Laboratory Approach to Modeling the Initiating Mechanism in the Piping Failure of Sandy Soils

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Finally, Glory be to God Almighty for making it all this possible.

Olalekan Olorunsola
LABORATORY APPROACH TO MODELING THE INITIATING MECHANISM IN THE PIPING FAILURE OF SANDY SOILS

By

Olalekan O. Olorunsola

A report submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

Approved:

_________________________  __________________________
Dr. John D. Rice               Dr. Paul Barr
MAJOR PROFESSOR                COMMITTEE MEMBER

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Dr. James A. Bay
COMMITTEE MEMBER

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Logan, Utah
2010
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INTRODUCTION

This research intends to develop a testing apparatus to measure the critical gradient in sandy soils. The designed apparatus will be used in subsequent studies to develop a relationship between critical hydraulic gradient, soil properties and the inclination of the exit face.

This study evaluates several design modification to assess the effects of the modifications, and develop a design that most closely models the field mechanism of piping initiation. The design is initiated from a conceptual design and is executed into the first version. This design is called the Alpha Version. The next version, or more precisely, the Beta Version, corrects the inadequacies of the Alpha Version. Further modification would result in the Final Version.
BACKGROUND

Piping is defined as the erosion of soil due to concentration of internal seepage forces. Piping failure occurs when a developing pipe progresses from the point of initiation to an exit, forming an open pathway or “pipe” beneath a dam or levee (Schmertmann, 2000). Therefore, to fully understand piping it is important to understand that piping amounts to a progressive failure and thus requires continued transportation of sand grains until failure occurs.

Piping in sand is a phenomenon that is not well understood. The current state of practice assumes that piping will initiate when the hydraulic gradient reaches a critical value, the critical gradient, $i_{cr}$. Although many factors affect the critical gradient, current practice generally assumes it is a function of the buoyant unit weight and the unit weight of water, or;

$$i_{cr} = \frac{\gamma_b}{\gamma_w}$$  \hspace{2cm} (1)

Previous research has shown critical gradient to be a function of

- Length factor,
- Grain size,
- Exit faces inclination.

Length factor- Sellmeijer et al, (1988) proposed a mathematical relationship that predicts $i_{cr}$ varies inversely with $L^{1/3}$. Further research conducted at the Delft laboratory indicates a need for the introduction of a length correction factor.

Grain size - Presence of finer particles makes it easier for piping development, the current relationship is that

$$i_{crit} \approx \delta_{10}^z$$  \hspace{2cm} (2)

Where $\delta_{10}$ is the equivalent grain size that 10% of the sample by weight are smaller than and $z$ is a correlation factor back calculated from experimental result to be about 0.20 (Sellmeijer, 1988)
**Pipe inclination** - In current practice, $i_{cr}$ is derived from buoyant unit weight which assumes a horizontal exit face (vertical soil movement). In actual field cases, exit faces may be inclined and piping may even initiate in the horizontal. We can investigate the effect of exit face inclination variation on $i_{crit}$ by varying the angle of our experiments.

**Binary Image model** - Researchers at Pennsylvania State University have conducted a numerical investigation to understand the behavior of fluids through glass beads (Chen and Qiu, 2010). Their experimental results suggest the availability of preferential channels. Preferential channels are paths in sand structures in which fluid flow concentrates during seepage. Figure 1 shows a binary image model of a fluid (blue) flowing through glass beads (black spheres). The preferential flow paths represent concentrations of seepage forces that can affect the initiation of piping.

![Binary Image Representation](image)

Figure 1. Binary image representation (Chen, W. and Qiu, T., 2010).

(a) Top View, (b) vertical slice with plot of fluid.

This project develops a testing approach to measure the validity of critical gradient $i_{cr}$. The results of this laboratory tests will be used to calculate $i_{cr}$ using the following equation:

$$i_{cr} = \frac{\Delta h}{L}$$

(3)

Where $\Delta h$ is the change in pressure head and $L$ is the length of the sample.
Current analysis method

Currently, the approach to analyzing the potential for the initiation of piping is by comparing the vertical exit gradient, $i_{exit}$, to the critical gradient, $i_{cr}$. The values of $i_{exit}$ are determined from finite element analyses, while the $i_{cr}$ values are generally determined from the Terzaghi’s equation, (Equation 1).

