



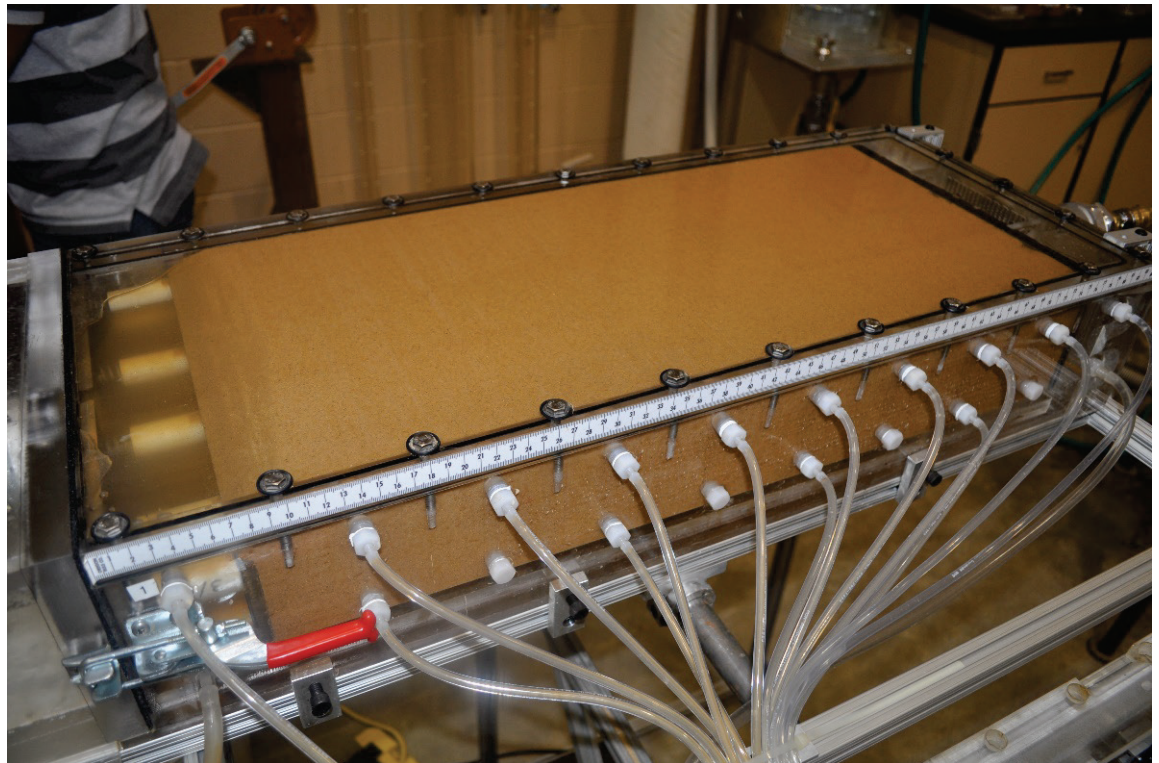
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Backward Erosion Progression Rates from Small-Scale Flume Tests

Axel M. Montalvo-Bartolomei, Bryant A. Robbins,
and Jamie F. López-Soto

September 2021



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Backward Erosion Progression Rates from Small-Scale Flume Tests

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Abstract

Backward erosion piping (BEP) is an internal erosion mechanism by which erosion channels progress upstream, typically through cohesionless or highly erodible foundation materials of dams and levees. As one of the primary causes of embankment failures, usually during high pool events, the probability of BEP-induced failure is commonly evaluated by the U.S. Army Corps of Engineers for existing dams and levees. In current practice, BEP failure probability is quantitatively assessed assuming steady state conditions with qualitative adjustments for temporal aspects of the process. In cases with short-term hydraulic loads, the progression rate of the erosion pipe may control the failure probability such that more quantitative treatment of the temporal development of erosion is necessary to arrive at meaningful probabilities of failure. This report builds upon the current state of the practice by investigating BEP progression rates through a series of laboratory experiments. BEP progression rates were measured for nine uniform sands in a series of 55 small-scale flume tests. Results indicate that the pipe progression rates are proportional to the seepage velocity and can be predicted using equations recently proposed in the literature.

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Preface

This study was conducted for the Flood and Coastal Systems R&D Program under Project 476926, "Internal Erosion Investigations." The Funding Account Code was U4375173; AMSCO Code was 031398. The technical monitor was Dr. Julie D. Rosati.

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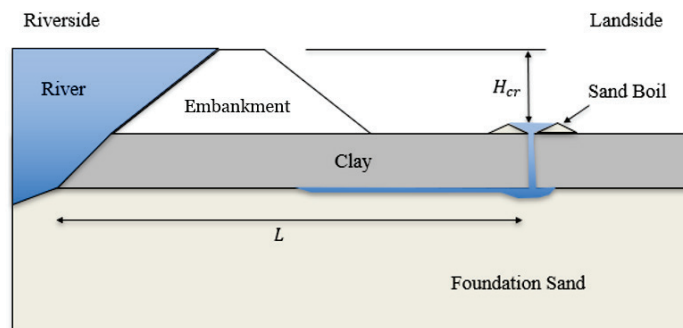
COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

The authors thank the U.S. Army Corps of Engineers (USACE) for the opportunity to conduct the present study. Further, the authors would like to thank Mr. Isaac Stephens for assistance in designing and constructing the flume apparatus. Lastly, the authors thank the students and interns at USACE for their assistance in conducting the experiments using the flume.

1 Introduction

Backward erosion piping (BEP) refers to a phenomenon by which shallow erosion pipes progress upstream through foundation sands and non-plastic silts beneath an embankment as illustrated in Figure 1. The erosion initiates near the downstream toe and progresses upstream along the contact between the sand and a cover layer capable of bridging over the erosion channel that forms. The sand is transported through the erosion channel and carried to the ground surface where it is deposited, often forming a cone of sand commonly referred to as a sand boil. If the erosion pipe can progress to the river or upstream reservoir, the erosion rapidly progresses, leading to subsidence of the embankment and possible failure. In Figure 1, the critical differential head H_{cr} is the differential head at which BEP progresses completely through the foundation under steady state conditions while L is the minimum seepage path length. The critical average hydraulic gradient, i_{cr} , is defined as H_{cr}/L . Historically speaking, BEP is one of the most common causes of failure prior to overtopping for both dams and levees (Foster et al. 2000; USACE 2018). As a result, developing an improved understanding of the BEP process such that it can be predicted and managed is of critical importance.

Figure 1. Idealized illustration of the process of backward erosion piping.



In 2014, the U.S. Army Corps of Engineers (USACE) initiated this laboratory investigation into the critical hydraulic gradients required to initiate BEP in uniform sands and the rate at which erosion progressed. Previous investigations had evaluated primarily fine-to-medium sands (van Beek et al. 2011; Townsend et al. 1981) with focus solely on identifying the critical differential head at failure due to piping. Therefore, this investigation expanded the range of soil types to include coarse sands, and carefully tracked the pipe progression to be able to extract average erosion rates. The

flume apparatus was modelled after the small flume used by van Beek et al. (2011). A scaled experiment minimized the sample size such that a testing program on numerous sands could be completed in an efficient manner. The Engineer Research and Development Center (ERDC) flume was commissioned in the spring of 2014, and the testing program was completed during the summer of 2014. Shortly thereafter, van Beek et al. (2014) published an analysis of the critical hydraulic gradient for initiation of BEP in their small-scale flume tests that provided a mechanics-based approach for predicting the initiation of piping. Montalvo-Bartolomei et al. (2018) performed a series of experiments that confirmed aspects of the work by van Beek et al. (2014) and also demonstrated that the hydraulic gradient occurring over an extremely small distance (approximately 10 times the d_{50} of the sand) controlled initiation of piping. Because analysis procedures at this scale are impractical in geotechnical engineering practice due to uncertainties in the field (e.g., silted in ditches, soil variability, livestock footprints in ditches, etc.), further analysis of the critical gradients for initiation of piping in the small-scale flume experiments was deemed to have no practical value. Instead, USACE research on BEP became focused on assessing the critical conditions for pipe progression through novel laboratory devices, which resulted in substantial progress towards understanding the mechanics of piping (Robbins et al. 2018; van Beek et al. 2019).

While the measurements of critical head for BEP initiation in the small-scale experiments were not considered to be of practical value, the rate at which the erosion pipes progressed through the samples is still of significance. Accurate prediction of erosion rates may be of great value in highly transient situations (e.g., flash floods and tidal loadings) where the pipe does not have sufficient time to progress to failure. The purpose of this report is to present the results of the small-scale flume experiments with special emphasis on the pipe progression rates observed. As the rates are dependent on the hydraulic loading, the average gradients at initiation are also presented. However, it should be recognized that because these small-scale experiments are controlled by initiation rather than progression (van Beek et al. 2014; Bonelli 2013), the measured average hydraulic gradients at initiation of BEP are higher than the average hydraulic gradient required for progression. As such, the test data should be interpreted with caution if used for assessment of BEP progression as the critical gradients for pipe progression in the field will be lower.

In the chapters that follow, background information regarding BEP pipe progression rates is provided followed by a description of the experiments and analyses of results.

2 Background

Little research has been conducted on the rates at which BEP pipes progress through foundations. The earliest work assessing this topic was a theoretical description of the progression rate put forward by Kézdi (1979), where the progression rate was considered proportional to the average pore velocity upstream of the pipe. Under this assumption, the pipe progression rate, \dot{x} , is given by Equation 1.

$$\dot{x} = \frac{2ckH_c}{Ln} \quad (1)$$

where

c = constant of proportionality

k = hydraulic conductivity

H_c = critical hydraulic head

L = seepage length

n = soil porosity

Although Kézdi proposed Eq. 1, it does not appear that the equation was calibrated to laboratory or field data, and no recommendations for the constant of proportionality, c , were made. In 2011, van Beek et al. conducted experiments in which data regarding the piping progression rates were collected. However, the progression rates were not presented in the original publication, and no further analysis of the rates was made. Not long after, Robbins et al. (2018) presented quantitative measurements of pipe progression rates made in small-scale, cylindrical flume tests that demonstrated that the progression rate was indeed proportional to the velocity in the sand upstream of the pipe as proposed by Kézdi. Allan (2018) presented further information from large-scale, rectangular laboratory tests that also confirmed this was the case. Vandenboer et al. (2019) conducted small-scale flume experiments using supercritical loads. By using supercritical loads, the pipe progressed completely through the sample at a fixed hydraulic head such that the influence of average hydraulic gradient on progression rates could be assessed. The results once again confirmed that the pipe progression rate varied linearly with the applied gradient (or velocity).

Pol et al. (2019) compiled the information on pipe progression rates from Sellmeijer et al. (2011), van Beek et al. (2011), Robbins et al. (2018), Vandenboer et al. (2019), and Yao (2014) to evaluate two equations for predicting pipe progression rates. The first equation Pol et al. (2019) considered was Eq. 1 above as proposed by Kézdi. Calibrating Eq. 1 to available data, Pol et al. (2019) found that a value of $c=1.6$ yielded the best fit. The second equation evaluated was derived through a multivariate regression on the combined data set. The resulting equation is given by Eq. 2.

$$\frac{\dot{x}}{\bar{\dot{x}}} = 6.2(H/L)^{1.4} \left(k/\bar{k}\right)^{0.57} \quad (2)$$

where:

\dot{x} = pipe progression rate (m/s)

$\bar{\dot{x}}$ = the mean pipe progression rate for the data set (m/s)

H = the differential head across the sample (m)

L = the seepage length (m)

k = the sample hydraulic conductivity (m/s)

\bar{k} = the mean hydraulic conductivity for the data set (m/s)

While the combined data set of Pol et al. (2019) consisted of 45 experiments, the data were limited to fine sands with a maximum d_{50} of 0.45 mm. The limited range of sand sizes used results in the equations being assessed over a very limited range of seepage velocities such that the validity of Eq. 1 and Eq. 2 in a general sense are questionable. In the present study, the sands tested ranged in size from 0.3 mm to 2.52 mm. The range of grain sizes tested in this study provides an excellent opportunity to evaluate the validity of Eq. 1 and Eq. 2 over a broad range of seepage velocities and erosion rates.

3 Experimental Approach

3.1 Equipment

The experimental apparatus consisted of a small, acrylic flume box attached to an aluminum frame. Figures 2 and 3 show a schematic of this flume and a photograph of the flume on its frame with the rest of the equipment, respectively. The use of clear acrylic material for the flume box was advantageous as the soil sample could be viewed from any angle during sample preparation and testing. The thickness of the acrylic was 2.54 cm (1 in.). The bottom, sides, and inlet wall panels of the box were permanently fixed to one another with acrylic adhesives, whereas the top and outlet wall panels were both removable. The outlet wall was removed in between tests to facilitate sample preparation. The outlet wall was attached to the flume using two adjustable quick-release latches. The top of the flume, through which erosion was viewed, was attached to the flume walls using 25 bolts. O-ring gaskets in a shallow groove combined with vacuum grease produced a water-tight seal between the top of the flume and its sidewalls. Likewise, the removable outlet wall had a closed-cell, foam-rubber gasket that sealed the flume at its downstream end.

The inner dimensions after the box was assembled were 82.5 cm long, 30.0 cm wide, and 10.0 cm tall (32.5 in. x 11.8 in. x 3.9 in.). The external dimensions of the flume were approximately 94.0 cm long, 35.0 cm wide, and 15.0 cm tall (37.0 in. x 13.8 in. x 5.9 in.). The top side of the box had three bleed valves, i.e., two near the outlet wall and one near the inlet wall that permitted the release of trapped air in the flume during saturation of the system. More schematics and dimensions of the small flume can be found in Appendix A.

Figure 2. Schematic of small flume.

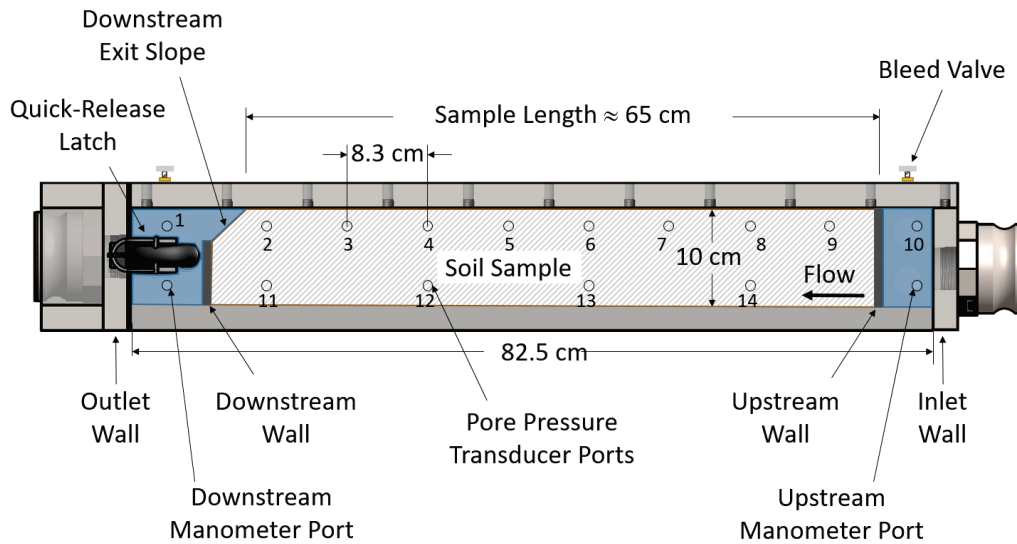
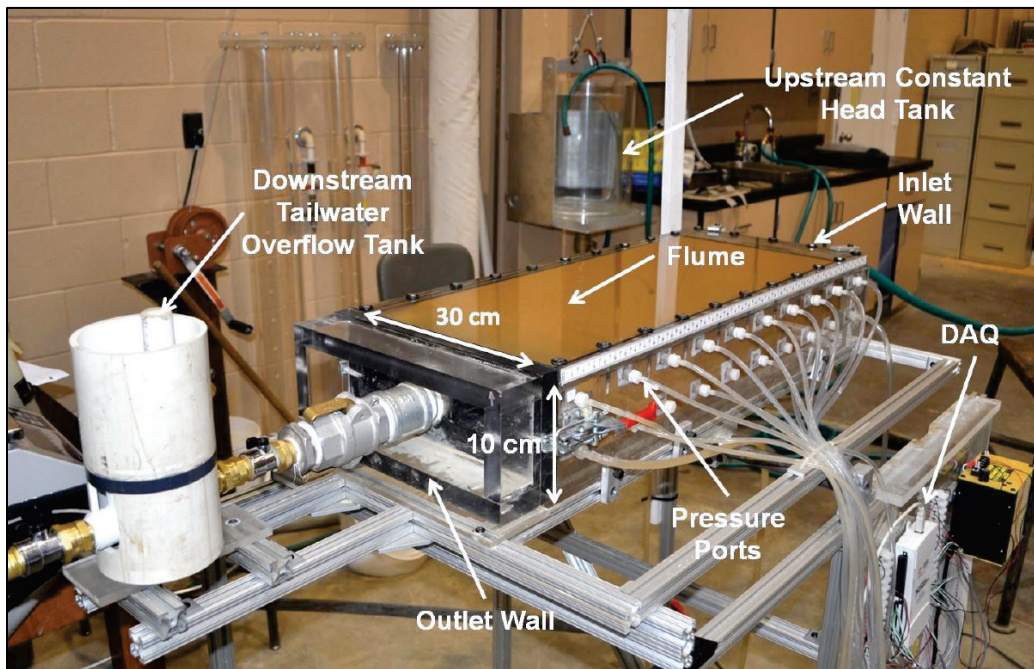


Figure 3. Photograph of the small flume on aluminum frame and its major system components.



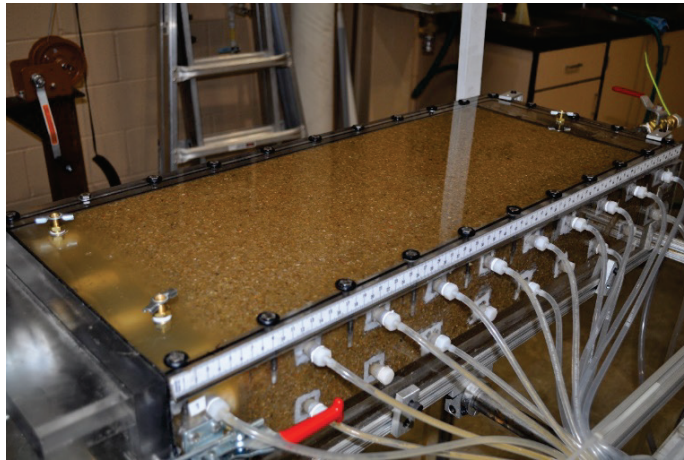
The bottom and sidewalls of the flume were attached to a custom-built aluminum frame (Figure 3). The frame was constructed of 80/20 aluminum, T-slot framing extrusions. The flume was directly attached to a free-standing, rectangular support frame also constructed from 80/20 aluminum pieces that was connected to a 1-in.-diam steel rod with

brackets containing ball bearing pivots. This steel rod and the ball bearings allowed the flume to rotate 180 deg. Rotating the flume to the vertical position (Figure 4) facilitated convenient sample preparation and removal, while tests were conducted with the flume in the horizontal position. Further, preparing the sample in the vertical position ensured integral contact between the soil and the acrylic, similar to the tests by van Beek et al. (2011). To prepare the samples, the flume was rotated until the inlet wall was at the bottom and the outlet wall at the top. While in this position, the outlet wall was removed, and the flume was partially filled with water before being filled with sand by water pluviation. After completing the sample preparation, the flume was placed in the horizontal position and locked in place to begin a test (Figure 5). When the testing had finished, the flume was rotated to a vertical position with the outlet end at the bottom, and sand was removed from the flume.

Figure 4. Small flume in vertical position after finishing the sample preparation.



Figure 5. Isometric view of small flume in horizontal position with soil sample inside ready for testing.



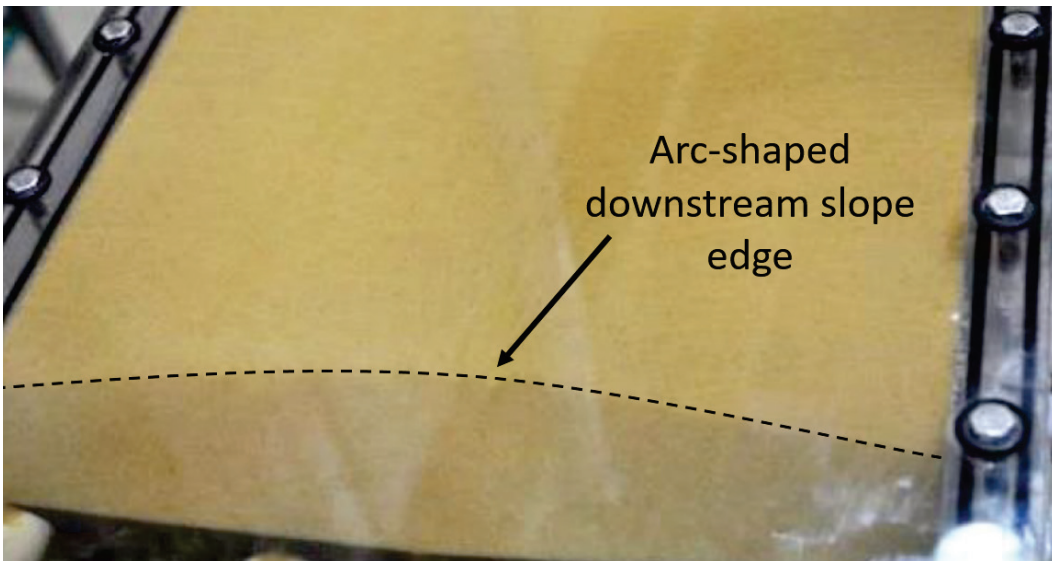
Inside the flume, an upstream wall and a downstream wall (Figure 2) held the sample in place. The upstream wall was separated 5.08 cm (2 in.) from the inlet wall by two small, perpendicular plates. The upstream wall had neoprene rubber all the way around the edge. In addition to holding the sample, the upstream wall was used to diffuse the inflow and provided a uniform upstream boundary condition. The wall had 1.27-cm-diam (0.5-in.) holes throughout and a filter fabric cover to prevent soil from going through the holes. The dimensions of this plate were 30.0 cm wide by 10.0 cm tall (11.8 in. by 3.9 in.) with a thickness of 1.0 cm (0.4 in.).

After sample preparation, the downstream wall was placed on top of the soil with the flume in its vertical position. The downstream wall consisted of a perforated plate held in place with six steel springs that pushed against the outlet wall, thereby applying a nominal confining pressure on the samples (Figure 6). The width of this plate was 30.0 cm (11.8 in.), and its thickness was 1.0 cm (0.4 in.). This plate had a 1:12 v-notch centered on the top edge while the flat edge rested on the bottom of the flume. A natural slope formed at the angle of repose as the flume was tilted from its vertical position to the horizontal position. As sand came to equilibrium at its angle of repose, an arc formed at the top of the slope as shown in Figure 7 due to the v-notch shaped end plate. The arc-shaped end slope on the sample resulted in the shortest seepage path being located in the center of the sample such that BEP initiation was forced to occur in the center of the sample as mentioned in Montalvo-Bartolomei et al. (2016). The height of the plate from the bottom to the top was 6.5 cm (2.6 in.) at the center of the v-notch and 7.5 cm (3.0 in.) at the edges. Similar to the upstream wall, this plate also had 1.27-cm- (0.5-in.-) diam holes drilled throughout the plate to allow flow through it and was covered by filter fabric to prevent movement of sand through the plate.

Figure 6. Downstream wall with v-notch and springs.



Figure 7. Naturally formed arc at the top of downstream slope of sample.



One of the side walls of the flume had 20 ports for pore pressure measurements, each with a diameter of 0.635 cm (1/4 in). These threaded holes were split into two rows of 10, each row 6 cm (2.63 in.) apart from each other. Sixteen of these holes were used for pore pressure measurements, while the other four were plugged and not used. Pressure sensors or pore pressure transducers (PPTs) were connected to 14 of these 16 ports to automatically record pressures. The other two ports were used as manometers to obtain manual readings of both the upstream and downstream heads. The total head difference between the two manometers provided a quick estimate of the hydraulic gradient at any time during the test. Due to head losses that occurred across the upstream

plate, particularly in the tests with the coarsest sands, this manometer gradient was not used in the analyses of results. Filter fabric was placed over the pressure port holes on the inside of the flume to prevent soil from entering the tubes, which would have influenced pressure measurements and disturbed the samples. The manometers and the transducers were fixed to the free-standing support frame. The reference datum used for head measurements was the bottom of the sample.

Pore pressures were constantly collected during each test using Honeywell 26PC pressure transducers with a measuring range of ± 34.5 kPa (± 5 psi). The 10 holes on the top row and 4 on the bottom row had national pipe threads (NPT) to barbed fittings that connected the pore pressure transducers through 0.31-cm (1/8-in.) clear tubing. The pore pressure transducer ports, upstream manometer port, and downstream manometer port are identified in Figure 2. The pressure at each location was converted to head to calculate the horizontal gradient through the sample. Each sensor was wired to a direct current power supply with a constant excitation voltage of 10V. The output signal in millivolts (mV) was read by 14 differential channels in a National Instruments USB-6218 isolated bus data acquisition (DAQ) device connected to a computer. A LabVIEW graphical user interface was used to obtain and record the voltage from the PPTs. All sensors were calibrated before testing. The pore pressure measurements were recorded at discrete time intervals of one second into a text file that was processed after each test. The two manometers allowed for real-time verification of the PPT measurements during testing.

Flow measurements were obtained either with flowmeters or with a weighing scale. The flowmeters used were a 0.95-cm-diam (3/8-in.) FPR132 and a 3.81-cm-diam (1.5-in.) TM Series 150-N-P. The flowmeter for each test was selected based on anticipated flow rates and was installed upstream of the flume to reliably measure inflow. These sensors were also wired to the DAQ device to obtain flow measurements at one second intervals. In addition, a scale was used in some tests as either the sole method to measure flow or to verify flowmeter measurements. An Omega WSB-8150 scale was connected to the same computer to obtain the weight of the water collected over timed intervals (Figure 8). The duration of measurements was recorded to estimate the outflow and compare it with the inflow readings obtained from the flowmeters for verification.

Figure 8. Complete setup of small flume with weighing scale.



The inlet and outlet walls of the flume had 3.81-cm (1.5-in.) male stainless-steel connectors. The valve and tube sizes for inflow and outflow were modified from test to test to accommodate the increased flow rate associated with the coarser sands. A constant head was maintained using either a constant head tank or a pump (Figures 9 and 10). The height of the constant head tank was adjusted with a pulley and a hand winch. A hose, connected to the municipal water supply, constantly fed water to this head tank to keep it full; the excess water overtopped this tank and exited to a drain (Figure 10a). Due to the limitation of the flow from the tap and hydrodynamic head losses in the system, a pump was required to keep a constant head for the two coarsest sands (see Section 3.1). The pump (Figure 10b) supplied water from a 1.89-m³ (500-gal) reservoir tank. Two valves controlled the flow from the pump, i.e., one controlled the water flowing to the flume while the other controlled how much water recirculated to the reservoir tank. The pump used 3.81-cm (1.5-in.) tubes and fittings. A small, constant head tailwater tank was installed on the outflow to maintain a constant head condition downstream.

Figure 9. (a) Schematic of setup of small flume device with constant head tank. (b) Schematic of setup of small flume device with pump.

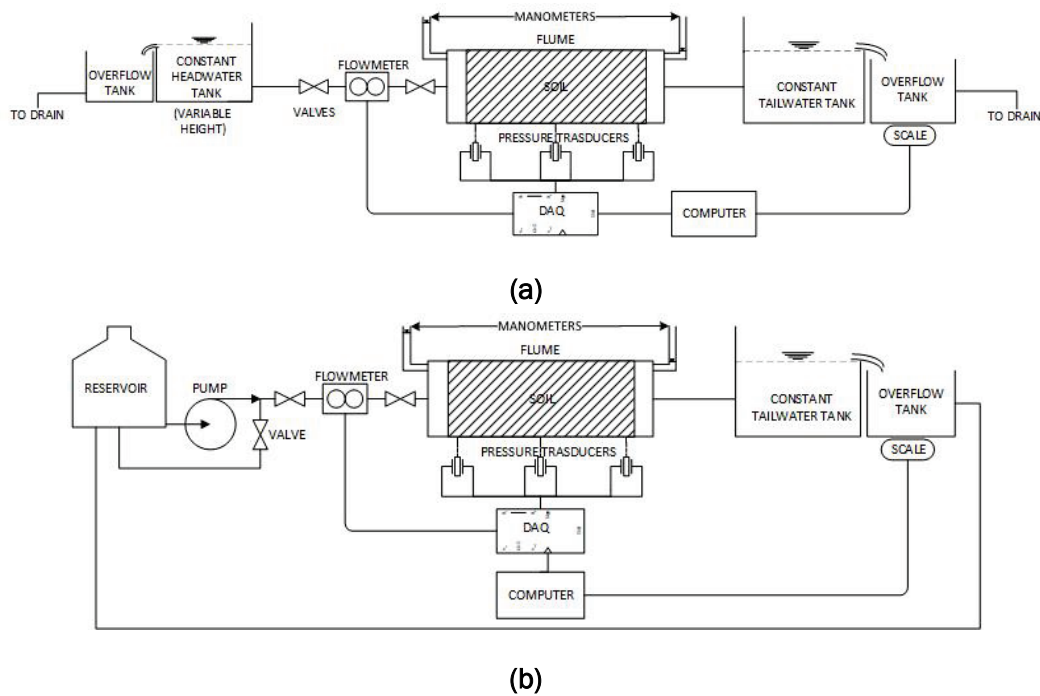


Figure 10. (a) Constant head tank with hose supplying water. (b) Pump with 3.81-cm (1.5-in.) tubes.



3.2 Sand types

The small flume was designed to measure the critical average hydraulic gradient for initiation of BEP and the pipe progression rate in sands with different grain sizes. Nine different sands were tested in the small flume. The granular materials increased in size while maintaining a similar coefficient of uniformity. The coefficients of uniformity of the sands tested ranged between 1.3-1.6 indicating that all materials were quite uniform. The first sand tested in the small flume was mason sand.

Figure 12. Microscope images of (A) 6-9, (B) 8-12, (C) 8-16, (D) 12-20, (E) 16-30, (F) 20-40, (G) 30-50, and (H) 40-70 sands.

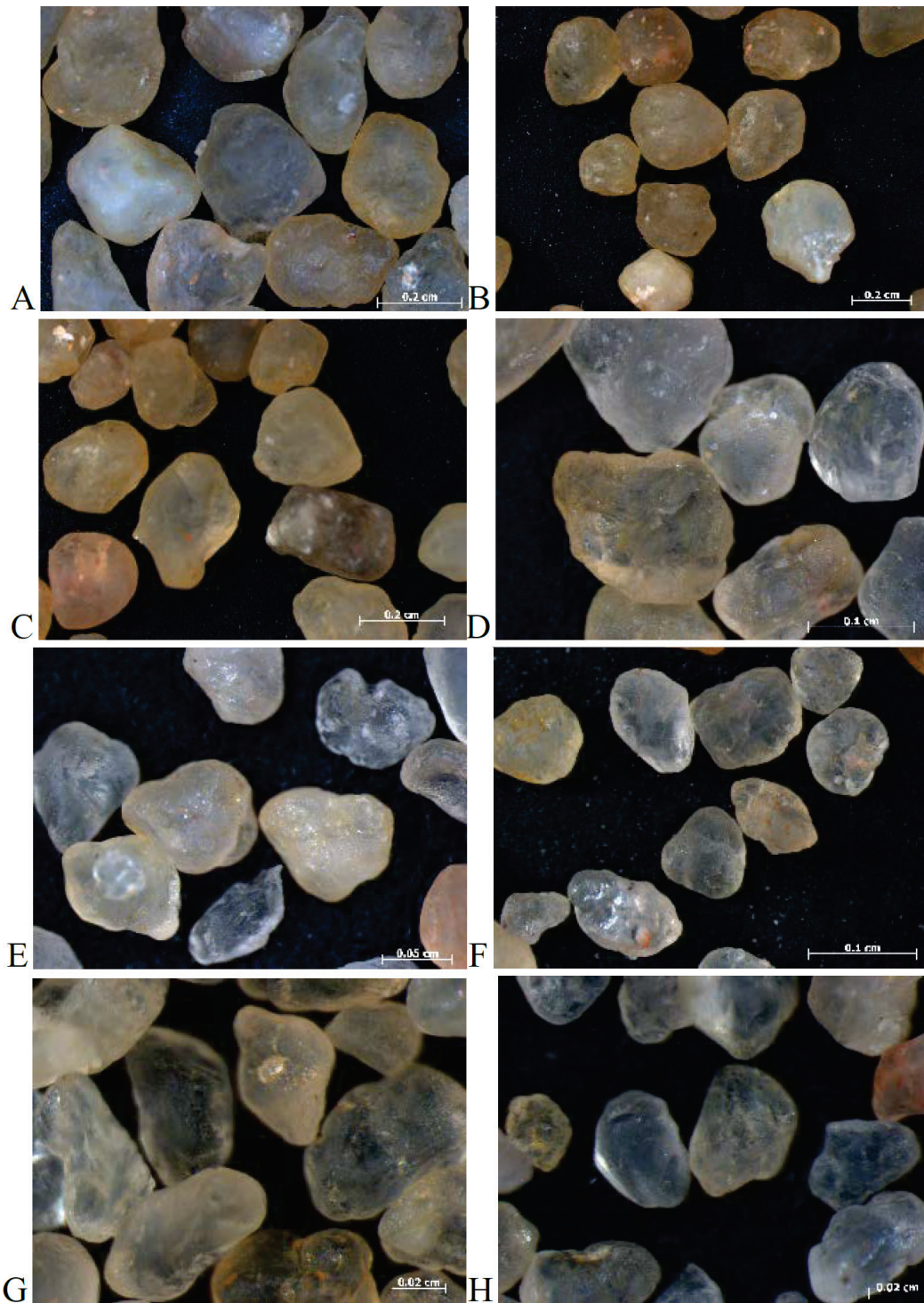


Table 1. Sand properties.

Sand Type	d10 (mm)	d15 (mm)	d30 (mm)	d50 (mm)	d60 (mm)	d70 (mm)	C _u	C _c	γ _{min} (kN/m ³)	γ _{max} (kN/m ³)	R
Mason Sand	0.22	0.24	0.28	0.33	0.36	0.39	1.61	1.00	14.66	17.17	-
40-70	0.23	0.24	0.27	0.30	0.32	0.35	1.42	0.98	14.42	16.69	0.77
30-50	0.32	0.34	0.38	0.43	0.45	0.49	1.42	0.98	14.61	16.96	0.65
20-40	0.47	0.49	0.54	0.61	0.64	0.69	1.39	0.98	14.80	17.11	0.77
16-30	0.64	0.67	0.75	0.85	0.91	0.95	1.41	0.98	14.91	17.14	0.73
12-20	0.89	0.93	1.01	1.13	1.20	1.30	1.34	0.96	14.70	16.82	0.83
8-16	1.27	1.31	1.42	1.57	1.65	1.70	1.30	0.97	14.95	17.19	0.85
8-12	1.59	1.71	1.98	2.29	2.44	2.60	1.54	1.02	15.00	16.90	0.75
6-9	2.02	2.09	2.28	2.52	2.64	2.80	1.31	0.97	14.95	16.81	0.75

The goal with the small flume testing program was to obtain results for at least two tests in a loose state and two tests in a dense state for each of the nine uniform sands. By having two or more tests that were performed with similar densities in both conditions, a comparison was made of how the critical gradient rates varied with density or void ratio. Further, as Eq. 1 considers the pore velocity, it is important to test both dense and loose samples to consider the influence of density on erosion rates.

Before and after every test, measurements were taken to obtain the properties of the sample being tested. The sample properties obtained were dry density, dry unit weight, relative density (using the minimum and maximum unit weights as the reference densities), void ratio, porosity, exit slope angle, and the shortest seepage length. Densities were calculated from the weight of the dry sample and the volume of the sample while it was in the vertical position. The properties of each sample and their corresponding critical gradients and pipe progression rates are presented in the Results chapter.

3.3 Test setup

The steps followed to prepare a sample and initialize the equipment were as follows.

1. All hoses that led into the inflow wall were fully saturated before each test. After ensuring no air was trapped in the hoses, the flume was rotated from its horizontal position to the vertical position with the outlet wall at the top. This wall was removed for sample preparation. Using the constant head tank (or the pump for coarser sands), the flume was filled with approximately 40 cm of water. This amount of water was usually enough for full saturation of the sample. Water could be added or removed later as needed.
2. Air was released from the pressure ports that were submerged by disconnecting the vinyl tubing from the PPT for each sensor (Figure 13). As water flowed out of the flume, air bubbles were pushed out of the vinyl tubing. Once the tubes were saturated, they were reconnected to the PPTs. The lines were saturated one at a time following this procedure until no air bubbles were observed in the system. The upstream manometer was also saturated by using suction.

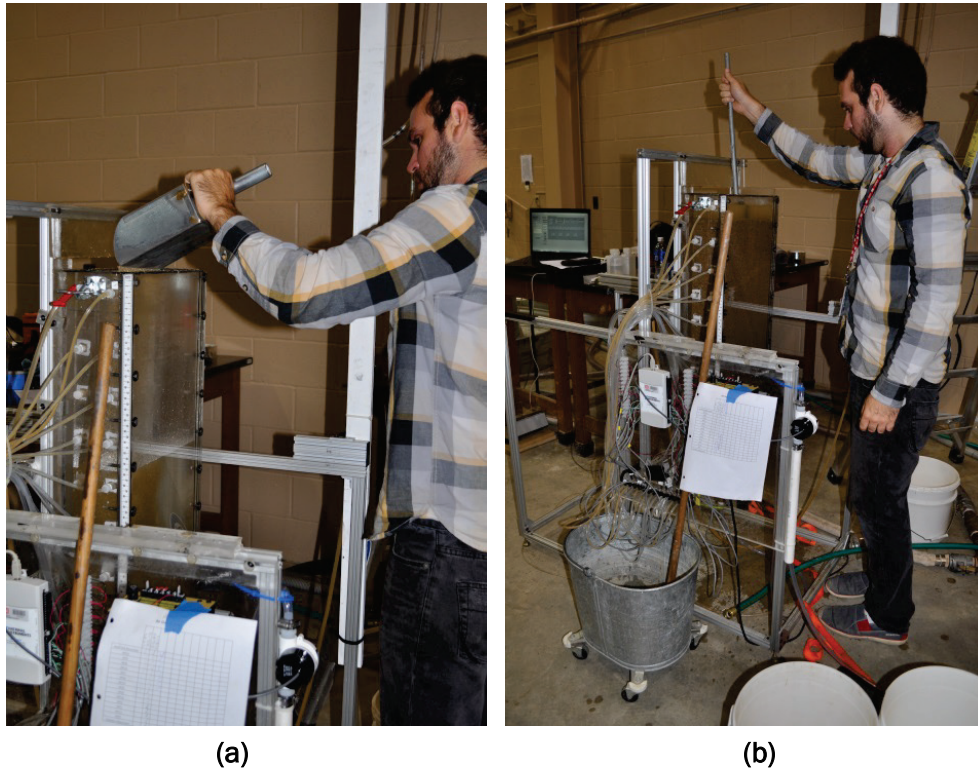
Figure 13. Draining tubes connected to the transducers for saturation.



3. Oven-dried sand was weighed and slowly poured with a scoop into the flume (Figure 14a). Segregation during sample preparation was not an issue as these materials were uniformly graded, washed sands. For loose sample preparation, the soil was poured into the water until a sample height of approximately 69 cm (27.2 in.) was obtained. For dense sample preparation, samples were prepared in

layers of approximately 10 cm (3.94 in.) in height. Each layer was then compacted with a steel rod (Figure 14b). It took seven layers to obtain a dense sample. A screed was used to level the sample after all the sand was placed. The tubes connected to the PPTs that were not initially submerged were saturated upon becoming submerged by the rising water level during sample placement.

Figure 14. (a) Pouring sand into small flume with a scoop. (b) Compacting sample with a rod for maximum density.



4. After finishing the sample preparation and ensuring that all tubes had been saturated, the downstream wall was carefully positioned on top of the soil with its flat part in contact with the bottom of the flume and the v-notch facing the top of the box. Vacuum grease was added to the edge contacts of the flume, and the outlet wall of the flume was cautiously placed on top of the springs of the downstream wall. Using the latches, the flume was closed, thereby compressing the springs that held the end wall in place (Figure 15). The soil sample dimensions were measured to calculate its volume (Figure 16), and the dry unit weight of the sample was determined using the final weight of the sand in the flume.

