Interaction of Soil and Seepage Barrier Cracks under Seepage Flow

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Interaction of Soil and Seepage Barrier Cracks under Seepage Flow

by

Justin Whitmer

A project report submitted in partial fulfillment
of the requirements for the degree
of
MASTER OF SCIENCE
in
Civil and Environmental Engineering

Approved:
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Introduction

Seepage barriers are commonly installed in earthen dams and levees all over the world and consist of slurry walls, concrete walls, jet grouted walls, secant pile walls, sheet pile walls, and deep soil mixed walls. The purpose of the barrier is to reduce the amount of flow and seepage through the embankment and the foundation of the dam or levee. When seepage barriers were first being used it was under the impression that barriers would be a permanent mitigation of seepage problems. However, in prior research (Rice, 2007) it is mentioned that there are several cases where the seepage barriers did not perform as expected, concluding that there may be failure mechanisms that are unique to each seepage barrier. When a crack is introduced to the seepage barrier, in some cases internal erosion may be taking place causing the crack to widen. As the crack gets wider the flow through that crack may increase until a point when the soil controls the amount of flow into the crack or soil starts to fill the crack.

This study compares theoretical values vs. measured values of flow and head readings using a laboratory test cell for the measured values and a finite element analysis computer program for theoretical. Also looked at is the interaction of the sand and the crack for variables of flow and erosion. Taken into account are variables for crack type (smooth and fractured), crack aperture, and the hydraulic conductivity of the sand placed around the seepage barrier. This is done by modeling the crack through a seepage barrier test cell for different apertures and different head values.
Test Methodology

A drawing of the test cell used to perform the laboratory testing is presented in Figure 1. The cell is constructed of ½ - inch steel plates with 5-inch steel channel section reinforcements as shown in Figure 2. The cracked seepage barrier is simulated by creating a jointed concrete block with fine threaded bolts capable of controlling the crack’s aperture. Two blocks were fabricated, one with a smooth crack and one with a fractured crack. Sand will be placed on both sides of the concrete seepage barrier. An inflow pipe regulated how much water pressure was applied to the cell, this varied with each test. The outflow pipe has a constant head of 3 feet, due to the height of the pipe before the water exits the cell.

Figure 1 - AutoCAD drawing of the test cell.
Tests were run with two sand types placed on both sides of the crack: 20-30 Ottawa sand and Graded Ottawa sand. The purpose for choosing these sands was they each have an ASTM specification which allows for consistency and repeatability of the tests. The Ottawa sand particles are very rounded making them easily compactable which helps to maintain a consistent level of compaction and permeability.

Figure 2 - Test cell showing 5-inch steel channel section reinforcements.

The water used in the tests came from the city of Logan municipal water supply. Before the water was used for testing, it was de-aired using two six-inch diameter by eight-foot tall de-airing cells. Water was sprinkled into the tubes through a standard copper sprinkler to increase the surface area of the water. The water level in the tubes was monitored using piezometers installed on the sides of both tubes. To achieve the desired flows into the test cell, the water was pushed by compressed air from the de-airing tubes into the cell using a panel.
board to control the air pressure. An in-line pressure regulator between the de-airing tanks and the test cell regulated the water pressure entering the cell.

Data was collected using a Campbell Scientific CR3000 data logger. Data was collected every four seconds with the data logger. The collected data was averaged every 10 seconds and sent to the laboratory computer. Information sent to the computer via the data logger included the water pressure from each piezometer and the weight of the water collection bucket on the end of the test cell. Sixteen piezometers were installed in different locations on the side of the test cell to measure water pressure at key locations. Each piezometer was calibrated before it was installed.

The first tests performed for each block (smooth, fractured) were run with no sand in the test cell in order to measure the flow versus aperture relationship for each crack type. For these water only tests, the procedure consists of the following:

1) Water is filled in the de-airing tubes and forced out by air into the tank.
2) At each aperture opening there were a series of five tests run at different upstream pressures (see Table 1).
3) Data collected to computer from data logger for flow and head.
Table 1 - Different tests ran at different head and apertures.