The problem with this current method is that it only accounts for the buoyant unit weight of the sand, $\gamma_b$. This situation ignores the remaining soil properties. Another problem is that the analysis does not take into consideration the orientation of the exit face, instead the analysis is one dimensional in the vertical direction.
CONCEPTUAL DESIGN AND OBSERVATION

The objective of the test apparatus design is to output a numerical value of differential head, Δh, which is the difference in head between the pressure of the upper and lower water reservoirs required to initiate piping recorded in inches. A sample holder was designed with a mesh retention screen at the base. The height of the soil sample is constant at 5 in. This device provides the numerical value to calculate the critical gradient as Δh/L.

**Design** - The apparatus is comprised of a differential pressure transducer, a demodulator (to read the transducer), the two head reservoirs (one constant and another variable), a sample holder, a pressure cell divided into upper pressure cell and lower pressure cell as shown schematically in Figure 2.

![Figure 2. Schematic illustration of testing apparatus](image)

**Apparatus Elements**

**Pressure Cell.**

The pressure cell is made of six pieces of Plexiglas joined together by acrylic to make a rectangular box as shown in Figure 3. The top and bottom of the rectangular box was designed to be easily removed. The top is designed for easily retrieving the sample holder and reloading the sample with soil samples to be tested. The pressure cell is separated into two chambers called the upper pressure cell and lower pressure cell. The two chambers are separated by a 1/2 inch thick Plexiglas plate with a cut out in the center to accept the prepared sand sample in the sample holder.
Reservoirs and lifting platform.

The reservoir platform lift is made from wood and is presented schematically in Figure 4. The variable head tank is supported on four threaded steel rods and wing nuts allow lifting the variable head tank. This allows us to gradually vary the pressure head in the upper pressure cell. The constant head reservoir stands on a wood and is immovable.
Sample holder

The sample holder, presented in Figure 5, is designed to hold the sample between the two pressure cells. A retention screen is installed at the base of the holder to prevent sample loss through the bottom of the sample holder. The retention screen was designed to be easily changeable to allow testing of soils of different grain sizes. The sample holder also includes a compressible rubber gasket to allow the sample holder to fit tightly and prevent water flow between the two pressure chambers.

![Sample holder illustration](image)

Figure 5 - Schematic illustration of sample holders.

(a) Short sample holder, (b) Long sample holder.

Differential pressure transducer

The differential pressure transducer is connected between the two pressure cells as shown in Figure 6. The differential pressure is displayed on the screen of the demodulator. The zero and span knobs are used to correct and calibrate the reading so the output can be read directly on the display in inches. The zero knobs are used to zero the reading and this is done at the beginning of each test.
Figure 6. Schematics of differential pressure transducer.

**Standpipe**

The standpipes are mechanisms which are designed to manually measure the head in the pressure cells as shown in Figure 7. The purpose of the stand pipes is to provide a mechanical means of measuring the differential head between the pressure cells and to check the calibration of the deferential pressure transducer.

Figure 7. Schematic illustration of standpipes
ALPHA VERSION

Design

The Alpha version was the first execution of the conceptual idea. It was designed without full understanding of the entire behavior of the system. The Alpha version’s pressure reservoir is designed to withstand the relatively low pressures resulting from raising the variable head reservoir.

When designing this device, the most important functionality was to have water, through the soil sample in the sample holder and exit into the constant head tank. The Alpha version also included two piezometers to measure pressure in the individual cells. A vent port at the top of the bottom reservoir was designed to release air displaced while filling the pressure cell with water. An over flow pipe was added to release the excess water in the variable head tank. All these are shown in the Figure 8 below and discussed in the following sections.

![Figure 8. Picture of Alpha version setup](image)

Figure 8. Picture of Alpha version setup
**Alpha Design Element**

**Sample holder**

In the Alpha design the sample holder (Figure 9) is smooth sided. The sample failed at gradients similar to those calculated using Terzaghi’s equation, Equation 1. All samples tested in this sample holder failed by heaving a major portion of the sample. The heave mechanism was thought to be due to two factors: 1) air bubbles in the sample blocking the flow and causing pressure building, and 2) the very low friction between the sample holder and the sand.