Figure 15. Small flume in vertical position with sample and tailwater tank.

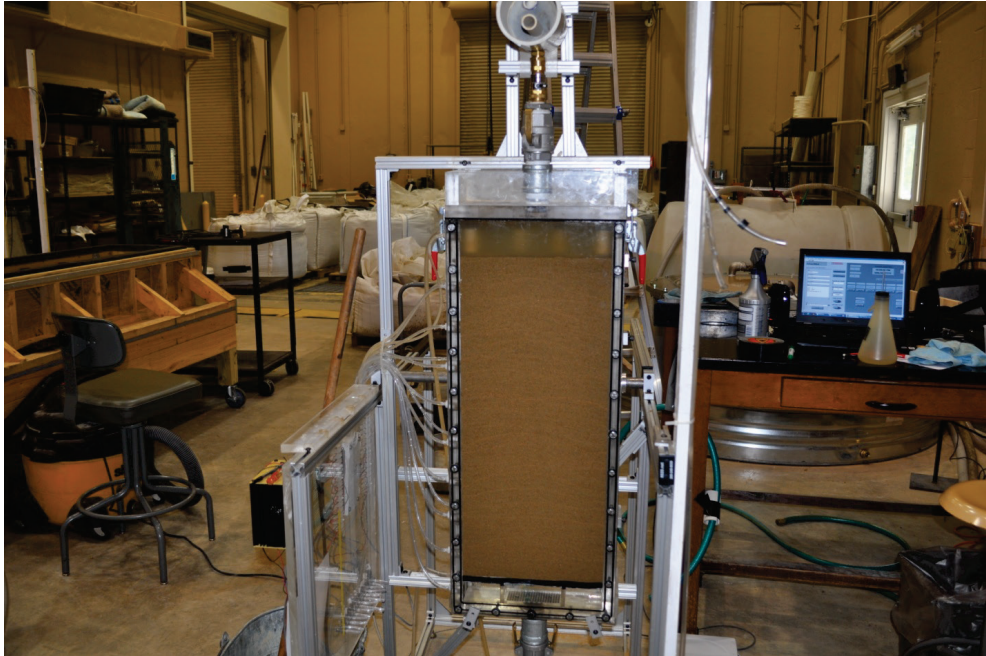


Figure 16. Measuring height of sample for the determination of volume.



5. The water level was raised slowly until the flume was completely full of water. The last tube to be saturated was the downstream manometer. A vacuum was applied to the manometer tube to raise the water level in the manometer and eliminate air that would influence the measured head. The water was let out from the downstream tailwater tank and then all the valves were closed. The entire system at this point was saturated and ready for testing. The flume was then tilted back slowly to the horizontal position. The sample's shortest seepage length was measured on the top of the sample from the upstream wall to the top, center location on the downstream slope (Figure 17).

Figure 17. Measuring the shortest sample length (or seepage length) from the top of the sample with small flume in horizontal position.



3.4 Test procedure

The following steps explain the procedure used to conduct a test from beginning to end.

1. With the inflow valve closed, the valve that connected the flume to the tailwater tank was opened to obtain a constant head throughout the sample. This head was recorded from the manometers at a zero-flow condition, and the pore pressure transducers were zeroed in LabVIEW with reference to this height. The initial conditions were also entered in the LabVIEW interface and logged to file.

2. To begin the test, the upstream valve was slowly opened. The upstream head was raised slowly until the average hydraulic gradient was between 0.05 and 0.10, approximately. This ensured a sufficiently low hydraulic gradient to avoid any particle movement but provided adequate flow to test the data acquisition system. Data logging was initiated if all the instrumentation worked correctly.
3. The upstream head was slowly increased in 0.02-0.10 increments of the average hydraulic gradient using either the pump or constant head tank. The increments depended on grain size and density of the sample being tested. The process of increasing the head was slow and steady to avoid sudden particle movements in the downstream slope. The upstream head was held constant for several minutes with readings at equilibrium to ensure piping would not initiate at each level. The exit slope of the sample was observed for any movement. Rearrangement or sloughing could occur during the test before BEP initiation. The time and description of any movements were recorded.
4. Measurement of flow was obtained by weighing the outflow while using a stopwatch. The collected outflow was weighed in a bucket by using the weighing scale connected to a computer. This bucket had a valve that was closed during flow rate measurements. The valve was opened again to drain the bucket once measurements were obtained. The manual flow rates were compared to the flowmeter readings displayed on the monitor.
5. After all readings were taken, the head was slowly increased up to the next target gradient. Measurements were taken again after a stabilized gradient and flow rate had been reached.
6. When BEP initiated on the downstream slope, the time and heads of the manometers were recorded. The position of the pipe tip and time were marked on the acrylic top as erosion progressed to the upstream end to obtain the pipe progression rate. The flow was stopped once the pipe reached the upstream wall. At this point, the test had finished. The final data were recorded, and the end of the test was documented by taking photos of the sample and its pipe.
7. The flume was then tilted to the vertical position with the inlet wall at the bottom, water was drained, and the outlet wall was taken off. The downstream wall was removed from the flume and washed. The flume was rotated again but with the inlet wall at the top so sand could be poured into a pan. The sand was placed in an oven to dry overnight.

4 Results

4.1 Summary of test results

The results of 55 tests are presented in this chapter. Figures 18 and 19 show typical data obtained from a single test. Figure 18a shows the heads of each pore pressure transducer with time during a test. The average gradients, i_{avg} , were calculated after finishing the tests by analyzing the PPT data. These gradients were obtained from a least-squares linear fit of the heads measured by the pore pressure transducers versus their location along the sample. Figure 18b shows the time record of the calculated average gradients and associated flow rate. It can be seen in Figures 18a and 18b that BEP initiation is clearly distinguished by the moment when the pressures and gradient drop as the pipe begins to progress. The maximum hydraulic gradient achieved at the moment of initiation of BEP is recorded as the critical gradient, i_c . Figure 19 is an example of the slope of heads versus distance for a 40-70 sand sample at the moment of initiation of BEP. Only the heads for PPTs located in the sample were used for the calculation of the slope to avoid issues with head loss occurring through the filter fabric wrapped walls. For example, the upstream transducer and the downstream transducers were not included in any of the calculations. The critical gradient and flow rate during initiation of BEP were used to calculate the hydraulic conductivity, seepage velocity, intrinsic permeability, and pore velocity.

Figure 18. (a) Pore pressure measurements with time for test 40-70-4. (b) Average gradient and flow rate with time for test 40-70-4.

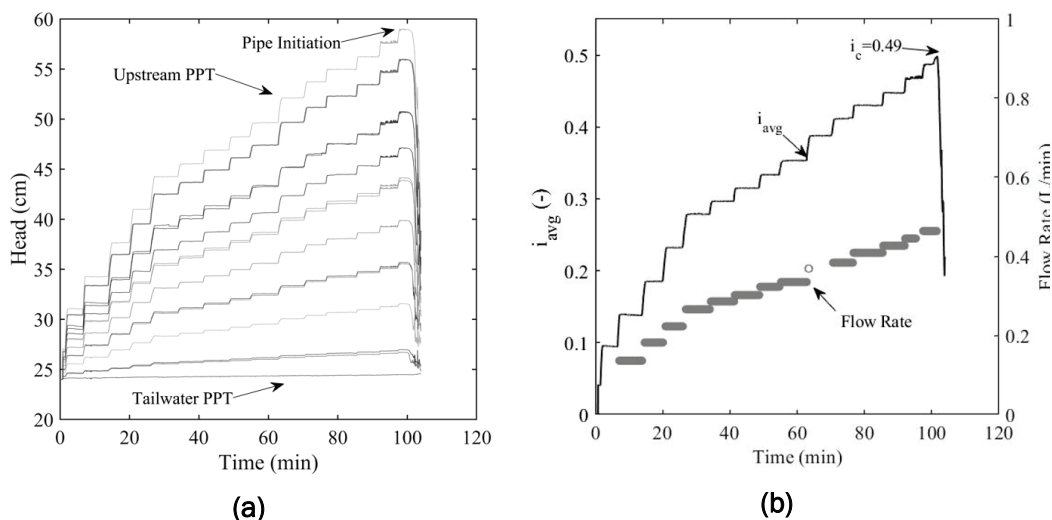
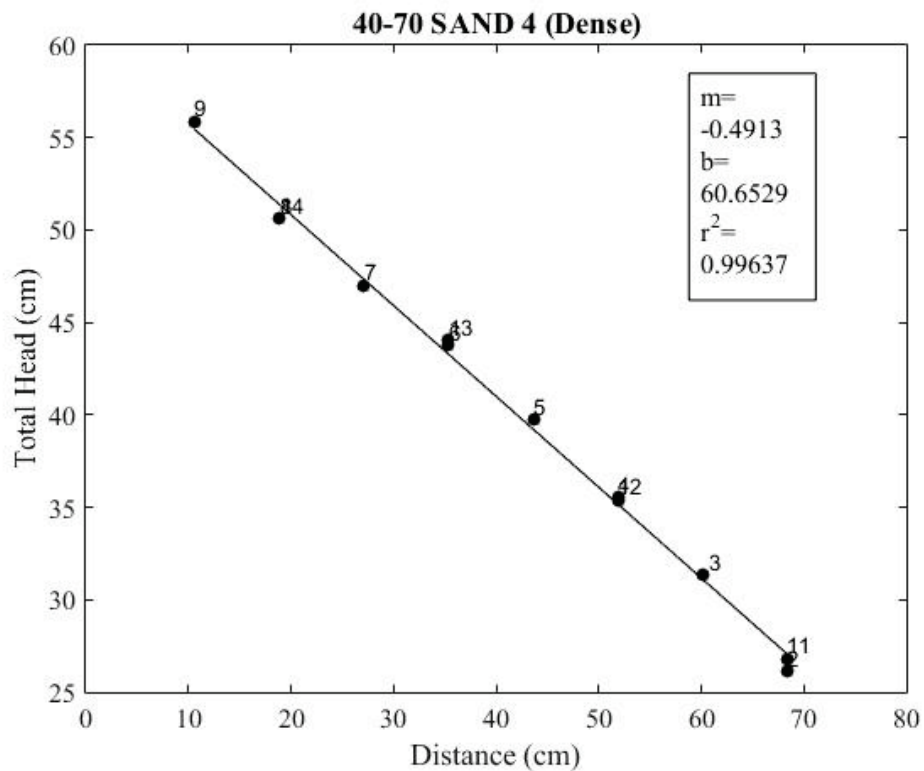


Figure 19. Calculation of slope for the determination of the critical gradient in test 40-70-4.

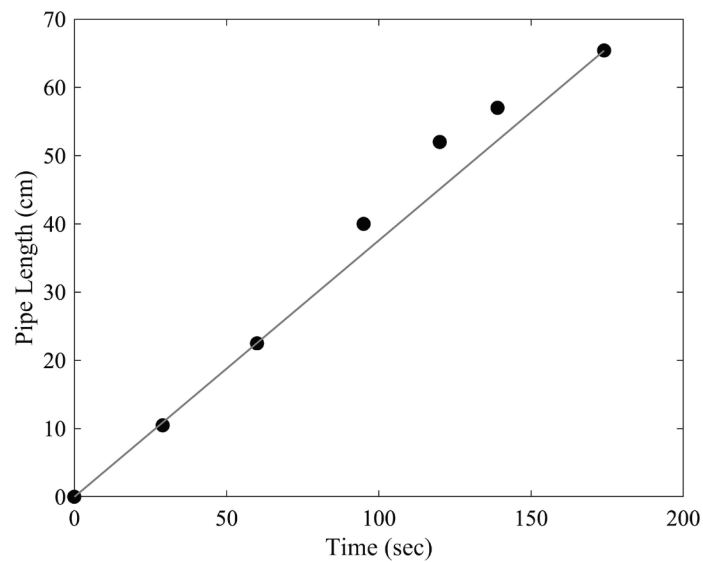


Pipe position with time was marked on the acrylic top as the pipe progressed upstream through the sample. The photograph in Figure 20 shows an example of the pipe path with time for a test. For the smallest sands, the pipe could split into two or more pipes as the meandering pipe progressed. Only the positions of the farthest pipe tip from the downstream slope were marked. For tests where the pipe progressed quickly (coarse sands), the pipe position and time were obtained from videos of the tests. The average pipe progression rate (\bar{x}) for each test was calculated using only the first and last points of pipe position versus time as seen in Figure 21.

Figure 20. Final pipe path with pipe positions marked for Test 40-70-4.



Figure 21. Pipe position with time in Test 40-70-4 with the pipe progression rate calculated from the slope between the first and last observations.



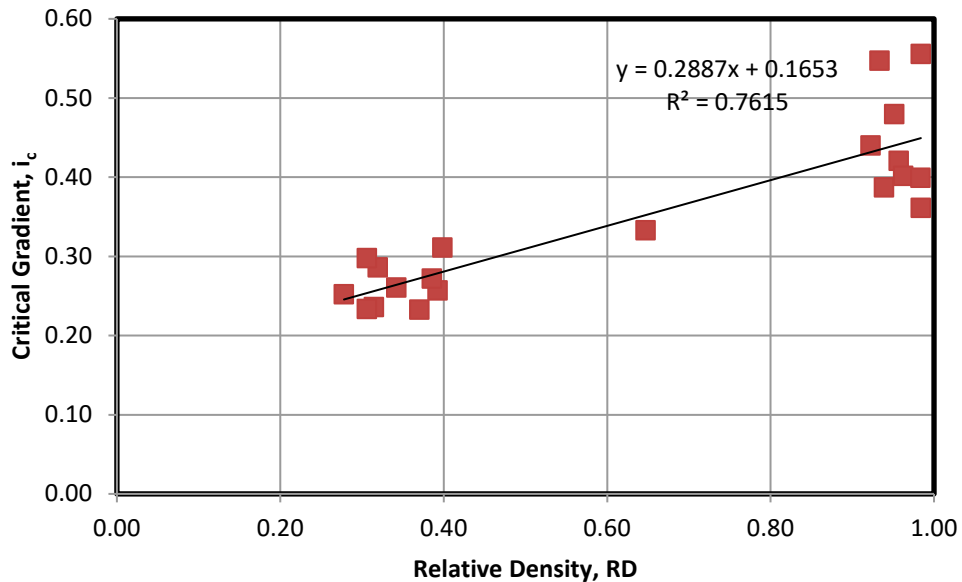
The testing program started with mason sand. This sand had the largest coefficient of uniformity (1.61) of all the sands tested. There were several reasons why there are more test results for this sand than for any other sand. The primary reason was that mason sand was able to be procured in large quantities from a local supplier. As such, mason sand was used to develop the testing procedure, making necessary changes to the setup as needed, and confirm repeatability. This allowed adjustments to be

made to the test procedures before moving on to the other sands for which limited quantities were available. Figure 22 shows the results of the BEP tests for mason sand. Table 2 contains the information for each test, i.e., test number, critical hydraulic gradient (horizontal) at initiation of BEP (i_c), relative density (RD), dry unit weight (γ_d), void ratio (e), hydraulic conductivity (k), shortest sample length (L), the calculated downstream slope angle (θ), and pipe progression rate (\dot{x}). The results show a general trend of higher critical gradient required for initiation of BEP at higher densities. It is worth noting that there is more variability in the results of the dense samples than the loose samples.

Table 2. Experimental results for mason sand tests.

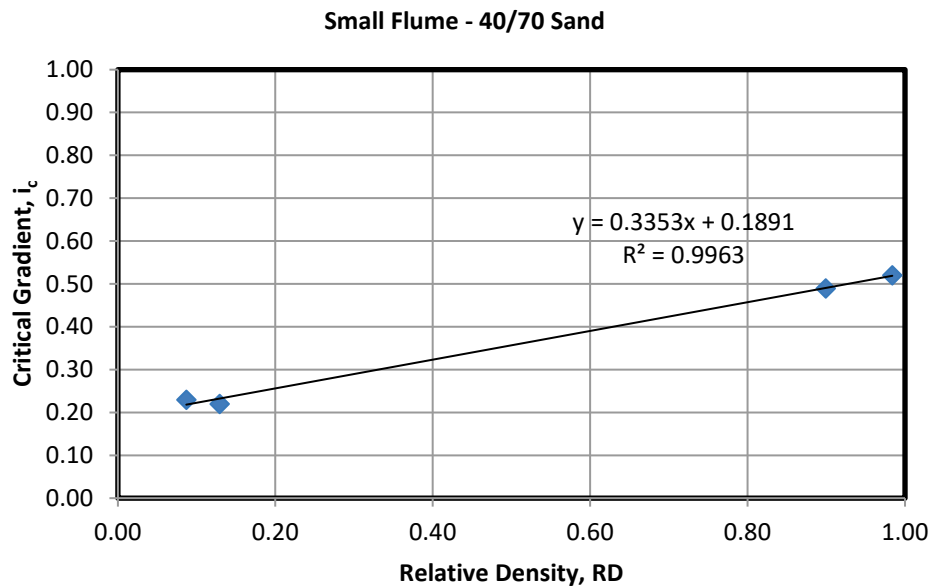
Sand Type	Test Number	i_c	RD (%)	γ_d (kN/m ³)	e	k (cm/s)	L (m)	θ	\dot{x} (cm/s)
Mason sand	4-1	0.55	93	16.98	0.53	3.82E-02	0.664	39.2	-
	5-1	0.39	94	16.99	0.53	4.16E-02	0.653	39.8	0.19
	7-1	0.56	98	17.12	0.52	3.50E-02	0.662	39.2	0.55
	8-1	0.33	65	16.19	0.60	6.67E-02	0.655	35.0	0.11
	9-1	0.29	32	15.38	0.69	8.45E-02	0.650	29.7	0.08
	10-1	0.26	39	15.55	0.67	7.99E-02	0.657	36.3	0.07
	12-1	0.27	39	15.54	0.67	8.79E-02	0.642	32.0	0.11
	13-1	0.30	31	15.35	0.69	8.68E-02	0.642	33.4	0.23
	17	0.25	28	15.28	0.70	8.67E-02	0.642	32.9	0.12
	18	0.24	31	15.37	0.69	8.60E-02	0.643	34.0	0.08
	19	0.23	37	15.50	0.68	8.21E-02	0.645	35.5	0.06
	23	0.26	34	15.43	0.68	8.16E-02	0.646	35.5	0.10
	25	0.23	31	15.35	0.69	8.75E-02	0.651	38.5	0.16
	28	0.31	40	15.57	0.67	7.67E-02	0.645	35.0	0.14
	29	0.44	92	16.95	0.53	4.17E-02	0.656	36.7	0.25
	30	0.42	96	17.04	0.52	4.23E-02	0.656	39.8	0.17
	31	0.48	95	17.03	0.53	3.80E-02	0.655	38.5	0.42
	32	0.40	96	17.06	0.52	4.15E-02	0.653	39.1	0.11
33	0.36	98	17.12	0.52	4.00E-02	0.652	39.1	0.15	
34	0.40	98	17.12	0.52	3.67E-02	0.656	41.9	0.22	

Figure 22. Measured critical gradient results for mason sand.



As mentioned before, at least four tests were performed to obtain a trend line, i.e., two with low density and two with high density. As an example, Figure 23 shows the results of the four tests conducted with the 40-70 sand. The plot shows the critical gradient i_c at initiation versus the RD of the sample. The initiation of BEP in two samples that were prepared with low density occurred at i_c of 0.22 and 0.23. The two dense samples had i_c of 0.49 and 0.52.

Figure 23. Results of all the 40-70 sand tests in the small flume.



In general, two trends were found as tests were progressing, i.e., critical gradient required for initiation of BEP piping increased as both particle size and density increased. These two trends matched the results previously described by many (Schmertmann 2000; de Wit et al. 1981; van Beek et al. 2011). The testing program continued with the 40-70 sand after the mason sand tests were finished, and the size of the sands was increased until finishing with the 6-9 sand. Adjustments to the small flume had to be made, in terms of tubing, water supply, and data acquisition, as the sand size was increased due to the increased flow rates given the higher permeabilities of the coarser sands.

Figure 24 shows the results for all the sands, mason sand included, of all the i_c versus RD. A similar plot, Figure 25, shows the i_c versus the dry unit weight in kN/m^3 . As can be seen in Figures 24 and 25, mason sand, 40-70, and 30-50 had the lowest critical gradients for BEP initiation while 8-16, 8-12, and 6-9 had the highest gradients. Table 3 summarizes the results for the rest of the sands tested in the small flume. The i_c and the k of the samples correspond to the values at the moment when piping was initiated. A summary sheet for each test can be found in Appendix B. Each summary contains a total head contour, a plot of flow rate versus gradient, photographs of the test before and after piping, initial conditions of the sample, and properties after piping.

Figure 24. Critical gradient (i_c) versus relative density (RD) for uniform sands.

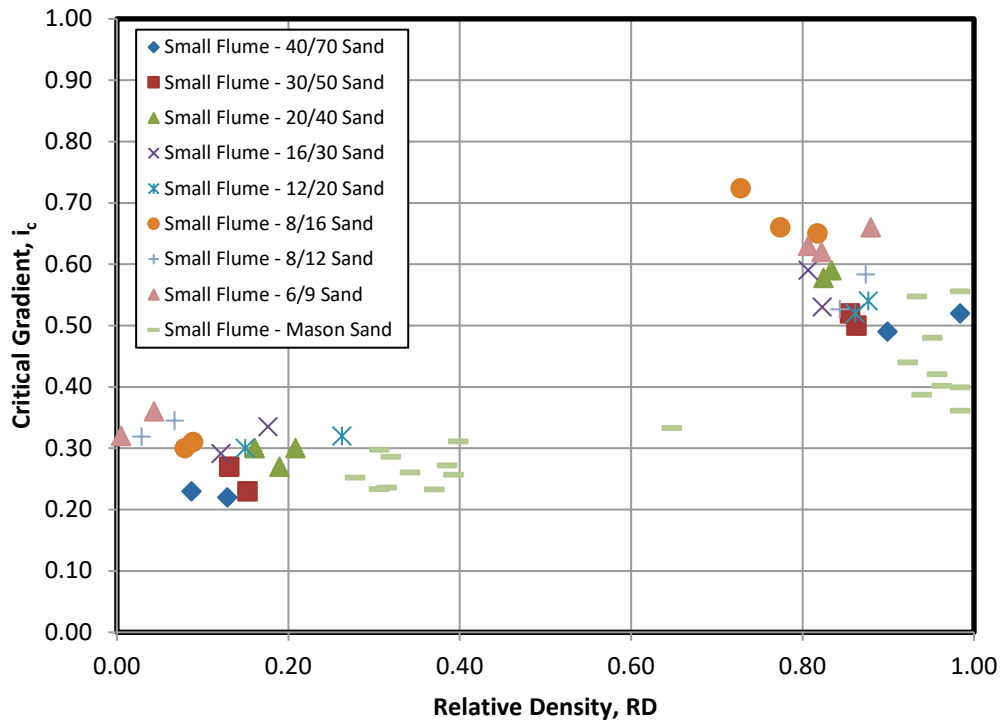


Figure 25. Critical gradient (i_c) versus dry unit weight for uniform sands.

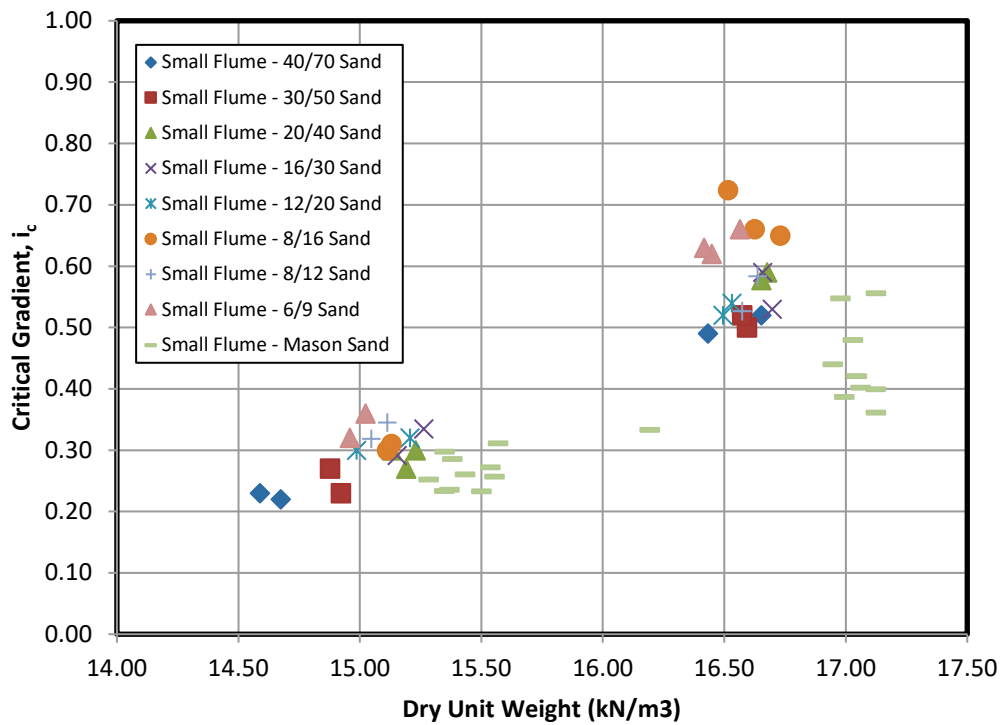


Table 3. Test results for uniform sands.

Sand Type	Test Number	i_c	RD (%)	γ_d (kN/m ³)	e	k (m/s)	L (m)	θ	\dot{x} (cm/s)
40-70	1	0.23	9	14.59	0.78	0.115	0.645	36.7	0.11
	2	0.22	13	14.67	0.77	0.122	0.645	41.2	0.15
	3	0.52	98	16.65	0.56	5.13E-02	0.649	38.5	0.69
	4	0.49	90	16.43	0.58	5.26E-02	0.654	39.8	0.38
30-50	1	0.23	15	14.92	0.74	0.232	0.650	40.1	0.21
	2	0.27	13	14.88	0.75	0.220	0.647	38.5	0.27
	3	0.50	86	16.59	0.57	0.103	0.656	39.1	0.47
	4	0.52	86	16.57	0.57	0.100	0.657	40.5	0.41
20-40	1	0.30	21	15.23	0.71	0.451	0.646	37.6	0.43
	2	0.27	19	15.19	0.71	0.419	0.650	39.8	0.40
	3	0.30	16	15.13	0.72	0.448	0.653	40.5	0.54
	5	0.59	83	16.67	0.56	0.211	0.656	38.5	1.07
	6	0.58	82	16.65	0.56	0.215	0.663	41.9	1.30
16-30	1	0.34	18	15.26	0.70	0.614	0.652	41.2	0.62
	2	0.29	12	15.15	0.71	0.690	0.649	38.5	0.53
	3	0.53	82	16.70	0.56	0.336	0.658	39.8	1.65
	4	0.59	81	16.66	0.56	0.313	0.660	36.7	1.16
12-20	1	0.32	26	15.21	0.71	1.111	0.649	41.2	0.84
	2	0.30	15	14.99	0.73	1.28	0.649	41.2	1.07
	3	0.52	86	16.49	0.57	0.557	0.660	40.5	1.61
	4	0.54	88	16.53	0.57	0.593	0.662	44.2	1.16
8-16	2	0.66	77	16.62	0.56	1.34	0.664	44.1	3.91
	3	0.30	8	15.11	0.72	2.77	0.664	52.4	1.79
	5	0.31	9	15.13	0.72	2.60	0.658	41.2	1.03
	6	0.65	82	16.73	0.55	1.31	0.662	44.2	4.41
	7	0.72	73	16.51	0.57	1.32	0.668	44.2	5.00
8-12	4	0.53	84	16.57	0.57	2.21	0.660	42.6	2.00
	5	0.58	87	16.64	0.56	2.03	0.658	41.2	1.99
	6	0.35	7	15.11	0.72	3.57	0.660	47.6	1.05
	7	0.32	3	15.05	0.73	3.87	0.659	47.6	1.35
6-9	4	0.36	4	15.02	0.73	3.99	0.658	44.2	1.57
	5	0.62	82	16.45	0.58	2.30	0.662	45.0	4.73
	7	0.63	81	16.42	0.58	2.31	0.662	44.2	3.15
	9	0.66	88	16.56	0.57	2.18	0.668	54.5	4.18
	10	0.32	0.5	14.96	0.74	4.05	0.657	43.4	-

4.2 Evaluation of pipe progression rates

Evaluating the predictive performance of Eq. 1 and Eq. 2 is a primary objective of the present study. The equations were calibrated to the data sets previously described. The present data set provides an opportunity for a completely independent evaluation of the predictive performance using the regression values found in Pol et al. (2019). All information required for application of the equations is found in Tables 2 and 3. A comparison of the calculated erosion rates to the observed erosion rates for Eq. 1 and Eq. 2 is given in Figures 26 and 27, respectively. As can be seen by the figures, both equations provide a reasonable prediction of the pipe progression rate across the range of conditions assessed. Eq. 1 tends to slightly underpredict velocities for small rates and overpredicts velocities for large rates. Meanwhile, Eq. 2 consistently underpredicts the observed erosion rates. However, both equations seem to provide adequate estimates of erosion rates for use in assessing BEP failure probabilities for uniform sands. It should be noted that for this application, overprediction of the erosion rate is conservative.

Figure 26. Comparison of observed pipe progression rates to predicted rates using Equation 1.

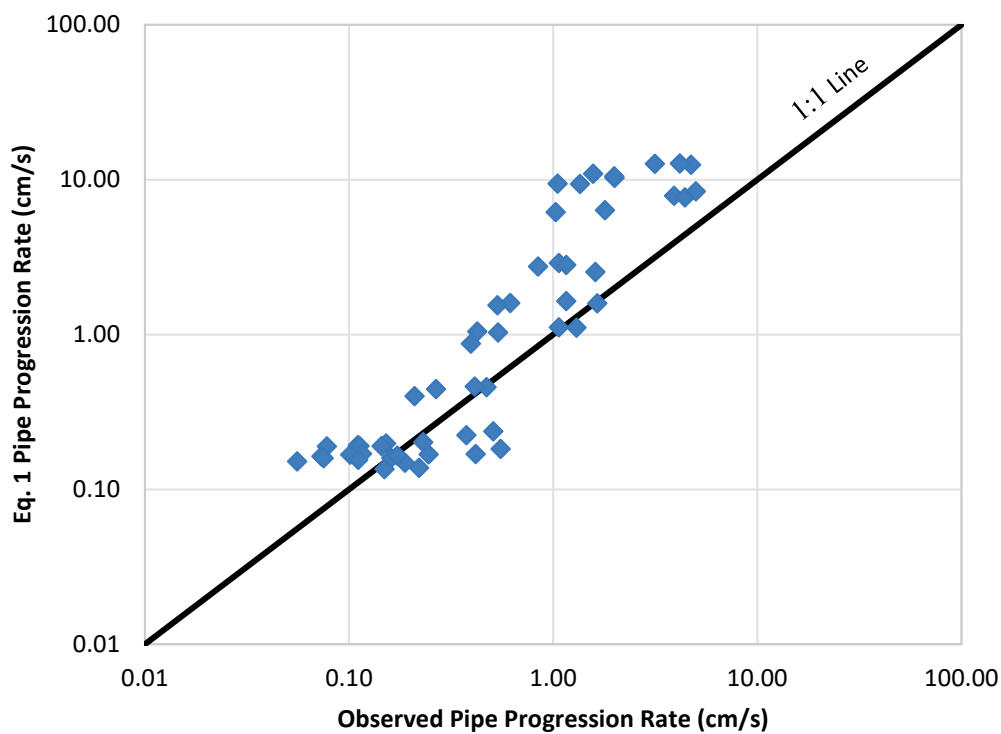
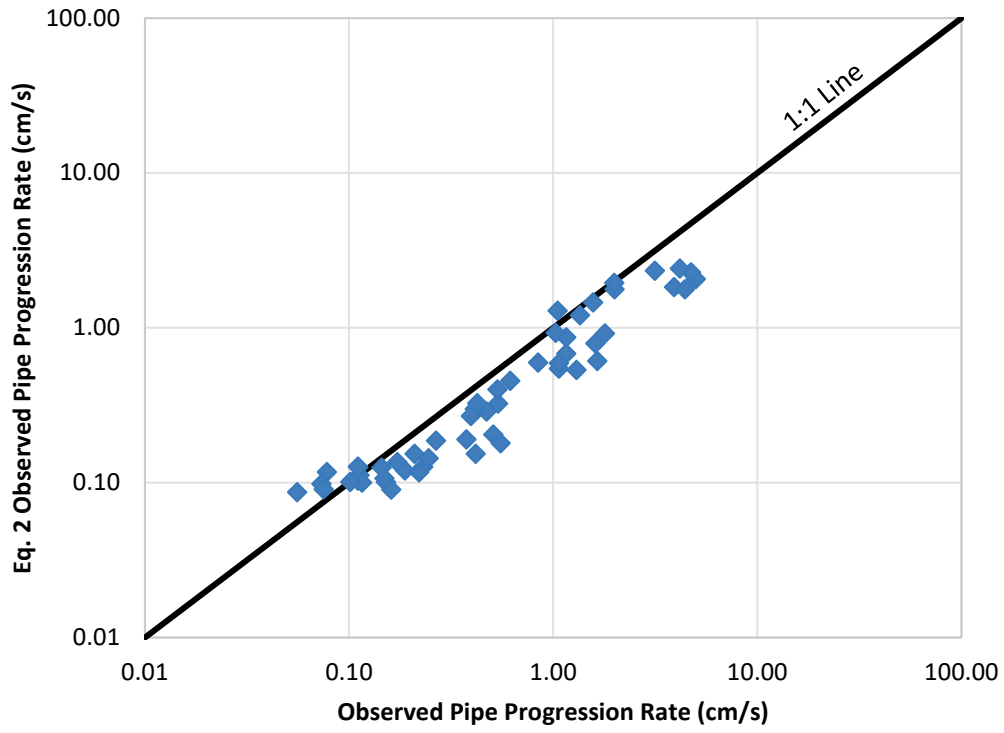


Figure 27. Comparison of observed pipe progression rates to predicted rates using Equation 2.



5 Conclusions

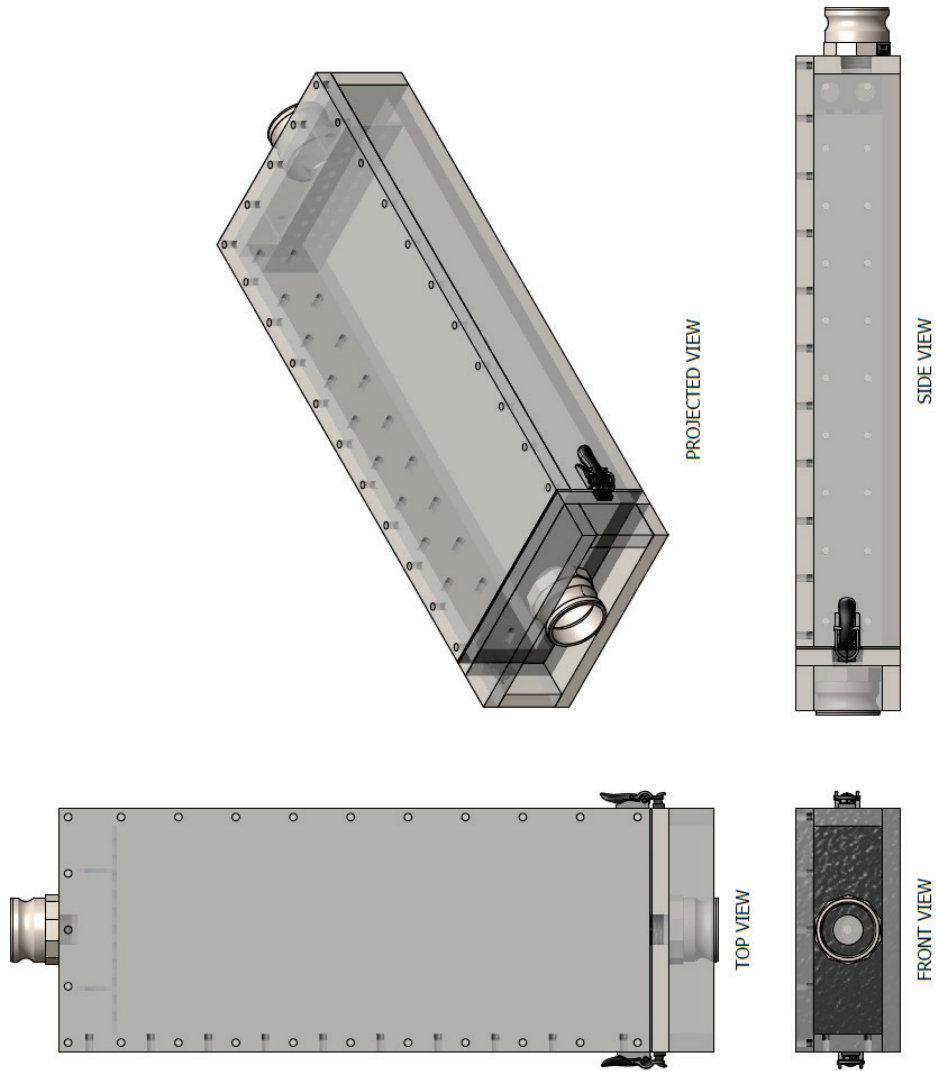
Small-scale laboratory flume tests were conducted on nine uniform sands to investigate both the critical average gradient for initiation of piping and the pipe progression rate. The i_{avg} across the samples at initiation of piping increased with increasing grain size and density, exhibiting trends consistent with the results of previous test programs documented in the literature. Further analyses of the initiation conditions were not undertaken due to the impractical nature of computing gradients over small distances (<10 grains) as noted by Montalvo-Bartolomei et al. (2018). The measured pipe progression rates from this study confirm that BEP pipes progress at rates proportional to the seepage velocity. The measured pipe progression rates were compared to rates predicted using equations proposed by Kézdi (1979) and Pol et al. (2019). The results confirm that the predictive equations yield reasonable pipe progression rates in uniformly graded sands over a broad range of grain sizes. These findings are significant because the model equations in the literature were calibrated to an independent data set. Further research is needed to evaluate the predictive equations for pipe progression rate for larger scales, more broadly graded soils, and differing sample geometries.

