Chapter 2

Experimental Work

2.1 Introduction

This chapter discusses the methods and procedures used to carry out experiments performed in order to study the behavior of water filled tubes. The research described in this chapter was joint work with Matt Moler, a graduate student in the geotechnical engineering program area. Most of the information that follows was taken directly out of the report "Pilot-Scale Tests of Stacked Three-Tube Configuration of Water-Filled Tubes for Resisting Floodwaters" by Moler, Freeman, Filz, and Plaut (2001). This research is a continuation of research conducted at Virginia Tech, as described in "Pilot-Scale Tests of Water-Filled Tubes Resisting Floodwaters" by FitzPatrick, Nevius, Filz, and Plaut (2001). In recently-completed work, single-tube and double-tube configurations were tested to determine the deformation and stability of the arrangements. The research presented in this chapter focuses on a three-tube configuration, and it includes the following work:

- Construct two additional tubes in order to perform tests of the three-tube configuration.
- Develop a strapping scheme for the three-tube configuration.
- Develop more accurate measurement techniques for determining relative deformations of the tubes.
- Perform tests on the three-tube configuration.
- Determine relative deformations of the tubes at increasing water levels during testing.
- Assess the global stability and failure mode of the three-tube configuration.
- Perform interface shear tests between two pieces of the tube material and between the tube material and the strapping material.

Details of the testing program and the test results are presented in the following sections.

2.2 Tube Construction

Two additional water-filled tubes were constructed in a manner identical to that used in the previous work (FitzPatrick et al. 2001). This brought the total number of tubes constructed and usable to three tubes. There were additions made to the two new tubes and to the existing tube in order to decrease the amount of time needed for tube drainage. The additions were drains that allowed a substantial amount of water to be released from the tube at the end of testing. This addition decreases teardown time needed from one test to another.

For the two new tubes, one release drain was installed 30 inches away from one end of the tube on the main seam. For this addition, a 2-inch circular hole was cut into the tube material. Aluminum washers 1/8-inch thick with a 4½-inch outer diameter and 2-inch inner diameter were then glued both on the underside and topside of the hole. The washers were attached using GOOP^{TM} adhesive. A 2-inch to 1½-inch female pipe thread PVC drain was then placed on top of the topside washer such that the lip of the drain rested on the top of the outside washer. GOOP^{TM} was then liberally applied to the connection areas where the drain and outside washer came in contact. A 1½-inch plug with teflon tape applied to the threads was then installed into the drain. This drain system, shown in Figure 2-1, allowed the tube to drain within ten minutes.

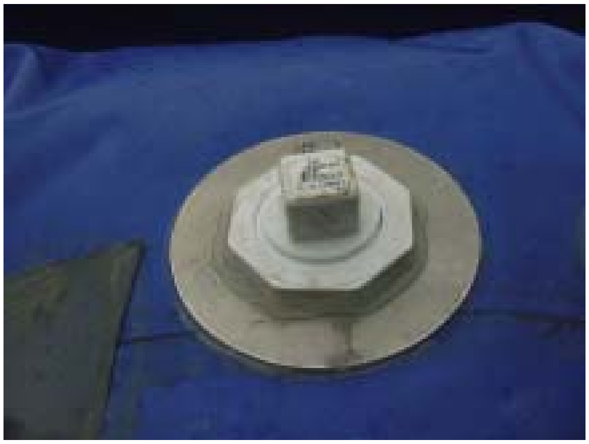

Figure 2-1: Release Drain Installed on Two New Tubes

For the tube existing from previous research, there was no manner in which to attach the drain system mentioned above without having access to the inside of the tube. Therefore, another type of drain system was installed. Two 3/4-inch circular holes were cut 30 inches from each end of the tube along the main seam. At each hole, a 1-inch to 5/8-inch PVC reducer was then inserted from above, such that the small end of the reducer extended out from the tube. A brass washer was placed over the reducer, and an electrical conduit nut was used to fasten the reducer to the tube. Teflon tape was then applied to the threads of the reducer, and a 5/8-inch PVC cap was screwed onto the threads. This drain system was placed at both ends of the tube in order to expedite draining the tube. With this drain system, as shown in Figure 2-2, the tube could be drained within 30 minutes.