The heave failure mechanism made it impossible to model the failure mode as predicting the critical gradient needed to initiate piping failures. This situation made it necessary for a modification to this part of the apparatus.

![Sample holder with 20-30 Ottawa sand sample during a test](image)

**Figure 9. Picture of a sample holder with 20-30 Ottawa sand sample during a test**

**Pressure cell**

The pressure cell is box-shaped with an easily removable cover for quickly replacing the sample and conducting experiments. This pressure cell is basically a prototype to test the behavior of the experiments. The performance of the box during experiments was poor. De-airing was a big challenge in this pressure cell due to the susceptibility of the cell to collapse if a vacuum was applied to the cells. Therefore, the samples tested were not completely saturated and the bubbles affected the test results. Leakage of water was also another challenge. This made it
necessary to overhaul the design and replace it with a cylindrical cell that can withstand the vacuum pressure.

![Image](image_url)

**Figure 10. Picture of the pressure cell in the alpha version**

**Reservoir/ Lifting platform**

The reservoir tanks shown in Figure 11 are constructed from Plexiglas. The dimensions of both tanks are equal. The reservoirs maintain constant head levels in the pressure cells during testing. The pipe shown in Figure 11, is attached to the overflow port which keeps the reservoir at a constant level to get the water into the sink. The upper variable head tank is allowed to raise and vary the differential head in the pressure reservoir. The wing nuts at the bottom of the upper reservoir are used to raise the tank slowly to increase the differential pressure on the soil sample. The constant head reservoir stands on a wooden platform and is designed to remain at the same elevation.

![Image](image_url)

**Figure 11. Picture of the reservoir and the lift platform**
Differential pressure transducer

The differential pressure transducer (Validyne DP 15-26), Figure 12, is connected between the two reservoirs. The differential pressure measurement system is made up of two parts, the demodulator and the transducer. Pressure readings from the transducer go into the demodulator as electric signals, and the demodulator converts the electric signals to inches for output on the digital output screen, as shown in the Figure 13 below. The zero knob is used to zero the pressure before experiments and the span knob is used to scale the readings to the desired unit of measurement.

Figure 12. Picture of the differential pressure transducer

Figure 13. Picture of the demodulator

The transducer, as shown above in Figure 12 contains a diaphragm (a metal plate) located between the connections. The diaphragm is interchangeable to match the pressure range needed for the experiments. The installed diaphragm is sufficient for the 0 – 14 inches of water range of differential pressure. The needle valves were placed in the connection lines to vent air out of the line, this is done frequently to keep the readings accurate.
Standpipes

The standpipes are made of transparent acrylic and are installed on the side of the lower pressure cell and the top of the upper pressure cell (Figure 14). When the taps are opened, the elevation in each piezometer matches the head of the respective head tank.

![Picture of standpipes]

Figure 14. Picture of standpipes

Problems with the Alpha Version

The resulting output data of the alpha version varied a lot because of the incomplete level of saturation of the sand in the soil cell. It was difficult to evenly saturate the sample and get water flowing through due to collection of air bubbles in the sample. In addition to this, leaks often form at the top of the upper pressure because of gaps in the seal at the top leads to a lower pressure in the upper pressure reservoir.

Solution

To address this problem, a re-design of the pressure cells was needed to allow pulling a vacuum on the pressure cells. The vacuum was pulled directly from the top of the sample while $CO_2$ was pushed from the bottom of the sample. The $CO_2$ replaces the air in the sample, and then readily dissolves in the de-aired water allowing the sand sample to be well saturated.
BETA VERSION

Design

The Beta Version is a modified version with the capability of withstanding high stresses due to pulling of a vacuum and the pressure of forcing $CO_2$ through the sample.

The Beta Version’s pressure cell is designed from a cylindrical section of Plexiglas spliced into the two pressure cells, upper pressure chamber and the lower pressure chamber, remains consistent with notation on the Alpha Version. Two 1-inch thick, 12-inch-square plates are bolted at the top and the bottom and sealed with O-Rings. The top and the bottom plates are both held in place by four steel all-thread rods tightened at the top and the bottom. The vacuum port is located on the top of the cell and $CO_2$ is placed in the lower reservoir. The piezometers still remain a part of the design and the locations are unchanged, as shown in the Figure 15 below.

