not have a C_u of 3, the favorable comparison of the results of this study with previous measurements suggests that Figure 21 can be used to predict the critical gradients for $C_u = 3$ material at the Magnolia Levee site. In this case, Figure 21 suggests that critical gradients of approximately 0.25–0.65 should be considered in evaluations of the risk for BEP progression at Magnolia Levee cross section C-C′. After applying corrections for field conditions, this range of gradients can be used in conjunction with seepage analyses and stage frequency curves to develop site-specific fragility curves for BEP.

Figure 21. Comparison of adjusted measurements of critical gradient using Schmertmann's method to the distribution of measurements obtained from the literature (Robbins and Sharp 2016).



6 Conclusion

Naturally occurring materials were tested in this laboratory study to determine the critical gradient for BEP. The site selected for the study was the Magnolia Levee, which is owned and operated by USACE–Huntington District. Samples collected from a quarry were found to be similar to the levee foundation material in terms of grain size, roundness, and geological history. Nine tests were conducted in a horizontal flume to estimate the critical gradient for backward erosion piping. The range of average critical gradient for the first bulk sample with a C_u of 1.60 was between 0.21 and 0.30, while the second bulk sample with a C_u of 2.5 ranged from 0.31 to 0.36. These measurements compared favorably to data in the literature, with an increase in critical gradient observed with increasing C_u. Because of the uncertainty of critical gradients, the authors recommend the use of the probabilistic approach to estimate a range of possible values using the C_u of a soil for BEP.

7 References

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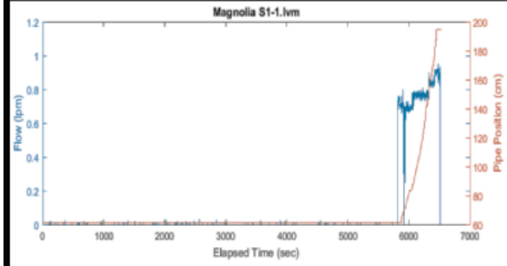
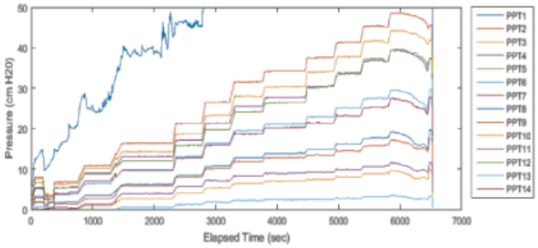
8 Appendix A: Summary Sheets for Each Test

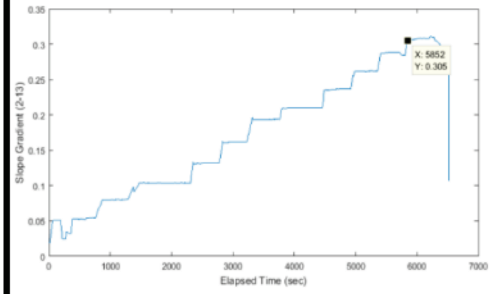
Sand Type	**Magnolia S1**	**Date**	**9-Mar-17**
Test Number	**1**	**Start Time**	**21:15:22**
Tested by	**A.M., J.L.**	**End Time**	**23:04:13**

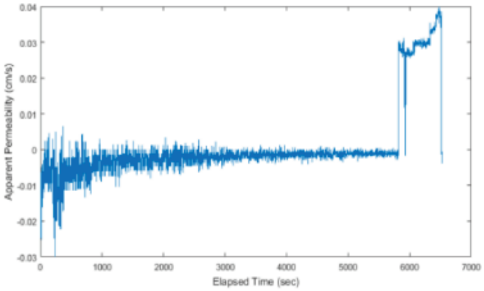
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	421.300	kg	Time at Piping	22:52:54	
Soil Volume	0.260482	m^3	Critical Gradient (Slope)	0.30	
Dry Unit Weight	15.867	kN/m^3	Flow Rate	0.710	L/min
Porosity	0.389		Average Velocity	8.49E-03	cm/s
Sample Length	177.000	m	Sample Permeability	2.832E-02	cm/s
Area	0.139	m^2			
Relative Density	74.41%				

Notes: Sample was prepared on 08-09MAR2016. Test was conducted on 09MAR2016 with FMG84. Flow meter started acquiring measuements at 22:52:23 (30 seconds before piping started). Sample permeability and velocity at piping estimated from flow at the moment of piping. Sample piped on the left side of sample and progressed toward the center of the sample. Sample was confined to a bladder pressure of 7 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample. The total sample length was 177.4 cm (slope at 61.6 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume). PPTs for gradient were 2-13. In the video recorded for the test, the piping initiated at 01:37:34.