Figure 2-2: Release Drain Installed on Existing Tube

2.3 Instrumentation and Measurement Procedures

Measurements required for this research included the cross-sectional deformations of the tubes, the pore pressures beneath the tubes, and the underseepage flow rates. These measurements were taken in a fashion similar to that used in previous work (FitzPatrick et al. 2001), with only slight modifications. These modifications were made in order to increase the accuracy of measurements and the efficiency of testing with the tubes. The modifications are discussed below.

The first modification concerned the addition of a leveling trough system extending around the box. The leveling trough was utilized to ensure that the measuring beam was level and at a consistent datum throughout the measurement process. The leveling trough consisted of four 8-foot sections of PVC gutter material approximately 3 inches high and 4 inches wide. Each section was sealed at both ends using a cap and gasket attachment that clicked into place on either end. A hole was then drilled into the base of the end caps to allow for a later insertion of 3/8-inch inner diameter flexible tubing. Each 8-foot gutter section was then placed on top of the upper 2-inch by 8-inch supporting brace extending around the outside of the box. The two gutter sections placed on the 16-foot sides of the box were placed such that each end of the gutter section was 36 inches away from the end of the brace. The two gutter sections placed on the 12-foot sides of the box were placed such that each end of the gutter section was 11½-inches away from the end of the brace. On the 12-foot sides of the box, a 2-inch by 4-inch by 8-foot piece of lumber was needed under the gutter section in order to ensure that each gutter section was roughly at the same elevation around the box.

In order to connect the gutter sections, 3/8-inch inner diameter flexible tubing was extended from end cap to end cap. The end of the hose was inserted into one end cap through the hole previously drilled, then extended around the box corner to the adjacent end cap, inserted into that end cap, and snipped (see Figure 2-3). This process was continued until all gutter sections were connected with the hose material.

Figure 2-3: End Cap and Connecting Hose Used in Leveling Trough

An inflow drip line and an outflow drip line were installed on the leveling trough system as well. The inflow drip line consisted of ¼-inch inner diameter polyethylene tubing extending from the reservoir system to an adjustable valve. The adjustable valve, as shown in Figure 2-4, was placed in the gutter section on the side nearest the reservoir system. During normal testing operations, the adjustable valve was opened such that the flow was approximately two drops of water per second.

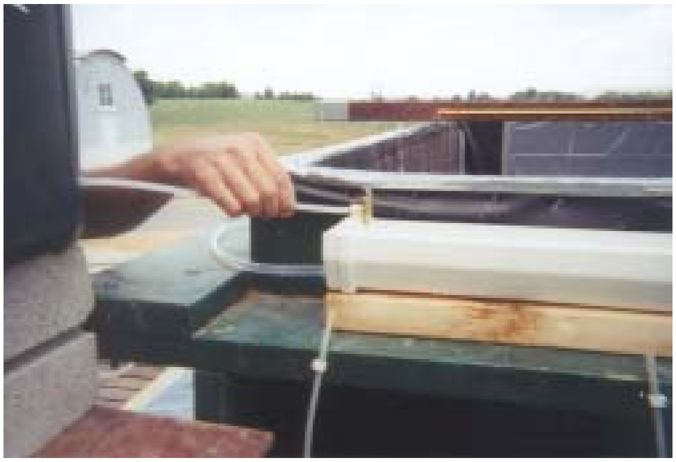

Figure 2-4: Inflow Drip Line with Adjustable Valve

The outflow drip line consisted of 3/8-inch inner diameter flexible tubing extending from the gutter section opposite the inflow system to an elbow. The elbow was set at a constant elevation during testing operations. A piece of 3/8-inch inner diameter flexible tubing was attached to the elbow and extended away from the box area, as shown in Figure 2-5. In this manner, a constant head of water was maintained completely around the box.

Figure 2-5: Outflow Drip Line with Fixed Head Location

Based on this constant head of water encompassing the perimeter of the box, the measurement beam could be referenced from the trough system in order to obtain accurate vertical deformation (Y-coordinate) measurements. The process of setting up the measurement beam began by first setting the beam over a given series of tube targets. The beam was adjusted in the horizontal direction so that the exterior plumb bobs extending from wires on both ends of the beam were aligned with the existing reference lines outside of the box. As a result, the measurement beam was aligned in the horizontal direction.