![Figure 15. Picture of cylindrical pressure cell in the Beta version](image)

The $CO_2$ is pulled from the top of the upper pressure cell. The lower bottom cell’s vacuum port is now located on the side. The $CO_2$ port and the vacuum ports have been modified with quick release connectors and are used interchangeably as transducer connectors, as shown in the Figure 15 above.
In this new approach we constantly cycle the \( CO_2 \) pressure and the vacuum. The sequencing of supplying both is alternated to ensure that there is no air in the sample. This approach solved the saturation problems and resulted in less bubbles in the sample.

**Problems**

The vacuum port has a pulling effect on the soil with finer particles, and the \( CO_2 \) flowing from the bottoms also has an effect of disturbing the sample. At slower flow rates these problems don’t seem to occur. Also, the samples continue to fail mainly in heave due to sliding of the soil against the Plexiglas in the soil cell. This is due to low friction between the Plexiglas and the sand.
FINAL VERSION

**Final Design**

Based on the understanding of the Alpha version and the Beta version, the Final version is the final outcome of the pressure cell and sample holder modification. It is mainly the implementation of the modifications to the Beta version, the application of quick release valves are included to replace needle values and make it possible to use a port for multiple purposes. For instance, the transducer connector can be used for \( CO_2 \) and vacuum pump. This situation is possible because \( CO_2 \) and vacuum are needed during text preparation and the transducer is needed only during testing.

**Sample Holder Modification**

In addition to the changes in the pressure cell, changes were made to the sample holder to avoid heave failure. Several design modification were considered. First, the inside of the sample holder was grooved to produce more granular interlocking between the sand grains. Second, the inside of the sample holder was coated with a thin layer of silicon in order to provide contact friction between the sand and the contact area of the silicon. Third, a long sample holder was constructed to investigate the effects of sample length.

- **Grooved sample holder**- Grooving the inside of the sample holder would help increase the interlocking of the soil structure and the sample holder. The grooves are 1/4-inch wide by 1/8-inch deep and are spaced at every 1/2 –inch. Instead of creating a failure in heave, the soil particles are restrained and the individual soil particles are free to move on the exit surface. This is similar to field conditions where piping initiates. The grooves also interrupted the preferred seepage path along the side of the sampler.

Figure 16. Picture of grooved sample holder
- **Silicon sample holder** - The silicon coated sample holder was made by coating the inside of the sample holder with silicon in an attempt to restrain the sample from heaving, and model the failure mechanism we are trying to observe. The silicon coating also allowed the sand grains to interlock with the sides of the holder thus reducing the tendency for a preferred seepage pathway to form along the sides of the holder.

![Figure 17. Picture of silicon sample holder](image)

- **Long sample holder** - The longer sample holder increases the length of the sample from 5inches to 10inches. The sample holder investigates the effects of giving the water more distance to meander its way around the sand’s internal structure. There was still occurrence of heave failure in this sample but it was centrally located. The results of this modification are reported in the result chapter.

![Figure 18. Picture of long sample holder.](image)
**Performance**

The Final Version produced the most dependable results, sample preparation and testing operation became less cumbersome due to the modifications. This approach also enabled densification of sand samples in the sample holder as the $CO_2$ flowed from the top upper pressure cell to lower pressure cell, or doing the reverse by pulling a vacuum from the lower pressure cell.
TESTING

Overview

After designing the device, the results of testing using the various sample holders and two types of sand are compared. These results are used to understand what is going on during each test and to evaluate the performance at the various sample holders.

Recording

Each experiment was recorded by a video camera, and the video name is logged in an excel spreadsheet as well as the soil data and property and test outcome. The video recorded both the behavior of the soil and the differential head reading of the demodulator. The detailed sequence of conducting this experiment is documented below. The differential pressure is displayed on the screen of the transducer’s demodulator, at the instant the sand particles begin to erode. The critical gradient is recorded as the gradient in which soil particles begin to move, the gradient across the sample decreases after the soil movement due to a reduction in the flow resistance.