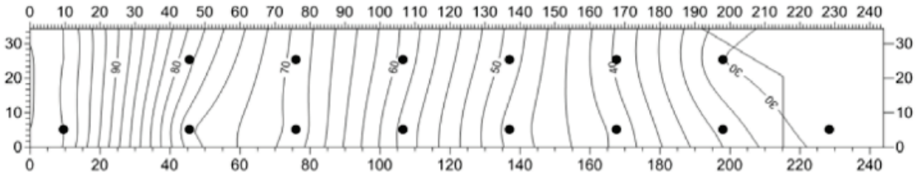




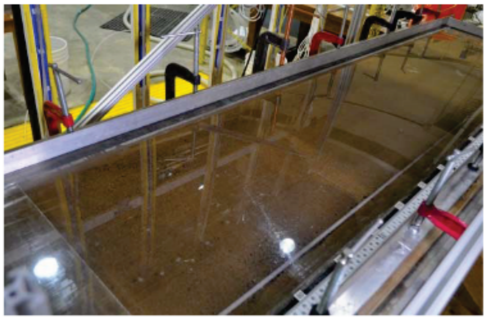




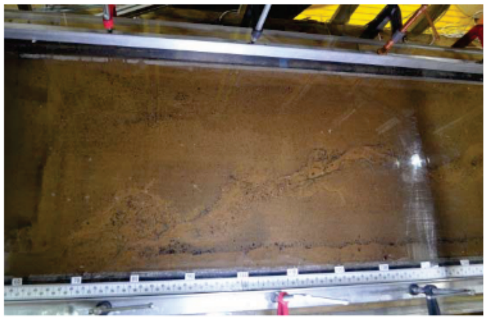
Total Head Contours at Initiation of Piping (units in cm)



Before Piping



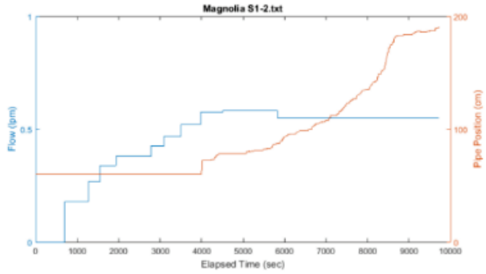
After Piping

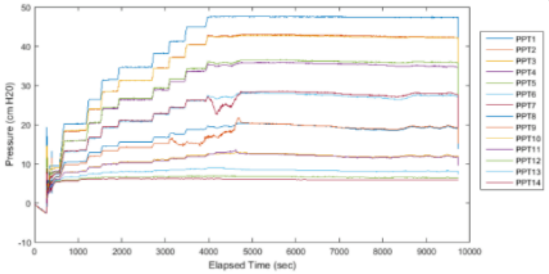


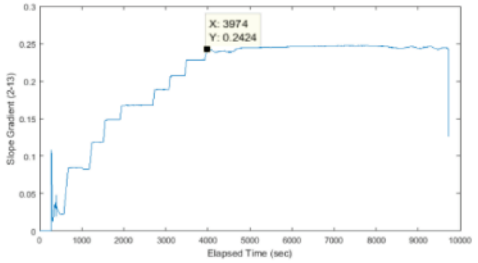
Sand Type	**Magnolia S1**	**Date**	**9-Mar-17**
Test Number	**2**	**Start Time**	**13:55:17**
Tested by	**A.M., J.L.**	**End Time**	**16:37:29**

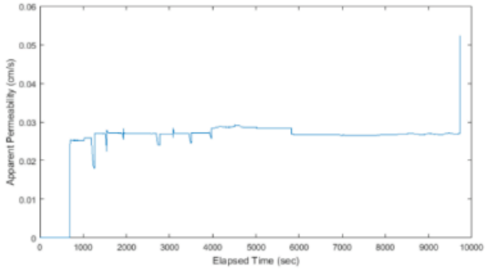
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	393.020	kg	Time at Piping	15:01:31	
Soil Volume	0.259037	m^3	Critical Gradient (Slope)	0.240	
Dry Unit Weight	14.884	kN/m^3	Flow Rate	0.571	L/min
Porosity	0.427		Average Velocity	6.83E-03	cm/s
Sample Length	179.000	m	Sample Permeability	2.84E-02	cm/s
Area	0.1394	m^2			
Relative Density	43.0%				

Notes: Sample was prepared on 08-09MAR2016. Test was conducted on 14MAR2016 with FMG84. Sample permeability and velocity at piping estimated from flow at the moment of piping. Sample piped on the left side of sample and progressed toward the center of the sample. Sample was confined to a bladder pressure of 6 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample. In the video recorded for the test, the piping initiated at 15:01:31.