Next, the beam elevation was standardized in the vertical direction by using wooden shims and a measurement implement. The wooden shims had dimensions of 8 inches by 2 inches by ½ inch (on the thickest end). The measurement implement consisted of an aluminum gutter spike cut down to a length of 3 inches. The shims were placed under the beam on each end where the beam touched the upper edge of the box. The gutter spike was placed perpendicular to the underside of the beam and referenced to the water level in the water trough system. If the end of the gutter spike extended into the water, then the beam was raised with the shims until the spike barely touched the surface of the water. This process was repeated on both ends of the beam, as shown in Figure 2-6. As a result, the measurement beam was aligned in the vertical direction.

Figure 2-6: Aligning of the Measurement Beam in Vertical Direction

After the measurement beam was aligned in both the horizontal and vertical directions, accurate measurements could be taken in those directions. A plumb bob was dropped from the side of the measurement beam until it was in contact with a particular target. The position of the plumb bob wire along the metric tape measure attached to the beam was then noted as the horizontal position (X-coordinate). After this X-coordinate measurement was recorded, an alligator clip was attached to the plumb bob wire where the wire contacted the measurement beam. With this length marked, the length from the alligator clip to the point of the plumb bob wire was measured using a measuring stand developed for this purpose. This Y-coordinate measurement was also recorded.

The locations at which the undersides of the tubes encounter the foundation material could not be obtained in the same fashion. For this reason, a special measurement tool was constructed in order to obtain these measurements. The tool was a 4-foot level with a yardstick glued to the end of the level. The yardstick was shortened to have dimensions of 12 inches by 1 inch. In order to obtain horizontal (X-coordinate) measurements in these critical locations, the yardstick end of the tool was inserted under the tubes to a point where the yardstick was wedged between the tube and the foundation material. The level was then plumbed in the vertical direction and the X-coordinate was noted. It was assumed that the Y-coordinate at these locations had the same value as the foundation material. Figure 2-7 depicts the measurement tool used to obtain these measurements. It should be noted that this measurement tool was not implemented into the measurement procedure until Trial 5 of the testing process.

Figure 2-7: Measurement Tool for Obtaining Measurements Under the Tubes

The Z-direction measurements, or distance from a series of targets to the edge of the box along the longitudinal length of the tubes, were not taken for a given set of tube targets. They were neglected since they were deemed unnecessary measurements in the understanding of the deformation of the tubes. However, the approximate Z-position of the targets is known from previous work, and it does not change much from test to test.

All measurements were recorded in metric values. Figure 2-8 illustrates the procedure for taking measurements.

Figure 2-8: Measurement Procedure Using Plumb Bob

The procedure for measuring the pore pressures beneath the tubes was very similar to that used in the previous work (see FitzPatrick et al. 2001). The only difference was that the measurements were based on the measurement beam aligned in the vertical direction using the leveling trough system.

The procedure for measuring the water seepage rates beneath the tubes was exactly the same as that used in the previous work (see FitzPatrick et al. 2001).

2.4 Test Procedure and Results

A configuration of three tubes was utilized with the goal of resisting higher headwater elevations than those achieved by a single tube. The configuration consisted of two tubes placed side by side, with a third tube placed on top and resting in the depression between the other two tubes. The important issues related to this configuration were the strapping system used to hold the tubes together, the location of the drainage layer, and end friction considerations. The stacked configuration has a typical cross section as shown below in Figure 2-9.