Testing Sequence

This operation guide details the sequences of conducting a test that measure the $\Delta h$ while maintaining the integrity of sample. The testing sequence is outlined below

Pretest Check

i. Filled up de-aired water tank.

ii. Check pressure in $CO_2$ Tank.

iii. Equal head tank elevation.

Sample Preparation

i. Fill up sample holder with sand to be tested.

ii. Tap the side of the sample holder until sand can’t be vibrated down into the cell. This is to increase the density of the sand to the maximum density of the sample.

iii. Weight the filled sample holder on the scale and record weight in Kg.
iv. Place sample in the pressure cell.

v. Ensure all valves and pressure cell bolts are tightly screwed to prevent leakage.

vi. Connect the vacuum line to the quick connect of the bottom pressure reservoir for about 10 min to 15 minutes (Beta Version only).

vii. Remove the vacuum, and then connect the $CO_2$ to the upper pressure reservoir for a minimum of 25 minutes to 35 minutes.

In lieu of vi and vii, another option is to pull the vacuum and have the $CO_2$ flow through the sample simultaneously.

Saturation

i. Fill up constant head tank and variable head tank with de-aired water.

ii. Before saturation it’s important to vent out excess $CO_2$ out of the top reservoir by using the vacuum hose to pull a vacuum.

iii. Immediately begin to fill the upper pressure reservoir by opening the water valve for the upper pressure cell. Fill until water reaches the top of the sample holder and shut off water.

iv. Fill the top lower pressure reservoir until the water slowly approaches the bottom of the sand. Then slowly use water inlet valve to control the rate of saturation until both reservoirs are connected by water.

v. After both cell are connected, fill upper pressure cell first then the lower pressure cell.

vi. Connect standpipes on the top and side of the cell.

Testing

i. Connect the differential pressure transducer to the pressure cell.

ii. Check zeros and range to match reading from the piezometer.

iii. Set camera to focus on sample and prepare to record.

iv. Proceed with the raising of the variable head tank until failure occurs.

Note: It is important to constantly compare the readings between the piezometers and differential pressures transducer.
RESULTS

The report is broken down into the three stages of modifying the equipment and how we approached a more representative result, the results are tabulated below

**Results of Alpha version**

The Alpha version produced results that were mainly early failure by heave, initiated by upwards movement of air pockets in the form of bubbles that displaced the sand. The presence of bubbles allowed for the buildup of pressure resulting in a lot of sudden heave failures.

However, the results of the Alpha version are consistent with the result of the Beta version. The results also correlations well with the calculated critical gradient using Terzaghi’s Equation (Equation 1). The predominant failure mode is heaving of the sand initiated by upward migration of air bubbles. The failure mode makes it difficult to assess critical gradients for the piping initiation process.

**Results of Beta version**

In the Beta version, the majority of the test results correlated with the critical gradient calculated using Terzaghi’s Equation, Equation 1. This is expected since the primary failure mode of these test was heave and upwards heave and upward movement of the sand. Terzaghi’s Equation is compared with the experimental critical gradient equation; Equation 3. The two results show a correlation as shown in Figure 19 on the next page.
Figure 19. Comparison of critical gradient using Clear sample holder.

Table 1. Results of Beta version testing.
Results of Final version

In the Final version we have incorporated grooves and a silicon coating on the inside of the sample holder making it possible to resist heave and produce a failure that is initiated by individual particle motion instead of heave. Tests using these sample holders resulted in higher critical hydraulic gradient results. We shall also compare the results between the silicon coated grooving. The results of these tests are represented in Tables 2 and 3. Furthermore, the gradients calculated using the results of tests conducted on the grooved and silicon sample holder are compared to critical gradients using Equation 1 in Figure 20 and Figure 21.