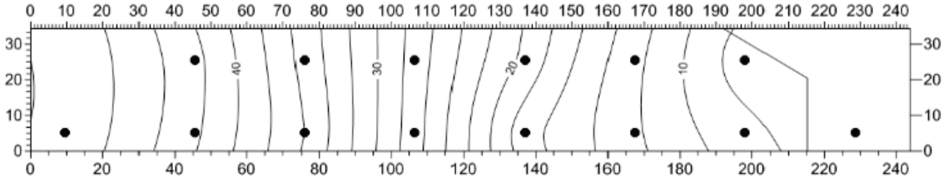




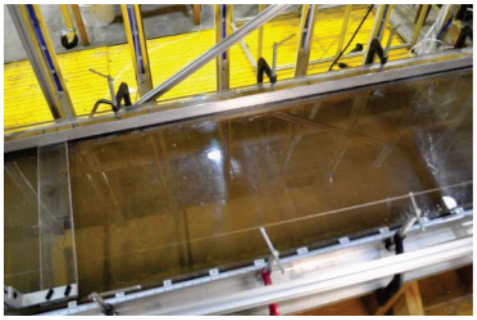




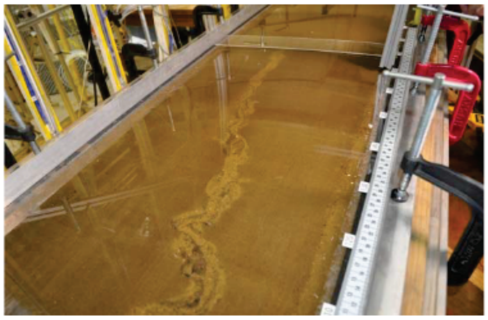
Total Head Contours at Initiation of Piping (units in cm)



Before Piping



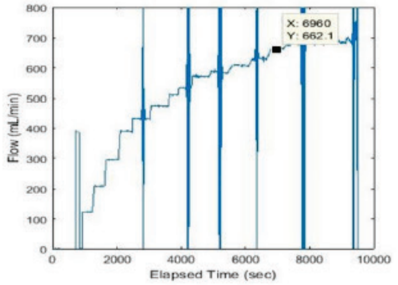
After Piping

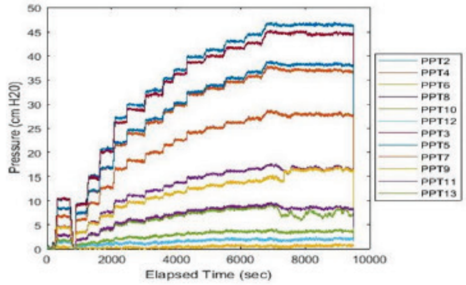


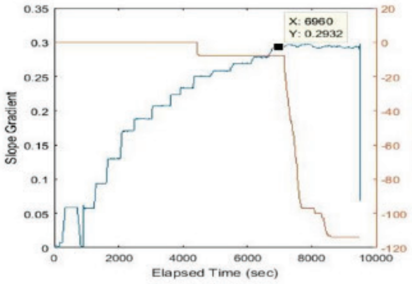
Sand Type Magnolia S1 **Date** 21-Mar-17
Test Number 3 **Start Time** 13:35:31
Tested by A.M., B.B. **End Time** 16:13:51

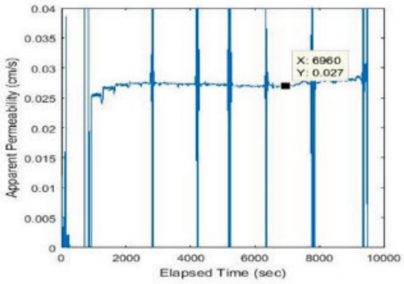
Initial Conditions			**Results (at Initiation of Piping)**	
Soil Weight for First Slope	396.310	kg	Time at Piping	15:34:05
Soil Volume	0.257452	m^3	Critical Gradient (Slope)	0.29
Dry Unit Weight	15.101	kN/m^3	Flow Rate	0.660 L/min
Porosity	0.4190		Average Velocity	7.92E-03 cm/s
Sample Length	176.8	cm	Sample Permeability	2.70E-02 cm/s
Area	0.139	m^2		
Relative Density	50.30%			

Notes: Sample was prepared on 20MAR2017. Test was conducted on 21MAR2017 with the load cell. Sample permeability and velocity at piping estimated from flow at the moment of piping. Sample piped on the right side of sample and progressed toward the center of the sample. Sample was confined to a bladder pressure of 6 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample for good contact. The total sample length was 176.8 cm (slope at 62.2 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume). This test was run with the presence of the Magnolia levee cadre.

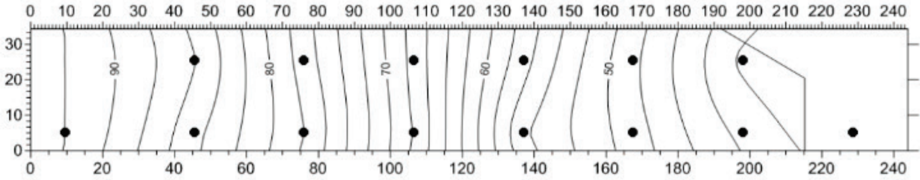




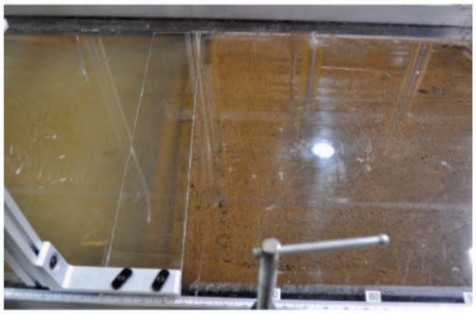




Total Head Contours at Initiation of Piping (units in cm)