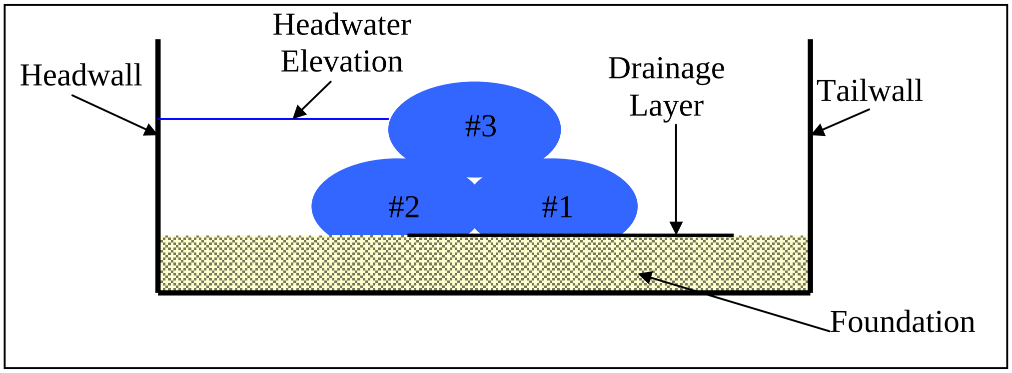

Figure 2-9: Typical Cross Section of Three-Tube Configuration

At the onset of the three-tube configuration testing, the intent was to produce two distinct scenarios. The first scenario was to overtop the stacked configuration with the tubes remaining stable. This would involve the headwater rising in increments until the upper tube was overtopped by water. A stable overtopped configuration would consist of the tubes not sliding or rolling. The second scenario was to have the tubes fail in a sliding manner. This would involve the headwater rising to a point such that the three-tube configuration would begin to move in a lateral fashion away from the headwater. The two scenarios would be achieved by adjusting the drainage layer location under the three-tube configuration. In this manner, the flow path and the pore pressures beneath the tubes could be altered.

Test Setup

In order to attain a stacked configuration of the tubes, it was necessary to utilize a strapping system that held the tubes together. The strapping system changed from trial to trial, mainly because it was learned that the strapping system played an integral role in the stability of the tubes. With the upper tube resting on the bottom two tubes, it was necessary to provide restraint so that the bottom two tubes did not roll away from one another. Also, the strapping system had to sufficiently grasp the tubes so that the tubes did not roll within the strapping system, thereby constituting a rolling-type failure. The strapping system consisted of four sets of straps, located at strategic locations along the longitudinal lengths of the tubes. The locations of the individual straps are depicted in Figure 2-10. Different strapping systems were utilized throughout the testing program and will be discussed in subsequent sections. It should be noted that while different strapping systems were utilized for different trials, the location of each strap along the longitudinal lengths of the tubes did not change from trial to trial.

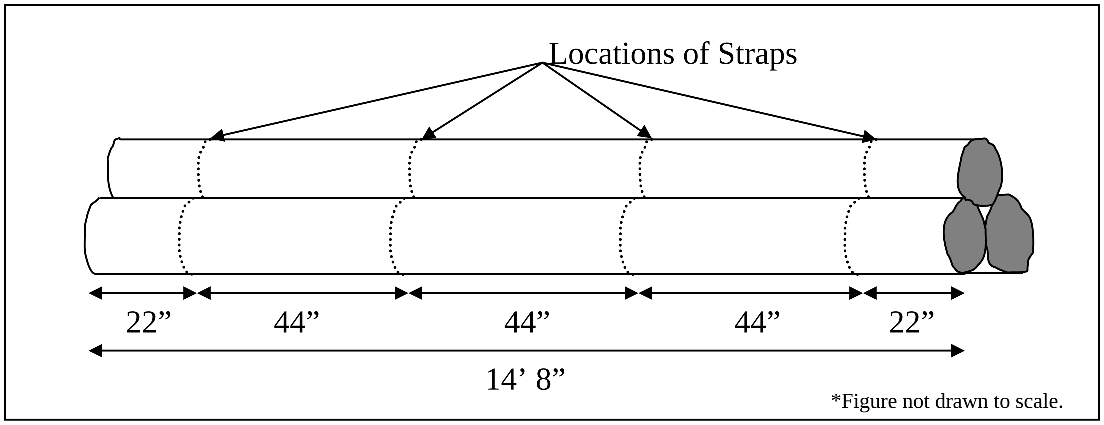

Figure 2-10: Locations of Straps along Longitudinal Length of Tubes

The drainage layer, consisting of the woven monofilament filter and a geonet drainage layer, was placed under the three-tube configuration. By adjusting the location of the drainage layer, the pore pressures exerted on the underside of the bottom two tubes and the flow path of the seepage water could be adjusted.

End effects on the three tubes located in the box were handled in much the same manner as in the previous work (FitzPatrick et al. 2001). The only difference was that bentonite paste was placed where the headwater side of both the upper and lower tubes encountered each side of the box.