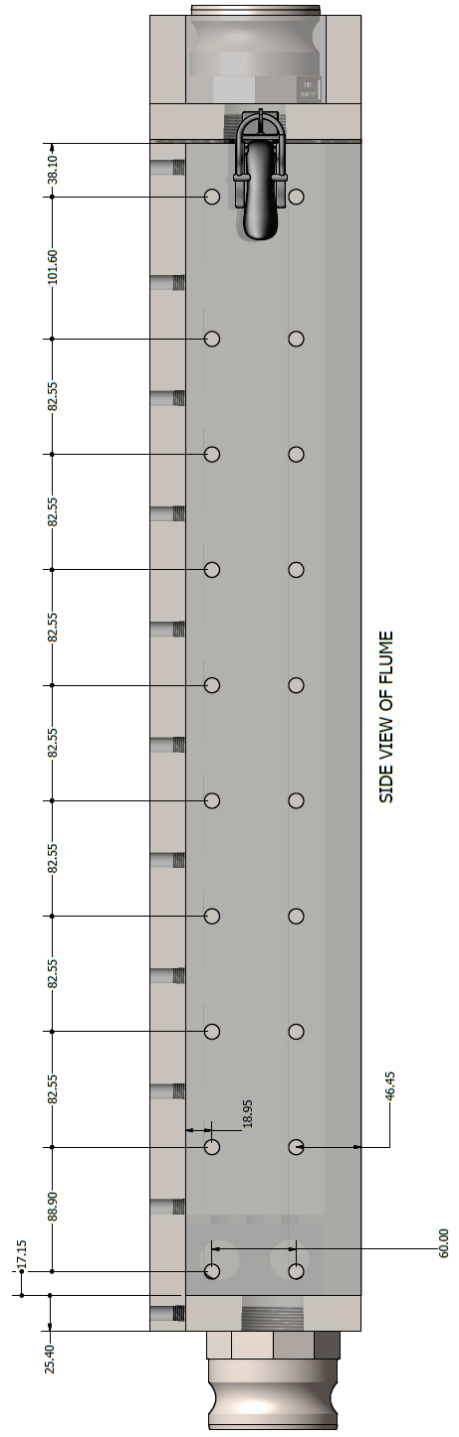
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Appendix A - Small Flume Sketches





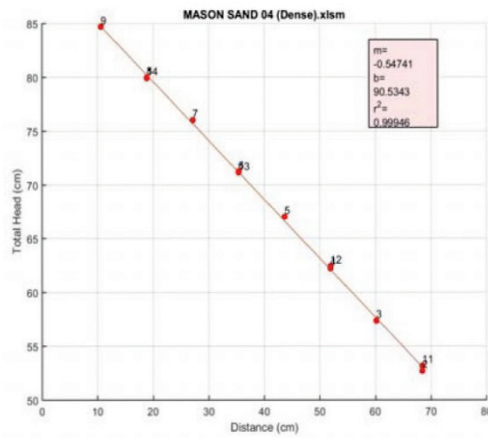
Appendix B - Test Sheets

Sand Type	<u>Mason Sand</u>	Date	<u>22-May-14</u>
Test Number	<u>4-1</u>	Start Time	<u>15:14:14</u>
Tested by	<u>A.M.,H.S.,A.B.</u>	End Time	<u>16:23:24</u>

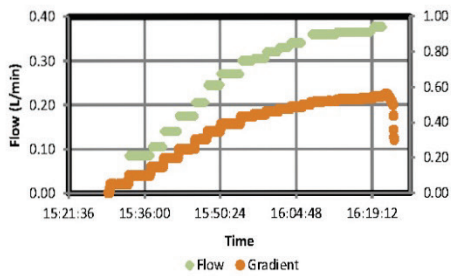
Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	36.27 kg	Time at Piping	16:21:10
Soil Volume	0.02091 m ³	Least-Squares Fit Gradient	0.55
Dry Unit Weight	17.02 kN/m ³		
Relative Density	93 %	Pipe Progression Rate	- cm/s
Sample Length	66.4 cm	Flow Rate	0.376 L/min
Measured Slope Angle	32.5 °	Darcy Average Velocity	2.09E-04 m/s
		Sample Permeability	3.82E-04 m/s

Notes: Measurements of pipe position not taken

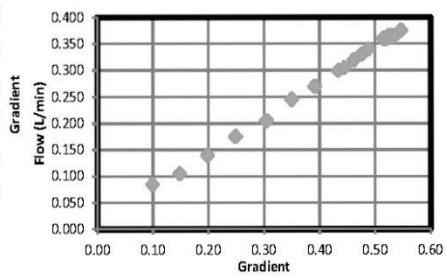
Heads at Initiation of Piping



Flow and Gradient with Time



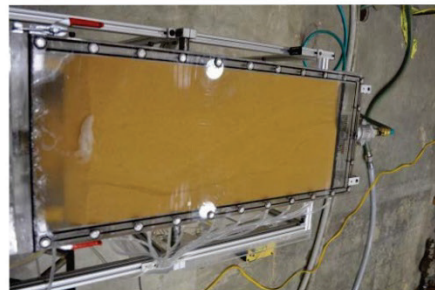
Flow Versus Gradient



Before Piping



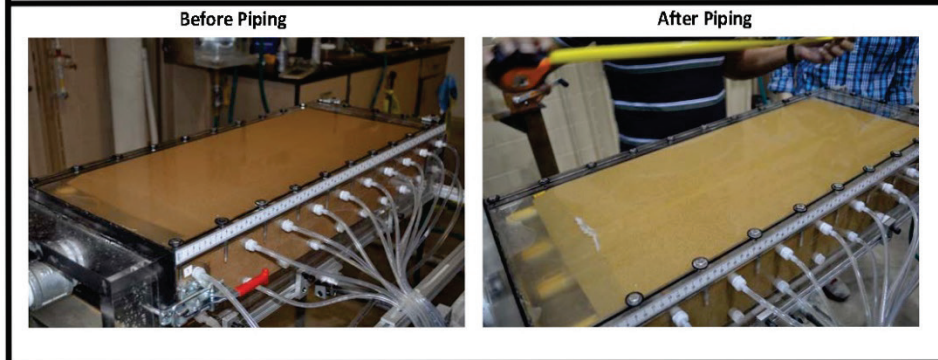
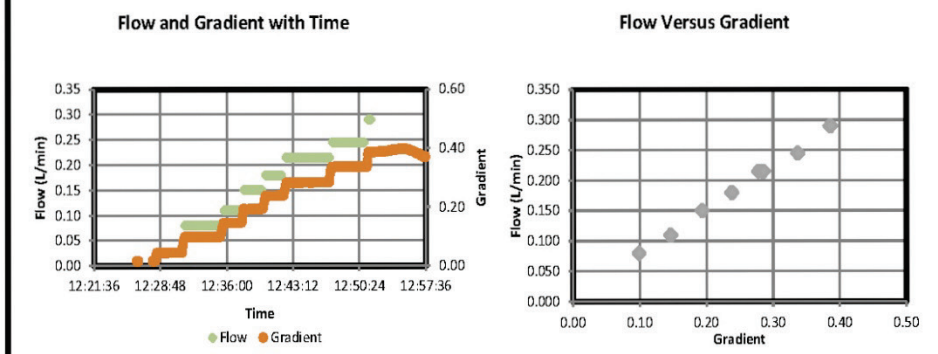
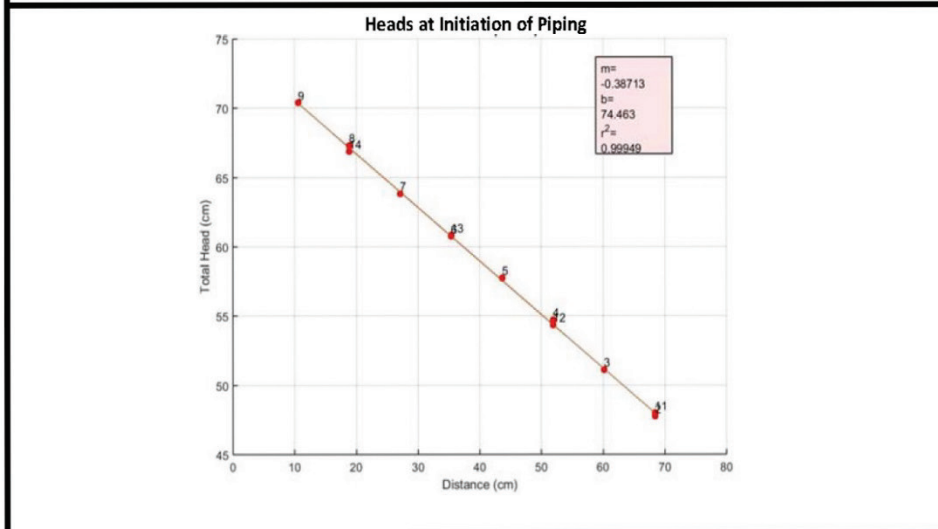
After Piping



Sand Type	<u>Mason Sand</u>	Date	<u>23-May-14</u>
Test Number	<u>5-1</u>	Start Time	<u>12:26:14</u>
Tested by	<u>A.M.,H.S.,A.B.,J.L.</u>	End Time	<u>12:59:03</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.68 kg	Time at Piping	12:51:37
Soil Volume	0.02055 m ³	Least-Squares Fit Gradient	0.39
Dry Unit Weight	17.03 kN/m ³		
Relative Density	94 %	Pipe Progression Rate	0.19 cm/s
Sample Length	65.3 cm	Flow Rate	0.29 L/min
Measured Slope Angle	32.5 °	Darcy Average Velocity	1.61E-04 m/s
		Sample Permeability	4.16E-04 m/s

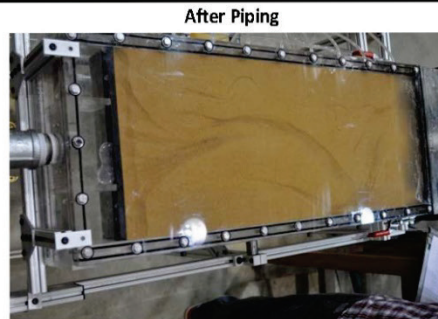
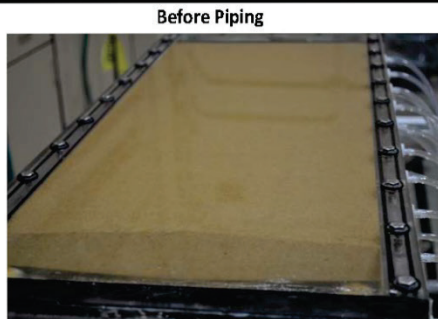
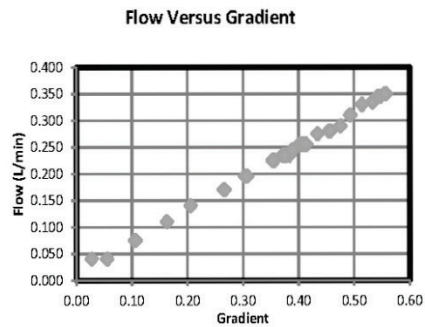
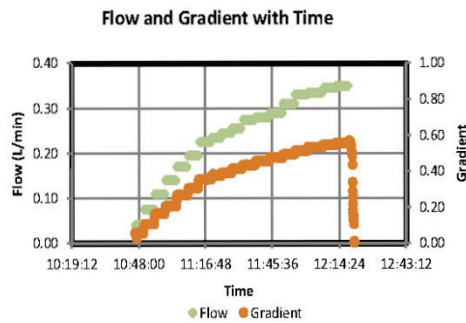
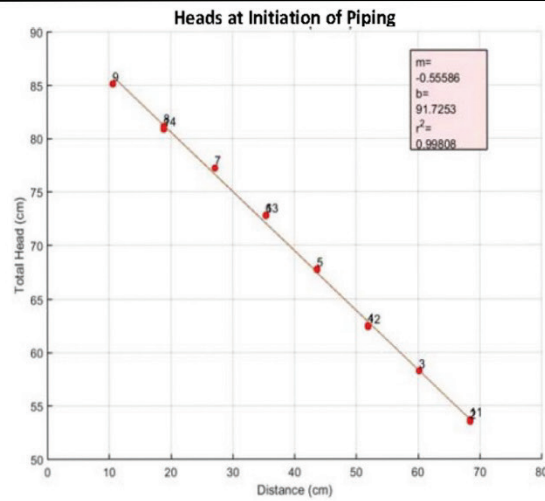
Notes:



Sand Type Mason Sand Date 27-May-14
 Test Number 7-1 Start Time 10:32:47
 Tested by A.M.,H.S.,J.L. End Time 12:21:01

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	36.50 kg	Time at Piping	12:18:05
Soil Volume	0.02085 m ³	Least-Squares Fit Gradient	0.56
Dry Unit Weight	17.17 kN/m ³		
Relative Density	98 %	Pipe Progression Rate	0.55 cm/s
Sample Length	66.2 cm	Flow Rate	0.35 L/min
Measured Slope Angle	35.5 °	Darcy Average Velocity	1.94E-04 m/s
		Sample Permeability	3.50E-04 m/s

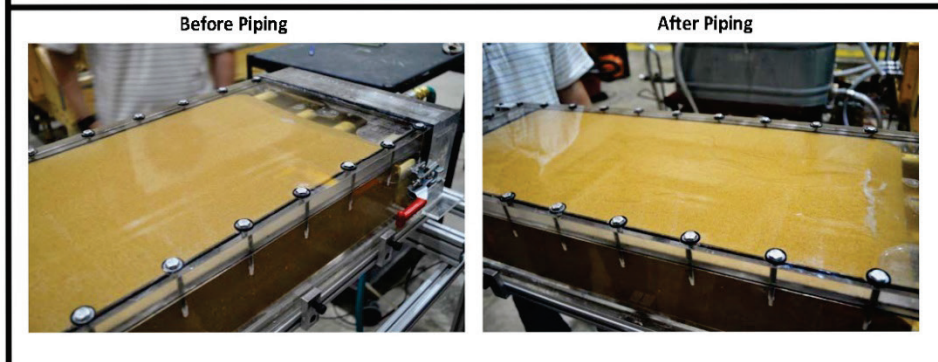
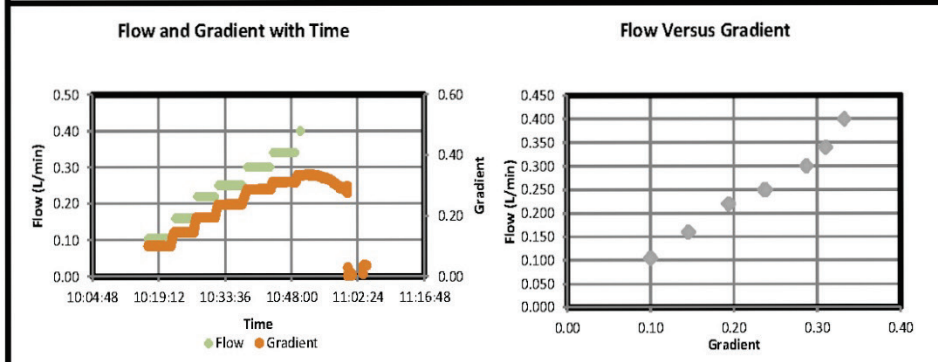
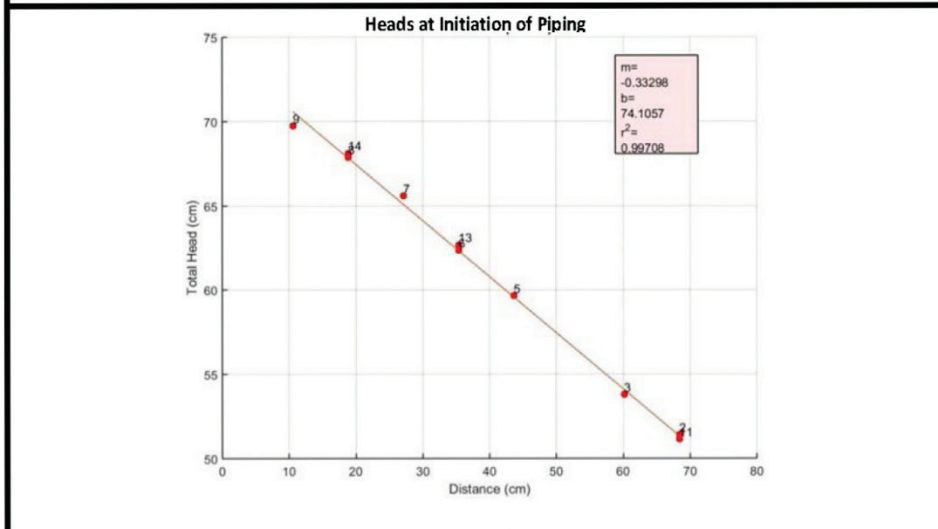
Notes: Measurements of pipe position not taken



Sand Type	<u>Mason Sand</u>	Date	<u>29-May-14</u>
Test Number	<u>8-1</u>	Start Time	<u>10:16:55</u>
Tested by	<u>A.M.,A.B.</u>	End Time	<u>11:04:18</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.50 kg	Time at Piping	10:50:00
Soil Volume	0.02085 m ³	Least-Squares Fit Gradient	0.33
Dry Unit Weight	16.23 kN/m ³		
Relative Density	65 %	Pipe Progression Rate	0.11 cm/s
Sample Length	65.5 cm	Flow Rate	0.400 L/min
Measured Slope Angle	32.0 °	Darcy Average Velocity	2.22E-04 m/s
		Sample Permeability	6.67E-04 m/s

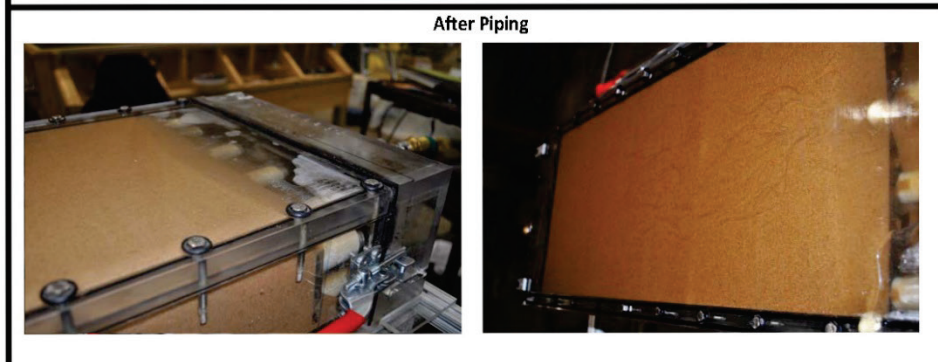
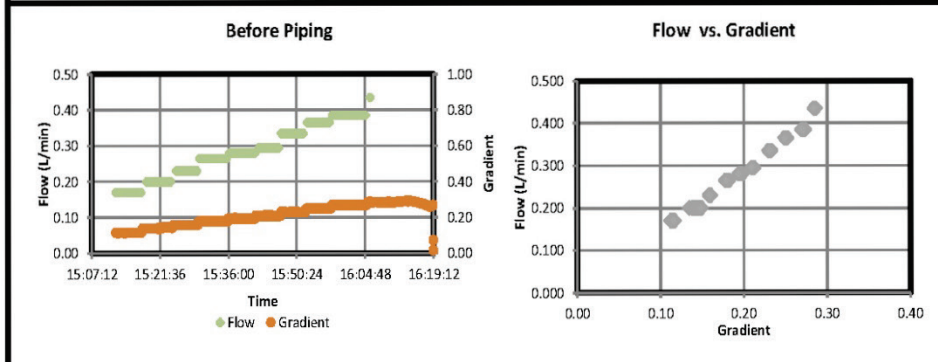
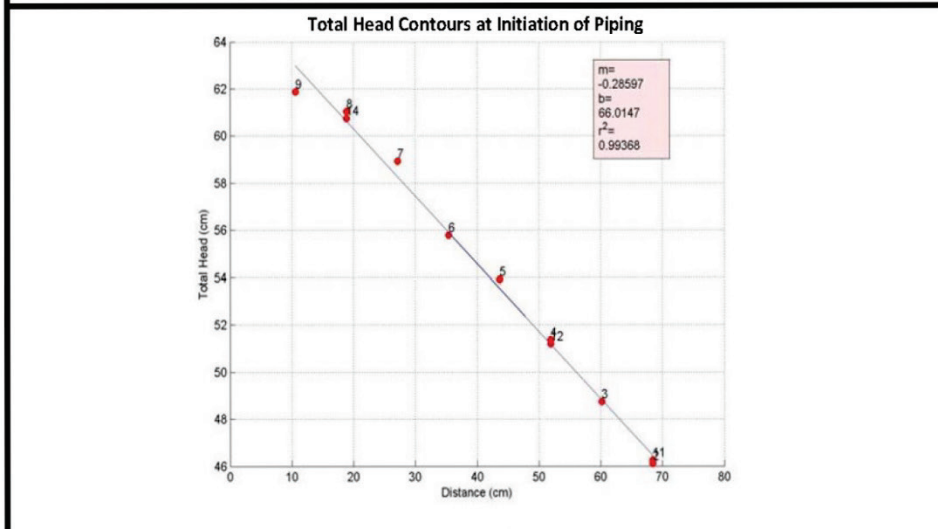
Notes:



Sand Type Mason Sand Date 2-Jun-14
 Test Number 9-1 Start Time 15:12:12
 Tested by A.M.,H.S. End Time 16:19:57

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	33.05 kg	Time at Piping	16:05:50
Soil Volume	0.02104 m ³	Least-Squares Fit Gradient	0.29
Dry Unit Weight	15.41 kN/m ³		
Relative Density	32 %	Pipe Progression Rate	0.08 cm/s
Sample Length	65.0 cm	Flow Rate	0.435 L/min
Measured Slope Angle	30.0 °	Darcy Average Velocity	2.42E-04 m/s
		Sample Permeability	8.45E-04 m/s

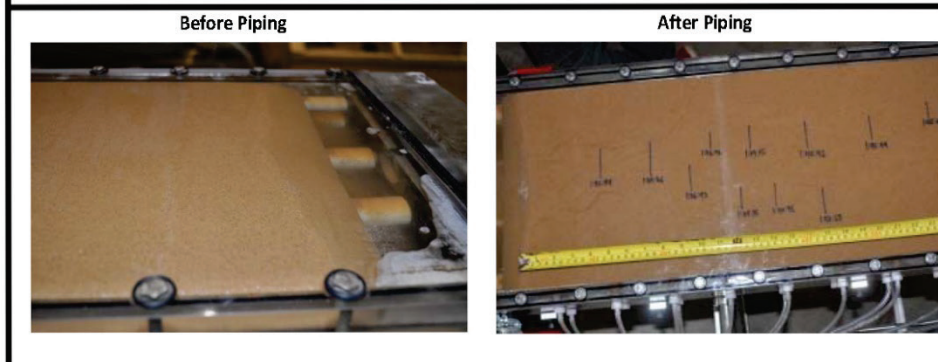
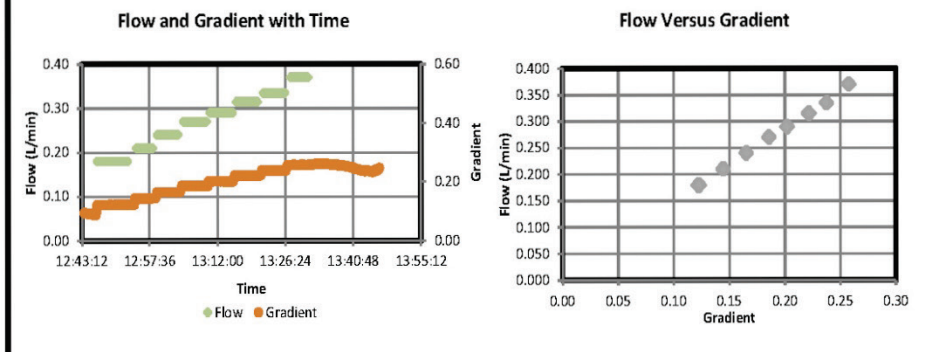
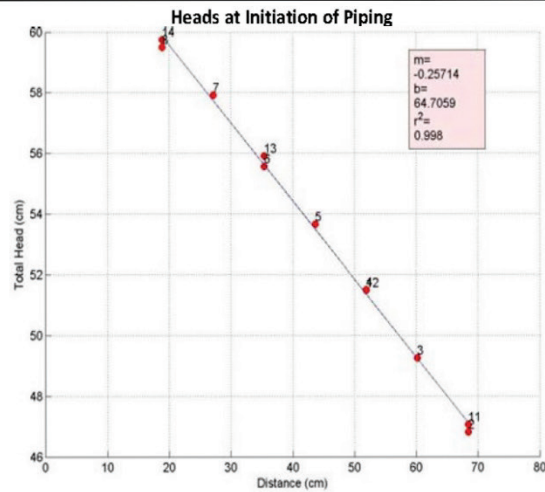
Notes: PPT13 not working properly



Sand Type	<u>Mason Sand</u>	Date	<u>3-Jun-14</u>
Test Number	<u>10-1</u>	Start Time	<u>12:43:43</u>
Tested by	<u>A.M.,H.S.</u>	End Time	<u>13:46:24</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	33.14 kg	Time at Piping	13:31:11
Soil Volume	0.02084 m ³	Least-Squares Fit Gradient	0.26
Dry Unit Weight	15.60 kN/m ³		
Relative Density	39 %	Pipe Progression Rate	0.07 cm/s
Sample Length	65.7 cm	Flow Rate	0.370 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	2.06E-04 m/s
		Sample Permeability	7.99E-04 m/s

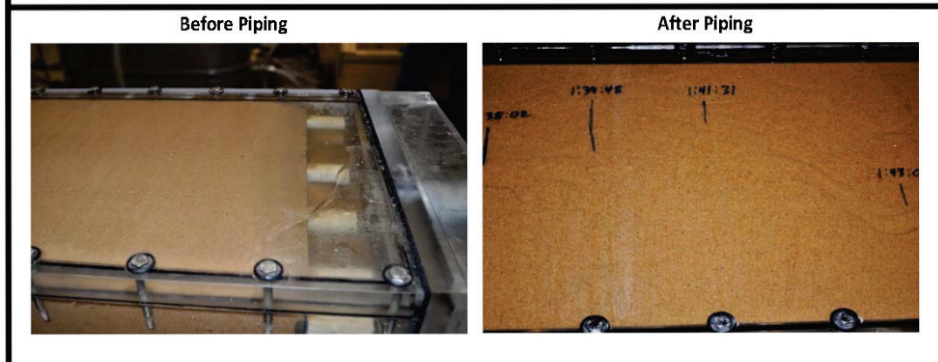
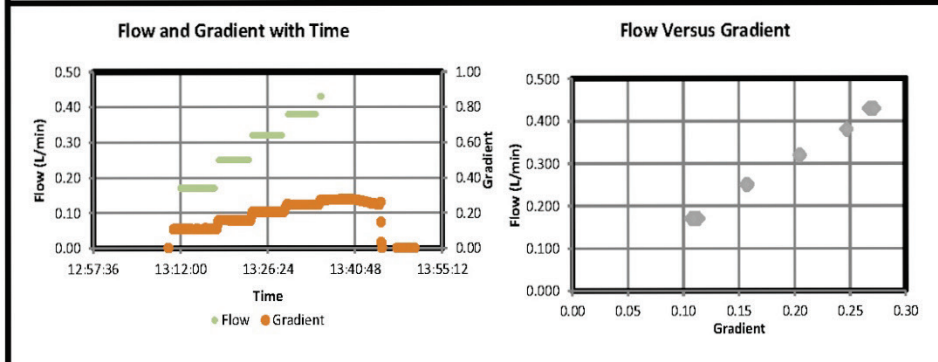
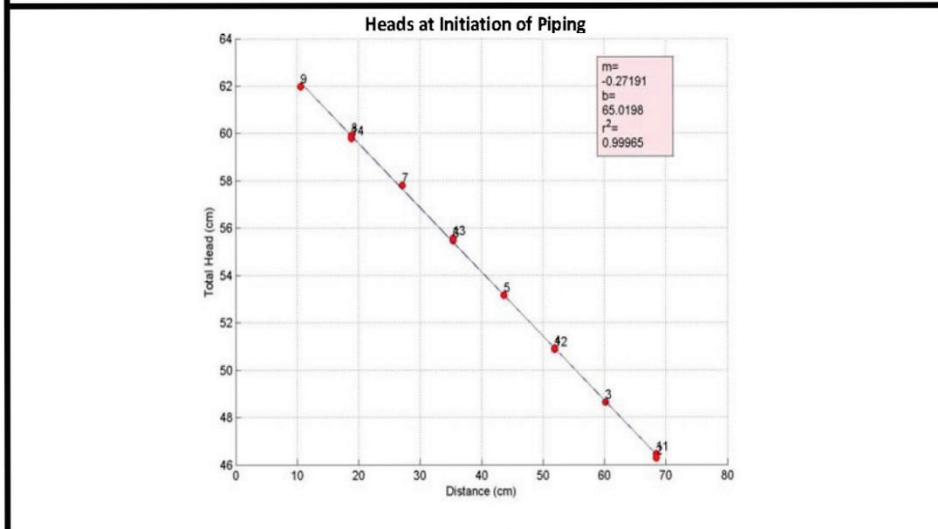
Notes: PPT13 not working properly



Sand Type Mason Sand Date 4-Jun-14
 Test Number 12-1 Start Time 13:10:02
 Tested by A.M.,H.S. End Time 13:50:51

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.77 kg	Time at Piping	13:35:15
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.27
Dry Unit Weight	15.58 kN/m ³		
Relative Density	39 %	Pipe Progression Rate	0.11 cm/s
Sample Length	64.2 cm	Flow Rate	0.43 L/min
Measured Slope Angle	31.0 °	Darcy Average Velocity	2.39E-04 m/s
		Sample Permeability	8.79E-04 m/s

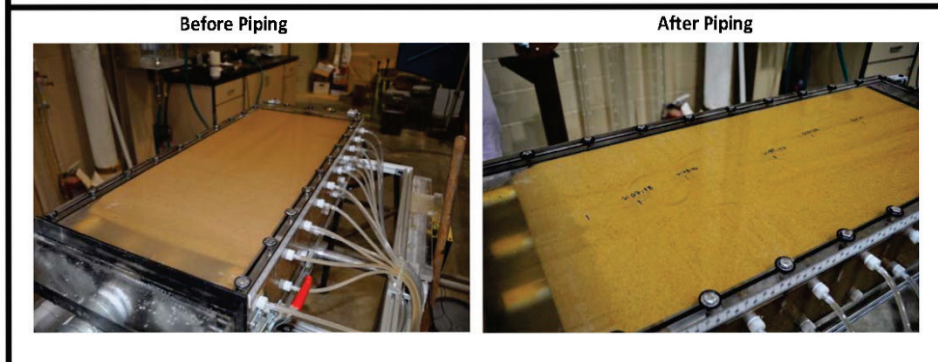
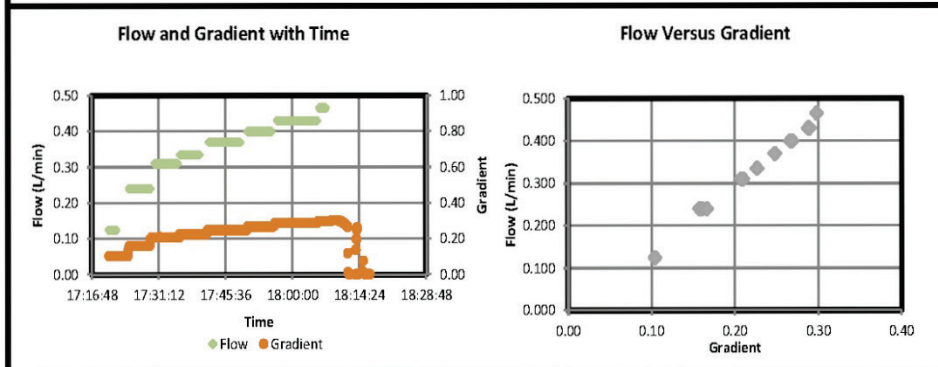
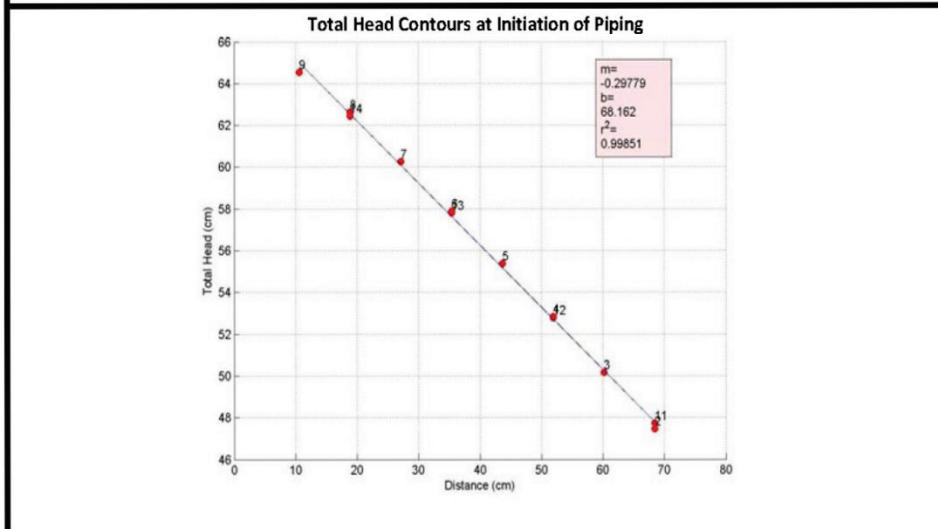
Notes:



Sand Type Mason Sand Date 4-Jun-14
 Test Number 13-1 Start Time 17:20:28
 Tested by A.M.,B.P.,J.R. End Time 18:16:38

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.23 kg	Time at Piping	18:07:04
Soil Volume	0.02055 m ³	Least-Squares Fit Gradient	0.30
Dry Unit Weight	15.38 kN/m ³		
Relative Density	31 %	Pipe Progression Rate	0.23 cm/s
Sample Length	64.2 cm	Flow Rate	0.465 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	2.58E-04 m/s
		Sample Permeability	8.68E-04 m/s

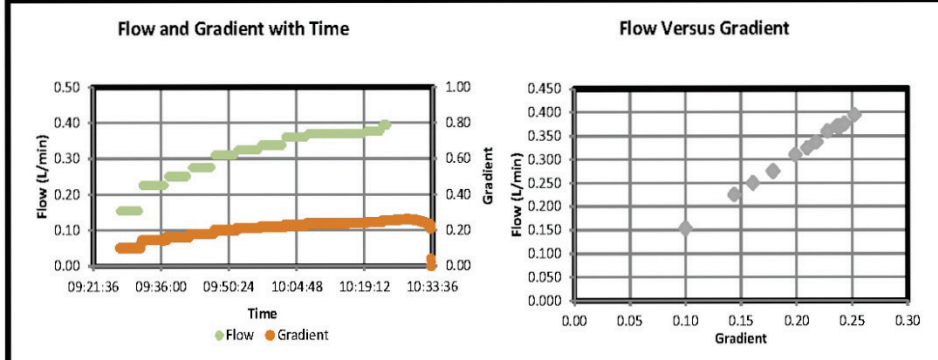
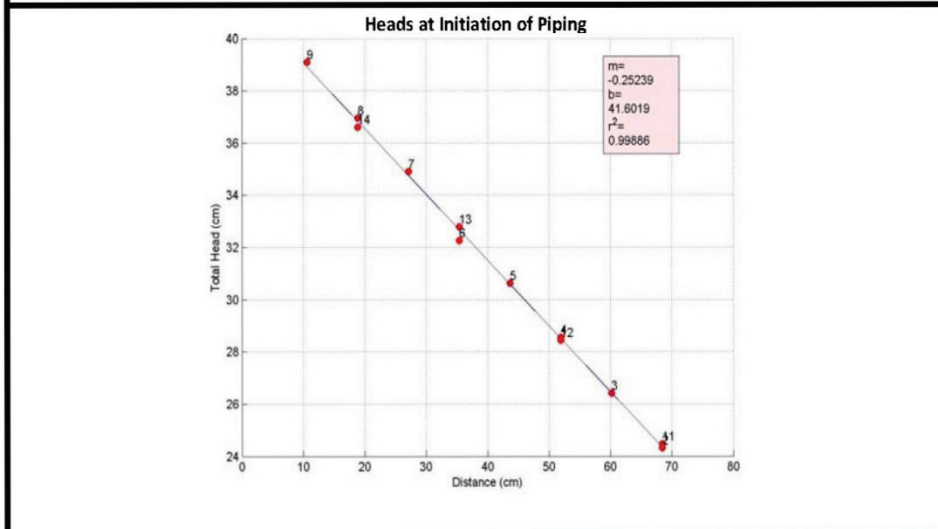
Notes:



Sand Type Mason Sand Date 12-Jun-14
 Test Number 17-1 Start Time 9:27:19
 Tested by A.M.,H.S. End Time 10:34:16

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.14 kg	Time at Piping	10:24:05
Soil Volume	0.02058 m ³	Least-Squares Fit Gradient	0.25
Dry Unit Weight	15.32 kN/m ³		
Relative Density	28 %	Pipe Progression Rate	0.12 cm/s
Sample Length	64.2 cm	Flow Rate	0.394 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	2.19E-04 m/s
		Sample Permeability	8.67E-04 m/s

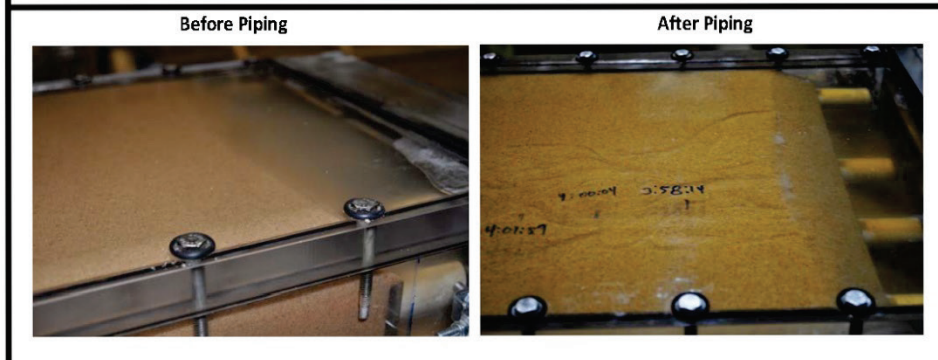
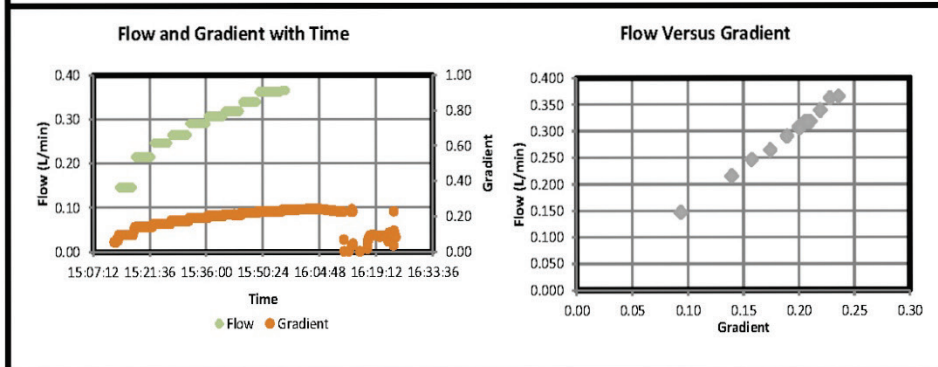
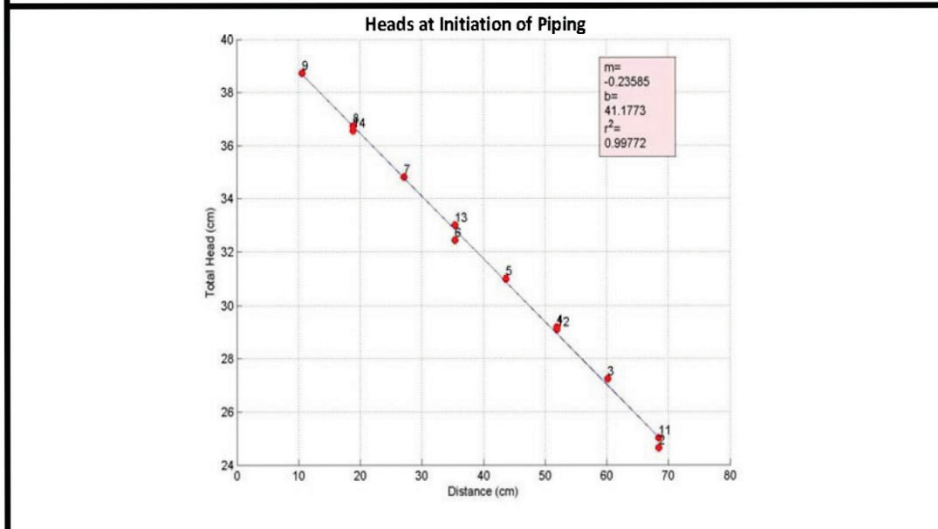
Notes:



Sand Type Mason Sand Date 12-Jun-14
 Test Number 18-1 Start Time 15:12:33
 Tested by A.M.,H.S. End Time 16:24:16

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.27 kg	Time at Piping	15:56:12
Soil Volume	0.02055 m ³	Least-Squares Fit Gradient	0.24
Dry Unit Weight	15.41 kN/m ³		
Relative Density	31 %	Pipe Progression Rate	0.08 cm/s
Sample Length	64.3 cm	Flow Rate	0.365 L/min
Measured Slope Angle	33.5 °	Darcy Average Velocity	2.03E-04 m/s
		Sample Permeability	8.60E-04 m/s