Before Piping

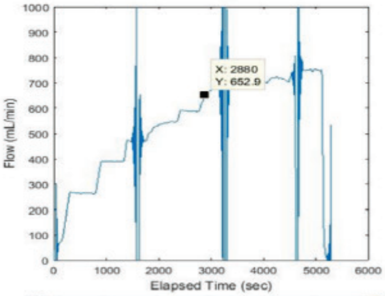


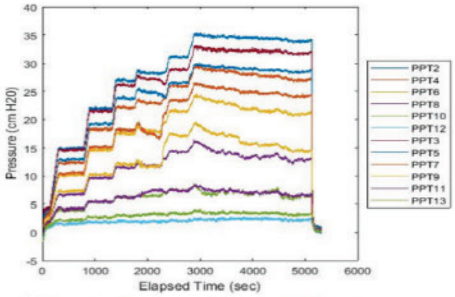
After Piping

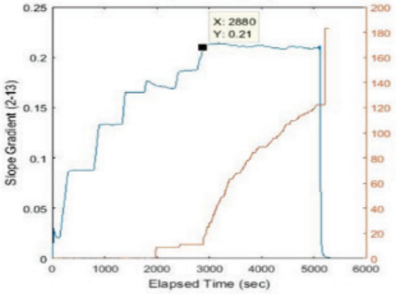
Sand Type	**Magnolia S1**	**Date**	**31-Mar-17**
Test Number	**4**	**Start Time**	**16:29:36**
Tested by	**A.M., B.B.**	**End Time**	**17:58:08**

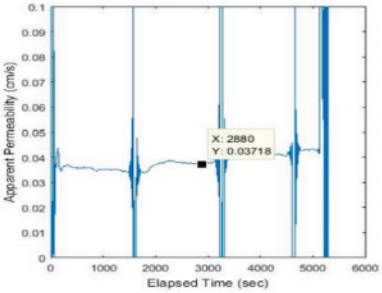
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	395.140	kg	Time at Piping	17:17:35	
Soil Volume	0.257830	m^3	Critical Gradient	0.210	
Dry Unit Weight	15.034	kN/m^3	Flow Rate	0.653	L/min
Porosity	0.421		Average Velocity	7.81E-03	cm/s
Sample Length	177.0	cm	Sample Permeability	3.72E-02	cm/s
Area	0.1393	m^2			
Relative Density	48.09%				

Notes: Sample was prepared on 30MAR2017. Test was conducted on 31MAR2017 with the load cell. Sample permeability and velocity at piping estimated from flow at the moment of piping. Some movement occurred during the test, and a small 9-cm-long pipe formed and stopped. Inititation and continuous piping started on the right side of sample and progressed toward the center of the sample at 17:17:35. A second pipe began to form on left side at the end of test. Sample was confined to a bladder pressure of 6 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample for good contact. The total sample length was 177.0 cm (slope at 62.0 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume).

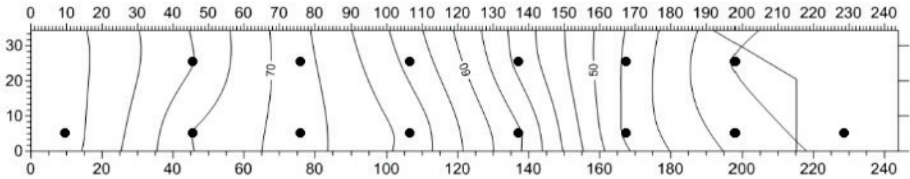




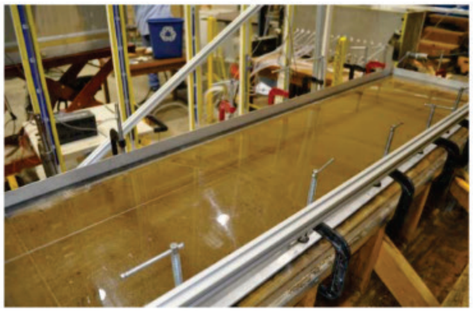




Total Head Contours at Initiation of Piping (units in cm)



Before Piping

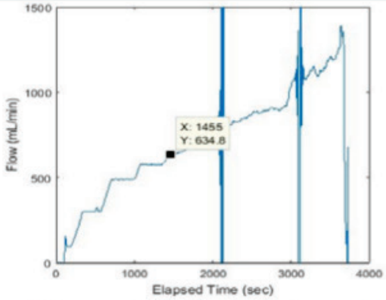


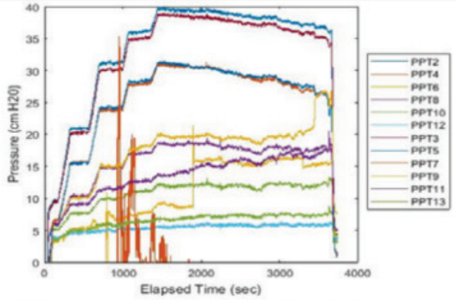
After Piping

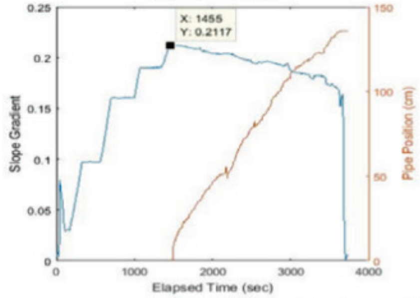
Sand Type	**Magnolia S1**	**Date**	**31-Mar-17**
Test Number	**5**	**Start Time**	**15:26:53**
Tested by	**A.M., B.B.**	**End Time**	**16:29:15**