<table>
<thead>
<tr>
<th>Crack Type</th>
<th>Sand/No Sand</th>
<th>Aperture (mm)</th>
<th>Upstream Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>No Sand</td>
<td>0.0 – 1.7</td>
<td>2,4,6,8,10</td>
</tr>
<tr>
<td>Smooth</td>
<td>20-30 Ottawa</td>
<td>0.0 – 2.9</td>
<td>2,4,6,8,10</td>
</tr>
<tr>
<td>Smooth</td>
<td>Graded Ottawa</td>
<td>0.0 – 2.7</td>
<td>2,4,6,8,10</td>
</tr>
<tr>
<td>Fractured</td>
<td>No Sand</td>
<td>0.0 – 1.8</td>
<td>2,4,6,8,10</td>
</tr>
<tr>
<td>Fractured</td>
<td>20-30 Sand</td>
<td>0.0 – 4.2</td>
<td>2,4,6,8,10</td>
</tr>
<tr>
<td>Fractured</td>
<td>Graded Ottawa</td>
<td>0.0 – 3.0</td>
<td>2,4,6,8,10</td>
</tr>
</tbody>
</table>

A different procedure is used when the tests were run with sand in the cell, these procedures are:

1) Knowing the unit weight of the sand and the volume of the tank, calculations were made in order to know how high up on the tank a 50 pound bucket of sand should reach at 100% relative density.

2) Using a scoop and carefully placing the sand in the tank in approximately 2 inch lifts, a rubber mallet was hit 15 times on both sides of the tank to get the desired 100% relative density. Previous tests show that minimal vibration is required to achieve the maximum density.

3) After the sand was placed and compacted in the tank, carbon dioxide \((\text{CO}_2)\) was forced up through the sand from the bottom of the tank displacing the air. Because \text{CO}_2 is much more soluble in water than air,
this made saturating the sand much easier. Figure 3 shows the cell filled with sand while the CO₂ is being forced up.

4) After the sand was placed and water was filled in the tank, an approximately a ½-inch thick layer of bentonite is placed on top of the sand.

5) Air bladders are then placed on top of the bentonite. With the top of the cell secured, 10 psi of air is applied to the bladders through the panel board. The air bladders and the bentonite maintain positive effective stress in the sand and along with the bentonite to reduce the possibility of having a flow path for the water near the top of the tank.

6) The procedures for getting water to the cell and measuring the flow through the crack are the same as the tests with no sand in the cell.

Figure 3 - Test cell filled and compacted with sand.
Computer Model Methodology

A bucket collected the water flowing through the test cell and was used as a weigh tank to measure the flow through the crack. Knowing the weight of the bucket at each time interval collected by the data analyzer, the flow through the crack was calculated. The upstream end of the cell is where the water was forced into the test cell and the downstream end of the cell was blocked off allowing only the water that flows through the crack to get to the bucket. Therefore the amount of water collected in the bucket and the calculated flow is precisely the amount of flow that gets through the crack.

The aperture of the crack was controlled by a set of screw jacks cast into the blocks. The screw jacks were fabricated so that a 56 degree turn of the bolts opened the crack 0.1 mm. After a few tests it was clear there was a little bit of slack in the bolts when first starting to open the crack aperture. This is corrected by taking the theoretical value of the flow of water through the crack aperture and comparing measured values for that same aperture. Therefore, a correction factor for both types of blocks was made to correct for the slack of the bolts. These correction factors were used to compare the measured values and Slide computer model values accurately. Figures 4 and 5 displays the theoretical values and what the correction factor is for each type of block.
Figure 4 - Correction factor of 0.6mm for the smooth crack.

Figure 5 - Correction factor of 0.5mm for the fractured crack.
The test cell is modeled using a program called Slide 5.0 (Rocscience, 2008), which is a finite element analysis computer program that calculates values of pressure head and flow through the crack. A finite element model of the test cell is presented in Figure 6. The upstream and downstream boundaries are modeled using constant head boundaries and the upper and lower boundaries are modeled with no flow boundaries. The hydraulic conductivity of the sand was previously tested and found to be 1.50 E-03 feet per second for the graded sand and 8.55 E-03 feet per second for the 20-30 sand. The seepage barrier is modeled with a very low hydraulic conductivity and the crack is modeled with a row of elements with an equivalent hydraulic conductivity calculated to represent the transmissivity of the crack.