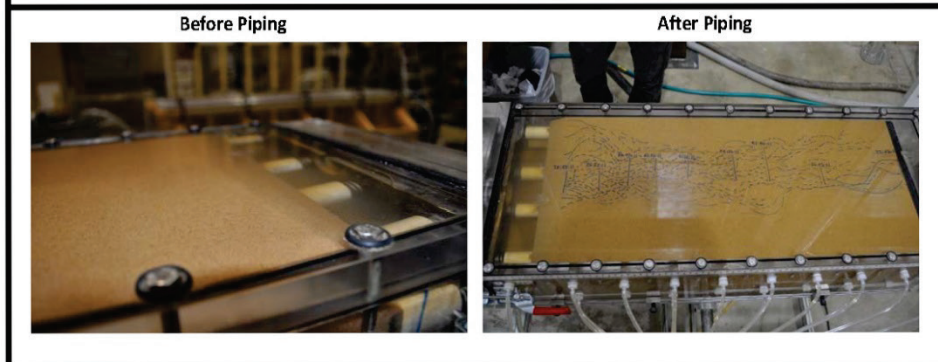
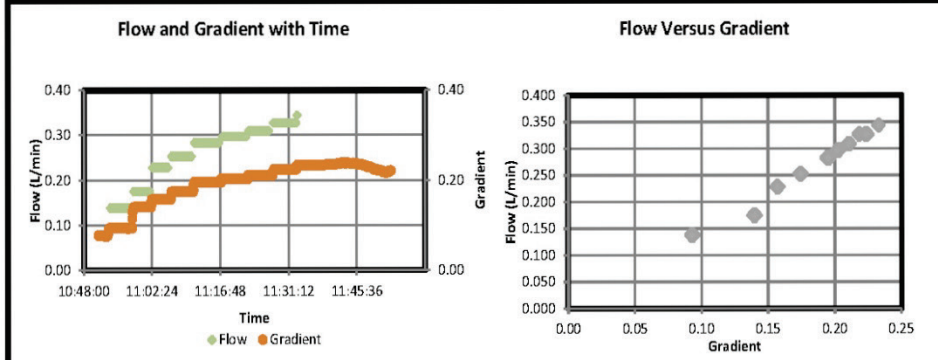
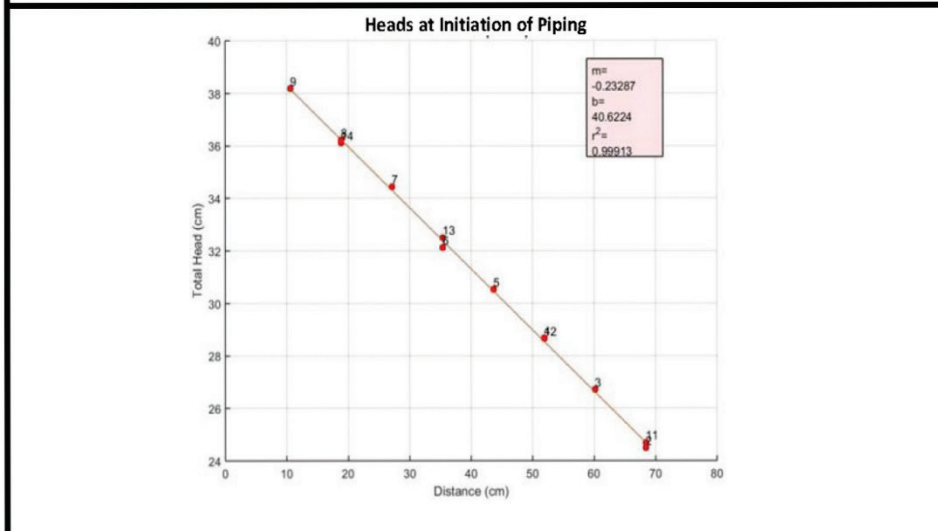
Notes:



Sand Type	<u>Mason Sand</u>	Date	<u>13-Jun-14</u>
Test Number	<u>19-1</u>	Start Time	<u>10:51:05</u>
Tested by	<u>A.M.,H.S.</u>	End Time	<u>11:52:47</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.50 kg	Time at Piping	11:33:02
Soil Volume	0.02052 m ³	Least-Squares Fit Gradient	0.23
Dry Unit Weight	15.54 kN/m ³		
Relative Density	37 %	Pipe Progression Rate	0.06 cm/s
Sample Length	64.5 cm	Flow Rate	0.344 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	1.91E-04 m/s
		Sample Permeability	8.21E-04 m/s

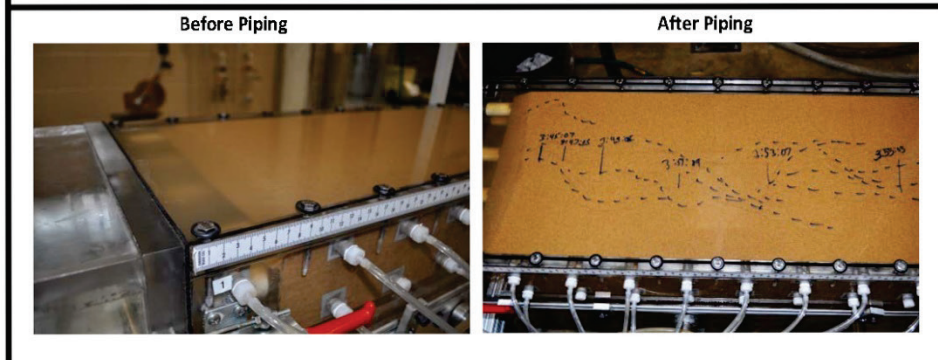
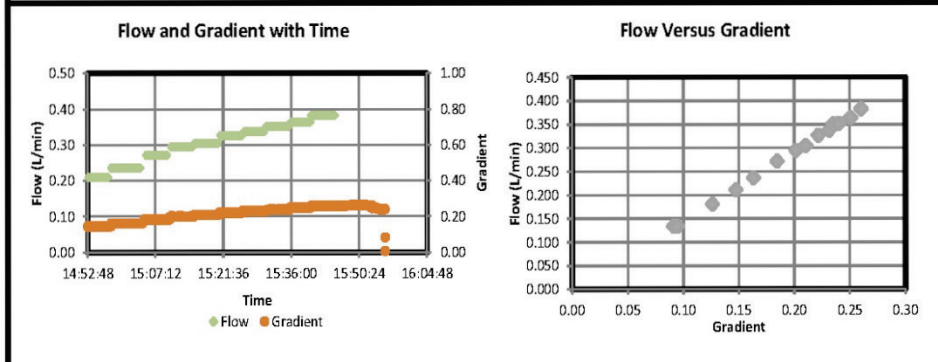
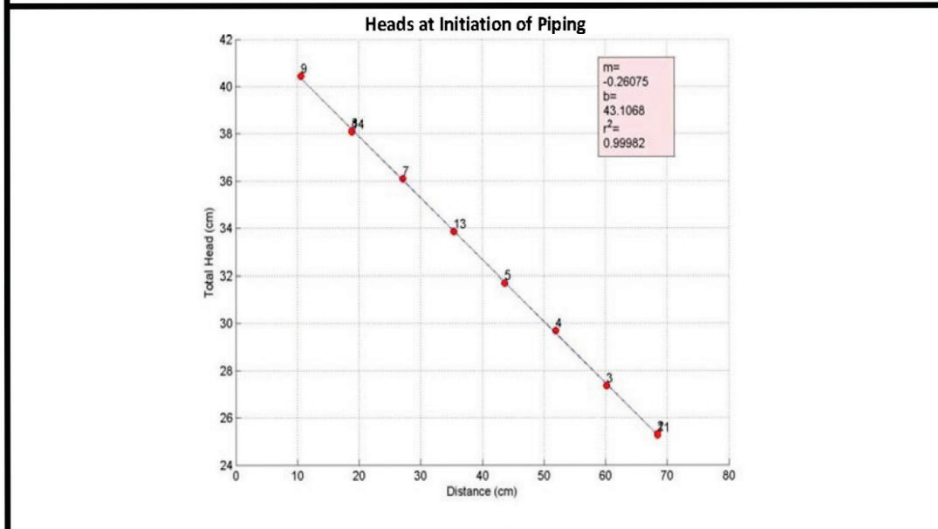
Notes:



Sand Type	<u>Mason Sand</u>	Date	<u>18-Jun-14</u>
Test Number	<u>23-1</u>	Start Time	<u>14:38:50</u>
Tested by	<u>A.M.,H.S.,A.W.</u>	End Time	<u>15:56:41</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.41 kg	Time at Piping	15:45:07
Soil Volume	0.02052 m ³	Least-Squares Fit Gradient	0.26
Dry Unit Weight	15.49 kN/m ³		
Relative Density	34 %	Pipe Progression Rate	0.1 cm/s
Sample Length	64.6 cm	Flow Rate	0.383 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	2.13E-04 m/s
		Sample Permeability	8.16E-04 m/s

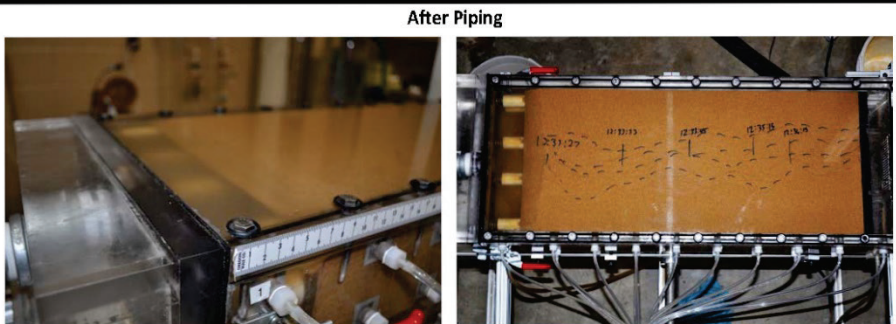
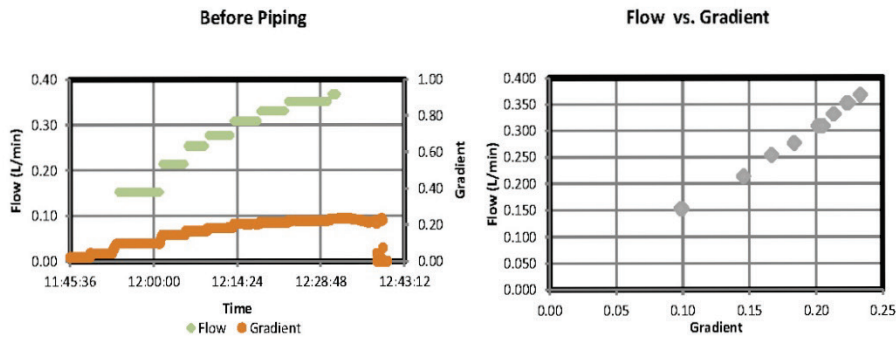
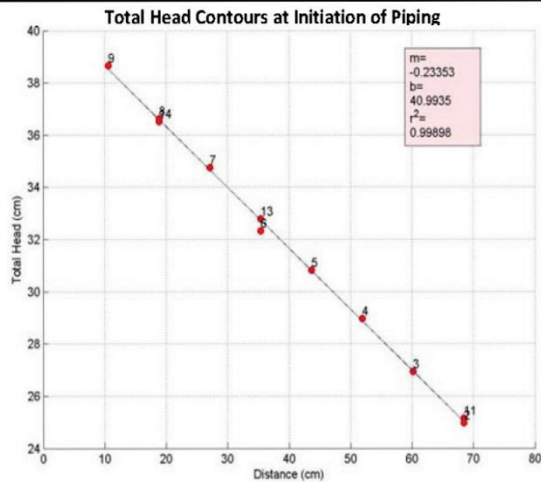
Notes: PPTs 6 and 12 not working properly



Sand Type	<u>Mason Sand</u>	Date	<u>20-Jun-14</u>
Test Number	<u>25-1</u>	Start Time	<u>11:39:23</u>
Tested by	<u>H.S.,A.W.</u>	End Time	<u>12:40:14</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.23 kg	Time at Piping	12:31:27
Soil Volume	0.02055 m ³	Least-Squares Fit Gradient	0.23
Dry Unit Weight	15.38 kN/m ³		
Relative Density	31 %	Pipe Progression Rate	0.16 cm/s
Sample Length	65.1 cm	Flow Rate	0.368 L/min
Measured Slope Angle	35.0 °	Darcy Average Velocity	2.04E-04 m/s
		Sample Permeability	8.75E-04 m/s

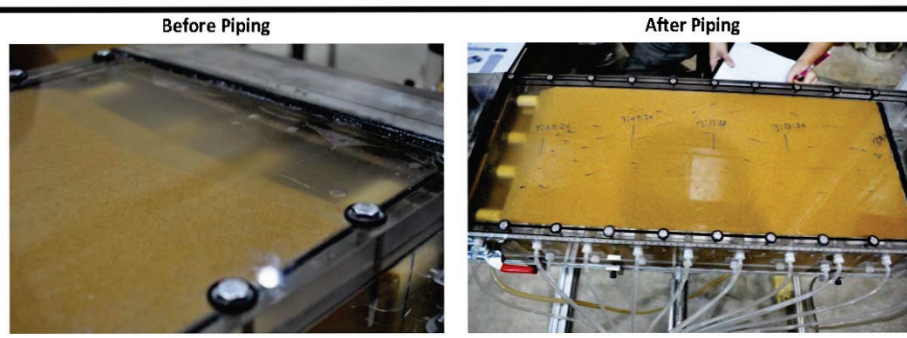
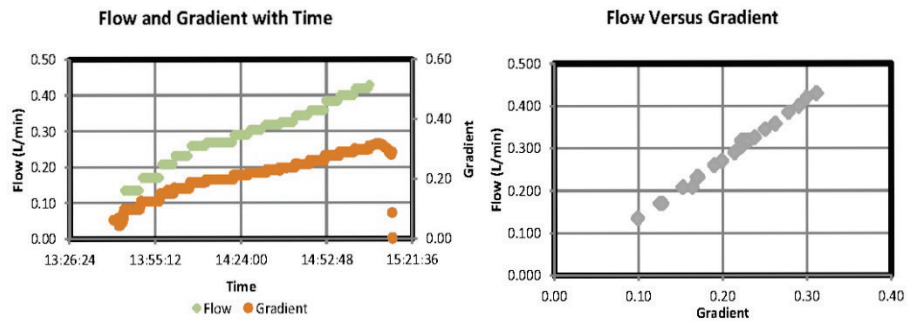
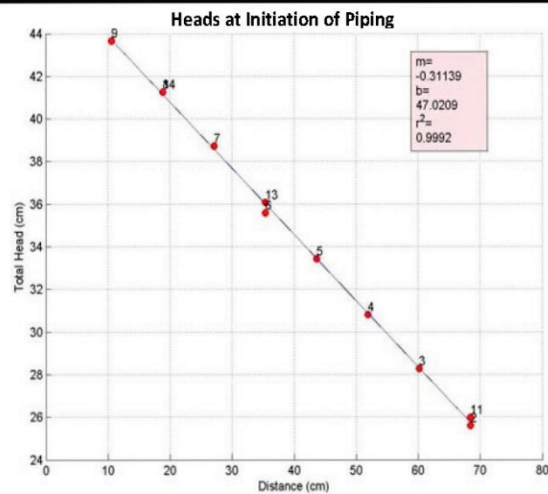
Notes: PPT12 not working properly
Air pockets in center of sample prior to test.



Sand Type Mason Sand Date 27-Jun-14
 Test Number 28 Start Time 13:41:15
 Tested by A.M.,J.L.,H.S.,A.W. End Time 15:15:25

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	32.68 kg	Time at Piping	15:07:20
Soil Volume	0.02055 m ³	Least-Squares Fit Gradient	0.31
Dry Unit Weight	15.60 kN/m ³		
Relative Density	40 %	Pipe Progression Rate	0.14 cm/s
Sample Length	64.5 cm	Flow Rate	0.430 L/min
Measured Slope Angle	32.0 °	Darcy Average Velocity	2.39E-04 m/s
		Sample Permeability	7.67E-04 m/s

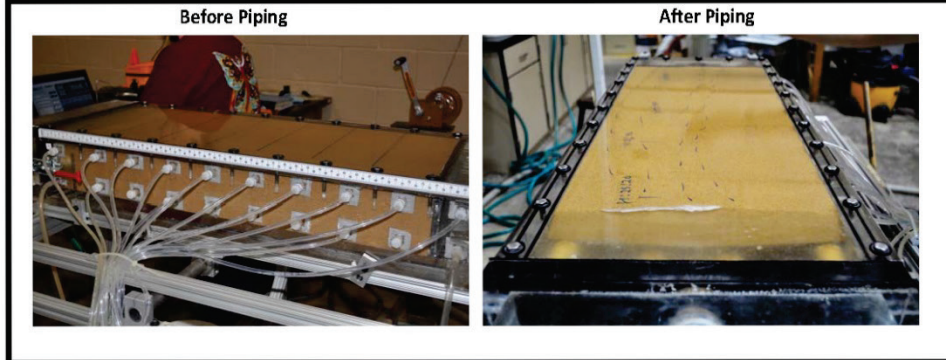
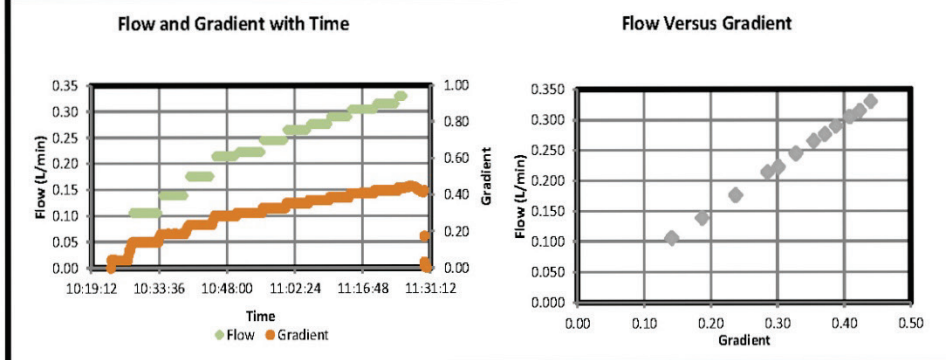
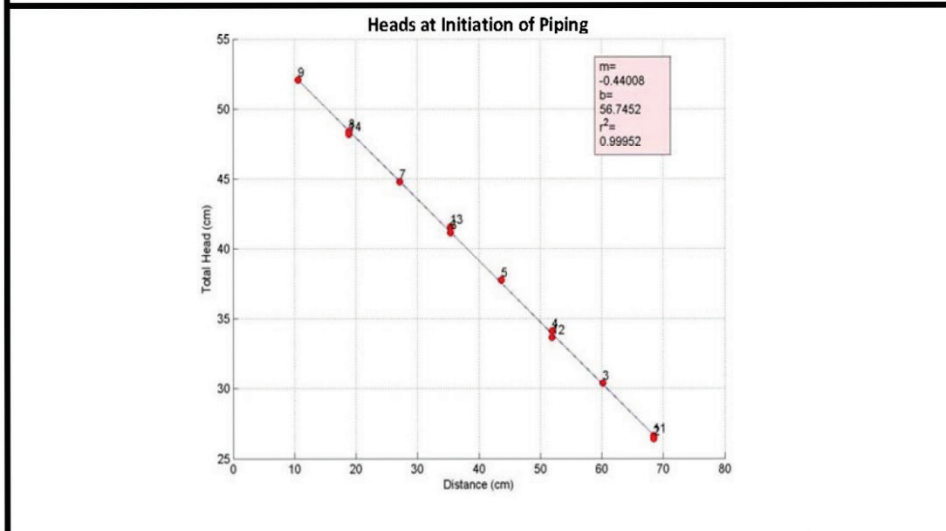
Notes: PPT12 not working properly



Sand Type Mason Sand Date 2-Jul-14
 Test Number 29 Start Time 10:23:20
 Tested by A.M.,H.S. End Time 11:30:25

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	36.00 kg	Time at Piping	11:25:20
Soil Volume	0.02079 m ³	Least-Squares Fit Gradient	0.44
Dry Unit Weight	16.99 kN/m ³		
Relative Density	92 %	Pipe Progression Rate	0.25 cm/s
Sample Length	65.6 cm	Flow Rate	0.330 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	1.83E-04 m/s
		Sample Permeability	4.17E-04 m/s

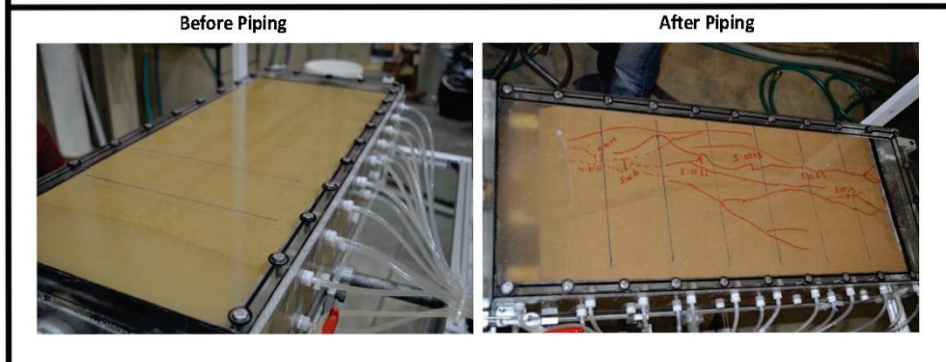
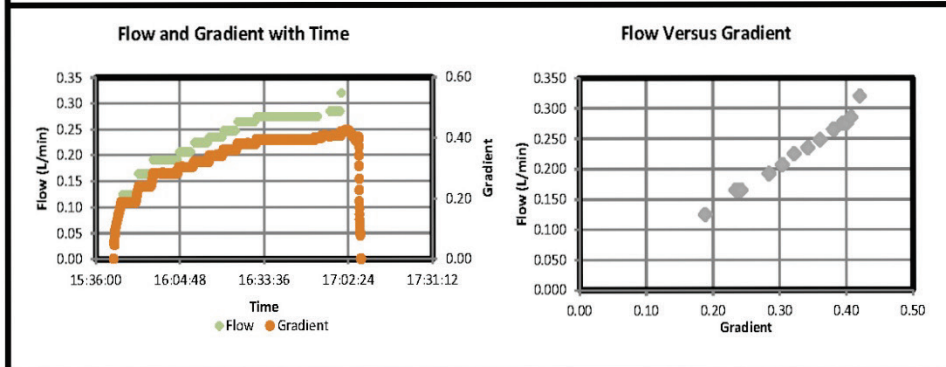
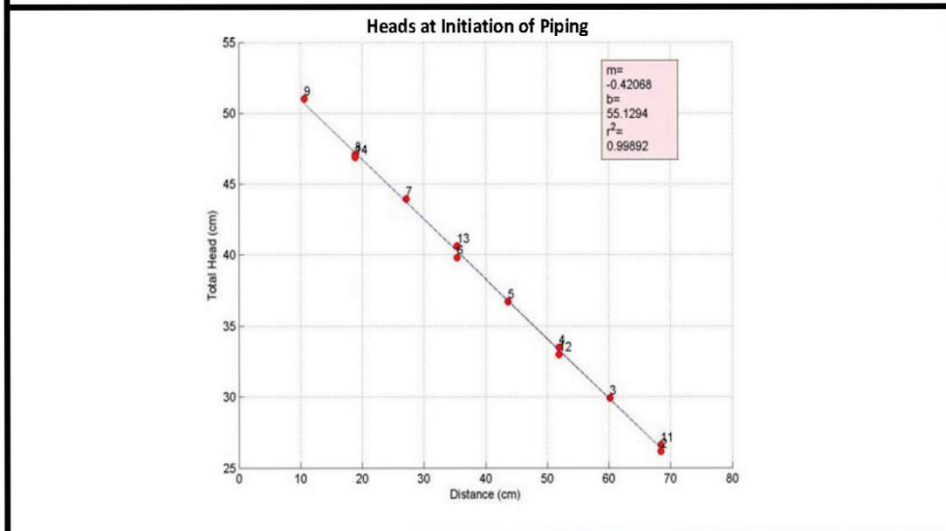
Notes:



Sand Type	Mason Sand	Date	2-Jul-14
Test Number	30	Start Time	15:42:00
Tested by	A.M.,H.S.,J.L,A.W.	End Time	17:06:55

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.95 kg	Time at Piping	16:59:58
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.42
Dry Unit Weight	17.09 kN/m ³		
Relative Density	96 %	Pipe Progression Rate	0.30 cm/s
Sample Length	65.6 cm	Flow Rate	0.320 L/min
Measured Slope Angle	35.0 °	Darcy Average Velocity	1.78E-04 m/s
		Sample Permeability	4.23E-04 m/s

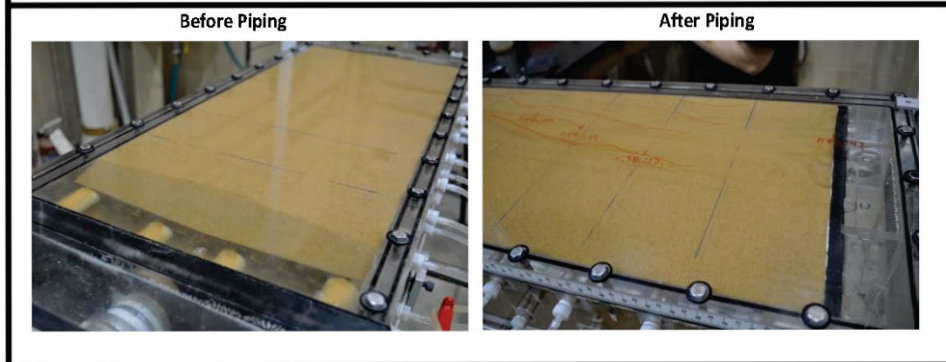
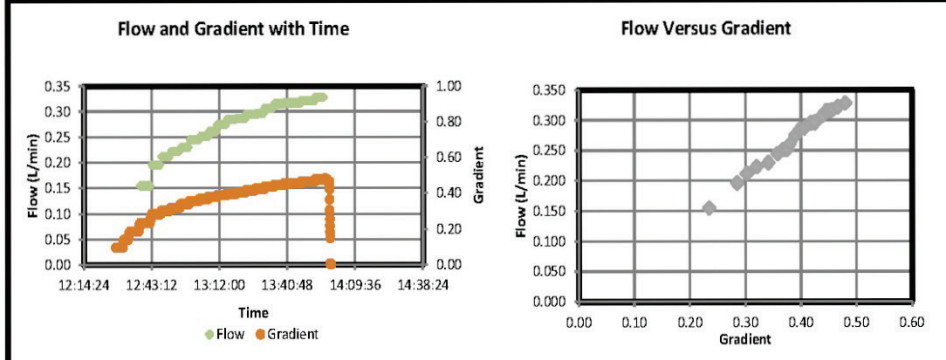
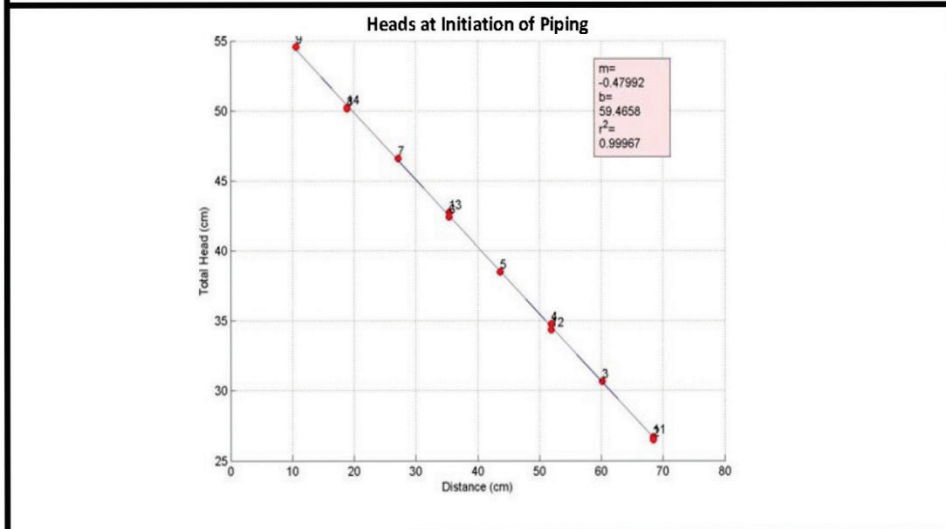
Notes: No pipe position measurements available
Small leaks at bolts during tests.



Sand Type Mason Sand Date 3-Jul-14
 Test Number 31 Start Time 12:28:00
 Tested by A.M.,H.S. End Time 13:59:32

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.95 kg	Time at Piping	13:56:05
Soil Volume	0.02067 m ³	Least-Squares Fit Gradient	0.48
Dry Unit Weight	17.06 kN/m ³		
Relative Density	95 %	Pipe Progression Rate	0.42 cm/s
Sample Length	65.5 cm	Flow Rate	0.328 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	1.82E-04 m/s
		Sample Permeability	3.80E-04 m/s

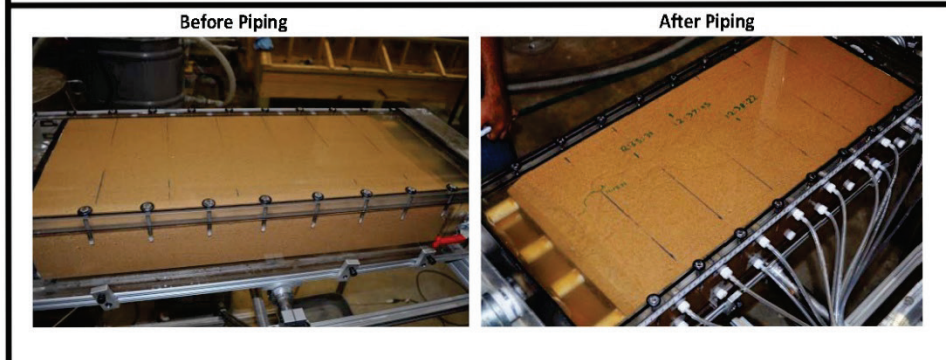
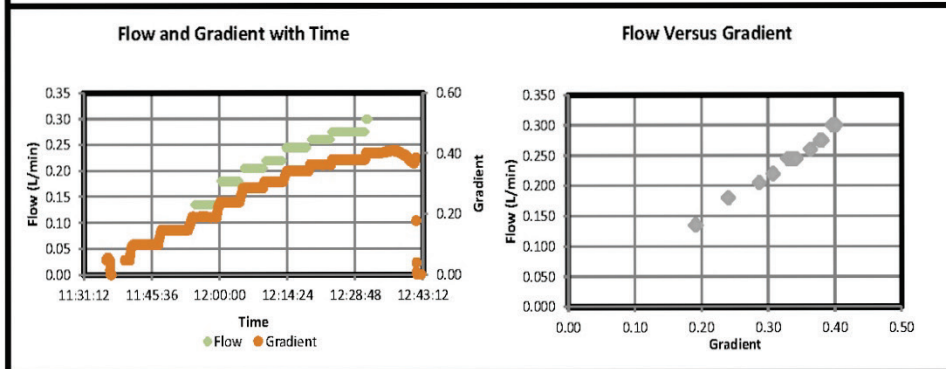
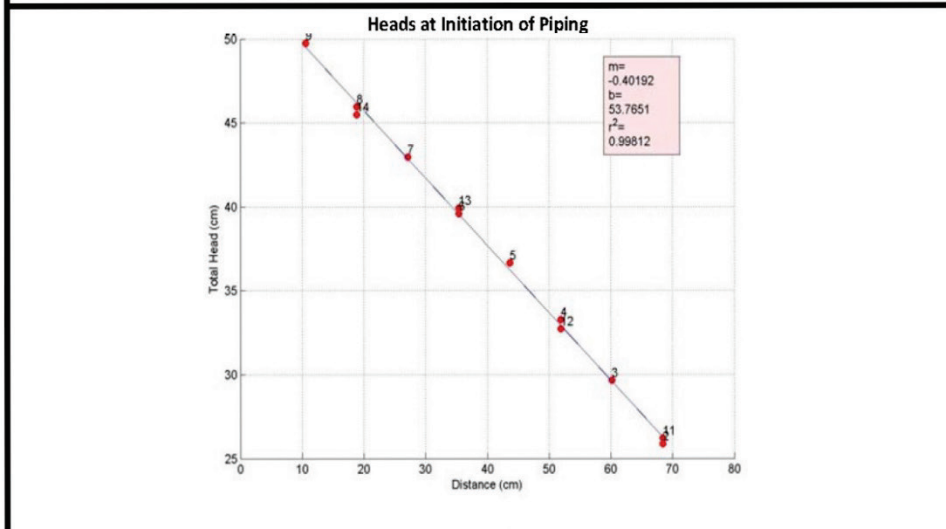
Notes:



Sand Type Mason Sand Date 7-Jul-14
 Test Number 32 Start Time 11:35:23
 Tested by A.M.,H.S.,J.L. End Time 12:42:51

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.86 kg	Time at Piping	12:31:35
Soil Volume	0.02058 m ³	Least-Squares Fit Gradient	0.40
Dry Unit Weight	17.10 kN/m ³		
Relative Density	96 %	Pipe Progression Rate	0.11 cm/s
Sample Length	65.3 cm	Flow Rate	0.300 L/min
Measured Slope Angle	35.0 °	Darcy Average Velocity	1.67E-04 m/s
		Sample Permeability	4.15E-04 m/s

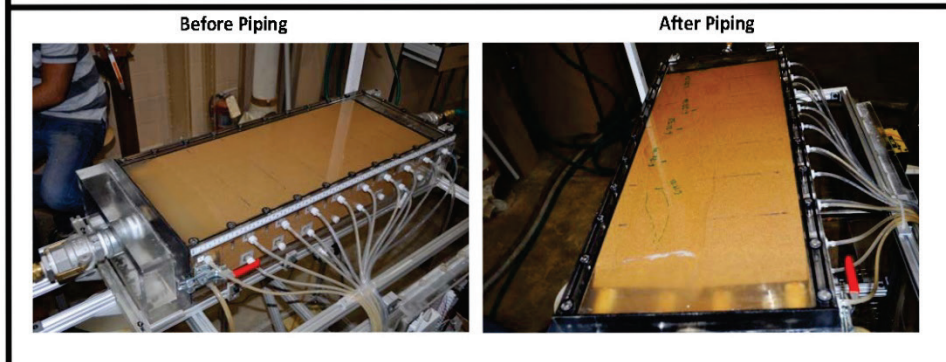
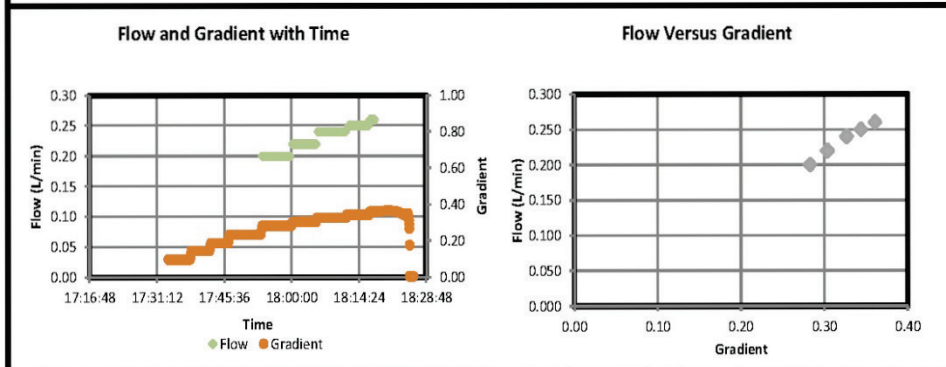
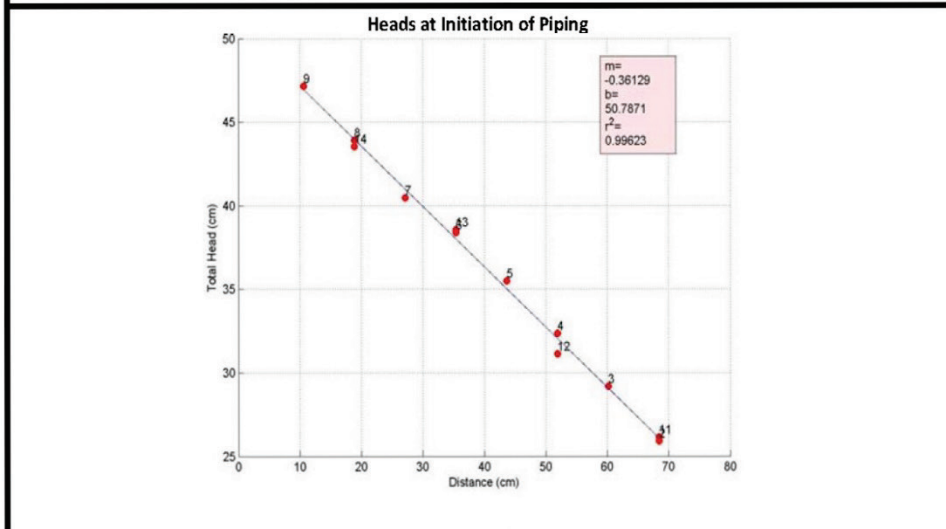
Notes:



Sand Type Mason Sand Date 7-Jul-14
 Test Number 33 Start Time 17:33:41
 Tested by A.M.,J.L. End Time 18:26:03

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.95 kg	Time at Piping	18:17:46
Soil Volume	0.02055 m ³	Least-Squares Fit Gradient	0.36
Dry Unit Weight	17.16 kN/m ³		
Relative Density	98 %	Pipe Progression Rate	0.15 cm/s
Sample Length	65.2 cm	Flow Rate	0.260 L/min
Measured Slope Angle	36.0 °	Darcy Average Velocity	1.44E-04 m/s
		Sample Permeability	4.00E-04 m/s

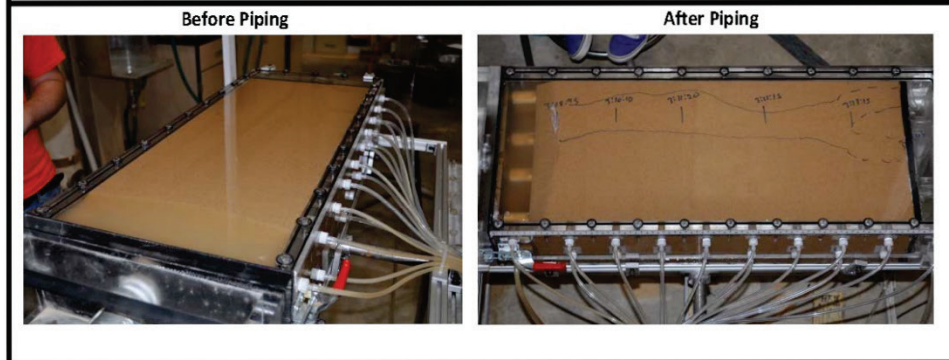
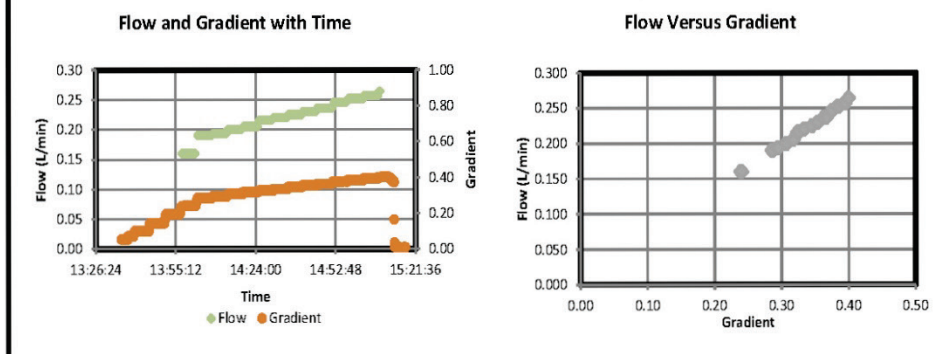
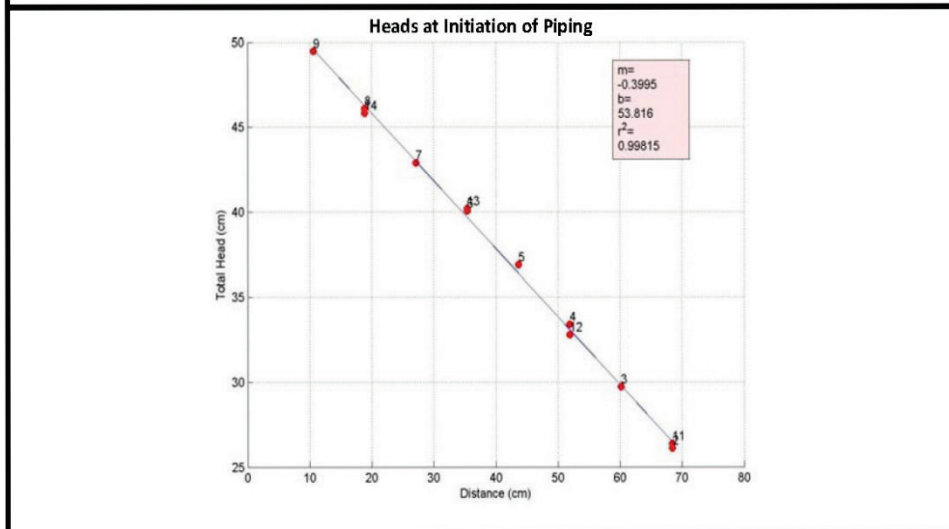
Notes:



Sand Type Mason Sand Date 8-Jul-14
 Test Number 34 Start Time 13:30:33
 Tested by A.M.,H.S.,A.W. End Time 15:17:58