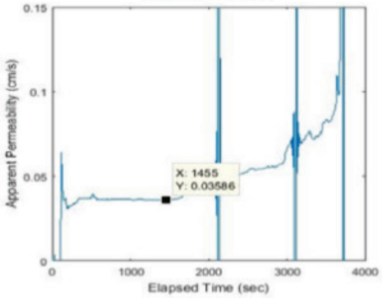
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	396.020	kg	Time at Piping	15:51:28	
Soil Volume	0.260199	m^3	Critical Gradient	0.21	
Dry Unit Weight	14.931	kN/m^3	Flow Rate	0.635	L/min
Porosity	0.425		Average Velocity	7.60E-03	cm/s
Sample Length	177.0	cm	Sample Permeability	3.59E-02	cm/s
Area	0.1394	m^2			
Relative Density	44.60%				

Notes: Sample was prepared on 9MAY2017. Test was conducted on 10MAR2017 with the load cell. Sample permeability and velocity at piping estimated from flow at the moment of piping. No movement occurred during the test until piping initiation. Piping started on the left side of sample and progressed toward the center of the sample at 15:51:28. Sample was confined to a bladder pressure of 6 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample for good contact. The total sample length was 177.0 cm (slope at 62.0 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume).

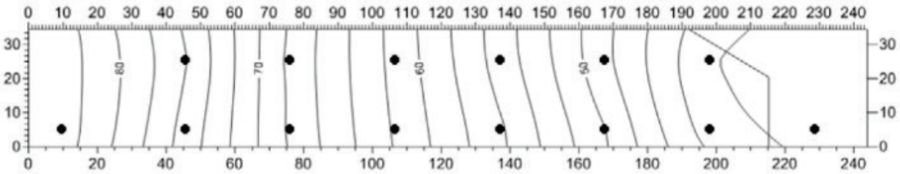




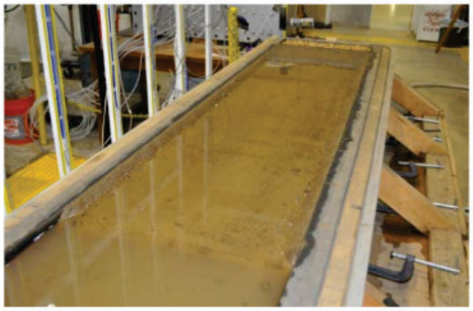




Total Head Contours at Initiation of Piping (units in cm)



Before Piping

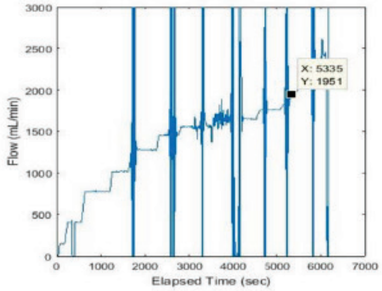


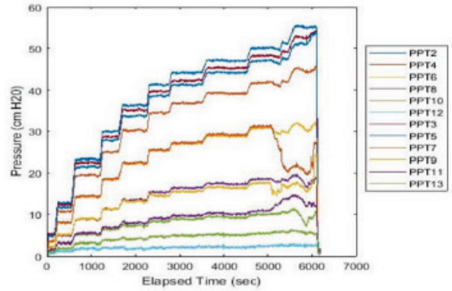
After Piping

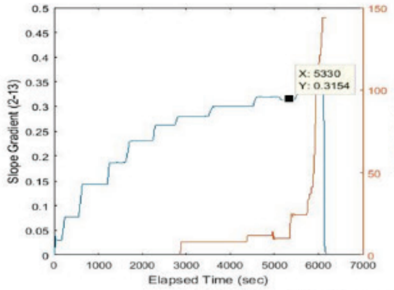
Sand Type	**Magnolia S2**	**Date**	**19-Apr-17**
Test Number	**1**	**Start Time**	**15:53:18**
Tested by	**A.M., B.B.**	**End Time**	**17:36:23**

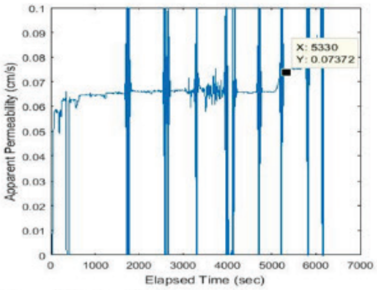
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	421.400	kg	Time at Piping	17:22:08	
Soil Volume	0.257139	m^3	Critical Gradient	0.31	
Dry Unit Weight	16.077	kN/m^3	Flow Rate	1.951	L/min
Porosity	0.383		Average Velocity	2.33E-02	cm/s
Sample Length	175.5	cm	Sample Permeability	7.37E-02	cm/s
Area	0.1394	m^2			
Relative Density	21.56%				

Notes: Sample was prepared on 18APR2017. Test was conducted on 19APR2017 with the load cell. Sample permeability and velocity at piping estimated from flow at the moment of piping. A 9-cm-long pipe formed on left side before piping initiatied. At 17:22:08, continuous progression on the left side of sample started and two pipes formed on center and right side. Sample was confined to a bladder pressure of 6 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample for good contact. The total sample length was 175.5 cm (slope at 63.5 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume).