![Figure 20. Comparison of critical gradient using silicon sample holder.](image)

<table>
<thead>
<tr>
<th>Test No</th>
<th>Sample Holder</th>
<th>Soil</th>
<th>$\gamma$ (Total unit weight)</th>
<th>$\gamma_{cr}=\gamma/b/\gamma w$</th>
<th>$\gamma_{cr}= \Delta H/L$</th>
<th>Failure description</th>
</tr>
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<tbody>
<tr>
<td>Final version</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Silicon Sample Holder</td>
<td>20-30 Ottawa sand</td>
<td>129.14</td>
<td>1.070</td>
<td>1.200</td>
<td>Center heave.</td>
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<td>2</td>
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<td>20-30 Ottawa sand</td>
<td>129.45</td>
<td>1.074</td>
<td>1.244</td>
<td>Center heave.</td>
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<td>3</td>
<td>Silicon Sample Holder</td>
<td>20-30 Ottawa sand</td>
<td>128.84</td>
<td>1.065</td>
<td>1.550</td>
<td>Localised failure</td>
</tr>
<tr>
<td>4</td>
<td>Silicon Sample Holder</td>
<td>20-30 Ottawa sand</td>
<td>128.54</td>
<td>1.060</td>
<td>1.064</td>
<td>Early failure low density.</td>
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<td>1.074</td>
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<td>20-30 Ottawa sand</td>
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<td>Silicon Sample Holder</td>
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<td>1.055</td>
<td>1.564</td>
<td>Center heave.</td>
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<td>Silicon Sample Holder</td>
<td>20-30 Ottawa sand</td>
<td>128.84</td>
<td>1.065</td>
<td>1.194</td>
<td>Visible sand deposition and then failure.</td>
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<tr>
<td>Final version</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Silicon Sample Holder</td>
<td>Graded Ottawa sand</td>
<td>130.35</td>
<td>1.089</td>
<td>1.680</td>
<td>Failure and sand boil.</td>
</tr>
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<td>Graded Ottawa sand</td>
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<td>1.070</td>
<td>2.006</td>
<td>Sand boils and center heave.</td>
</tr>
<tr>
<td>3</td>
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<td>Graded Ottawa sand</td>
<td>129.45</td>
<td>1.074</td>
<td>1.876</td>
<td>Sand deposition and center heave.</td>
</tr>
<tr>
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<td>Graded Ottawa sand</td>
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<td>1.692</td>
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<tr>
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<td>Graded Ottawa sand</td>
<td>129.14</td>
<td>1.070</td>
<td>1.690</td>
<td>Visible sand deposition, center heave.</td>
</tr>
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</table>

Table 2. Result of Final version using silicon sample holder
Table 3. Result of Final version using Grooved sample holder

<table>
<thead>
<tr>
<th>Test No</th>
<th>Sample Holder</th>
<th>Soil</th>
<th>$\gamma$ (Total unit weight)</th>
<th>$i_{cr} = \delta / \gamma_w$</th>
<th>$i_{cr} = \Delta H / L$</th>
<th>Failure description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final version</td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>Grooved Sample Holder</td>
<td>20-30 Ottawa sand</td>
<td>128.19</td>
<td>1.054</td>
<td>1.256</td>
<td>Sand movement and center heave.</td>
</tr>
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<td>1.050</td>
<td>1.476</td>
<td>Sand movement and center heave.</td>
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<td>1.524</td>
<td>Sand deposition, Sand boils then failure.</td>
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<td>1.398</td>
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<td>20-30 Ottawa sand</td>
<td>127.33</td>
<td>1.041</td>
<td>1.608</td>
<td>Sand deposition, Sand boils then failure.</td>
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</tr>
<tr>
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<td>Grooved Sample Holder</td>
<td>Gradated Ottawa sand</td>
<td>127.33</td>
<td>1.041</td>
<td>1.634</td>
<td>Sand transportation, localised failure.</td>
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<td>Gradated Ottawa sand</td>
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<td>1.054</td>
<td>1.996</td>
<td>Center heave and failure.</td>
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<td>1.698</td>
<td>Slowly Approaching the gradients.</td>
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<td>Sand deposition on top, localised failure.</td>
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<td>Gradated Ottawa sand</td>
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<td>1.041</td>
<td>1.736</td>
<td>Sand deposition, localised failure and heave.</td>
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</table>

Figure 21. Comparison of critical gradient using grooved sample holder.
The long sample holder produced results that are correlated with the result of the clear sample holder, Figure 19. This is due to the similarity in the failure mechanism, there was evidence of particle movements but failure occurred quickly due to upward heave before any visible preferential paths were developed.