Figure 6 - Main page of Slide 5.0, input values of equivalent hydraulic conductivity and values of head here.
The downstream head is a constant 3 ft; this is known by the level the water reaches the instant before it is drained into the load cell bucket from the water through the crack. A piezometer was placed at the entrance of the cell to know the head at the upstream end; this value is used for the upstream head and varies for the tests run.

The equivalent hydraulic conductivity representing the crack in the finite element model is calculated by making the transmissivity of the row of cells in the model equal to that in the crack. Transmissivity is directly proportional to horizontal hydraulic conductivity and thickness and is a measure of how much water can be transmitted horizontally. To model the flow through the crack, a constant thickness of the cells representing the crack was made to be 0.5 in. Transmissivity is calculated for each test and is used to get an equivalent hydraulic conductivity of the flow through the crack. This is done by taking the equation for transmissivity:

\[ T = k \cdot b \quad \rightarrow \quad k = \frac{T}{b} \quad (1) \]

Where \( T \) represents the transmissivity, \( k \) is the hydraulic conductivity, and \( b \) is the width of the crack as modeled in the finite element model. Inputting the hydraulic conductivity into the equation we get:

\[ Q = k \cdot i \cdot A \quad \rightarrow \quad Q = \frac{T}{b} \cdot A \quad (2) \]
Where $Q$ is the flow through the crack (measured with no sand in the cell) at a given aperture. Knowing that the area is one foot by the width of the crack (b), the equation simply becomes:

$$Q = T \cdot i \rightarrow T = \frac{Q}{i} \quad (3)$$

To get the equivalent hydraulic conductivity that is used to input into Slide, values from the tests with no sand were used in order to accurately predict the hydraulic conductivity for each aperture and for both the smooth and the fractured block. An equivalent hydraulic conductivity for the crack, hydraulic conductivity of the sand, flow through the crack, and heads at the upstream and downstream end of the cell are now known for each test run and is input into the program. Figure 7 shows values which Slide calculates for each piezometer and the value of flow through the crack. The coordinates are precisely known for each piezometer on the test cell, the precise coordinates are then transferred into Slide, therefore comparing the exact location for the measured values and the Slide values.
Figure 7 – Computer program Slide showing the values of head in psi for each piezometer and the value of flow through the crack.
Test Results

Comparison of Theoretical and Measured Pressures and Flow

Figure 8 shows the difference in the measured values and the Slide values for the fractured crack with 20-30 sand at aperture openings of 0.3 mm and 1.0 mm. The top numbers in each box are the Slide values, the bottom numbers are the measured values. Twelve tests were looked at for the difference in the Slide and measured values for each piezometer. It was noticed at low flows (i.e. the 0.3 mm aperture in Figure 8a) both the theoretical and measured water pressures and flows were similar, while at large flows (i.e. the 1.0 mm aperture in Figure 8b) the differences between the pressures and flow became greater. The discrepancy between the theoretical and measured values in Figure 8b is likely caused by the head losses in both ends of the test cell that occur at high flows. The head losses are caused from flow through the pipes and gravel sections on both ends of the test cell. This part of the test results will need to be looked further into to get more conclusions on exactly what is happening.
Figure 8 - Slide values and measured values for each piezometer and flow.
   a) aperture at 0.3 mm,  b) aperture at 1.0 mm
**Flow versus Aperture**

Using the entire test data collected for each type of crack and for each type of sand, comparisons were made. The actual measured values in the lab were compared with the values that Slide calculated for both the piezometer readings and the flow readings.

Figure 9 shows the relationship between the measured values and the values calculated in Slide on the smooth crack with 20-30 sand. The theoretical curve shows that at small apertures the flow through the model is controlled by the crack. When a certain aperture is reached, the rate of flow increase with aperture decreases because the flow becomes controlled by the soil. Comparing the measured curve to the theoretical, we can see that at a certain aperture the measured values peak and decrease while the Slide values continue to increase. We believe that this is due to the sand starting to fill into the crack at a certain aperture opening. While the sand initially starts to fill into the crack there is bridging occurring causing the flow to peak and eventually decrease. There is also going to be a certain aperture where the sand is going to completely fill the crack (the minimum flow) and the flow should then be able to increase as the aperture is increased. In Figure 9 this occurs at approximately 1.5 mm where we believe the sand has completely filled the crack. The flow is controlled by the opening size of the aperture and the flow will then start to increase with increasing aperture.
Figure 9 - Measured and Slide values of Aperture vs. Flow for smooth crack with 20-30 sand at 10 psi.