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.95 kg	Time at Piping	15:08:45
Soil Volume	0.02055 m ³	Least-Squares Fit Gradient	0.40
Dry Unit Weight	17.16 kN/m ³		
Relative Density	98 %	Pipe Progression Rate	0.22 cm/s
Sample Length	65.6 cm	Flow Rate	0.264 L/min
Measured Slope Angle	34.0 °	Darcy Average Velocity	1.47E-04 m/s
		Sample Permeability	3.67E-04 m/s

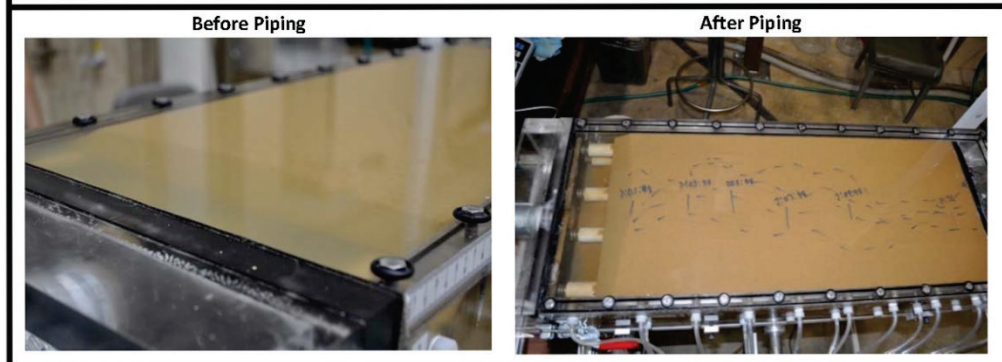
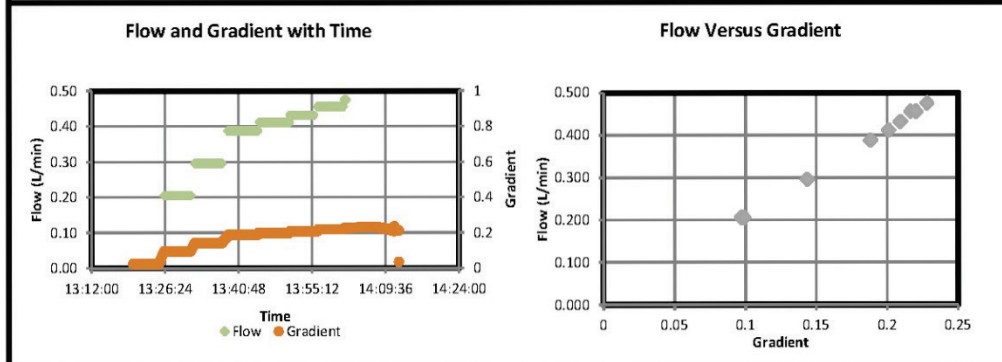
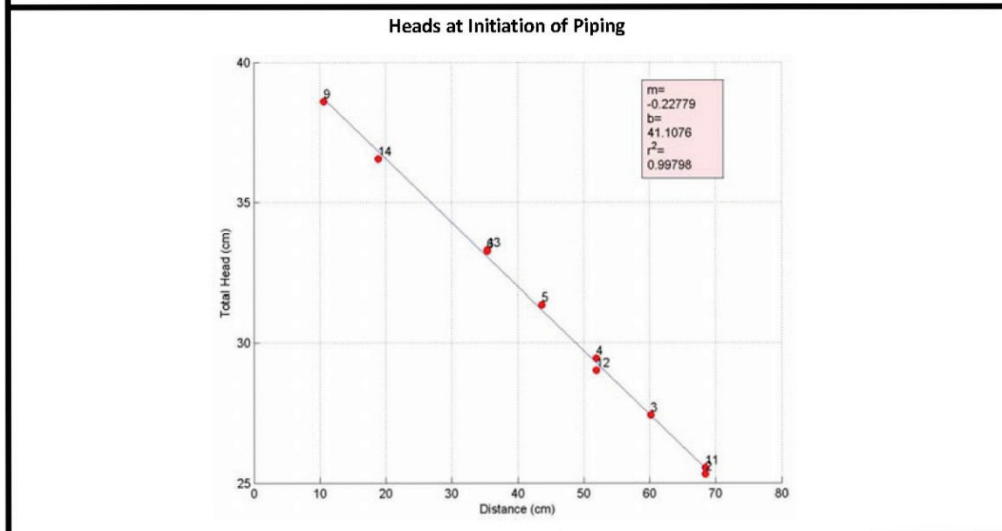
Notes:



Sand Type 40-70 Date 9-Jul-14
 Test Number 1 Start Time 13:20:09
 Tested by A.M.,H.S.,A.W. End Time 14:12:15

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	30.50 kg	Time at Piping	14:01:48
Soil Volume	0.02046 m ³	Least-Squares Fit Gradient	0.23
Dry Unit Weight	14.62 kN/m ³		
Relative Density	9% %	Pipe Progression Rate	0.11 cm/s
Sample Length	64.5 cm	Flow Rate	0.476 L/min
Measured Slope Angle	36.7 °	Darcy Average Velocity	2.64E-04 m/s
		Sample Permeability	1.15E-03 m/s

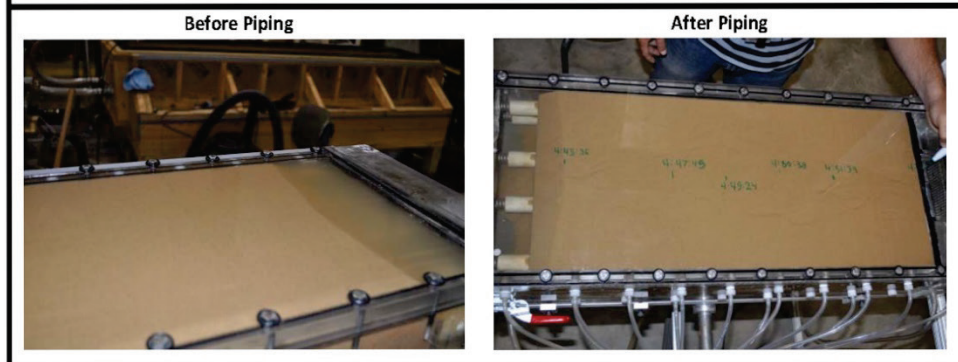
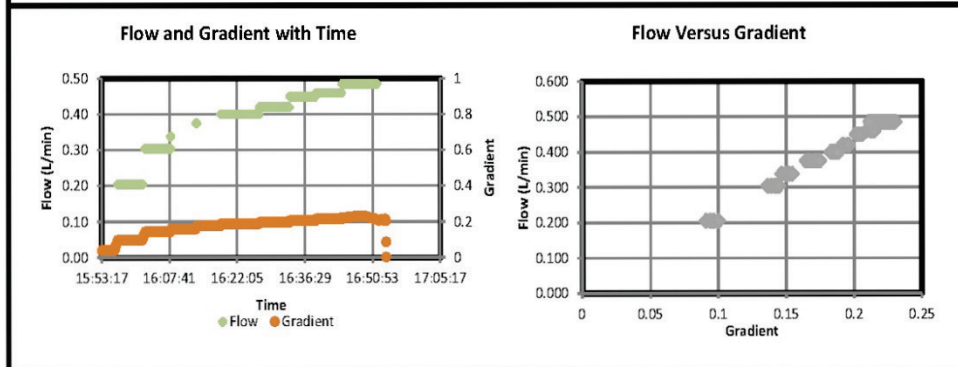
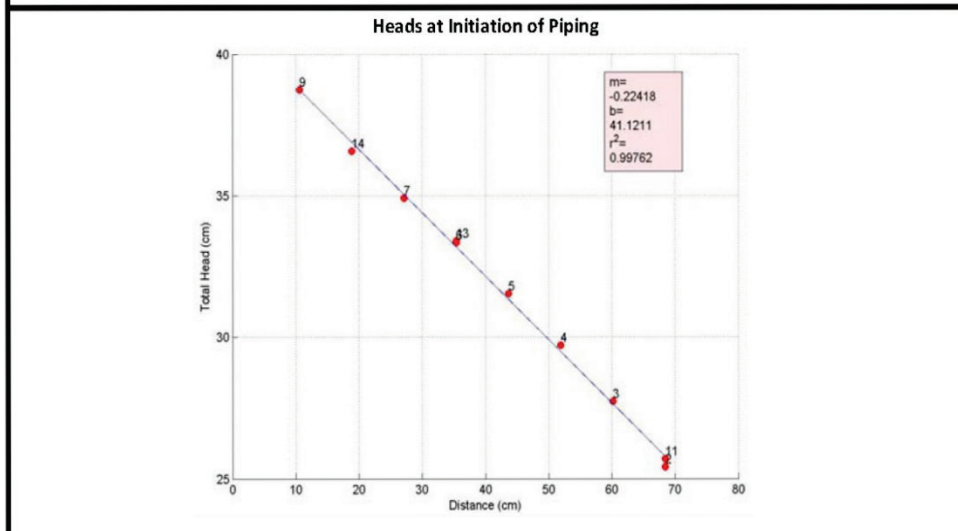
Notes: Air pockets in sample



Sand Type 40-70 Date 9-Jul-14
 Test Number 2 Start Time 15:49:30
 Tested by A.M.,H.S.,A.W. End Time 16:53:55

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	30.36 kg	Time at Piping	16:45:36
Soil Volume	0.02025 m ³	Least-Squares Fit Gradient	0.22
Dry Unit Weight	14.71 kN/m ³		
Relative Density	13 %	Pipe Progression Rate	0.15 cm/s
Sample Length	64.5 cm	Flow Rate	0.485 L/min
Measured Slope Angle	37.0 °	Darcy Average Velocity	2.69E-04 m/s
		Sample Permeability	1.22E-03 m/s

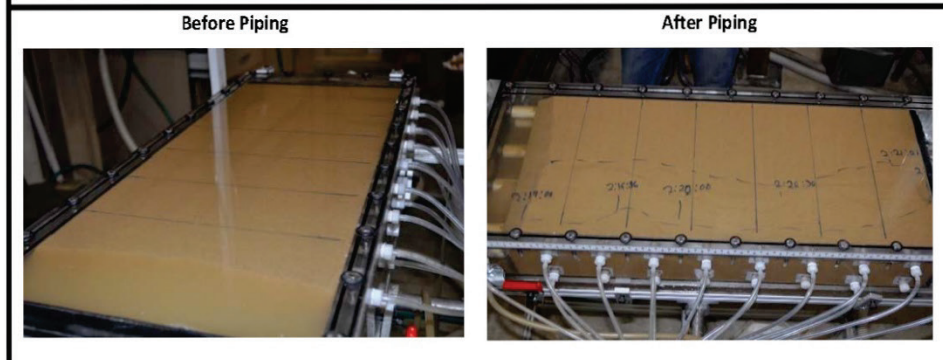
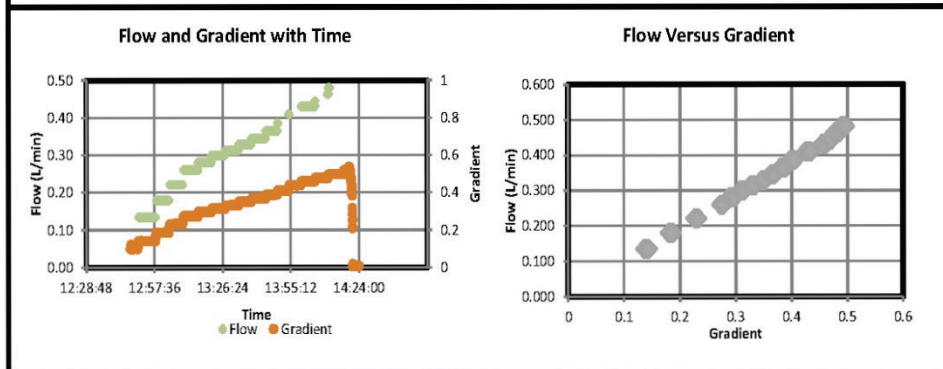
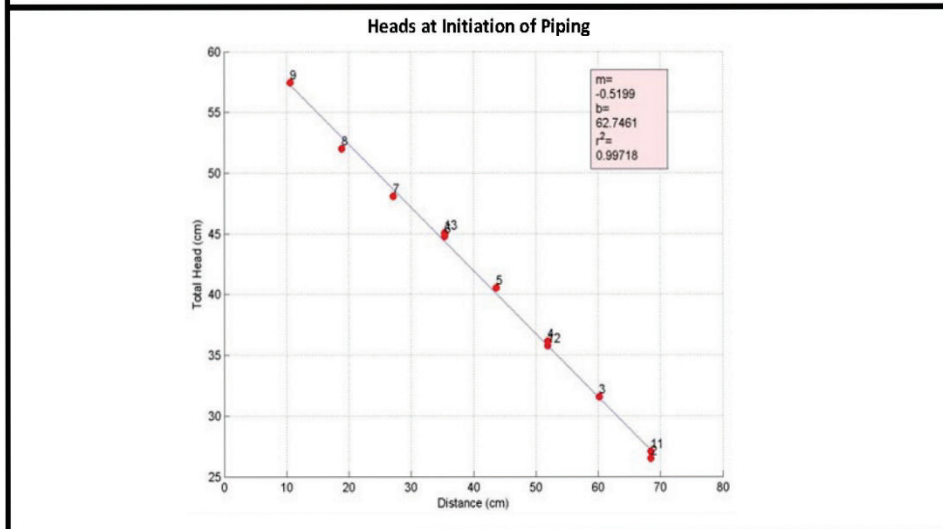
Notes:



Sand Type 40-70 Date 21-Jul-14
 Test Number 3 Start Time 12:47:26
 Tested by A.M.,A.W. End Time 14:24:06

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.86 kg	Time at Piping	14:19:01
Soil Volume	0.02049 m ³	Least-Squares Fit Gradient	0.52
Dry Unit Weight	16.69 kN/m ³		
Relative Density	98 %	Pipe Progression Rate	0.69 cm/s
Sample Length	64.9 cm	Flow Rate	0.480 L/min
Measured Slope Angle	35.0 °	Darcy Average Velocity	2.67E-04 m/s
		Sample Permeability	5.13E-04 m/s

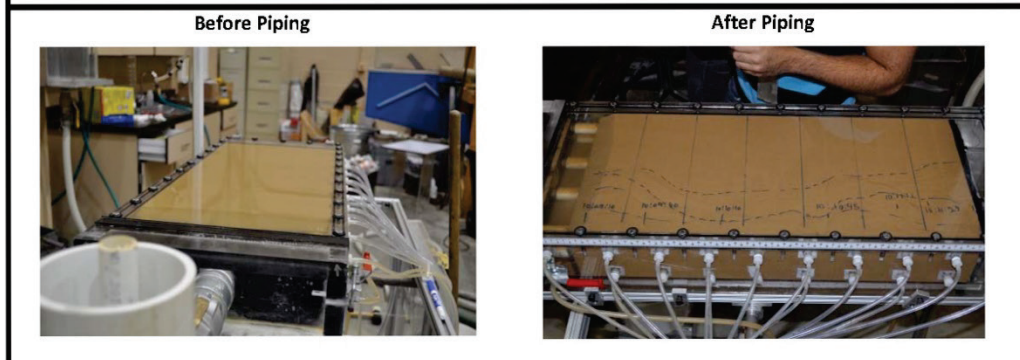
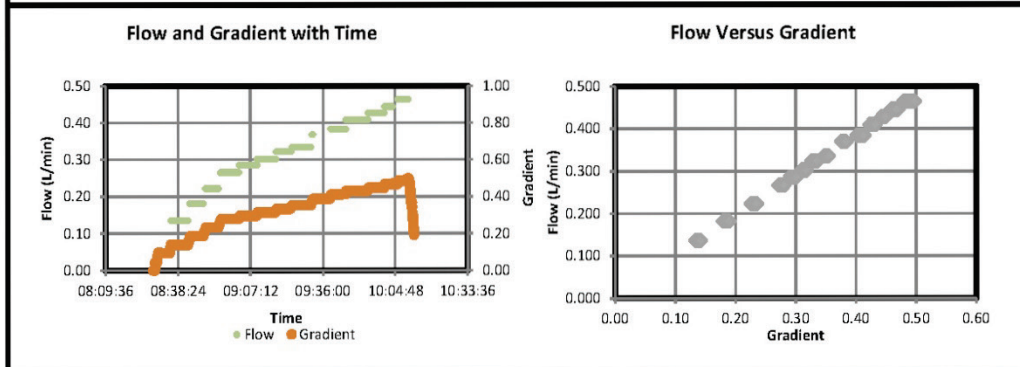
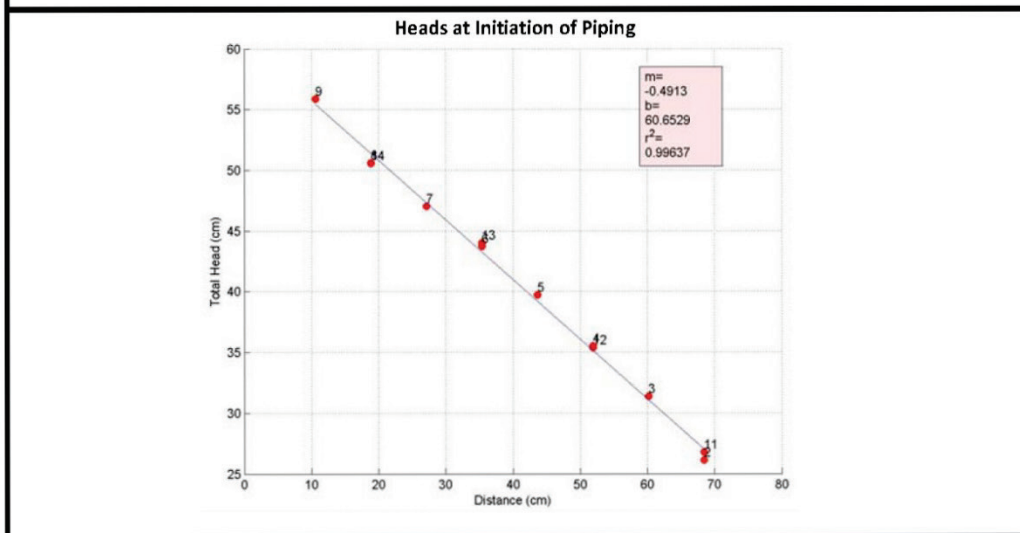
Notes:



Sand Type 40-70 Date 22-Jul-14
 Test Number 4 Start Time 8:28:26
 Tested by A.M.,A.W.,H.S. End Time 10:12:23

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.55 kg	Time at Piping	10:09:10
Soil Volume	0.02058 m ³	Least-Squares Fit Gradient	0.49
Dry Unit Weight	16.47 kN/m ³		
Relative Density	90 %	Pipe Progression Rate	0.38 cm/s
Sample Length	65.4 cm	Flow Rate	0.464 L/min
Measured Slope Angle	35.0 °	Darcy Average Velocity	2.58E-04 m/s
		Sample Permeability	5.26E-04 m/s

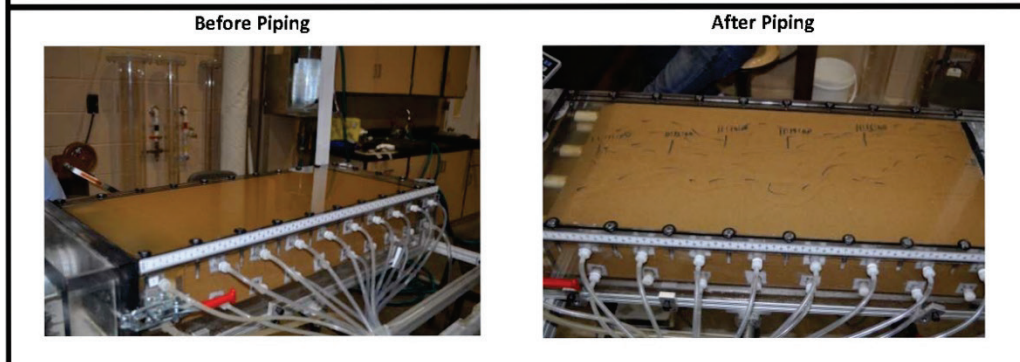
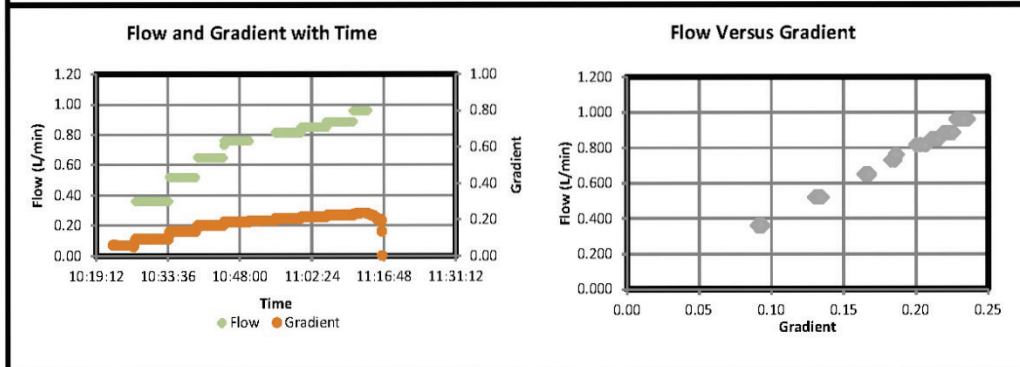
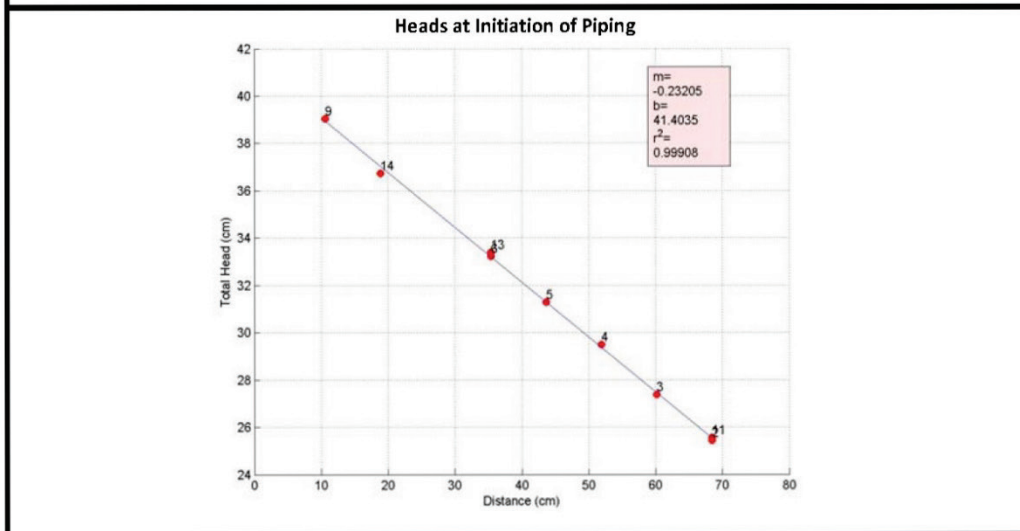
Notes:



Sand Type	<u>30-50</u>	Date	<u>10-Jul-14</u>
Test Number	<u>1</u>	Start Time	<u>10:22:34</u>
Tested by	<u>A.M.,J.L.,A.W.</u>	End Time	<u>11:16:26</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.18 kg	Time at Piping	11:11:00
Soil Volume	0.02044 m ³	Least-Squares Fit Gradient	0.23
Dry Unit Weight	14.96 kN/m ³		
Relative Density	15 %	Pipe Progression Rate	0.21 cm/s
Sample Length	65.0 cm	Flow Rate	0.960 L/min
Measured Slope Angle	36.0 °	Darcy Average Velocity	5.33E-04 m/s
		Sample Permeability	2.32E-03 m/s

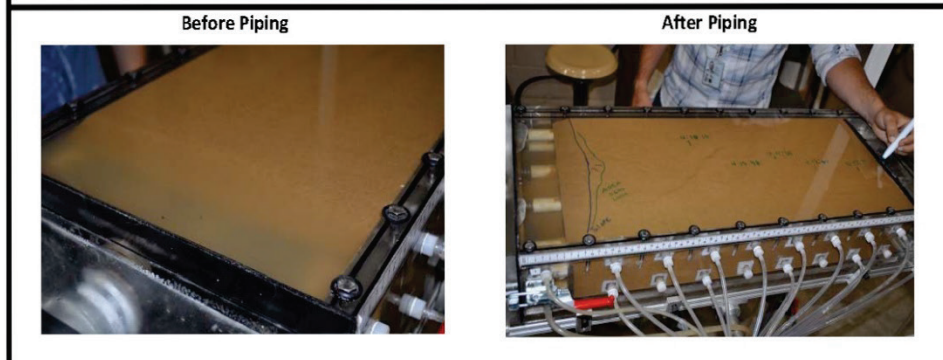
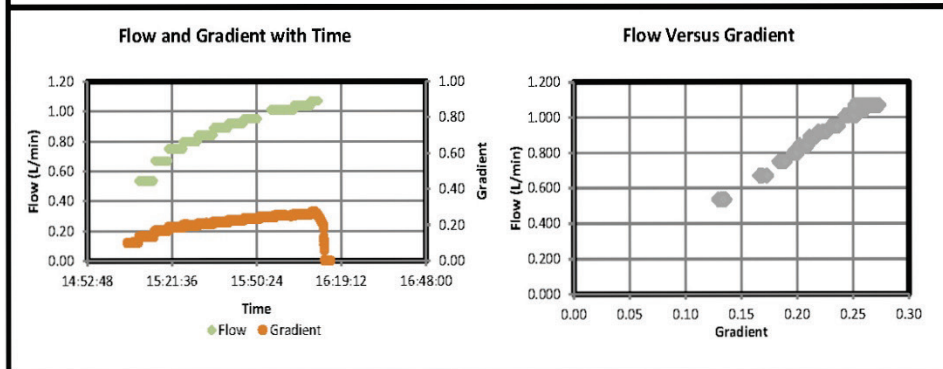
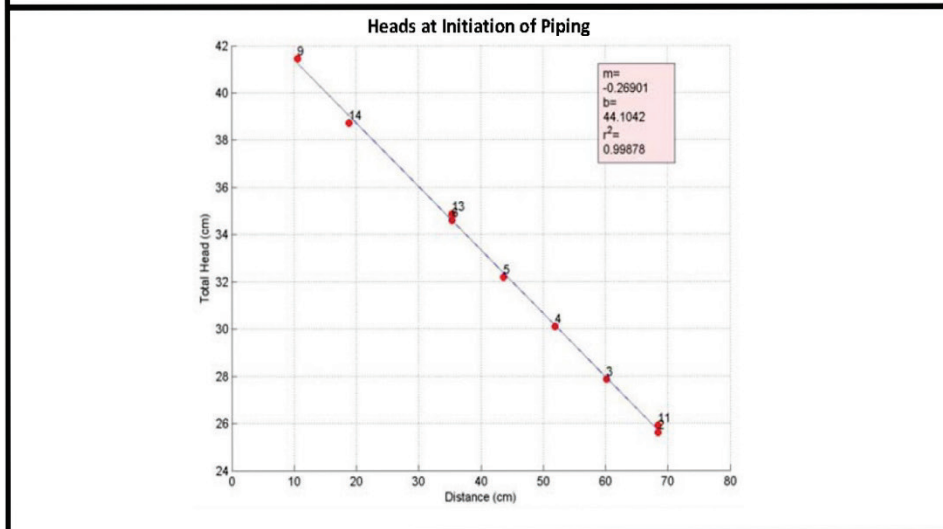
Notes:



Sand Type	<u>30-50</u>	Date	<u>10-Jul-14</u>
Test Number	<u>2</u>	Start Time	<u>15:06:26</u>
Tested by	<u>A.M.,J.L.,A.W.</u>	End Time	<u>16:16:20</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.05 kg	Time at Piping	16:08:54
Soil Volume	0.02043 m ³	Least-Squares Fit Gradient	0.27
Dry Unit Weight	14.91 kN/m ³		
Relative Density	13 %	Pipe Progression Rate	0.27 cm/s
Sample Length	64.7 cm	Flow Rate	1.070 L/min
Measured Slope Angle	36.0 °	Darcy Average Velocity	5.94E-04 m/s
		Sample Permeability	2.20E-03 m/s

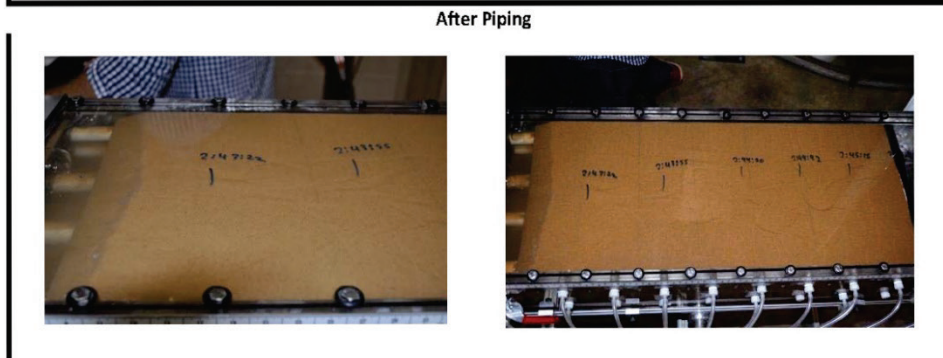
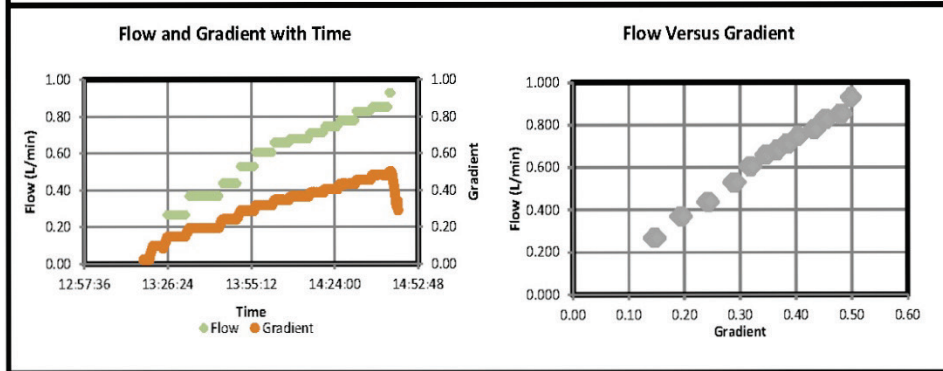
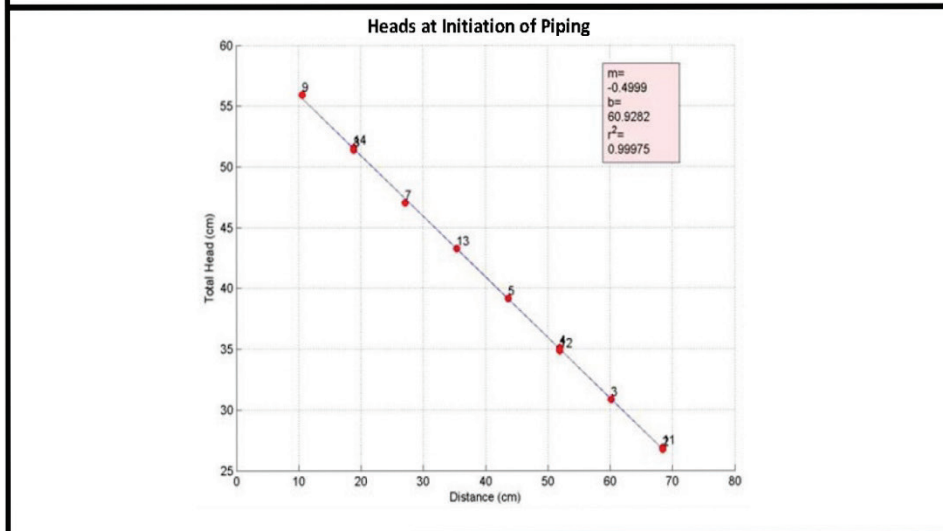
Notes:



Sand Type 30-50 Date 23-Jul-14
 Test Number 3 Start Time 13:18:03
 Tested by A.M.,H.S.,A.W. End Time 14:46:00

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.05 kg	Time at Piping	14:43:22
Soil Volume	0.020669848 m ³	Least-Squares Fit Gradient	0.50
Dry Unit Weight	16.63 kN/m ³		
Relative Density	86 %	Pipe Progression Rate	0.47 cm/s
Sample Length	65.6 cm	Flow Rate	0.929 L/min
Measured Slope Angle	35.0 °	Darcy Average Velocity	5.16E-04 m/s
		Sample Permeability	1.03E-03 m/s

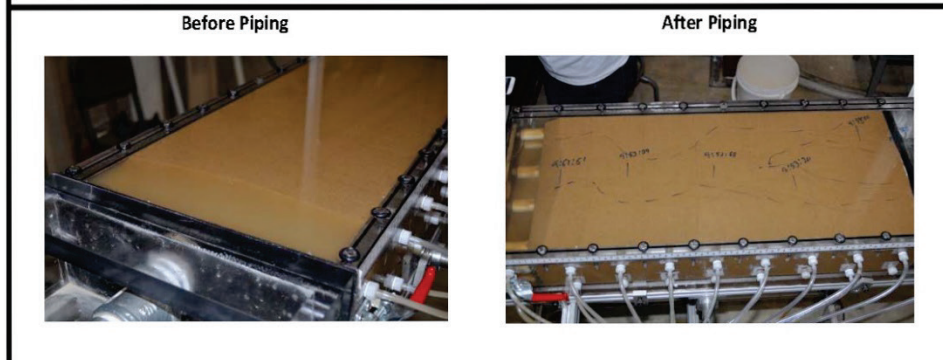
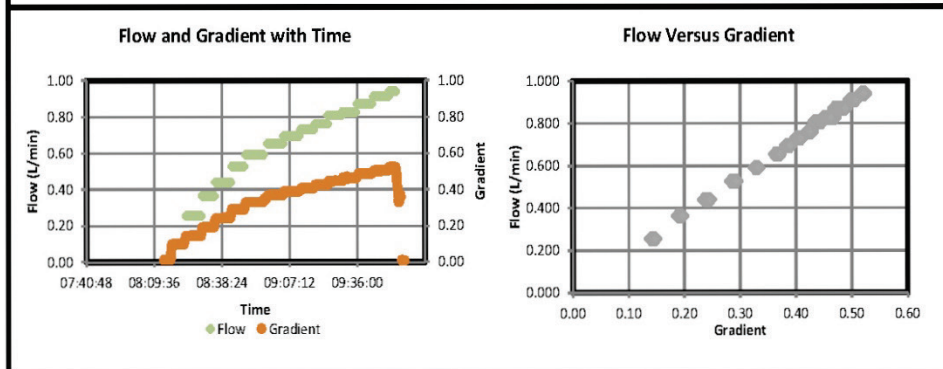
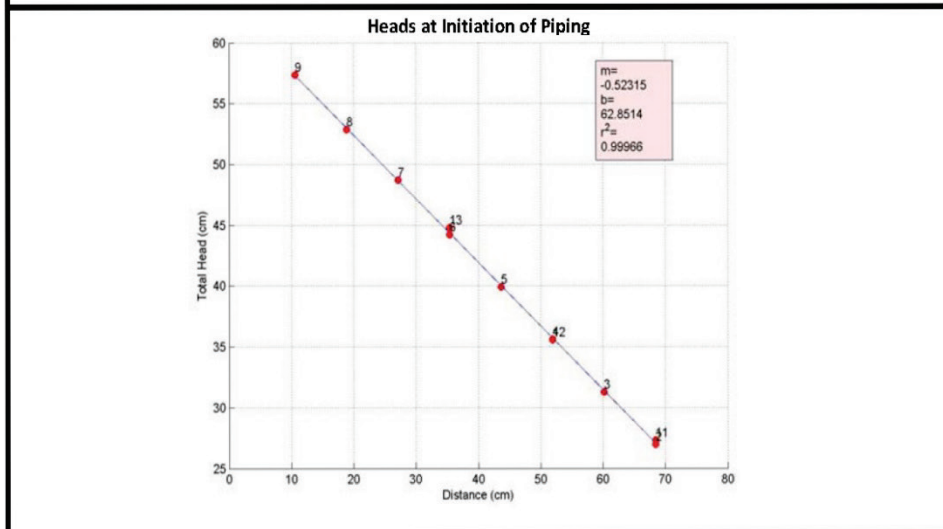
Notes:



Sand Type 30-50 Date 23-Jul-14
 Test Number 4 Start Time 8:13:51
 Tested by H.S.,A.W. End Time 9:56:10

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.95 kg	Time at Piping	09:51:51
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.52
Dry Unit Weight	16.61 kN/m ³		
Relative Density	86 %	Pipe Progression Rate	0.41 cm/s
Sample Length	65.7 cm	Flow Rate	0.940 L/min
Measured Slope Angle	36.0 °	Darcy Average Velocity	5.22E-04 m/s
		Sample Permeability	1.00E-03 m/s

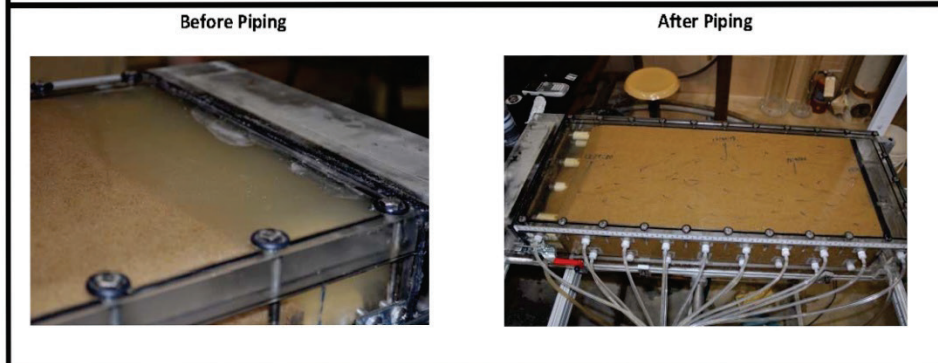
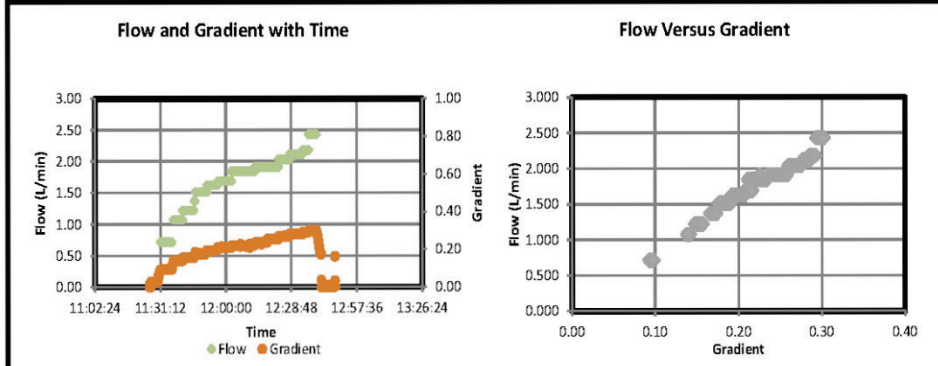
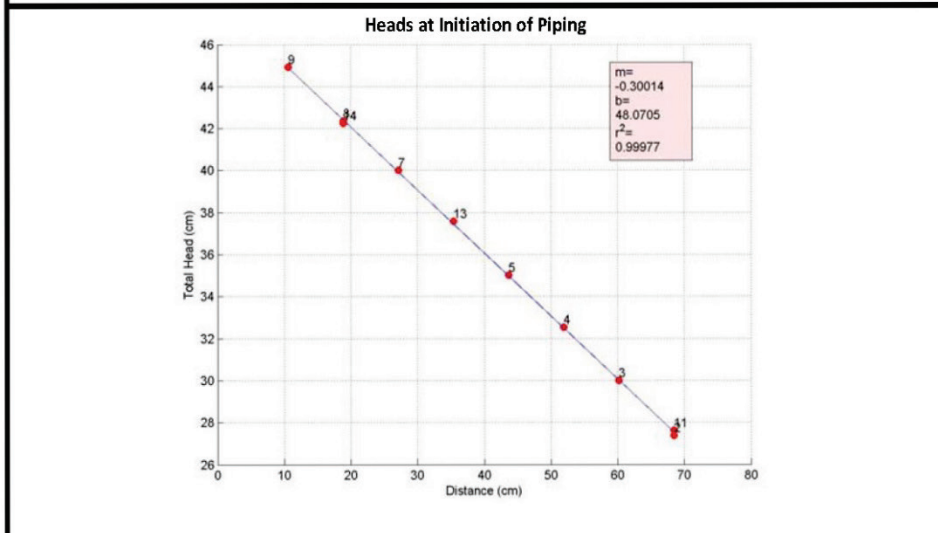
Notes: Air pockets in upstream end of flume before filters