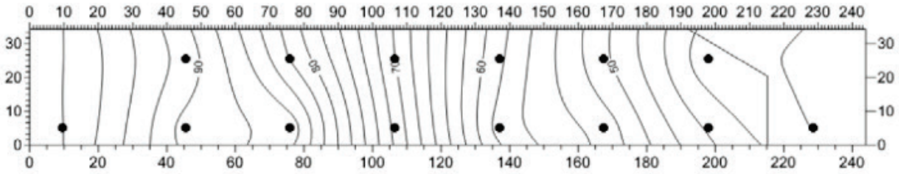




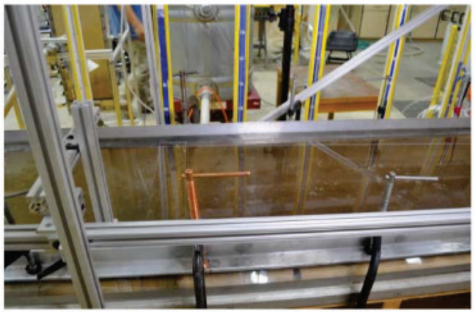




Total Head Contours at Initiation of Piping (units in cm)



Before Piping

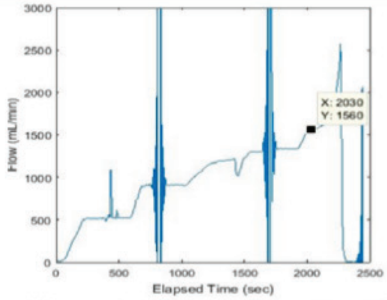


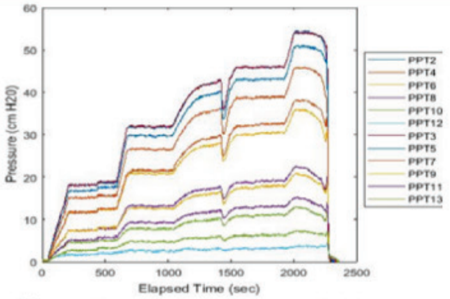
After Piping

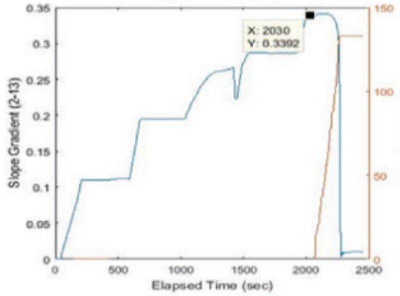
Sand Type	**Magnolia S2**	**Date**	**28-Apr-17**
Test Number	**3**	**Start Time**	**11:41:42**
Tested by	**A.M., B.B.**	**End Time**	**12:22:34**

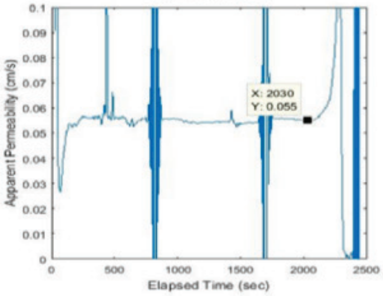
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	437.360	kg	Time at Piping	12:15:30	
Soil Volume	0.251102	m^3	Critical Gradient	0.34	
Dry Unit Weight	17.087	kN/m^3	Flow Rate	1.560	L/min
Porosity	0.344		Average Velocity	1.87E-02	cm/s
Sample Length	176.0	cm	Sample Permeability	5.50E-02	cm/s
Area	0.1394	m^2			
Relative Density	61.17%				

Notes: Sample was prepared on 27APR2017. Test was conducted on 28APR2017 with the load cell. Sample permeability and velocity at piping estimated from flow at the moment of piping. At 12:15:30, continuous piping initiated along the left abutment and moved towards the center. Sample was confined to a bladder pressure of 8 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample for good contact. The total sample length was 176 cm (slope at 63 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume).