Figure 22. Comparison of critical gradient using Long sample holder.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Sample Holder</th>
<th>Soil</th>
<th>$\gamma$ (Total unit weight)</th>
<th>$i_{cr}=\gamma_h/\gamma_w$</th>
<th>$i_{cr}=\Delta H/L$</th>
<th>Failure description</th>
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</thead>
<tbody>
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<td>Long Sample Holder</td>
<td>20-30 Ottawa sand</td>
<td>130.10</td>
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<td>20-30 Ottawa sand</td>
<td>131.00</td>
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<tr>
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<td>Graded Ottawa sand</td>
<td>130.10</td>
<td>1.085</td>
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<td>Graded Ottawa sand</td>
<td>129.95</td>
<td>1.082</td>
<td>1.230</td>
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<td>Graded Ottawa sand</td>
<td>131.00</td>
<td>1.099</td>
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</tr>
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</table>

Table 4. Result of Final Version using Long sample holder
Graphical plots of results

Figure 23. Sample holder comparison on 20/30 Ottawa sand.

Figure 24. Sample holder comparison on graded Ottawa sand.
Figure 25. Sand Sample in clear sample holder

Figure 26. Sand sample in silicon sample holder
Figure 27. Sand Sample in Grooved sample holder

Figure 28. Sand Sample in long sample holder
Results and Conclusions

In order to understand which sample holder gives the most accurate representation of piping phenomenon the graphical plots are compared based on the following criteria.

- **Comparison of critical gradient, $i_{cr}$** – Tests using the long sample holder and the clear sample holder both failed at a critical gradients of about 1.1. The silicon sample holder and the grooved sample holder both failed at much higher gradients (1.2 to 2.0). This observation is consistent for both the 20-30 Ottawa sand and the graded Ottawa sand. The relationship between the sample holders and critical gradients is shown in Figure 23 and Figure 24.

- **Observed failure mechanism** - The predominant failure mechanism in the Beta Version where the clear sample holder was used was the heave mechanism. This same mechanism was the failure mode for long sample in the final version. The silicon sample holder and grooved sample holder showed evidence of sand transportation to the top before failure and the failures were more localized; consistent with the piping failure mode. There was occasional evidence of weakness preferential flow path but it occurred for a short period of time before failure.

- **Consistency of results**- Both the long and clear sample holder provided the most consistent critical gradient values of the entire experiments (Figure 25 and Figure 28) but the failure mode does not accurately model the pipe failure mechanism that occurs in piping failure. The grooved sample holder showed the highest critical gradient results but provided a lot of scattered data (Figure 23). A graphical plot of the silicon sample holder, in Figure 26, showed a weak trend that predicts an increase in critical gradients as dry unit weight increases. This trend would be expected due to decreased flow paths with higher density. For both the silicon coated and grooved sample holder the graded Ottawa sand tests resulted in higher critical gradient than the 20-30 Ottawa sand. This is consistent with the finding in Schmertmann (2000) and Sellmeijer et al. (1988).

The observed failure mechanism for both the silicon-coated and grooved tests appeared to be movement of individual grains at the end of the preferential seepage path. This may
account for the greater variability in the results for these sample holders since the alignment of a preferential seepage path is the result of random grain structure.
Conclusions

In conclusion, this research project has been able to design a laboratory apparatus that makes it possible to see how piping initiates in confined condition, output results and compare output. Four different sample holders were used in the testing. Using the short (5 inch) and long (10 inch) smooth sided holders, the failure mechanism observed was heave and the critical gradients were similar to those calculated using Terzaghi’s Equation (Equation 1). Samples tested in the grooved and silicon-coated sample holders resulted in higher critical gradients with a failure mechanism closer to the piping mechanism. The broader range of critical gradient results may be the result of random grain orientation.

There is a lot to learn from critical gradient investigation and the piping phenomenon. In the future this apparatus provide an opportunity to try various sand mixtures, change exit-face orientation by varying the inclination of the pressure cell, and measure the internal pressure in the sand holder.