Sand Type	<u>20-40</u>	Date	<u>25-Jun-14</u>
Test Number	<u>1</u>	Start Time	<u>11:24:46</u>
Tested by	<u>H.S.,A.W.,B.P.</u>	End Time	<u>12:50:42</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.82 kg	Time at Piping	12:39:10
Soil Volume	0.02044 m ³	Least-Squares Fit Gradient	0.30
Dry Unit Weight	15.27 kN/m ³		
Relative Density	21 %	Pipe Progression Rate	0.43 cm/s
Sample Length	64.6 cm	Flow Rate	2.434 L/min
Measured Slope Angle	33.0 °	Darcy Average Velocity	1.35E-03 m/s
		Sample Permeability	4.51E-03 m/s

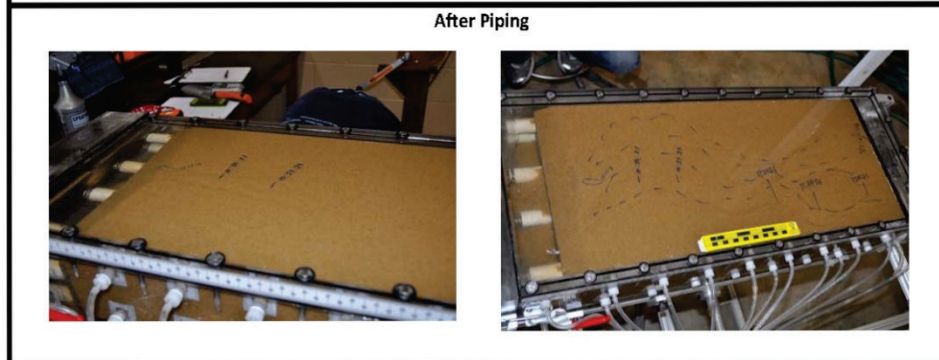
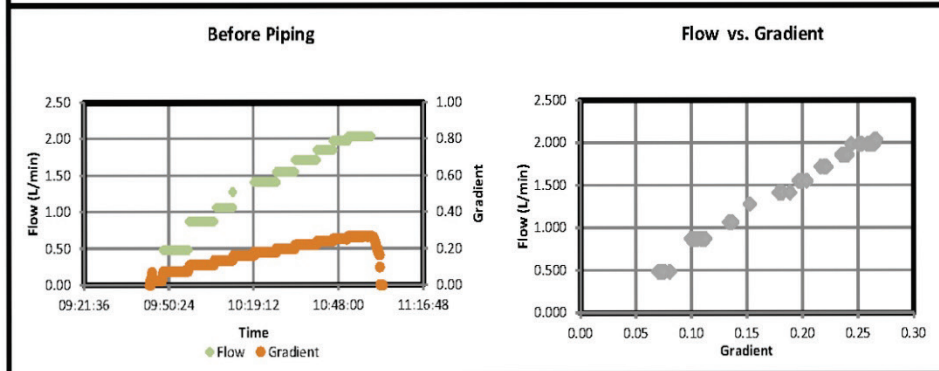
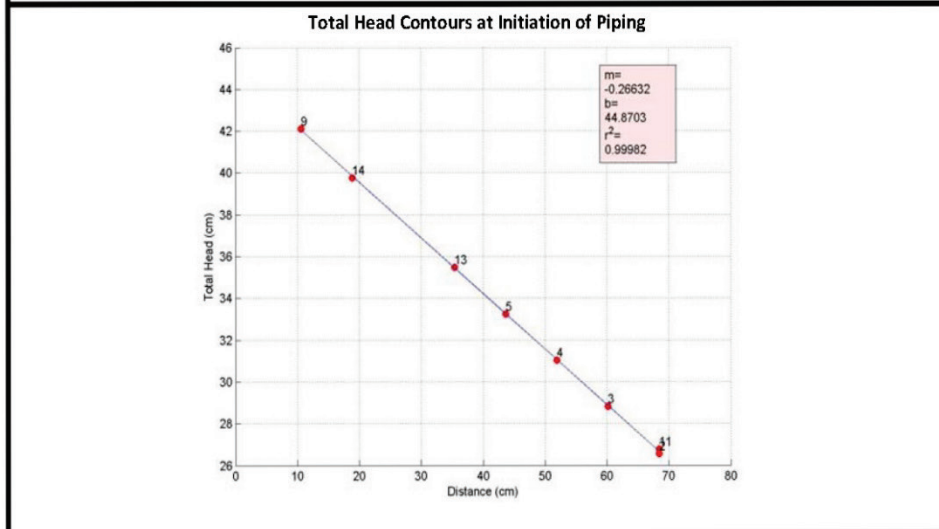
Notes: Air in upstream side of flume before test. Gaps between filter and sample observed in corners of sample



Sand Type	<u>20-40</u>	Date	<u>30-Jun-14</u>
Test Number	<u>2</u>	Start Time	<u>9:43:47</u>
Tested by	<u>A.W., J.L.</u>	End Time	<u>11:03:08</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.77 kg	Time at Piping	10:59:10
Soil Volume	0.02046 m ³	Least-Squares Fit Gradient	0.27
Dry Unit Weight	15.23 kN/m ³		
Relative Density	19 %	Pipe Progression Rate	0.40 cm/s
Sample Length	65.1 cm	Flow Rate	2.037 L/min
Measured Slope Angle	38.0 °	Darcy Average Velocity	1.13E-03 m/s
		Sample Permeability	4.19E-03 m/s

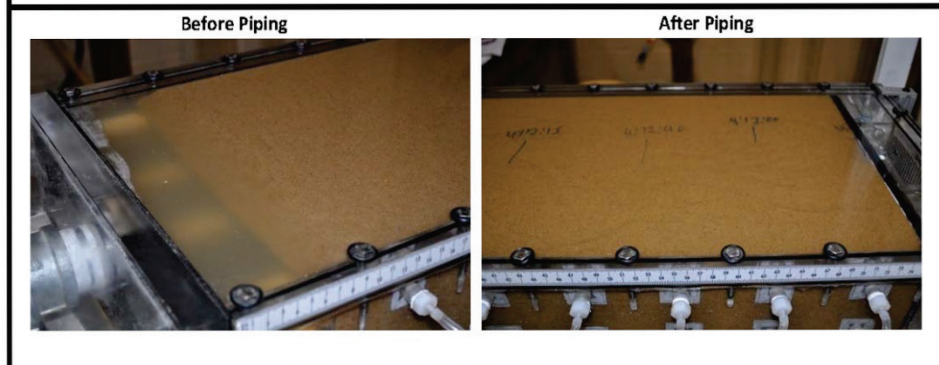
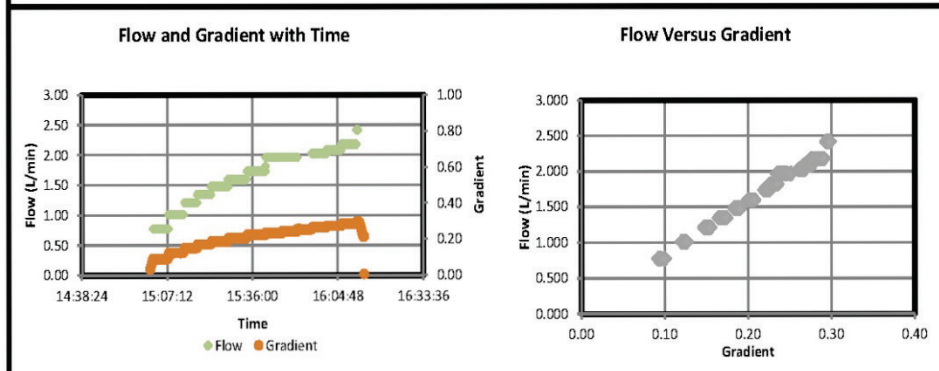
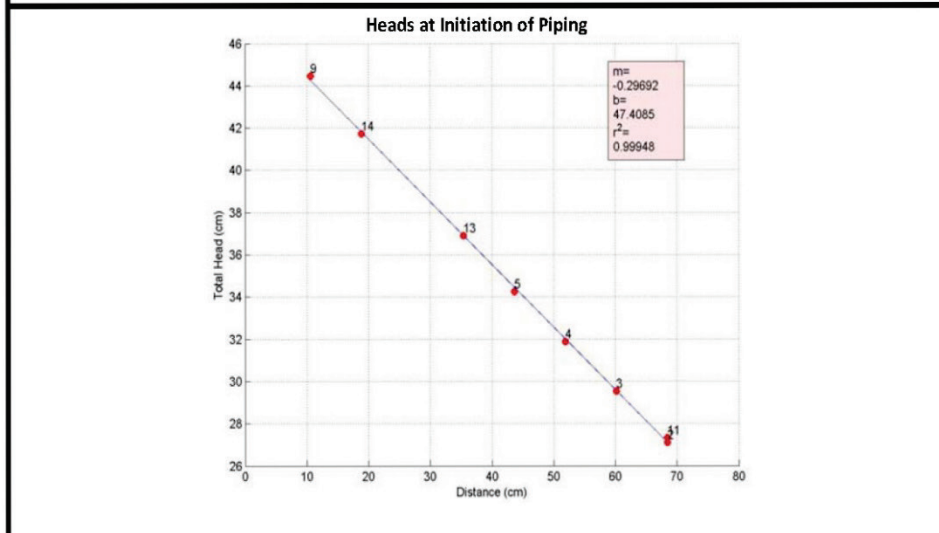
Notes: Transducer 7 and 12 not working
 Pipe exhibited stop and go behavior until 3.5 cm of pipe length.



Sand Type	<u>20-40</u>	Date	<u>30-Jun-14</u>
Test Number	<u>3</u>	Start Time	<u>14:59:45</u>
Tested by	<u>A.M.,A.W.</u>	End Time	<u>16:15:21</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.73 kg	Time at Piping	16:11:29
Soil Volume	0.02052 m ³	Least-Squares Fit Gradient	0.30
Dry Unit Weight	15.17 kN/m ³		
Relative Density	16 %	Pipe Progression Rate	0.54 cm/s
Sample Length	65.3 cm	Flow Rate	2.420 L/min
Measured Slope Angle	38.0 °	Darcy Average Velocity	1.34E-03 m/s
		Sample Permeability	4.48E-03 m/s

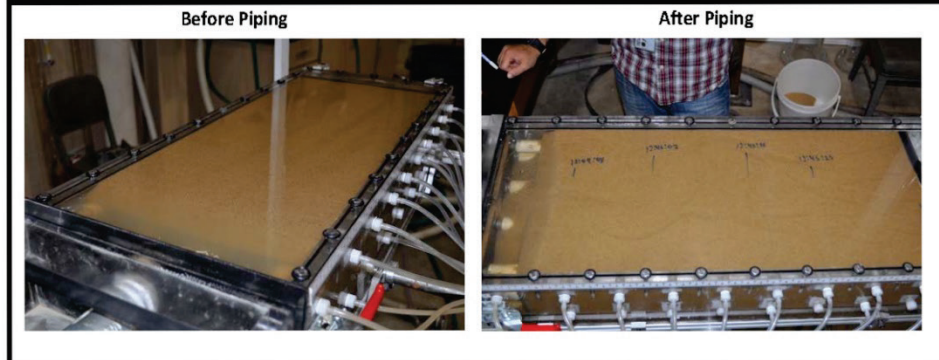
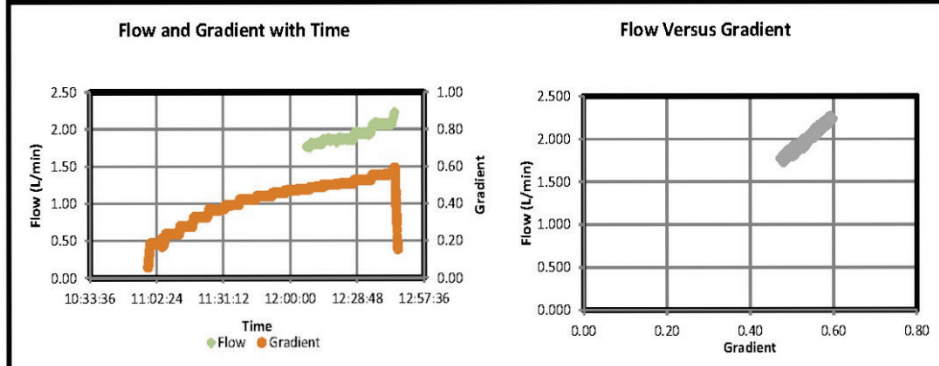
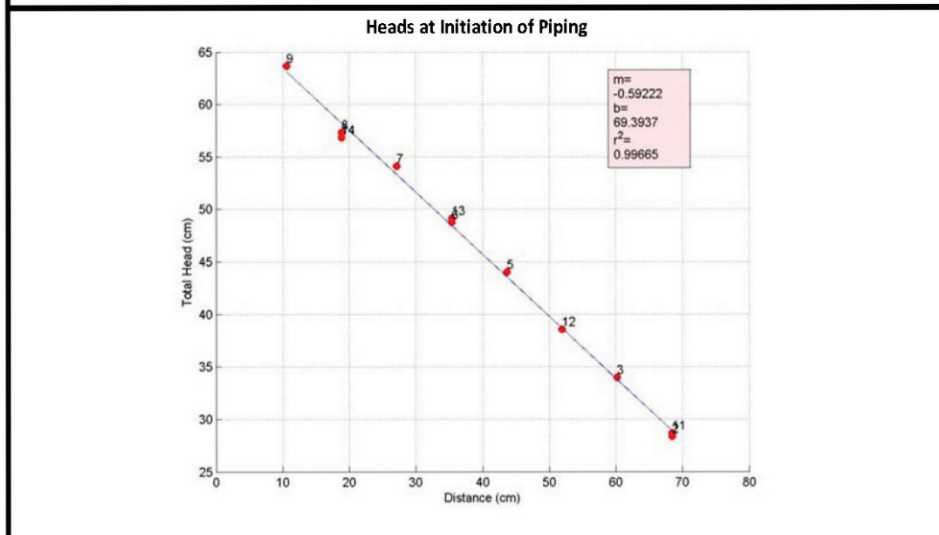
Notes: Transducer 7, 8 and 12 not working



Sand Type	<u>20-40</u>	Date	<u>25-Jul-14</u>
Test Number	<u>5</u>	Start Time	<u>10:58:36</u>
Tested by	<u>A.M.,A.W.</u>	End Time	<u>12:46:16</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.27 kg	Time at Piping	12:44:48
Soil Volume	0.02070 m ³	Least-Squares Fit Gradient	0.59
Dry Unit Weight	16.72 kN/m ³		
Relative Density	83 %	Pipe Progression Rate	1.07 cm/s
Sample Length	65.6 cm	Flow Rate	2.237 L/min
Measured Slope Angle	36.0 °	Darcy Average Velocity	1.24E-03 m/s
		Sample Permeability	2.11E-03 m/s

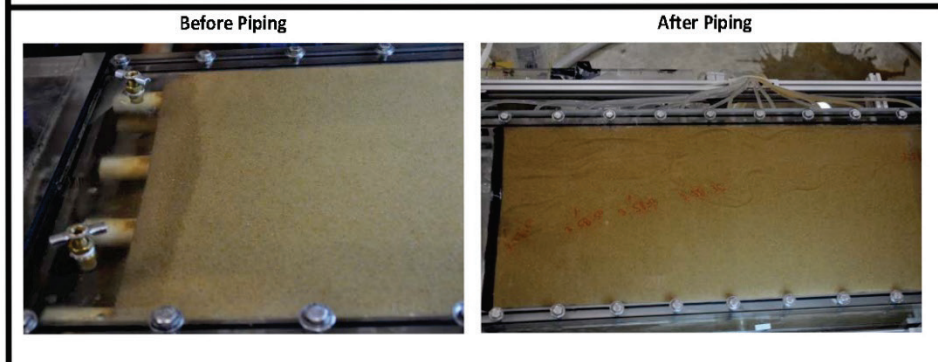
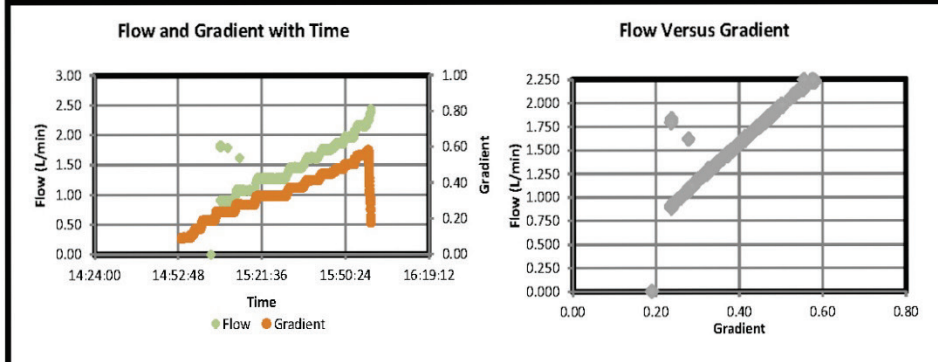
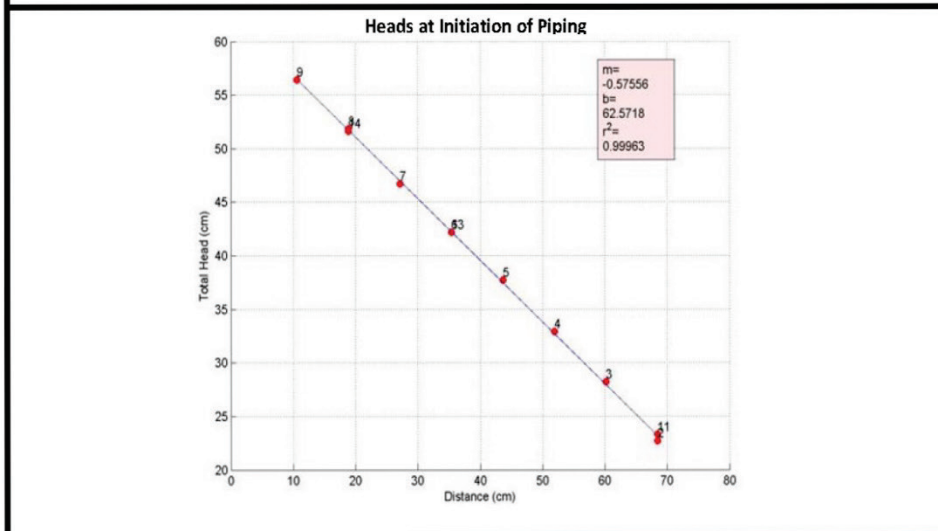
Notes: Transducer 4 not working properly
Flowmeter used for flow measurements



Sand Type	<u>20-40</u>	Date	<u>10-Oct-14</u>
Test Number	<u>6</u>	Start Time	<u>14:53:59</u>
Tested by	<u>A.M.,J.R.,S.S.</u>	End Time	<u>15:59:13</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.32 kg	Time at Piping	15:58:09
Soil Volume	0.02076 m ³	Least-Squares Fit Gradient	0.58
Dry Unit Weight	16.69 kN/m ³		
Relative Density	82 %	Pipe Progression Rate	1.30 cm/s
Sample Length	66.3 cm	Flow Rate	2.237 L/min
Measured Slope Angle	40.0 °	Darcy Average Velocity	1.24E-03 m/s
		Sample Permeability	2.15E-03 m/s

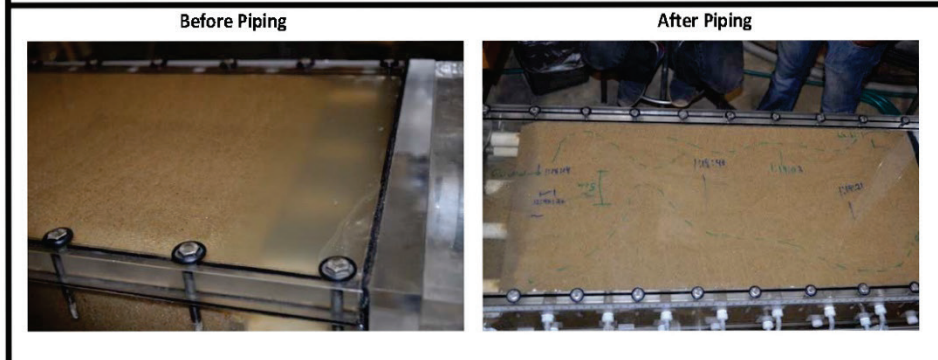
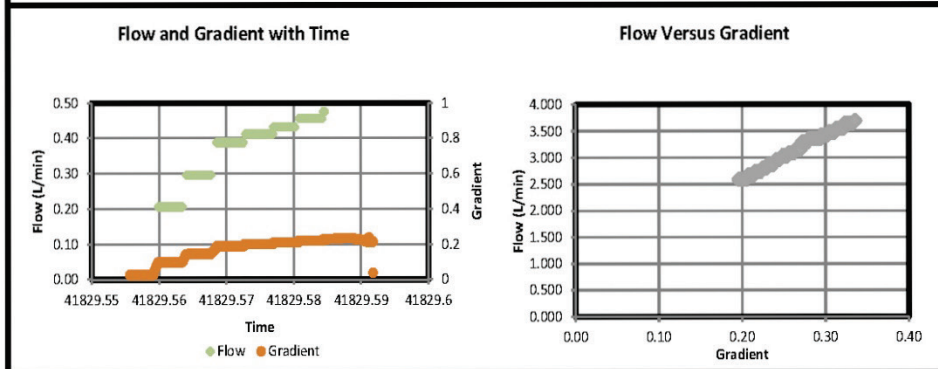
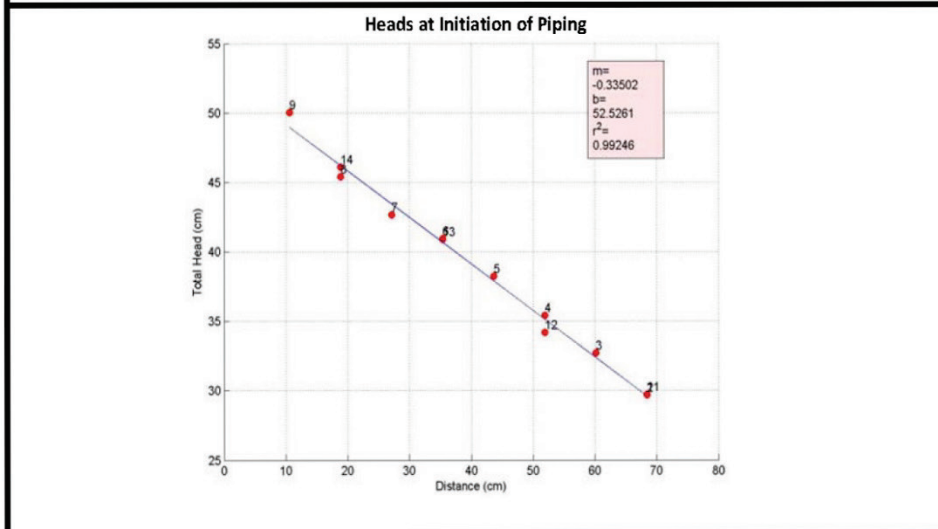
Notes: Transducer 12 not working properly
Flowmeter used for flow measurements



Sand Type	<u>16-30</u>	Date	<u>11-Jul-14</u>
Test Number	<u>1</u>	Start Time	<u>11:48:23</u>
Tested by	<u>A.M.,A.W.</u>	End Time	<u>13:20:15</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.91 kg	Time at Piping	13:18:14
Soil Volume	0.02046 m ³	Least-Squares Fit Gradient	0.34
Dry Unit Weight	15.30 kN/m ³		
Relative Density	18 %	Pipe Progression Rate	0.62 cm/s
Sample Length	65.2 cm	Flow Rate	3.700 L/min
Measured Slope Angle	36.0 °	Darcy Average Velocity	2.06E-03 m/s
		Sample Permeability	6.14E-03 m/s

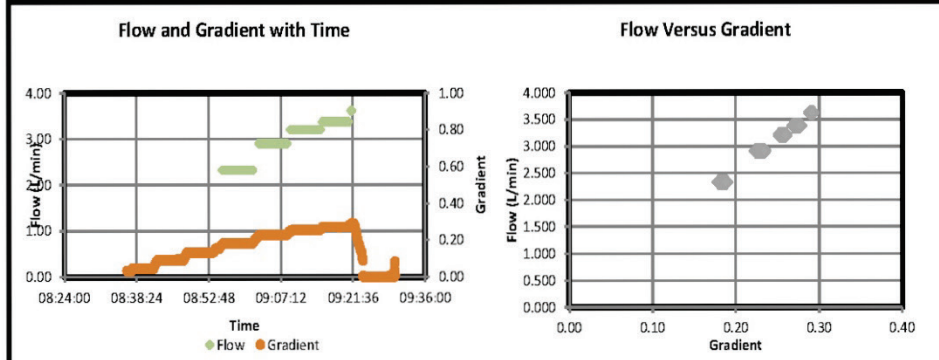
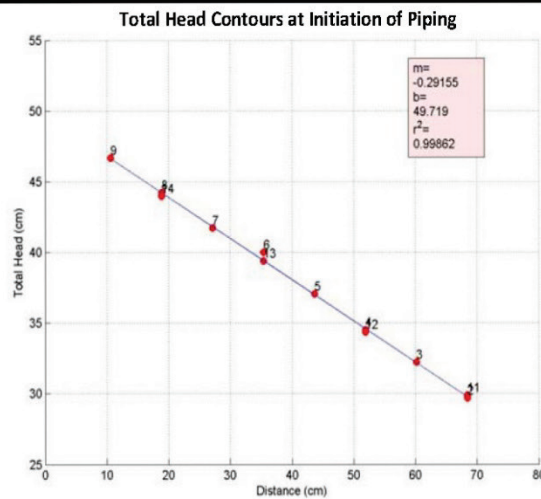
Notes: Transducer 12 not working properly
 Flowmeter used for flow measurements
 Initiated and piped at 0.33, but stopped after 2.5 cm



Sand Type	16-30	Date	11-Jul-14
Test Number	2	Start Time	8:36:29
Tested by	A.M.,A.W., H.S.	End Time	9:30:03

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.7 kg	Time at Piping	09:21:24
Soil Volume	0.02049 m ³	Least-Squares Fit Gradient	0.29
Dry Unit Weight	15.2 kN/m ³		
Relative Density	12 %	Pipe Progression Rate	0.53 cm/s
Sample Length	64.9 cm	Flow Rate	3.620 L/min
Measured Slope Angle	36.0 °	Darcy Average Velocity	2.01E-03 m/s
		Sample Permeability	6.90E-03 m/s

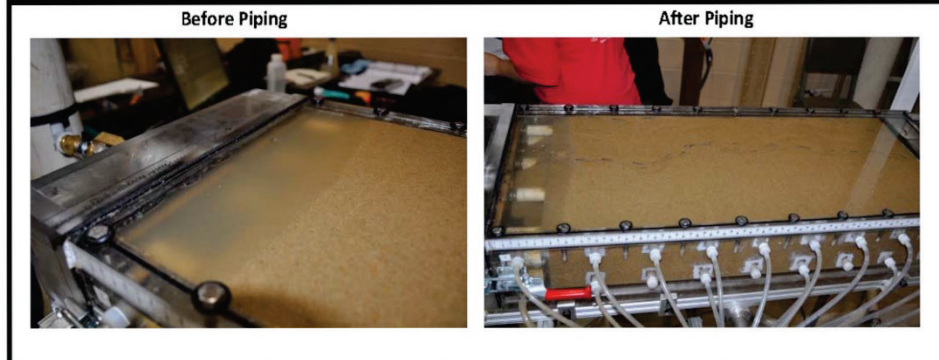
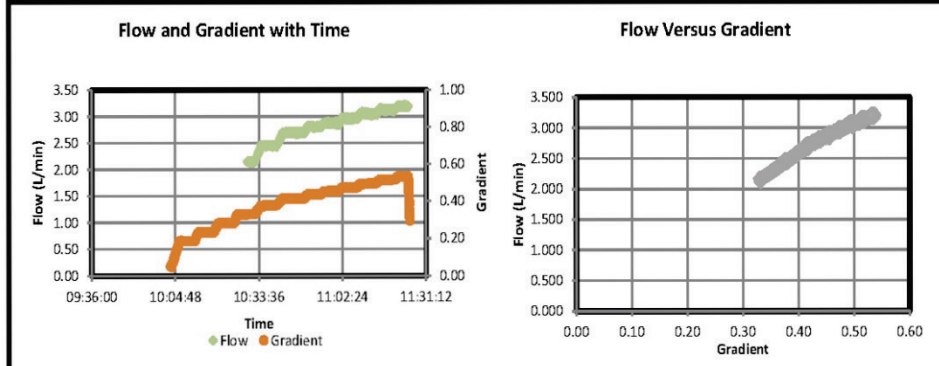
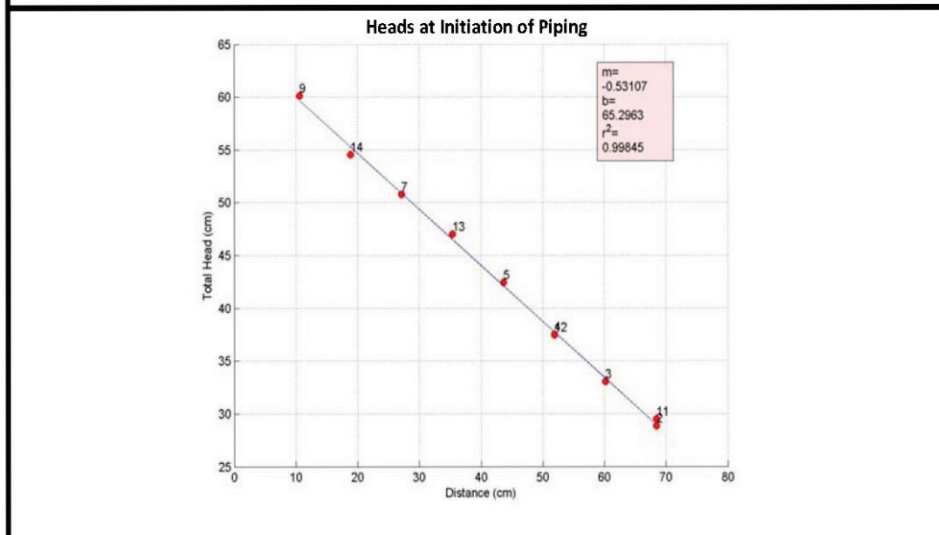
Notes: Transducer 12 not working properly
Flowmeter used for flow measurements



Sand Type	<u>16-30</u>	Date	<u>28-Jul-14</u>
Test Number	<u>3</u>	Start Time	<u>10:03:09</u>
Tested by	<u>A.M.,A.W., H.S.</u>	End Time	<u>11:25:43</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.32 kg	Time at Piping	11:25:00
Soil Volume	0.02070 m ³	Least-Squares Fit Gradient	0.53
Dry Unit Weight	16.74 kN/m ³		
Relative Density	82 %	Pipe Progression Rate	1.65 cm/s
Sample Length	65.8 cm	Flow Rate	3.203 L/min
Measured Slope Angle	37.5 °	Darcy Average Velocity	1.78E-03 m/s
		Sample Permeability	3.36E-03 m/s

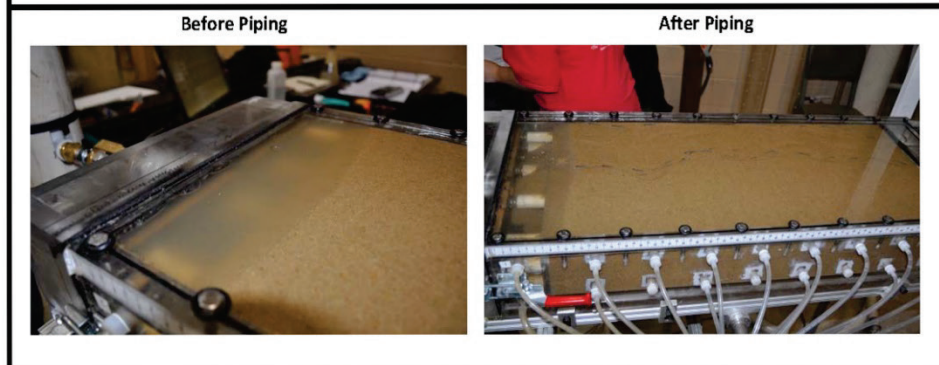
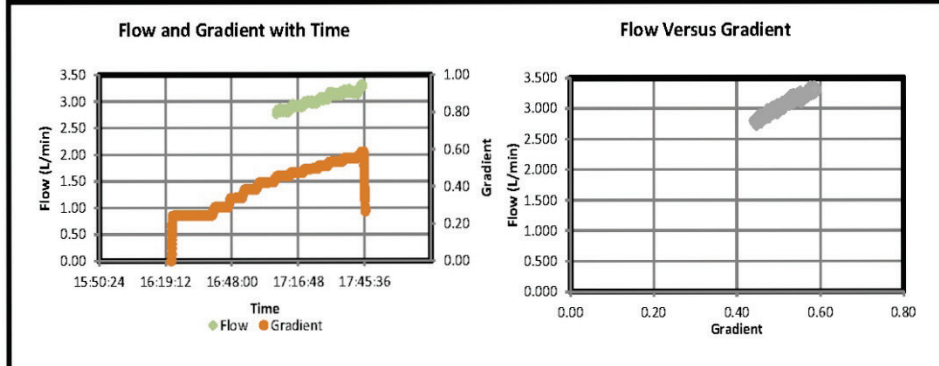
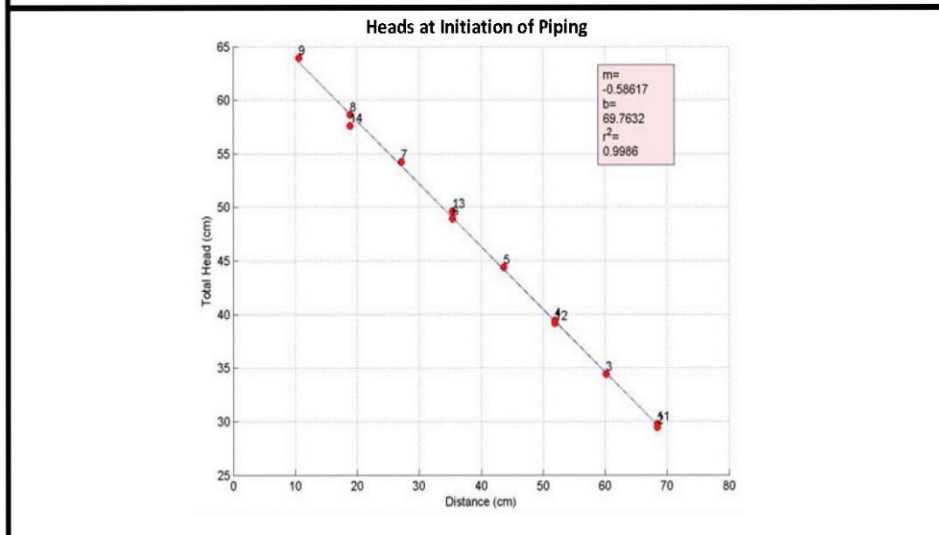
Notes: Flowmeter used for flow measurements
 Pipe initiated and stopped repeatedly until pipe was 6 cm long.