In Figure 10, with the fractured crack now instead of the smooth crack and with the same sand (20-30) as in Figure 9, there is a difference where the measured values deviate from the theoretical and peak flow. We believe that this is due to the tortuous nature of the fractured crack which lengthens the flow path in the crack and provides numerous pinch points where the sand particles can be caught and form bridging. This causes the sand to take longer to fill the crack than with the smooth crack, allowing the flow to peak at a larger aperture opening than with the smooth crack. Again there is a point where the crack is going to be completely filled with sand and the flows will then begin to increase. With the fractured crack and 20-30 sand the peak occurs at approximately 2.5 mm. There
is approximately 1.0 mm in difference from where the flows begin to increase in the smooth block compared to the fractured block.

**Figure 10** - Measured and Slide values of Aperture vs. Flow for fractured crack with 20-30 sand at 10 psi.

Figure 11 displays the gradation curve for the 20-30 sand. More than 90% of the particles are between 0.6 mm and 0.8 mm. Table 2 shows where the flows from the measured values and the Slide values begin to deviate from one another, where the flow is a maximum for the measured values, and where the flow is a minimum for the measured values. These values are the same for each of the heads that were tested for the 20-30 sand. The deviation of the flows for both the fractured crack and the smooth crack are the same. The minimum flows are also the same for both crack types. The main difference is in the maximum flows, the maximum flow for the fractured crack occurs when 99 percent of the
sand particles are smaller than the crack aperture, and maximum flow occurs in the smooth crack is when only two percent of the sand particles are small enough to pass through the crack aperture. We believe that this is due to the tortuous nature of the fractured crack, taking longer time for the sand particles to fill in the crack with the longer flow path and the jagged edges.

![Gradation curve for the Ottawa 20-30 Sand.](image)

**Figure 11 - Gradation curve for the Ottawa 20-30 Sand.**

**Table 2 – Showing where on the gradation curve each type of flow for the 20-30 sand.**

<table>
<thead>
<tr>
<th>Crack Type</th>
<th>Flow Deviates</th>
<th>Maximum Flow</th>
<th>Minimum Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractured</td>
<td>D₂ to D₃</td>
<td>D₉₉</td>
<td>D₁₀₀</td>
</tr>
<tr>
<td>Smooth</td>
<td>D₁ to D₂</td>
<td>D₂</td>
<td>D₁₀₀</td>
</tr>
</tbody>
</table>

Figures 12 and 13 show the relationship between the measured and the Slide values for the aperture versus flow for graded sand and both crack types.
There is a similar relationship with the fractured crack and the smooth crack with the graded sand as there was with the 20-30 sand, in that the area where the peak flow for the measured values are different. The peak flow for the smooth crack is approximately 0.35 mm, and the peak flow for the fractured crack is approximately at 0.95 mm.

Figure 12- Measured and Slide values of Aperture vs. Flow for smooth crack with graded sand at 10 psi.
The graded sand has a wider range of grain sizes and is generally finer than the 20-30 sand particles. Figure 14 shows that more than 90% of the particles are between 0.3 mm and 0.6 mm. Because the particle sizes are smaller with the graded sand, the flows through the crack are not as high. The smaller particle sizes also cause the peak flow to occur at a smaller aperture, because the sand will begin to fill in the crack at a smaller aperture and also completely fill the crack at a smaller aperture than that of the 20-30 sand.
Figure 14 - Gradation curve for the Ottawa Graded Sand.

Table 3 shows where the flow begins to deviate from the measured and the Slide values, this value is quite different for both crack types and is believed to be due to the tortuous nature of the fractured crack. The difference in the maximum flows is also believed to be related with the tortuous nature of the fractured crack, the flow path and number of catch points is increased, which increases when the crack can be completely filled with sand.

Table 3 - Showing where on the gradation curve each type of flow for the graded sand.