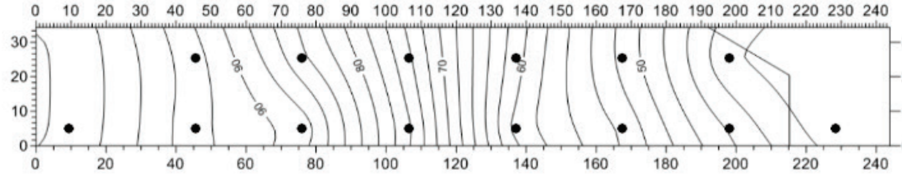








Total Head Contours at Initiation of Piping (units in cm)



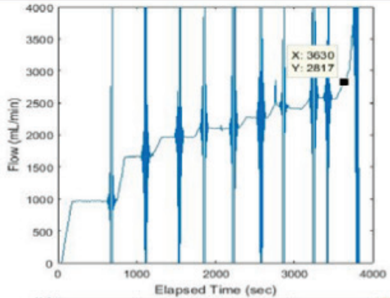
Before Piping

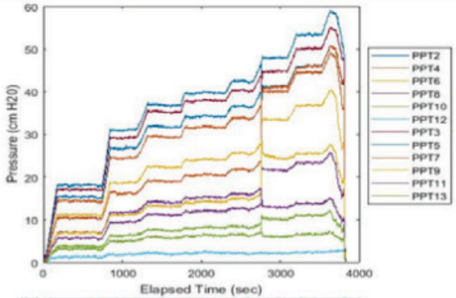
After Piping

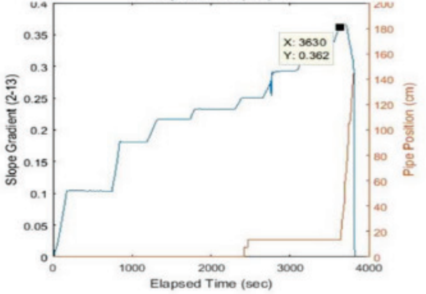
Sand Type	**Magnolia S2**	**Date**	**3-May-17**
Test Number	**4**	**Start Time**	**16:02:02**
Tested by	**A.M., B.B.**	**End Time**	**17:05:56**

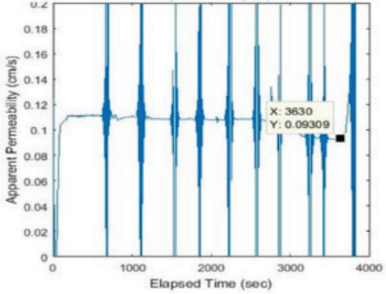
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	425.840	kg	Time at Piping	17:02:32	
Soil Volume	0.261330	m^3	Critical Gradient	0.36	
Dry Unit Weight	15.985	kN/m^3	Flow Rate	2.817	L/min
Porosity	0.386		Average Velocity	3.37E-02	cm/s
Sample Length	176.0	cm	Sample Permeability	9.31E-02	cm/s
Area	0.1394	m^2			
Relative Density	17.73%				

Notes: Sample was prepared on 02MAY2017. Test was conducted on 03MAY2017 with the load cell. Sample permeability and velocity at piping estimated from flow at the moment of piping. A 10-cm-long pipe slowly formed on the right side. At 17:02:32, continuous piping initiated along the right abutment and moved towards the center. Sample was confined to a bladder pressure of 6 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample for good contact. The total sample length was 176 cm (slope at 63 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume).

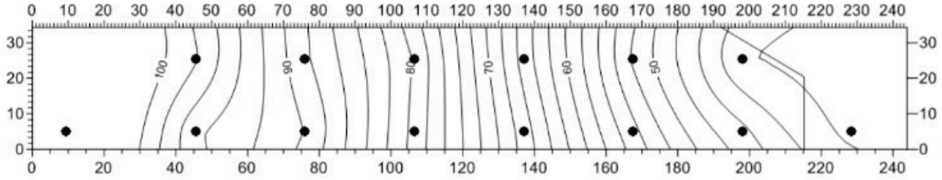






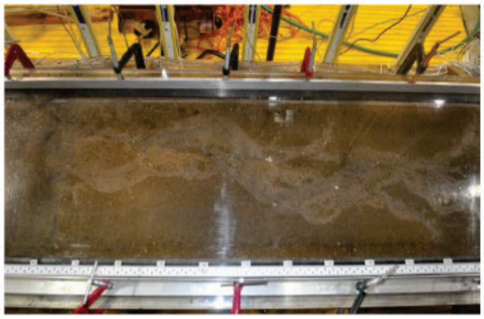


Total Head Contours at Initiation of Piping (units in cm)



Before Piping

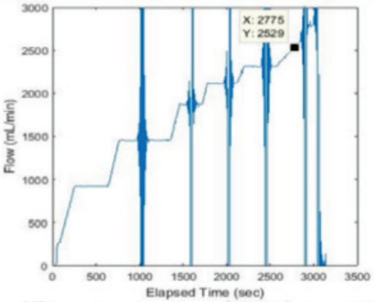
After Piping

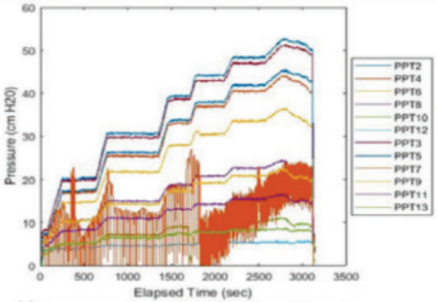


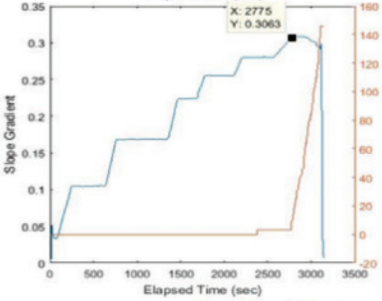
Sand Type	**Magnolia S2**	**Date**	**12-May-17**
Test Number	**6**	**Start Time**	**14:52:01**
Tested by	**A.M., B.B.**	**End Time**	**15:44:30**