Sand Type	<u>16-30</u>	Date	<u>28-Jul-14</u>
Test Number	<u>4</u>	Start Time	<u>16:21:31</u>
Tested by	<u>A.M.,A.W., H.S.</u>	End Time	<u>17:46:03</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.59 kg	Time at Piping	17:44:54
Soil Volume	0.02091 m ³	Least-Squares Fit Gradient	0.59
Dry Unit Weight	16.70 kN/m ³		
Relative Density	82 %	Pipe Progression Rate	1.16 cm/s
Sample Length	66.0 cm	Flow Rate	3.323 L/min
Measured Slope Angle	37.5 °	Darcy Average Velocity	1.85E-03 m/s
		Sample Permeability	3.13E-03 m/s

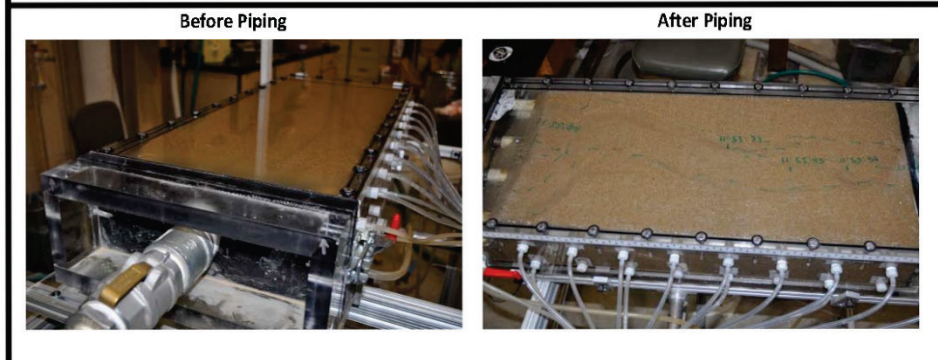
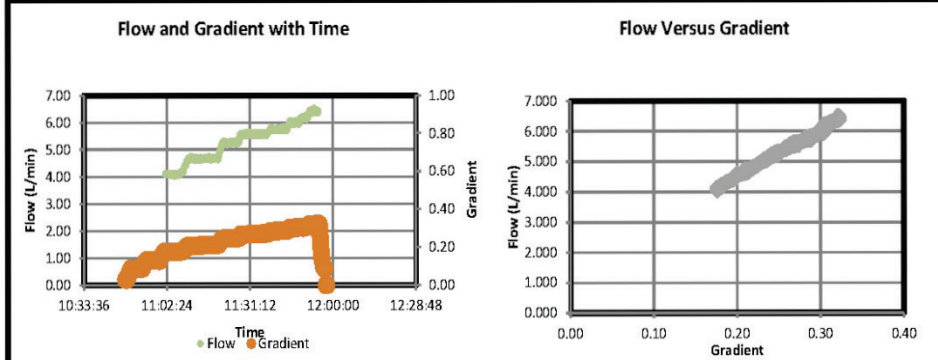
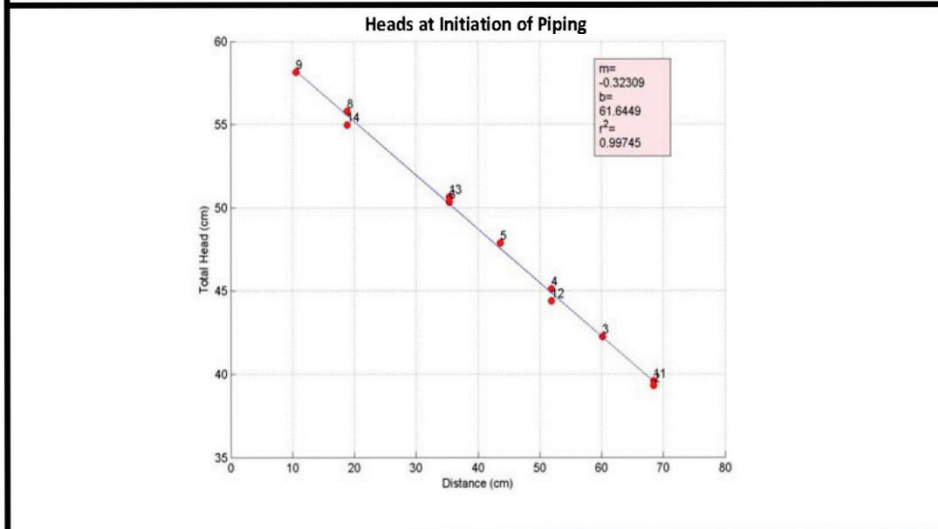
Notes: Flowmeter used for flow measurements



Sand Type 12-20 Date 19-Jul-14
 Test Number 1 Start Time 10:47:59
 Tested by A.M.,A.W. End Time 11:57:50

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.64 kg	Time at Piping	11:55:00
Soil Volume	0.02037 m ³	Least-Squares Fit Gradient	0.32
Dry Unit Weight	15.24 kN/m ³		
Relative Density	26 %	Pipe Progression Rate	0.84 cm/s
Sample Length	64.9 cm	Flow Rate	6.416 L/min
Measured Slope Angle	38.0 °	Darcy Average Velocity	3.56E-03 m/s
		Sample Permeability	1.11E-02 m/s

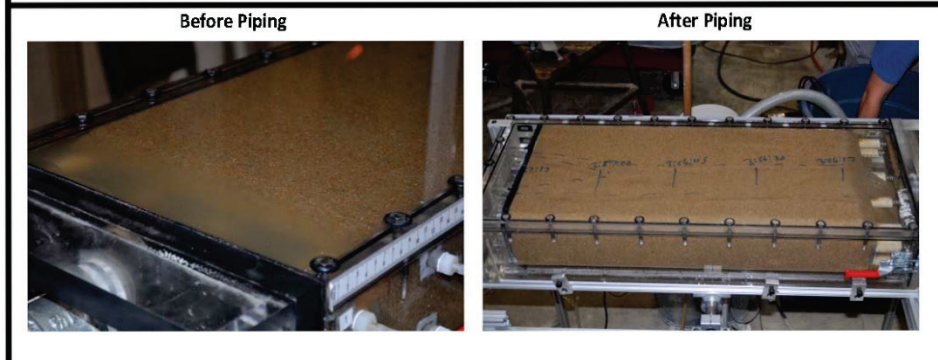
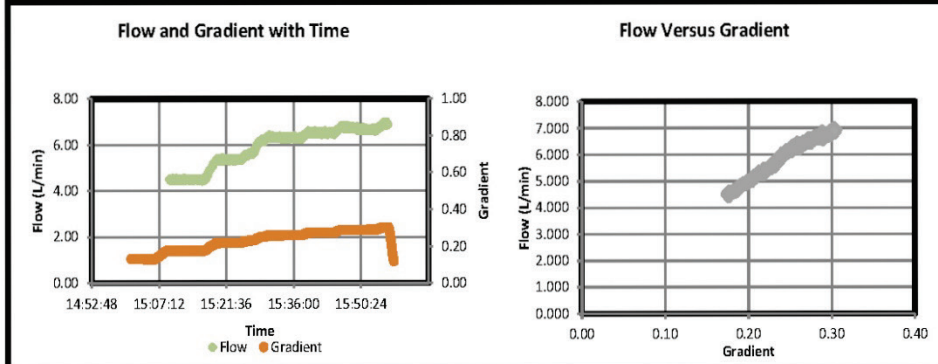
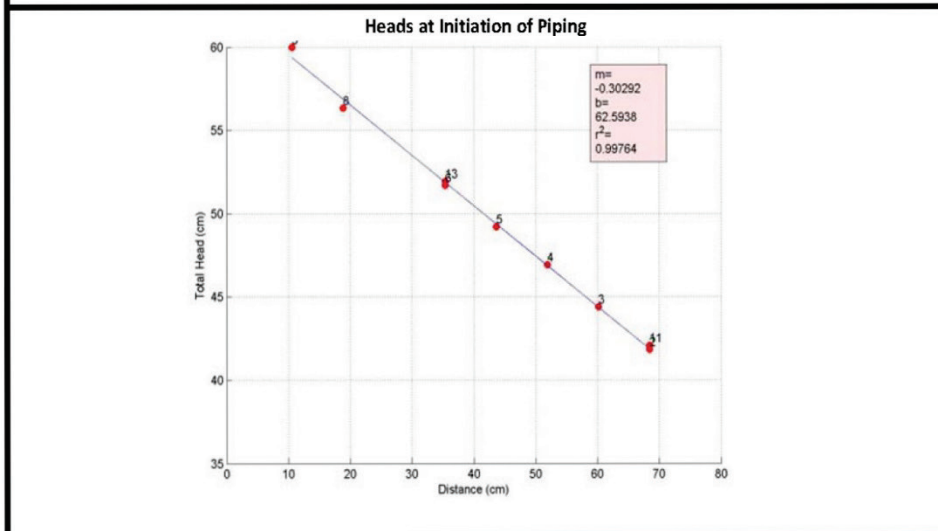
Notes: Flowmeter used for flow measurements



Sand Type 12-20 Date 19-Jul-14
 Test Number 2 Start Time 15:01:16
 Tested by A.M.,A.W. End Time 15:57:25

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.18 kg	Time at Piping	15:56:17
Soil Volume	0.02037 m ³	Least-Squares Fit Gradient	0.30
Dry Unit Weight	15.02 kN/m ³		
Relative Density	15 %	Pipe Progression Rate	1.07 cm/s
Sample Length	64.9 cm	Flow Rate	6.898 L/min
Measured Slope Angle	37.0 °	Darcy Average Velocity	3.83E-03 m/s
		Sample Permeability	1.28E-02 m/s

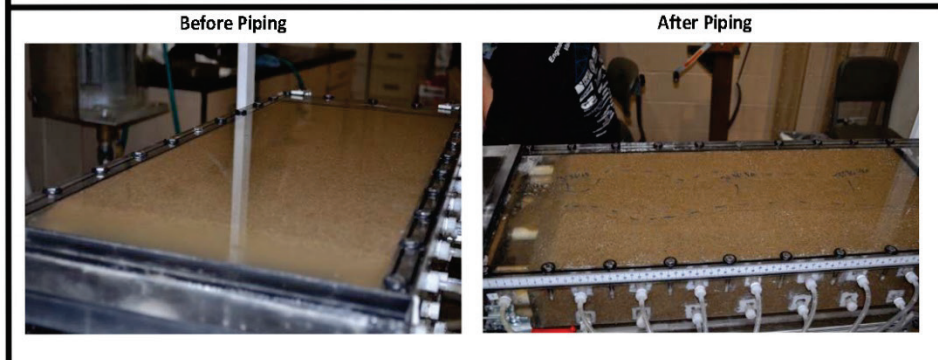
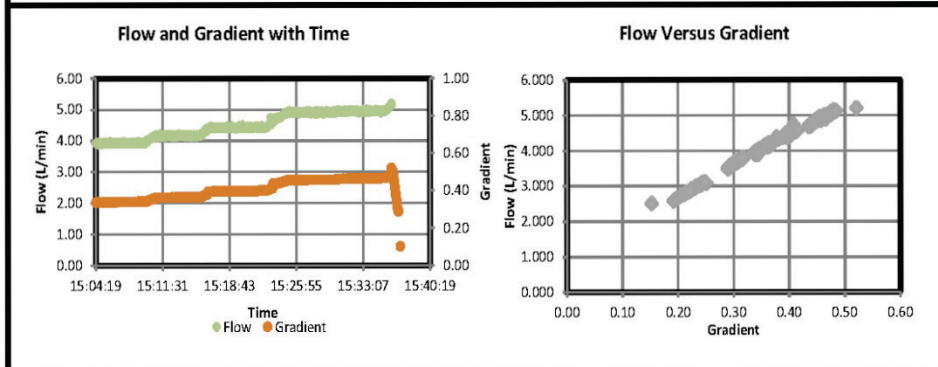
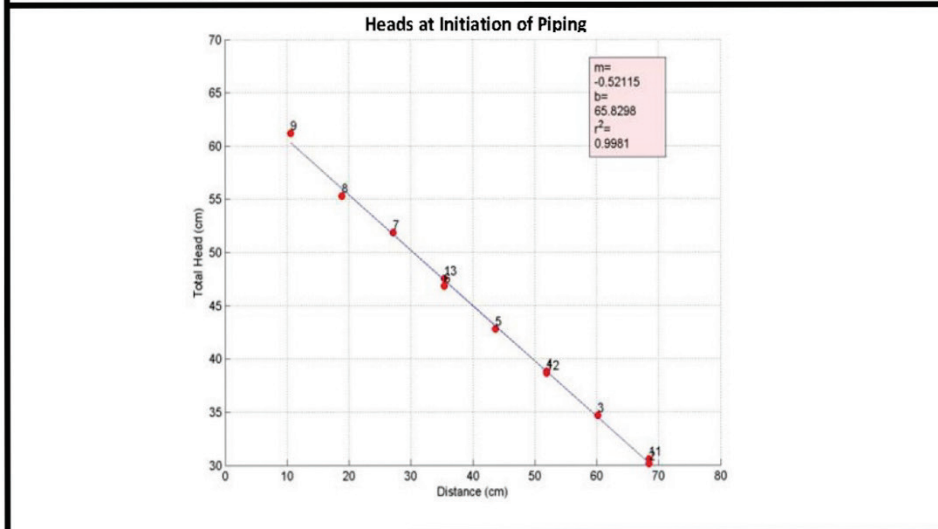
Notes: Flowmeter used for flow measurements



Sand Type	<u>12-20</u>	Date	<u>19-Jul-14</u>
Test Number	<u>3</u>	Start Time	<u>13:58:51</u>
Tested by	<u>A.M.,A.W.,H.S.</u>	End Time	<u>15:37:06</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.95 kg	Time at Piping	15:56:17
Soil Volume	0.02073 m ³	Least-Squares Fit Gradient	0.52
Dry Unit Weight	16.54 kN/m ³		
Relative Density	86 %	Pipe Progression Rate	1.61 cm/s
Sample Length	66.0 cm	Flow Rate	5.210 L/min
Measured Slope Angle	40.0 °	Darcy Average Velocity	2.89E-03 m/s
		Sample Permeability	5.57E-03 m/s

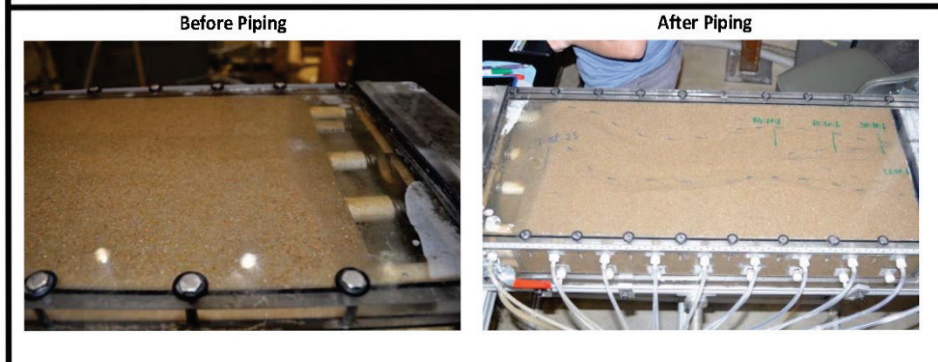
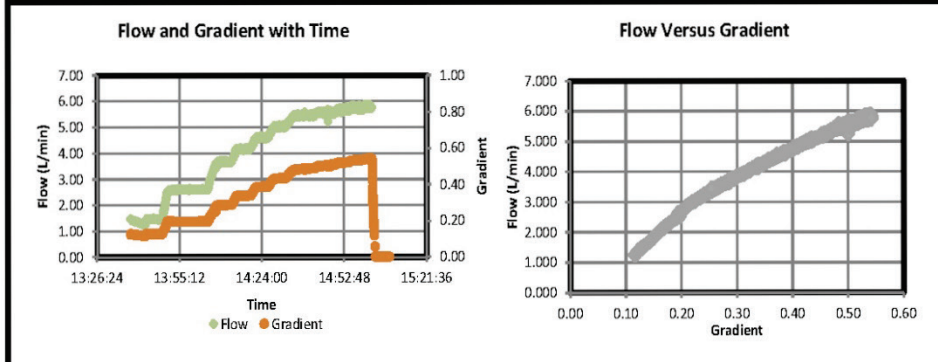
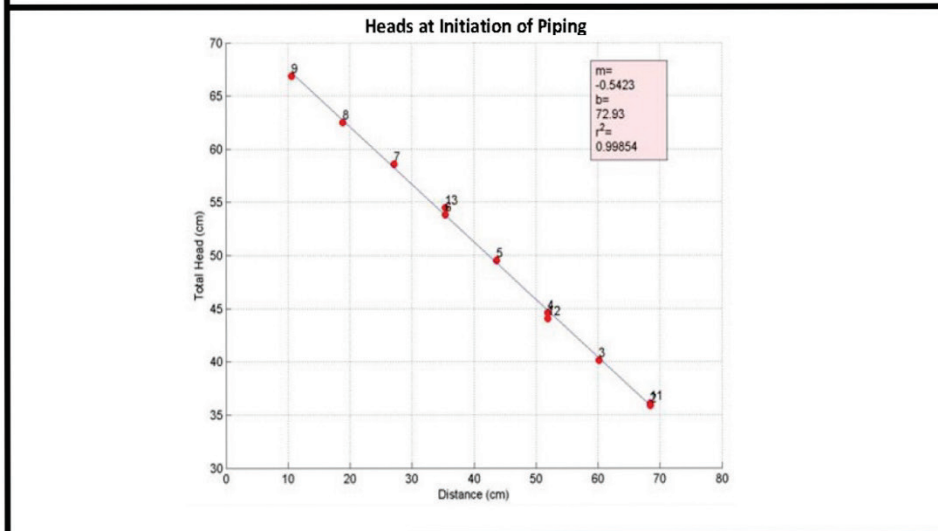
Notes: Flowmeter used for flow measurements
 Tailwater apparatus too small for flow, required replacement in the middle of test.
 Initially piped 3.5 cm and stopped.



Sand Type 12-20 Date 31-Jul-14
 Test Number 4 Start Time 13:38:09
 Tested by A.M.,A.W.,H.S. End Time 15:08:40

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.86 kg	Time at Piping	15:02:25
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.54
Dry Unit Weight	16.57 kN/m ³		
Relative Density	88 %	Pipe Progression Rate	1.16 cm/s
Sample Length	66.2 cm	Flow Rate	5.77 L/min
Measured Slope Angle	40.0 °	Darcy Average Velocity	3.20E-03 m/s
		Sample Permeability	5.93E-03 m/s

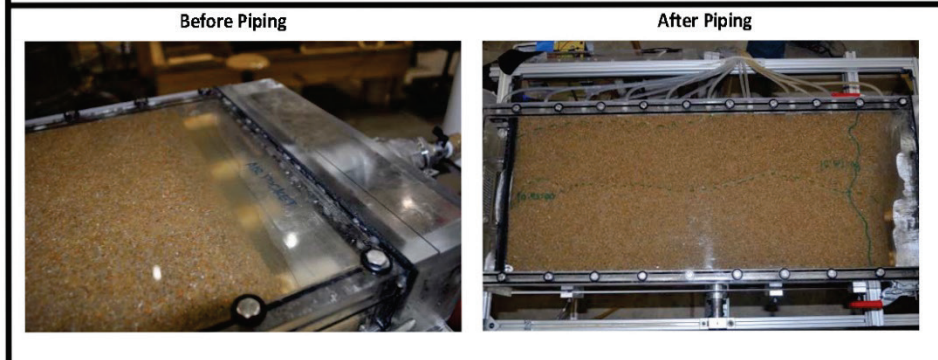
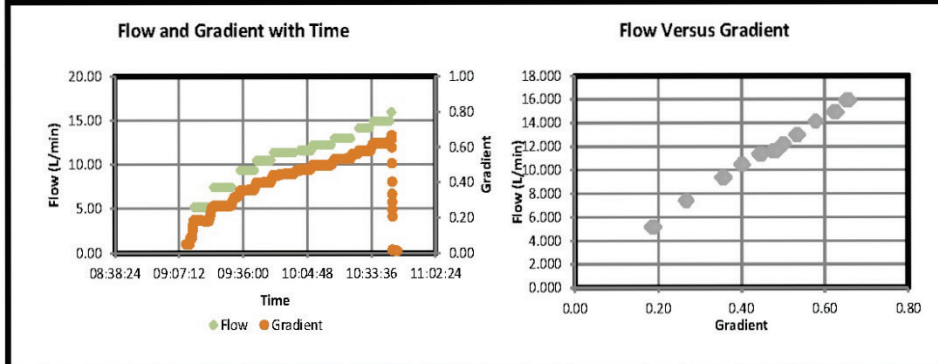
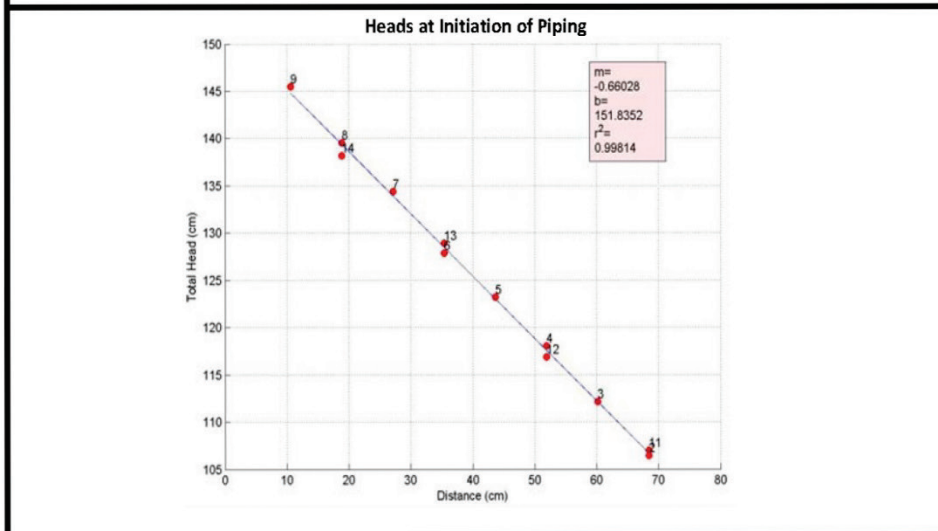
Notes: Flowmeter used for flow measurements



Sand Type 8-16 Date 4-Aug-14
 Test Number 2 Start Time 9:10:24
 Tested by A.M.,A.W.,H.S. End Time 10:45:17

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.32 kg	Time at Piping	10:42:43
Soil Volume	0.02071 m ³	Least-Squares Fit Gradient	0.66
Dry Unit Weight	16.73 kN/m ³		
Relative Density	77 %	Pipe Progression Rate	3.91 cm/s
Sample Length	66.4 cm	Flow Rate	15.938 L/min
Measured Slope Angle	40.0 °	Darcy Average Velocity	8.85E-03 m/s
		Sample Permeability	1.34E-02 m/s

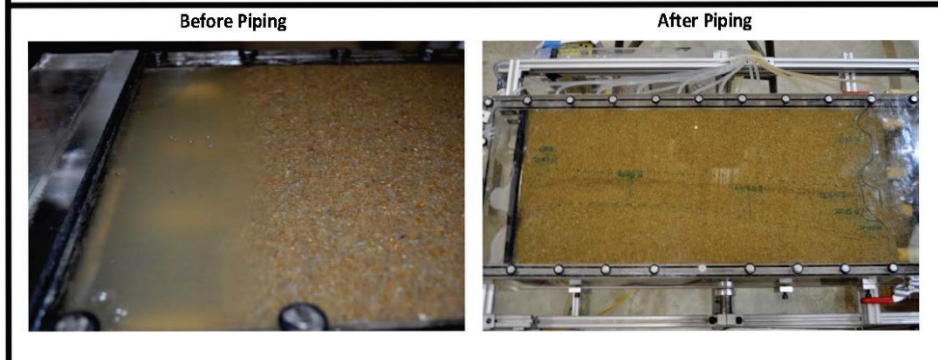
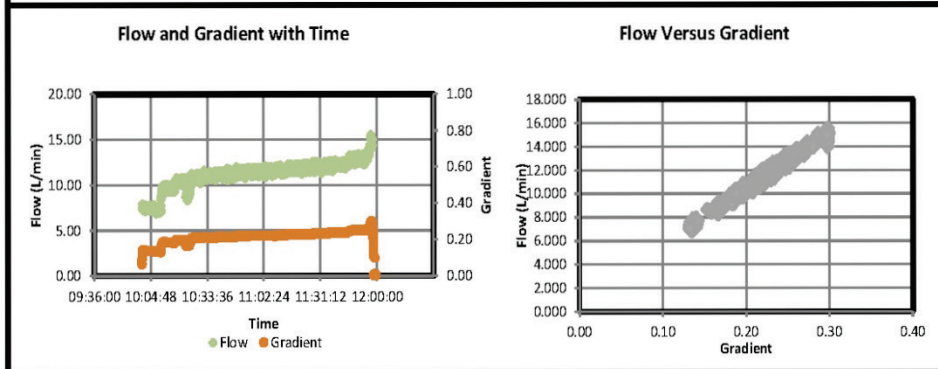
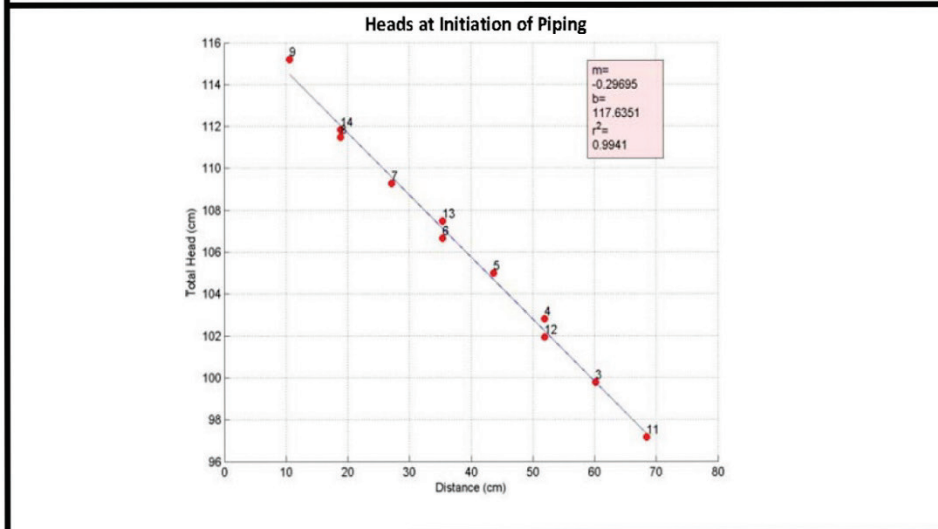
Notes: Leak occurred at top of flume during test.



Sand Type	<u>8-16</u>	Date	<u>8-Aug-14</u>
Test Number	<u>3</u>	Start Time	<u>10:00:12</u>
Tested by	<u>A.M.,H.S.,M.T.</u>	End Time	<u>11:59:33</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.55 kg	Time at Piping	11:57:37
Soil Volume	0.02043 m ³	Least-Squares Fit Gradient	0.30
Dry Unit Weight	15.15 kN/m ³		
Relative Density	8 %	Pipe Progression Rate	1.79 cm/s
Sample Length	66.4 cm	Flow Rate	14.976 L/min
Measured Slope Angle	40.0 °	Darcy Average Velocity	8.32E-03 m/s
		Sample Permeability	2.77E-02 m/s

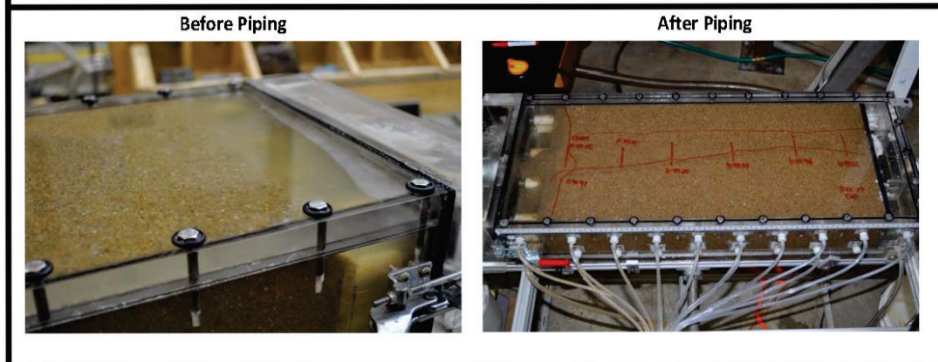
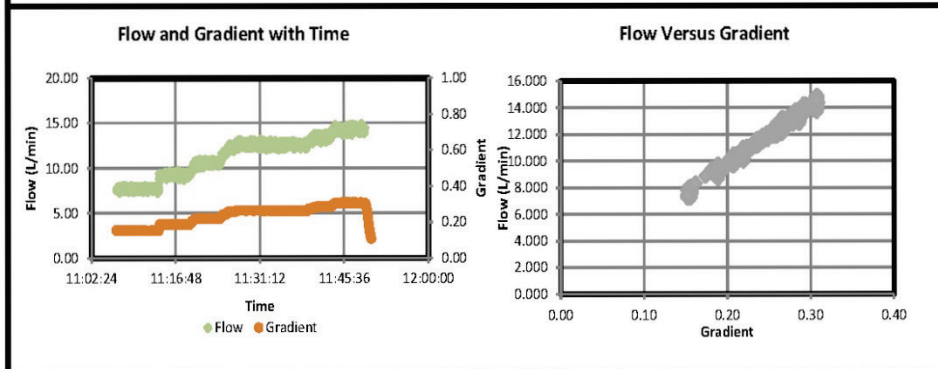
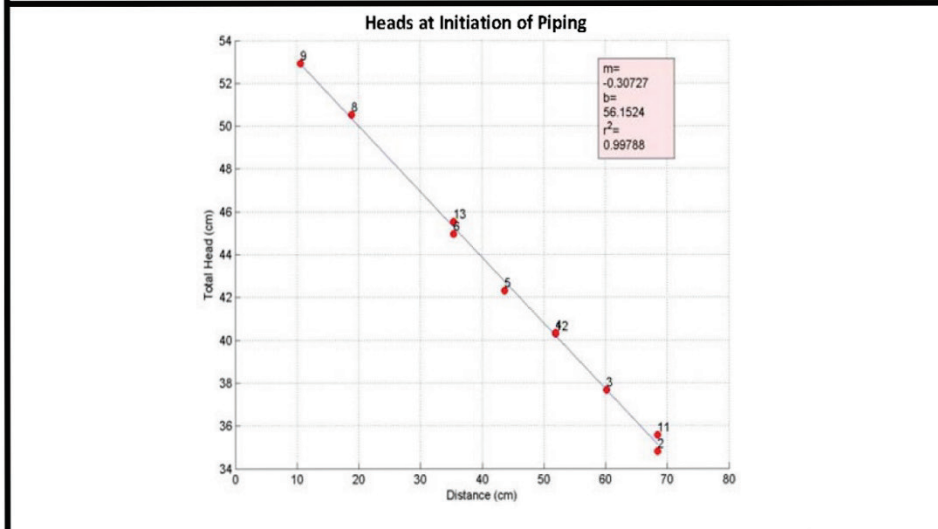
Notes: Flow measurements taken with flowmeter. Pump was used for water supply.
 Gradient from manometers very different due to head loss across upstream wall.
 PPT12 no working.



Sand Type 8-16 Date 18-Aug-14
 Test Number 5 Start Time 11:06:35
 Tested by A.M.,H.S. End Time 11:50:11

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.55 kg	Time at Piping	11:49:05
Soil Volume	0.02043 m ³	Least-Squares Fit Gradient	0.31
Dry Unit Weight	15.15 kN/m ³		
Relative Density	9 %	Pipe Progression Rate	1.03 cm/s
Sample Length	65.8 cm	Flow Rate	14.52 L/min
Measured Slope Angle	44.0 °	Darcy Average Velocity	8.07E-03 m/s
		Sample Permeability	2.60E-02 m/s

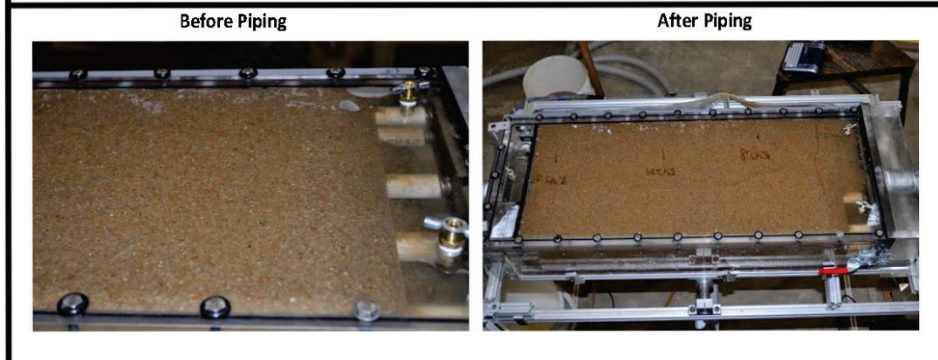
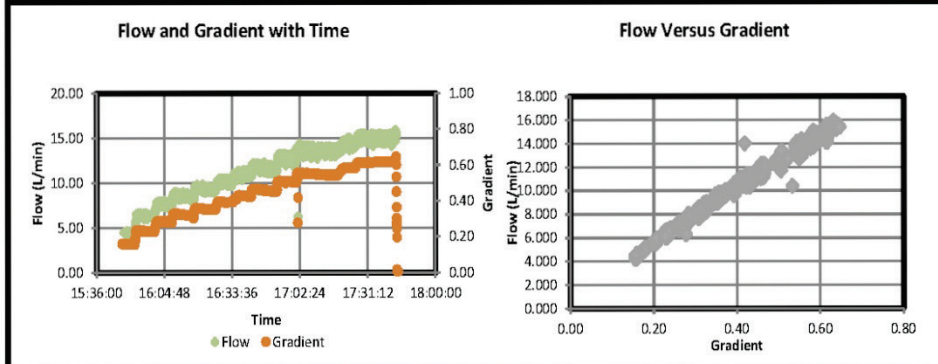
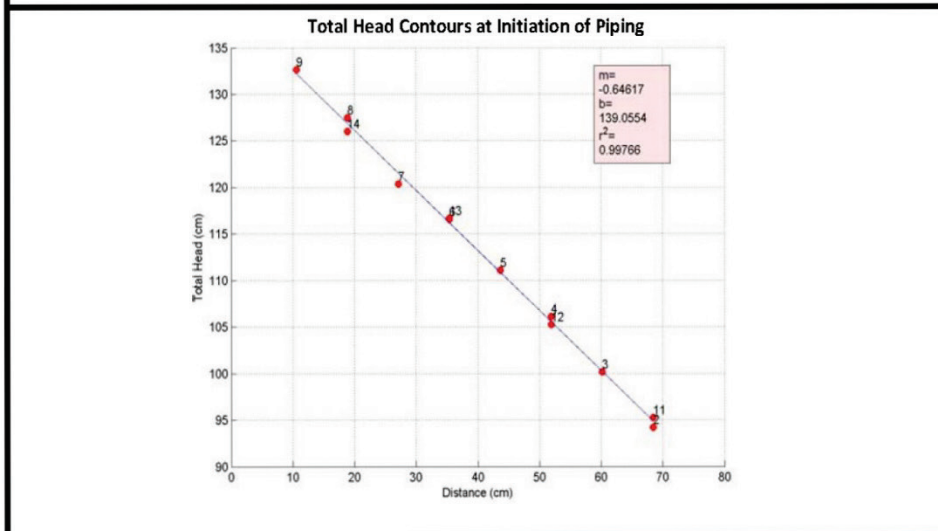
Notes: Flow measurements taken with flowmeter
 Transducers 7 and 14 not working properly
 Pump was used



Sand Type	8-16	Date	26-Aug-14
Test Number	6	Start Time	15:46:55
Tested by	A.M.,J.L.	End Time	17:44:06

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.1 kg	Time at Piping	17:43:16
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.65
Dry Unit Weight	16.7 kN/m ³		
Relative Density	81.7 %	Pipe Progression Rate	4.41 cm/s
Sample Length	66.2 cm	Flow Rate	15.377 L/min
Measured Slope Angle	41.0 °	Darcy Average Velocity	8.54E-03 m/s
		Sample Permeability	1.31E-02 m/s

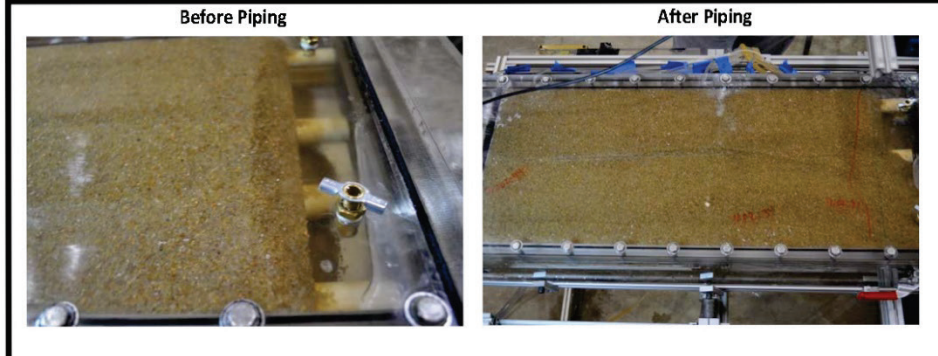
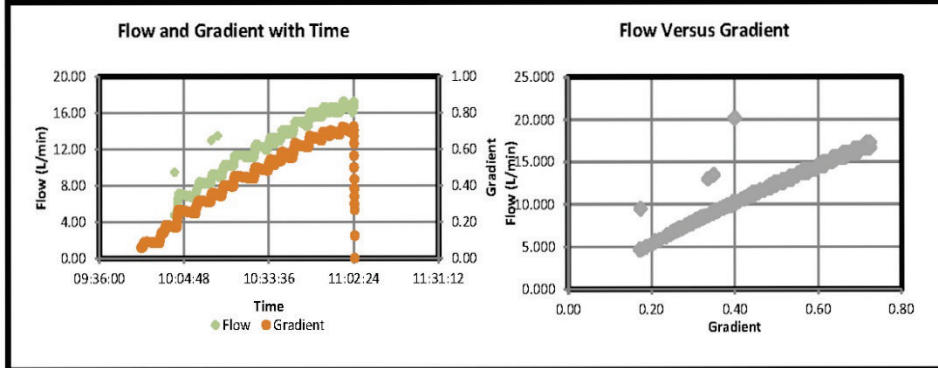
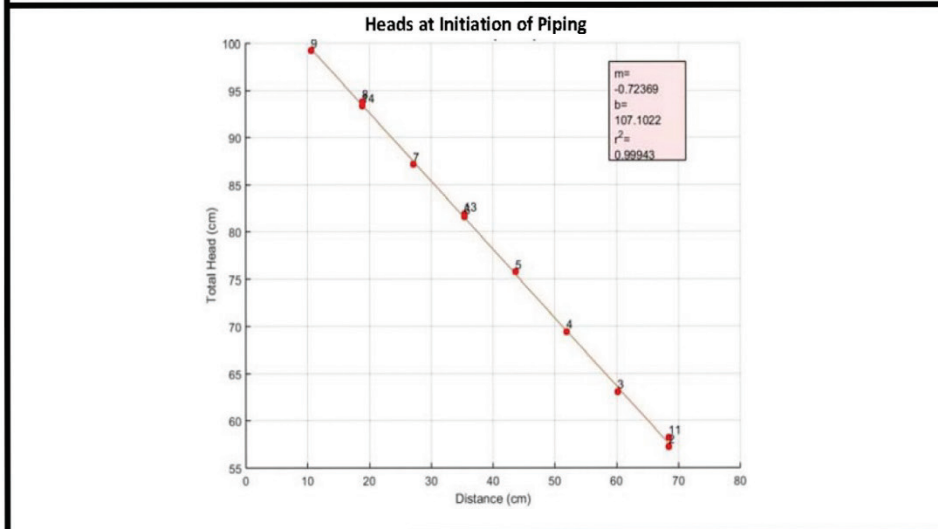
Notes: Flow measurements taken with flowmeter
While tilting the flume to horizontal position, air trapped moved through a passage on the left side.



Sand Type	<u>8-16</u>	Date	<u>20-Oct-14</u>
Test Number	<u>7</u>	Start Time	<u>9:50:07</u>
Tested by	<u>A.M.,S.S.,J.R.</u>	End Time	<u>11:02:48</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.1 kg	Time at Piping	11:02:30
Soil Volume	0.02082 m ³	Least-Squares Fit Gradient	0.72
Dry Unit Weight	16.6 kN/m ³		
Relative Density	72.8 %	Pipe Progression Rate	5.00 cm/s
Sample Length	66.8 cm	Flow Rate	17.250 L/min
Measured Slope Angle	48.0 °	Darcy Average Velocity	9.58E-03 m/s
		Sample Permeability	1.32E-02 m/s

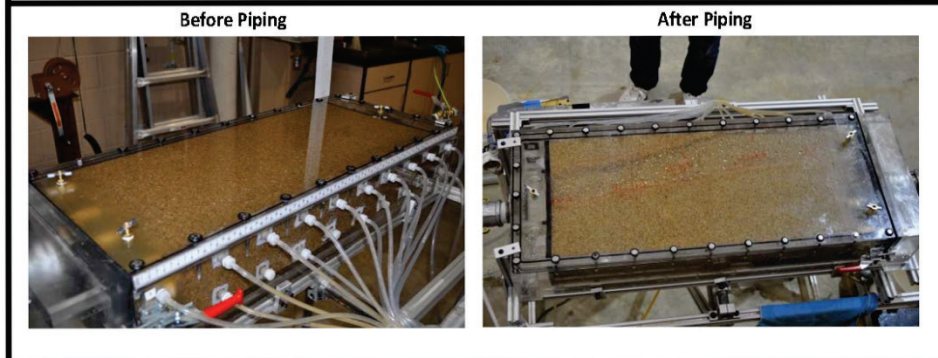
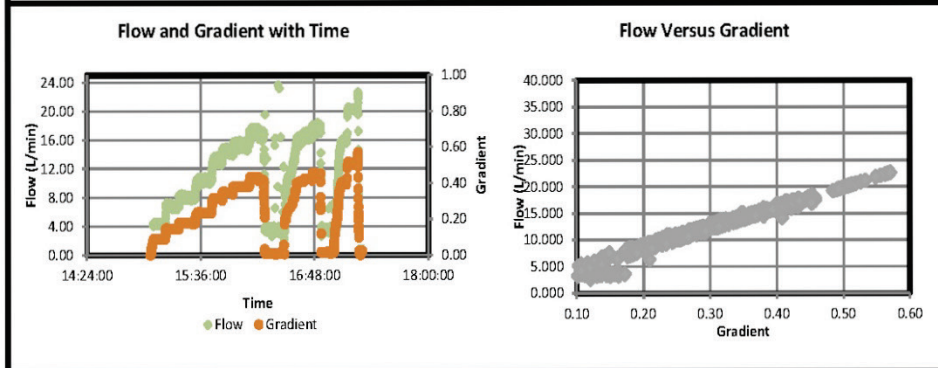
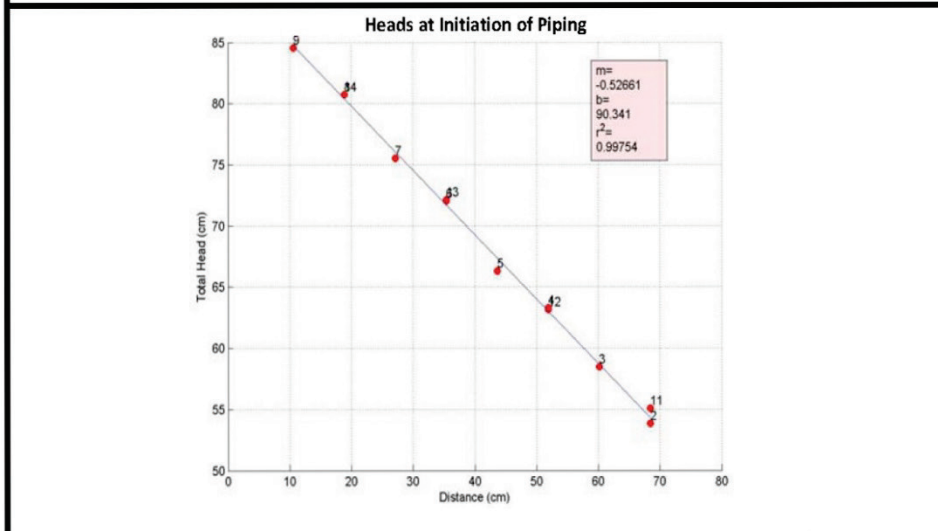
Notes: Flow measurements taken with flowmeter
Transducer 12 not working properly



Sand Type	<u>8-12</u>	Date	<u>28-Aug-14</u>
Test Number	<u>4</u>	Start Time	<u>15:03:55</u>
Tested by	<u>A.M.,J.L.</u>	End Time	<u>17:18:05</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.95 kg	Time at Piping	17:15:11
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.53
Dry Unit Weight	16.6 kN/m ³		
Relative Density	84.3 %	Pipe Progression Rate	2.00 cm/s
Sample Length	66.0 cm	Flow Rate	20.93 L/min
Measured Slope Angle	47.0 °	Darcy Average Velocity	1.16E-02 m/s
		Sample Permeability	2.21E-02 m/s

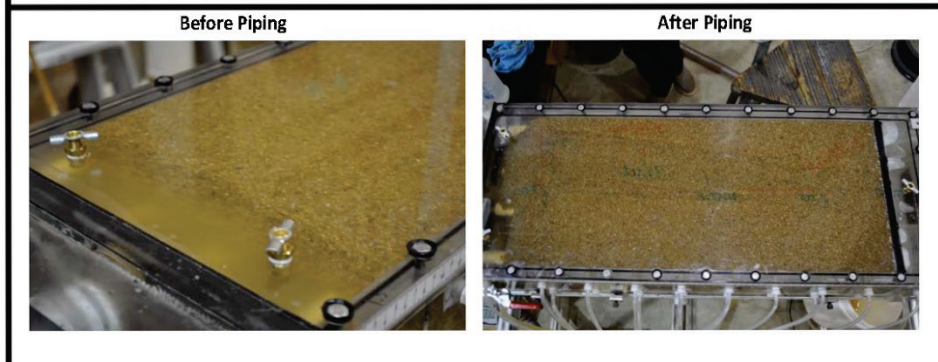
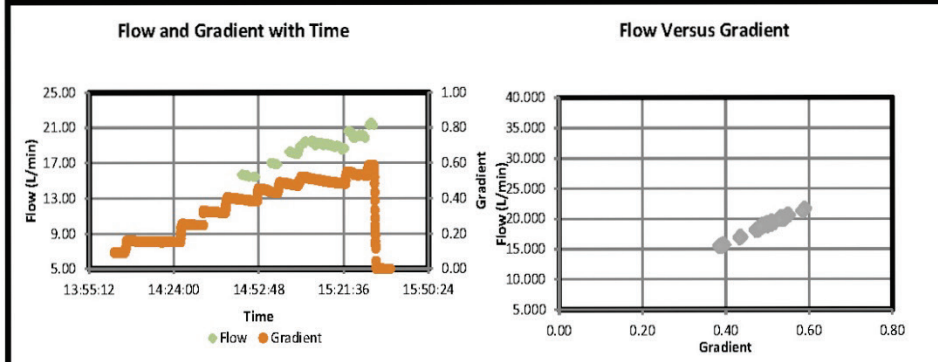
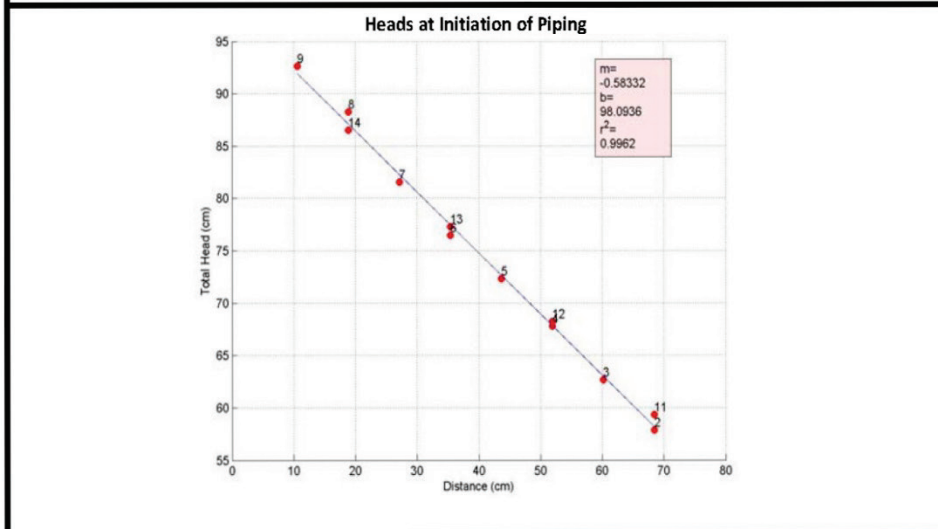
Notes: Flow measurements taken with flowmeter
 Test was paused due to overflow of head tank. Tests was paused and tailwater valve removed.