<table>
<thead>
<tr>
<th>Crack Type</th>
<th>Flow Deviates</th>
<th>Maximum Flow</th>
<th>Minimum Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractured</td>
<td>$D_{55}$ to $D_{80}$</td>
<td>$D_{99}$</td>
<td>$D_{100}$</td>
</tr>
<tr>
<td>Smooth</td>
<td>$D_{40}$ to $D_{65}$</td>
<td>$D_{65}$</td>
<td>$D_{100}$</td>
</tr>
</tbody>
</table>
Conclusion

The reason the Slide values and the measured values start deviating from one another is that the program Slide does not take into effect the sand particles filling in the crack and causing flow to decrease. As the sand particles start to fill in the crack there will to be bridging that occurs, only allowing a certain amount of sand particles to fill in the crack before the bridging takes place and block the remaining sand particles from getting into the crack. This is the point where the flow will begin to decrease. The sand eventually fills the entire crack when the aperture is opened wide enough, and beyond this point the flow will be controlled by the aperture of the sand filled crack and not further filling of the crack with sand.

The gradation of the soil particles is the main factor affecting when flows reach a maximum flow and a minimum flow, and when the flows begin to deviate from the theoretical values. For the 20-30 sand tested with the fractured crack, the maximum flows occurred at the $D_{99}$ on the gradation curve; this is when 99 percent of the particle sizes could fit through the crack aperture. The minimum flows occur at $D_{100}$; at this point all of the particles will be able to fit through the crack. For the 20-30 sand tested with the smooth crack, the maximum flows occurred at the $D_2$ on the gradation curve; this is when 2 percent of the sand particles can fit through the crack aperture. The reason for the difference of the maximum flows for the fractured crack and the smooth crack is due to the fractured crack being tortuous; this lengthens the flow path and provides catch
points where the sand particles can get caught, which then increases the time for sand to fill the crack.
References


Appendix A: Model Photos
Figure A-1. Test cell with load cell bucket and fractured crack

Figure A-2. Inserting block into test cell
Figure A-3. Inside view of the fractured crack

Figure A-4. Inside view of the smooth crack
Figure A-5. Air bladder installed on top of bentonite

Figure A-6. Test cell sealed off and ready to be tested
Appendix B: Aperture vs. Flow for Slide and Measured Values Fractured Crack: 20-30 Sand
Fractured Crack: 20-30 Sand

10 psi

Figure B-1. Head at 10 psi

Fractured Crack: 20-30 Sand

8 psi

Figure B-2. Head at 8 psi
Fractured Crack: 20-30 Sand

**6 psi**

[Graph showing flow rates at 6 psi for a fractured crack with 20-30 sand, with two lines indicating measured and slide data.]

Figure B-3. Head at 6 psi

Fractured Crack: 20-30 Sand

**4 psi**

[Graph showing flow rates at 4 psi for a fractured crack with 20-30 sand, with two lines indicating measured and slide data.]

Figure B-4. Head at 4 psi
Figure B-5. Head at 2 psi
Appendix C: Aperture vs. Flow for Slide and Measured Values Fractured Crack: Graded Sand
Fractured Crack: Graded Sand

Figure C-1. Head at 10 psi

Fractured Crack: Graded Sand

8 psi

Figure C-2. Head at 8 psi
Figure C-3. Head at 6 psi

Figure C-4. Head at 4 psi
Fractured Crack: Graded Sand
2 psi

Figure C-5. Head at 2 psi
Appendix D: Aperture vs. Flow for Slide and Measured Values Smooth Crack: 20-30 Sand
Smooth Crack: 20-30 Sand

**10 psi**

![Graph showing flow vs. aperture for 10 psi pressure.](image)

Figure D-1. Head at 10 psi

Smooth Crack: 20-30 Sand

**8 psi**

![Graph showing flow vs. aperture for 8 psi pressure.](image)

Figure D-2. Head at 8 psi
Figure D-3. Head at 6 psi

Figure D-4. Head at 4 psi
Figure D-5. Head at 2 psi
Appendix E: Aperture vs. Flow for Slide and Measured Values Smooth Crack: Graded Sand
Figure E-1. Head at 10 psi

Figure E-2. Head at 8 psi
Figure E-3. Head at 6 psi

Figure E-4. Head at 4 psi
Figure E-5. Head at 2 psi