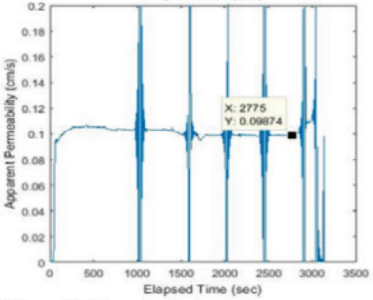
Initial Conditions			**Results (at Initiation of Piping)**		
Soil Weight for First Slope	423.900	kg	Time at Piping	15:37:58	
Soil Volume	0.260694	m^3	Critical Gradient	0.31	
Dry Unit Weight	15.951	kN/m^3	Flow Rate	2.529	L/min
Porosity	0.387		Average Velocity	3.03E-02	cm/s
Sample Length	177.5	cm	Sample Permeability	9.87E-02	cm/s
Area	0.1394	m^2			
Relative Density	16.30%				

Notes: Sample was prepared on 11MAY2017. Test was conducted on 12MAY2017 with the load cell. Sample permeability and velocity at piping estimated from flow at the moment of piping. At 15:37:58, continuous piping initiated along the left abutment and moved towards the center. Sample was confined to a bladder pressure of 6 psi and seating pressure of 2.75 psi. Additional sand was placed 30 cm from the upstream wall, and approximately 2 cm on the left and right sides of sample for good contact. The total sample length was 176 cm (slope at 61.5 cm and upstream wall at 239, with the plexiglass flush with the downstream side of the flume).

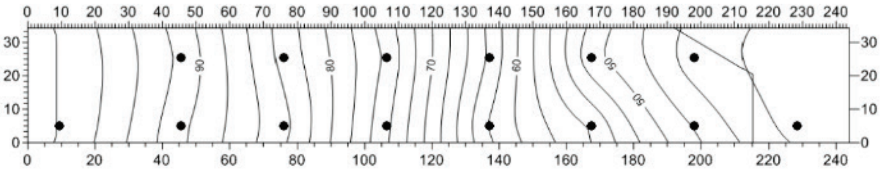




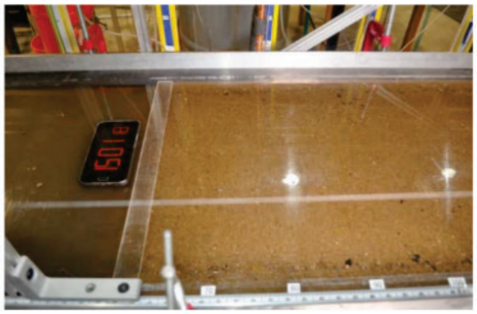




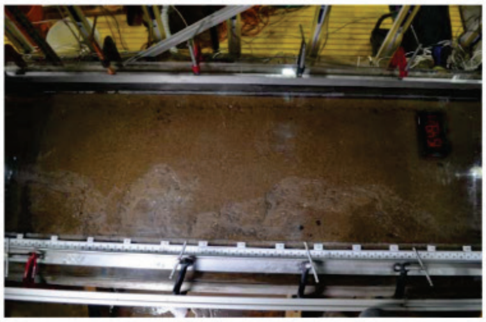
Total Head Contours at Initiation of Piping (units in cm)



Before Piping



After Piping



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Axel M. Montalvo-Bartolomei, Bryant A. Robbins, Erica Medley, and Benjamin Breland

5d. PROJECT NUMBER
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14. ABSTRACT

Using a confined flume device, an experimental study investigated the critical horizontal gradient of soils obtained from a site identified as potentially vulnerable to backward erosion piping (BEP). Tests were conducted on glacial outwash material obtained from a sand and gravel quarry in the vicinity of Magnolia Levee in the community of Magnolia, OH. The two bulk samples collected from the quarry had similar grain-size distributions, grain roundness, and depositional environments as the foundation materials beneath the levee. Samples were prepared at various densities and subjected to gradual increases of flow in a wooden flume with an acrylic top until BEP was observed. The critical average horizontal gradient ranged from 0.21 to 0.30 for a bulk sample with a coefficient of uniformity of 1.6, while tests conducted on a bulk sample with a coefficient of uniformity of 2.5 yielded critical average horizontal gradients of 0.31 to 0.36. The critical average gradients measured during these tests compared favorably to values in the literature after applying adjustments according to Schmertmann's method.

15. SUBJECT TERMS

Backward erosion piping
Laboratory testing
Seepage
Erosion
Internal erosion
Dams
Flood control
Levees
Piping—Erosion
Levees—Erosion
Flumes—Testing
Magnolia (Ohio)

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