Sand Type 8-12 Date 2-Sep-14
 Test Number 5 Start Time 14:03:50
 Tested by A.M.,J.L. End Time 15:37:23

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	35.09 kg	Time at Piping	15:31:51
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.58
Dry Unit Weight	16.68 kN/m ³		
Relative Density	87 %	Pipe Progression Rate	1.99 cm/s
Sample Length	65.8 cm	Flow Rate	21.310 L/min
Measured Slope Angle	47.5 °	Darcy Average Velocity	1.18E-02 m/s
		Sample Permeability	2.03E-02 m/s

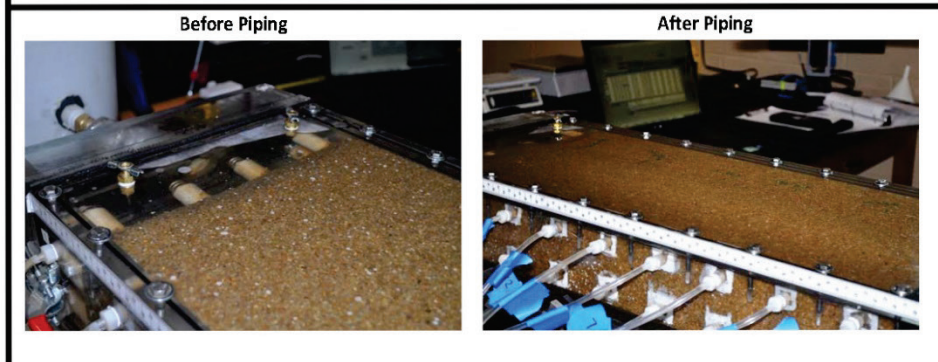
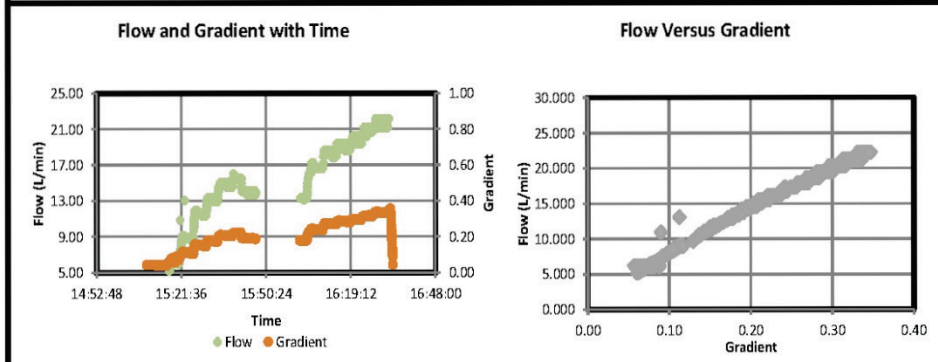
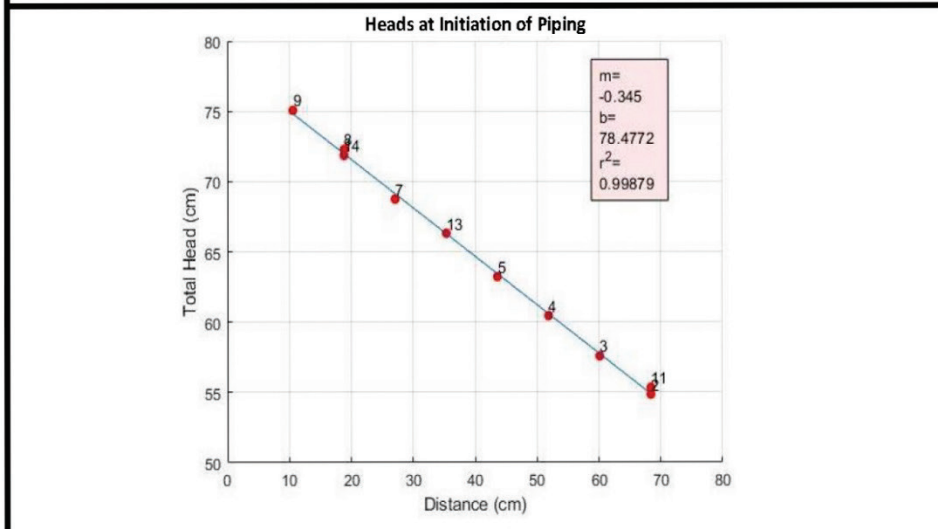
Notes: Flow measurements taken with flowmeter
 Flow measurements estimated at piping



Sand Type	<u>8-12</u>	Date	<u>20-Oct-14</u>
Test Number	<u>6</u>	Start Time	<u>15:09:47</u>
Tested by	<u>A.M.,S.S., J.R.</u>	End Time	<u>16:33:31</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.59 kg	Time at Piping	16:32:09
Soil Volume	0.02064 m ³	Least-Squares Fit Gradient	0.35
Dry Unit Weight	15.01 kN/m ³		
Relative Density	7 %	Pipe Progression Rate	1.05 cm/s
Sample Length	66 cm	Flow Rate	22.20 L/min
Measured Slope Angle	45.0 °	Darcy Average Velocity	1.23E-02 m/s
		Sample Permeability	3.57E-02 m/s

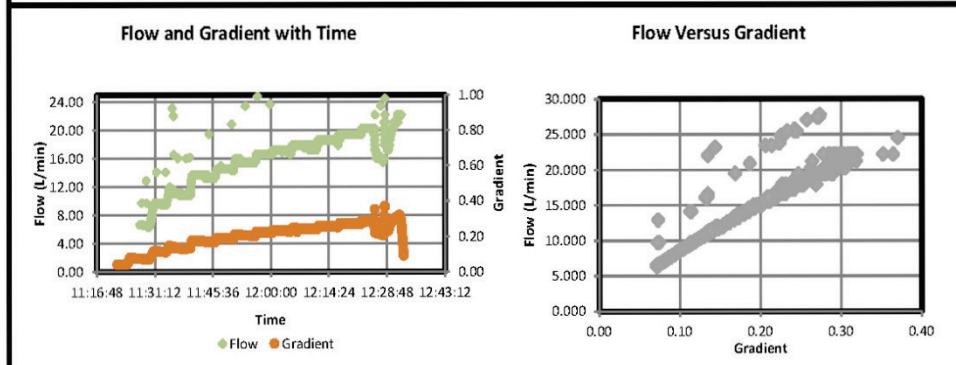
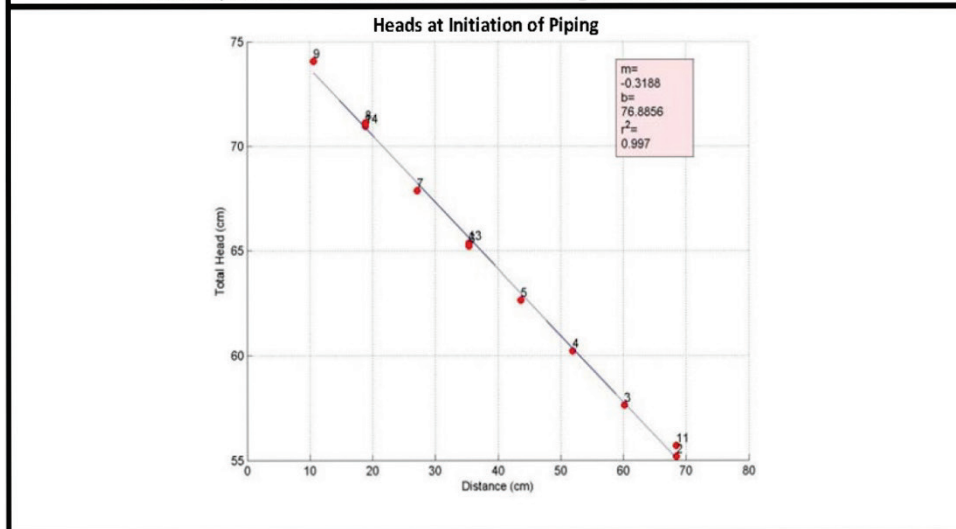
Notes: Flow measurements taken with flowmeter
PPTs 6 and 12 not working correctly



Sand Type 8-12 Date 21-Oct-14
 Test Number 7 Start Time 11:21:49
 Tested by A.M.,J.R. End Time 12:33:02

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.41 kg	Time at Piping	12:32:02
Soil Volume	0.02043 m ³	Least-Squares Fit Gradient	0.32
Dry Unit Weight	15.08 kN/m ³		
Relative Density	3 %	Pipe Progression Rate	1.35 cm/s
Sample Length	65.9 cm	Flow Rate	22.20 L/min
Measured Slope Angle	44.0 °	Darcy Average Velocity	1.23E-02 m/s
		Sample Permeability	3.87E-02 m/s

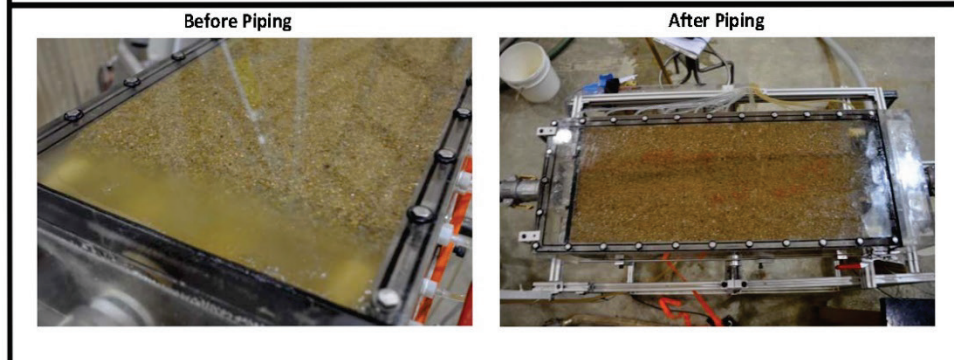
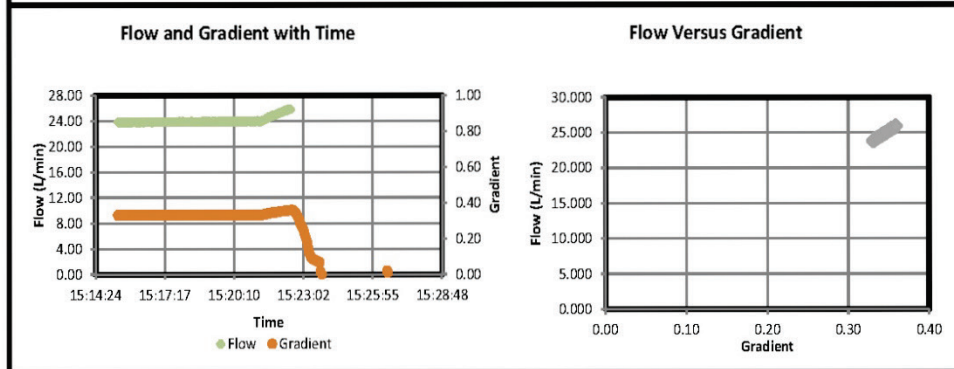
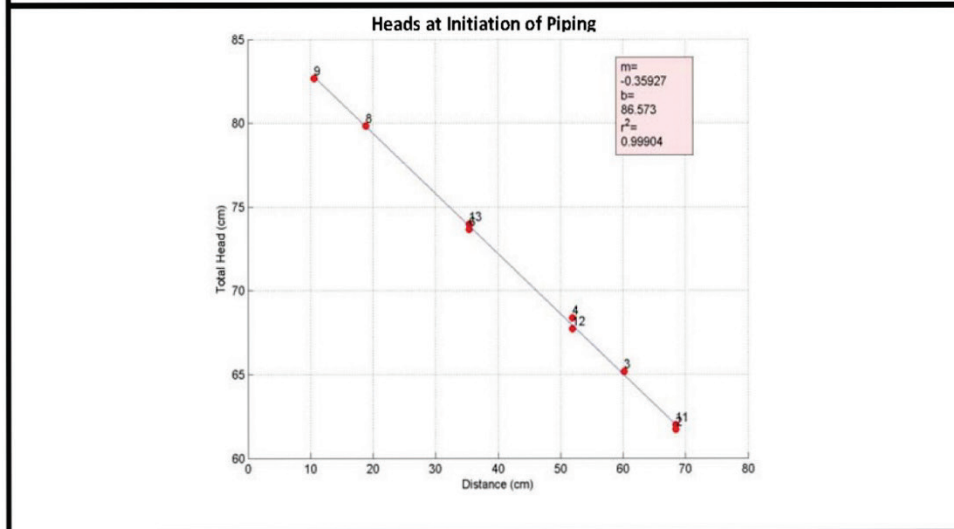
Notes: Flow measurements taken with flowmeter
 PPT 12 not working correctly
 Pressure spike occurred due to hose movement, causing some initial erosion



Sand Type 6-9 Date 16-Aug-14
 Test Number 4 Start Time 10:16:15
 Tested by A.M., A.W. End Time 15:29:16

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.50 kg	Time at Piping	15:22:30
Soil Volume	0.02052 m ³	Least-Squares Fit Gradient	0.36
Dry Unit Weight	15.06 kN/m ³		
Relative Density	4 %	Pipe Progression Rate	1.57 cm/s
Sample Length	65.8 cm	Flow Rate	25.86 L/min
Measured Slope Angle	40.0 °	Darcy Average Velocity	1.44E-02 m/s
		Sample Permeability	3.99E-02 m/s

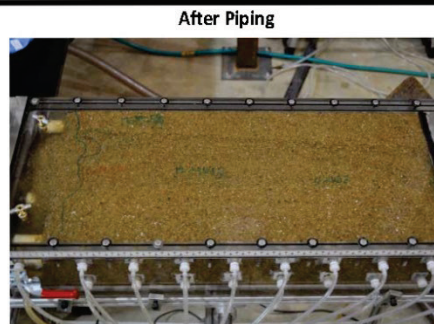
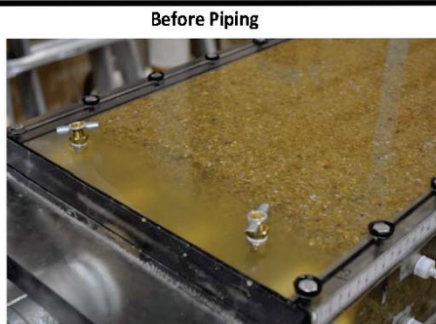
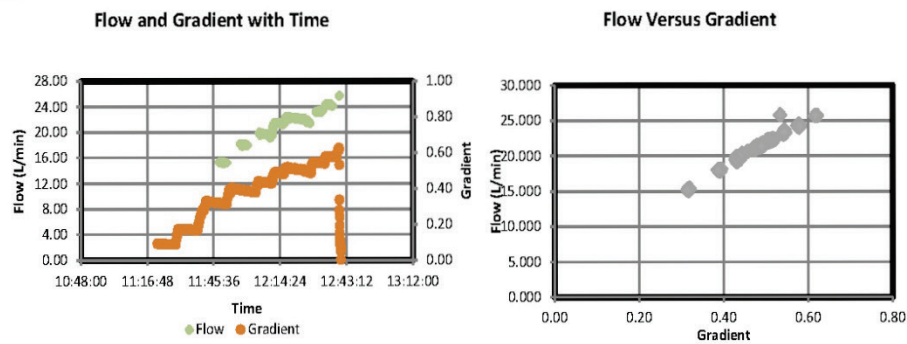
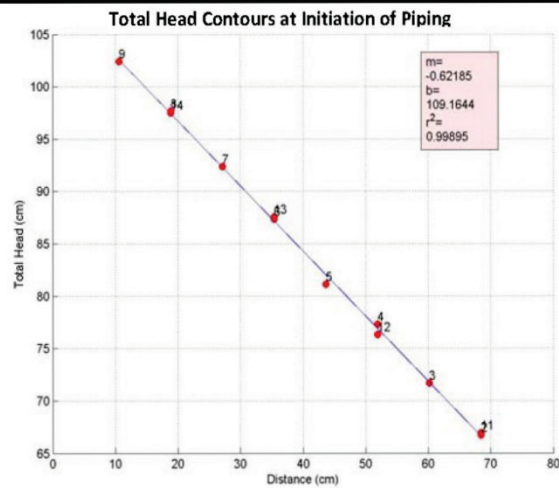
Notes: Flow measurements taken with flowmeter
 Data acquisition had to be restarted; data for pore pressures only for piping. PPTs 5 and 7 not working
 Pump was used for water supply.



Sand Type 6-9 Date 3-Sep-14
 Test Number 5 Start Time 11:21:10
 Tested by A.M., J.L. End Time 12:43:15

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.64 kg	Time at Piping	12:39:58
Soil Volume	0.02061 m ³	Least-Squares Fit Gradient	0.62
Dry Unit Weight	16.49 kN/m ³		
Relative Density	82 %	Pipe Progression Rate	4.73 cm/s
Sample Length	66.2 cm	Flow Rate	25.72 L/min
Measured Slope Angle	44.0 °	Darcy Average Velocity	1.43E-02 m/s
		Sample Permeability	2.30E-02 m/s

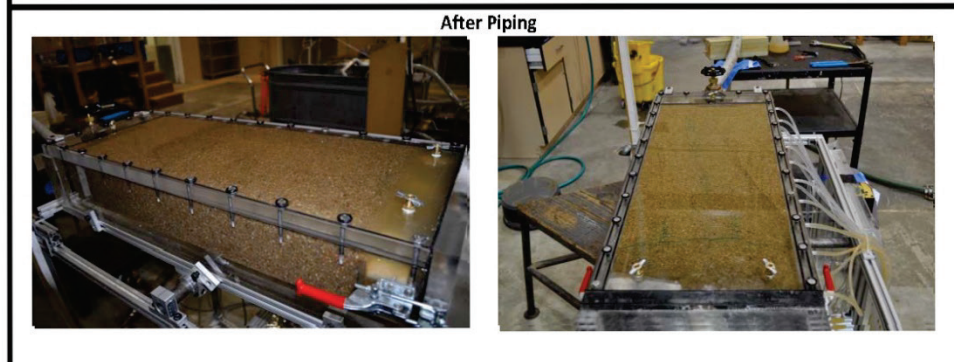
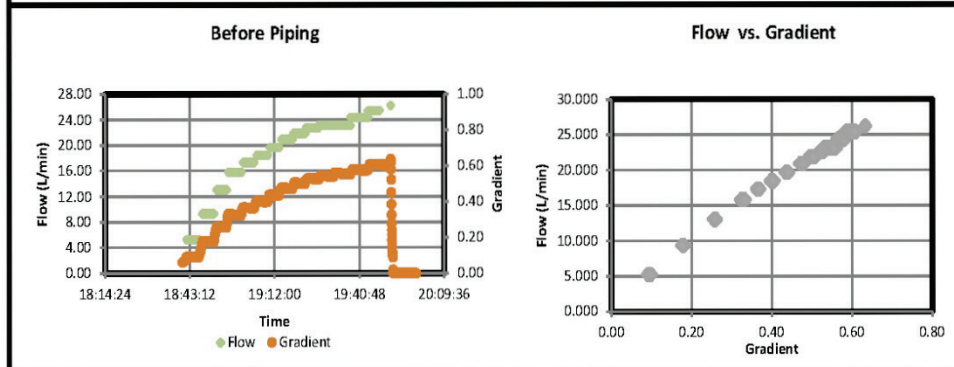
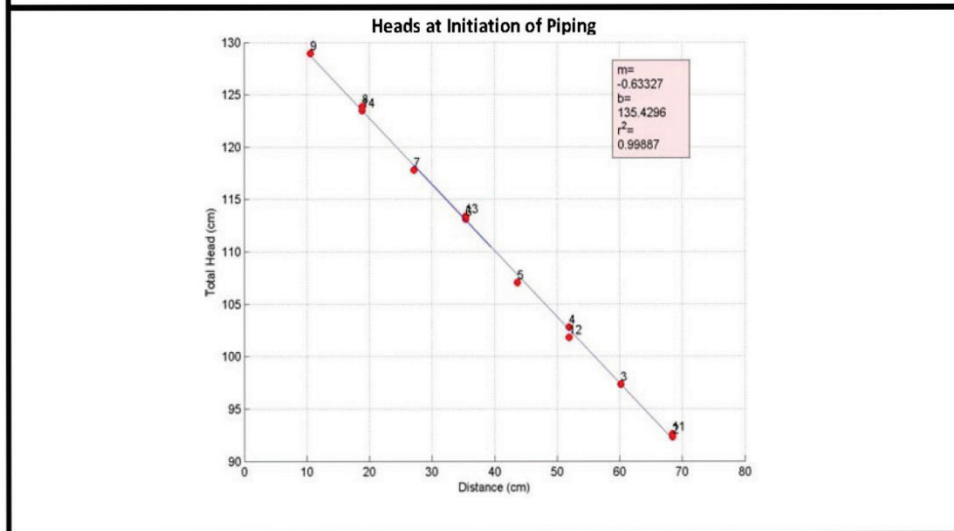
Notes: Flow measurements taken with flowmeter



Sand Type	<u>6-9</u>	Date	<u>4-Sep-14</u>
Test Number	<u>7</u>	Start Time	<u>18:40:43</u>
Tested by	<u>A.M., J.L.</u>	End Time	<u>20:00:16</u>

Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.68 kg	Time at Piping	19:51:32
Soil Volume	0.02067 m ³	Least-Squares Fit Gradient	0.63
Dry Unit Weight	16.46 kN/m ³		
Relative Density	81 %	Pipe Progression Rate	3.15 cm/s
Sample Length	66.2 cm	Flow Rate	26.21 L/min
Measured Slope Angle	44.0 °	Darcy Average Velocity	1.46E-02 m/s
		Sample Permeability	2.31E-02 m/s

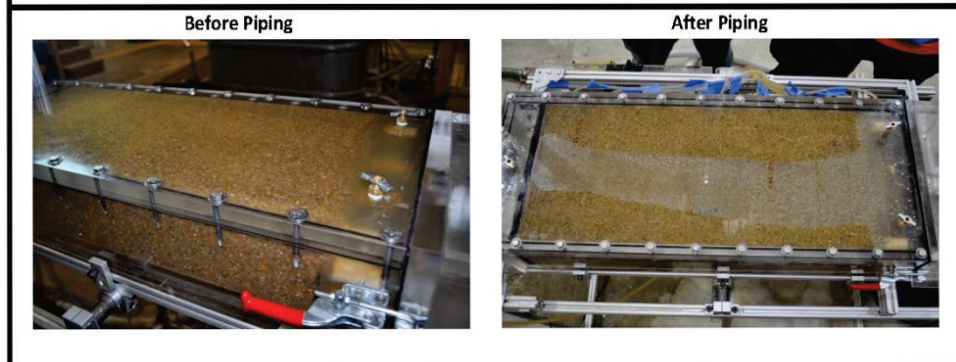
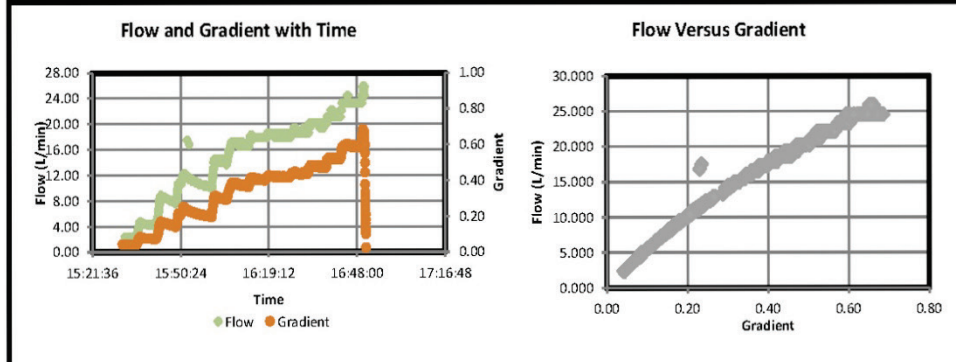
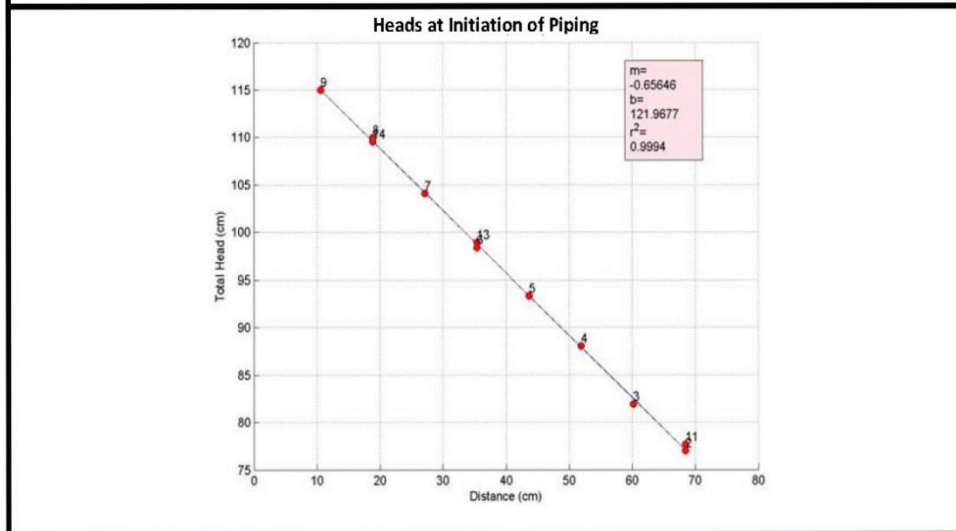
Notes: Flow measurements taken with flowmeter



Sand Type	<u>6-9</u>	Date	<u>22-Oct-14</u>
Test Number	<u>9</u>	Start Time	<u>15:31:23</u>
Tested by	<u>A.M., J.R.</u>	End Time	<u>16:51:00</u>

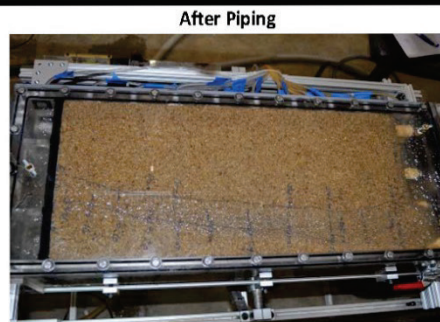
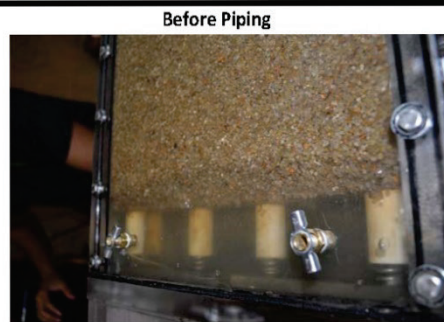
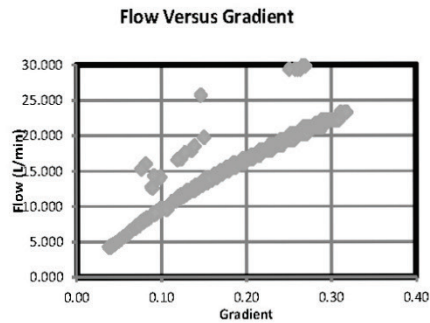
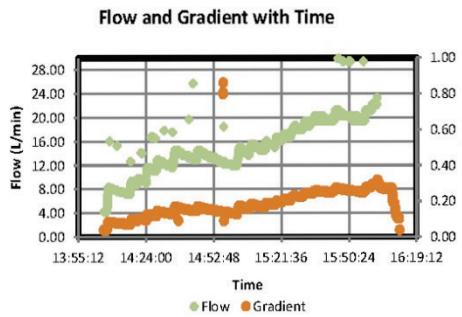
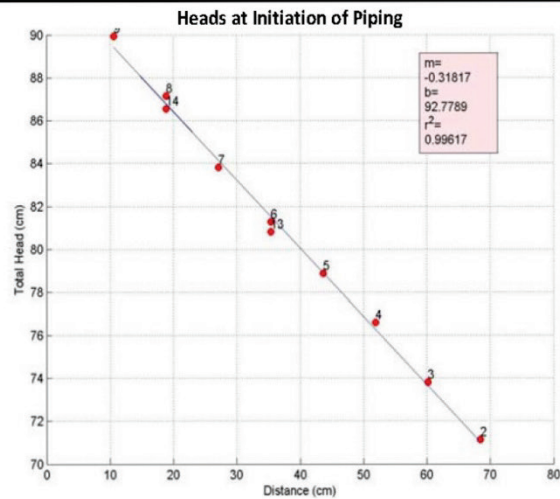
Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	34.68 kg	Time at Piping	16:50:29
Soil Volume	0.02049 m ³	Least-Squares Fit Gradient	0.66
Dry Unit Weight	16.60 kN/m ³		
Relative Density	88 %	Pipe Progression Rate	3.15 cm/s
Sample Length	66.8 cm	Flow Rate	25.90 L/min
Measured Slope Angle	42.0 °	Darcy Average Velocity	1.44E-02 m/s
		Sample Permeability	2.18E-02 m/s

Notes: Flow measurements taken with flowmeter
PPT 12 not working properly



Sand Type	6-9	Date	27-Oct-14
Test Number	10	Start Time	14:06:02
Tested by	J.L.,J.R.	End Time	16:12:02
Initial Conditions		Results (at Initiation of Piping)	
Soil Weight	31.36 kg	Time at Piping	16:02:36
Soil Volume	0.02052 m ³	Least-Squares Fit Gradient	0.32
Dry Unit Weight	14.99 kN/m ³		
Relative Density	0.5 %	Pipe Progression Rate	- cm/s
Sample Length	65.70 cm	Flow Rate	23.31 L/min
Measured Slope Angle	43.0 °	Darcy Average Velocity	1.29E-02 m/s
		Sample Permeability	4.05E-02 m/s

Notes: Flow measurements taken with flowmeter
 PPTs 11 and 12 not working properly
 Stop and Go Behavior throughout test



Appendix C – Sieve Analyses of Uniform Sands

GRAIN SIZE DISTRIBUTION TEST DATA

8/14/2013

Project: Internal Erosion Study
Location: Stockpile
Sample Number: Mason Sand
Material Description: Sand (SP), Brown
Tested by: LDD

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
92.00	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	0.00	100.0
			#16	0.00	100.0
			#20	0.20	99.8
			#30	2.70	97.1
			#40	18.50	79.9
			#50	57.30	37.7
			#70	85.30	7.3
			#100	90.50	1.6
			#140	91.10	1.0
			#200	91.20	0.9

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	20.1	79.0	99.1			0.9

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
0.2213	0.2385	0.2535	0.2805	0.3306	0.3571	0.4255	0.4518	0.4887	0.5517

Fineness Modulus	C _u	C _c
1.64	1.61	1.00

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study
Location: 40/70
Material Description: Sand (SP), Brown
Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
61.80	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	0.00	100.0
			#16	0.00	100.0
			#20	0.00	100.0
			#30	0.00	100.0
			#40	1.30	97.9
			#50	32.20	47.9
			#70	59.30	4.0
			#100	61.50	0.5
			#140	61.70	0.2
			#200	61.80	0.0

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	2.1	97.9	100.0	0.0	0.0	0.0

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
0.2270	0.2384	0.2487	0.2677	0.3038	0.3222	0.3643	0.3773	0.3922	0.4107

Fineness Modulus	C _u	C _c
1.52	1.42	0.98

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study

Location: 30/50

Material Description: Sand (SP), Brown

Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
61.30	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	0.00	100.0
			#16	0.00	100.0
			#20	0.00	100.0
			#30	0.50	99.2
			#40	31.50	48.6
			#50	58.10	5.2
			#70	61.00	0.5
			#100	61.10	0.3
			#140	61.10	0.3
			#200	61.10	0.3

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	51.4	48.3	99.7			0.3

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
0.3193	0.3358	0.3506	0.3777	0.4285	0.4540	0.5115	0.5288	0.5486	0.5727

Fineness Modulus	C _u	C _c
1.95	1.42	0.98

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study

Location: 20/40

Material Description: Sand (SP), Brown

Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
61.50	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	0.00	100.0
			#16	0.00	100.0
			#20	0.80	98.7
			#30	32.40	47.3
			#40	60.00	2.4
			#50	61.20	0.5
			#70	61.20	0.5
			#100	61.20	0.5
			#140	61.20	0.5
			#200	61.20	0.5

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	97.6	1.9	99.5			0.5

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
0.4650	0.4859	0.5050	0.5407	0.6093	0.6446	0.7260	0.7509	0.7795	0.8147

Fineness Modulus	C _u	C _c
2.52	1.39	0.98

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study

Location: 16/30

Material Description: Sand (SP), Brown

Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
65.80	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	0.00	100.0
			#16	0.90	98.6
			#20	33.50	49.1
			#30	62.80	4.6
			#40	65.60	0.3
			#50	65.70	0.2
			#70	65.80	0.0
			#100		
			#140		
			#200		

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	99.7	0.3	100.0	0.0	0.0	0.0

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
0.6422	0.6737	0.7022	0.7547	0.8546	0.9055	1.0205	1.0549	1.0935	1.1391

Fineness Modulus	C _u	C _c
1.97	1.41	0.98

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study
Location: 12/20
Material Description: Sand (SP), Brown
Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
69.80	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	0.00	100.0
			#16	29.40	57.9
			#20	66.80	4.3
			#30	69.50	0.4
			#40	69.70	0.1
			#50	69.70	0.1
			#70	69.70	0.1
			#100	69.70	0.1
			#140	69.70	0.1
			#200	69.70	0.1

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	0.0	99.9	0.0	99.9			0.1

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
0.8933	0.9252	0.9547	1.0108	1.1270	1.1957	1.3958	1.4720	1.5711	1.7148

Fineness Modulus	C _u	C _c
3.41	1.34	0.96

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study

Location: 8/16

Material Description: Sand (SP), Brown

Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
68.00	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	4.40	93.5
			#16	66.70	1.9
			#20	67.70	0.4
			#30	67.80	0.3
			#40	67.80	0.3
			#50	67.80	0.3
			#70	67.80	0.3
			#100	67.80	0.3
			#140	67.80	0.3
			#200	67.80	0.3

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	6.5	93.2	0.0	99.7			0.3

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
1.2664	1.3093	1.3491	1.4239	1.5704	1.6478	1.8278	1.8832	1.9469	2.1619

Fineness Modulus	C _u	C _c
4.01	1.30	0.97

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study

Location: 8/12

Material Description: Sand (SP), Brown

Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
60.80	0.00	0.00	#4	0.00	100.0
			#6	0.00	100.0
			#10	42.00	30.9
			#16	60.40	0.7
			#20	60.50	0.5
			#30	60.50	0.5
			#40	60.50	0.5
			#50	60.50	0.5
			#70	60.50	0.5
			#100	60.50	0.5
			#140	60.50	0.5
			#200	60.50	0.5

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	69.1	30.4	0.0	99.5			0.5

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
1.5860	1.7065	1.8093	1.9852	2.2872	2.4385	2.7834	2.8881	3.0074	3.1514

Fineness Modulus	C _u	C _c
4.43	1.54	1.02

GRAIN SIZE DISTRIBUTION TEST DATA

9/11/2013

Project: Internal Erosion Study

Location: 6/9

Material Description: Sand (SP), Brown

Tested by: AT

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
78.30	0.00	0.00	#4	0.00	100.0
			#6	0.60	99.2
			#10	71.40	8.8
			#16	77.80	0.6
			#20	77.90	0.5
			#30	77.90	0.5
			#40	78.00	0.4
			#50	78.00	0.4
			#70	78.10	0.3
			#100	78.10	0.3
			#140	78.10	0.3
			#200	78.20	0.1

Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0.0	0.0	0.0	0.0	91.2	8.4	0.3	99.9			0.1

D ₁₀	D ₁₅	D ₂₀	D ₃₀	D ₅₀	D ₆₀	D ₈₀	D ₈₅	D ₉₀	D ₉₅
2.0188	2.0912	2.1573	2.2800	2.5174	2.6415	2.9265	3.0124	3.1095	3.2249

Fineness Modulus	C _u	C _c
4.61	1.31	0.97

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
pounds (force)	4.448222	Newtons
pounds (force) per square foot	47.88026	Pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

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14. ABSTRACT

Backward erosion piping (BEP) is an internal erosion mechanism by which erosion channels progress upstream, typically through cohesionless or highly erodible foundation materials of dams and levees. As one of the primary causes of embankment failures, usually during high pool events, the probability of BEP-induced failure is commonly evaluated by the U.S. Army Corps of Engineers for existing dams and levees. In current practice, BEP failure probability is quantitatively assessed assuming steady state conditions with qualitative adjustments for temporal aspects of the process. In cases with short-term hydraulic loads, the progression rate of the erosion pipe may control the failure probability such that more quantitative treatment of the temporal development of erosion is necessary to arrive at meaningful probabilities of failure. This report builds upon the current state of the practice by investigating BEP progression rates through a series of laboratory experiments. BEP progression rates were measured for nine uniform sands in a series of 55 small-scale flume tests. Results indicate that the pipe progression rates are proportional to the seepage velocity and can be predicted using equations recently proposed in the literature.

15. SUBJECT TERMS	Dams and levees	Erosion rate
Internal erosion	Laboratory testing	Dams—Erosion
Backward erosion piping	Pipe progression rate	Levees—Erosion
Flood control	Flumes--Testing	Seepage

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