The sequence of tube setup for each respective test began by first filling the lower headwater tube to a pressure head of 6½ inches above the top of the tube. Next, the adjacent lower tailwater tube was filled to the same pressure. The bottom two tubes were then strapped together using the desired strapping system, and the upper tube was filled to a pressure head of 6½ inches above the top of the tube. The upper tube was then connected to the strapping system. Following the filling of the upper tube, the pressure head changed in both the bottom two tubes to an approximate value of 17½ inches above the top of each respective tube. In addition to filling the tubes and the subsequent effect on tube pressure head, the process of strapping the tubes together raised the pressure heads within each individual tube as well. Also, the testing process of increasing the headwater elevation during each individual trial changed the pressure heads within the tubes. Appendix A contains tables detailing the pressure heads within the tubes as the headwater elevation was increased during the trials. In addition, Appendix A contains tables of the pressure heads within the tubes as the strapping system was attached for two of the trials.

A number was assigned to each tube in the three-tube configuration. The lower tailwater tube was identified as tube #1, the lower headwater tube was identified as tube #2, and the upper tube was identified as tube #3. This numbering system is depicted in Figure 2-9.

Testing Preparation

A number of trials were performed to test the three-tube configuration setup. Multiple trials were needed since the testing of the three-tube configuration was an evolutionary process – something was learned and then changed so that the next trial would hopefully solve the problems of the previous trial.

Each trial consisted of a number of preparation steps. First, the top two inches of the foundation sand were leveled and recompacted to achieve a quality testing surface. The sides of the box were prepared with grease and 6-mil polyethylene sheeting as in the previous work (FitzPatrick et al. 2001). Next, the tubes were placed in predetermined locations within the box. The tubes were then filled with water as the strapping system was put in place (each trial description contains details concerning the order of filling and the strapping descriptions). The box was then filled with water to the depth of the foundation material. At this point, initializing measurements were taken. Finally, the headwater elevation was raised to predetermined elevations and measurements were taken again. Each trial concluded with a failure of some type. The tubes were then removed and any information that could be gleaned while removing the tubes was recorded.

Failure of each trial took the form of piping underneath the tubes, rolling of the tubes within the straps, or actual sliding failure of the three-tube arrangement. As previously mentioned, lessons learned from preceding trials were applied to each successive trial with the goal of achieving one of two scenarios: overtopping the stacked configuration with the tubes remaining stable or failing the tubes in a sliding manner.

Descriptions of each trial are presented below. Information that is explained for each trial includes the preliminary setup locations for the three-tube configuration and the drainage layer, a description of the strapping system, and the elevations of the headwater at which measurements were taken. Other items covered in each trial include the highest headwater elevation achieved, reasons for failure, and possible ideas for improvement for the next trial. Also included in each trial description are various pictures of the initial tube and box setup, testing at different headwater increments, and disassembly.

Trial 1

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-11. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 9 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #2 and tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 36 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2. The exact dimensions of the tubes relative to one another can be found in Appendix A for Trial 1 for a headwater elevation of 0 inches.

The strapping system for Trial 1 consisted of a 1-inch wide nylon strapping with a maximum tensile force capacity of 500 lbs. Approximately four separate sections of this nylon strapping

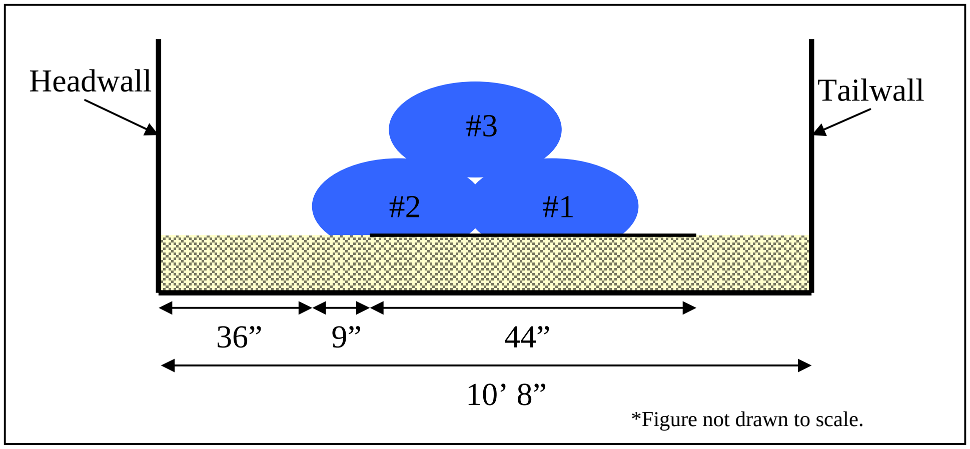

Figure 2-11: Cross Section of Trial 1 Setup

with lengths of 24 feet were needed for this strapping system. To hold the straps in place around each tube, two types of attachment pieces were utilized. The first was a 1½-inch buckle manufactured from high-density plastic. Twelve of these buckles were needed for the entire strapping system. The other attachment piece was a 1¼-inch D ring made from a metal alloy. Eight of these D rings were needed for the entire strapping system.

The strapping system was placed in four separate locations, as previously displayed in Figure 2-10. Figure 2-12 shows the strapping system, at any one location, as it wraps around the tubes.

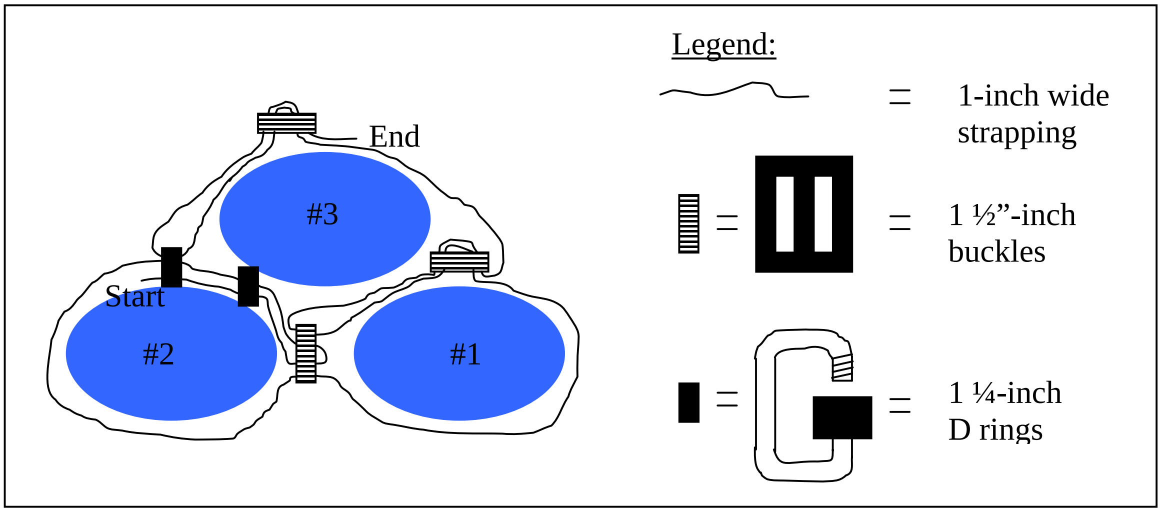

Figure 2-12: Strapping System for Trial 1

For this trial, measurements were taken at headwater elevations of 0 inch, 5 inches, and 10 inches (see Appendix A for a complete set of figures for this trial). The largest headwater achieved for this trial was 12.25 inches.

From the 0-inch to 5-inch headwater increments, the three-tube configuration moved only slightly. It was not until the 10-inch headwater elevation was achieved that movements were significant. At the 10-inch headwater elevation, tube #2 had noticeably rotated away from the rising headwater in a clockwise manner. This caused the plastic sheeting on the sidewalls to rotate as well, as depicted in Figure 2-13. It was apparent that because of this large amount of movement, the bentonite paste along the sidewalls would have to be constantly monitored to ensure that it would not separate from tube #2 and the sidewall. In addition to this, the tailwater elevation increased to an elevation of 1 inch above the sand elevation.

Figure 2-13: Tube #2 Rolling Away from Headwater at 7.5-Inch Water Height in Trial 1

Once the headwater elevation reached 12.5 inches, the headwater would not increase anymore, despite two inflow hoses supplying water to the headwater side of the box. The tailwater elevation had increased to 3.75 inches, and was continuing to increase. Based on visual observation, it was concluded that tube #2 had rolled back sufficiently such that there was unimpeded flow from the headwater side of the box to the drainage layer. The tailwater elevation was increasing since the outflow valves on the tailwater side could not handle the amount of water flowing beneath the tubes.

Based on the lessons learned from this trial, it was decided that the drainage layer should be placed further back under tube #2 towards the tailwater side of the box to alleviate the flow problem mentioned above. This would mean that more of tube #2 would be in contact with the sand foundation material.

Trial 2

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-14. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 19 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #2 and tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 36 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 2 for a headwater elevation of 0 inches.

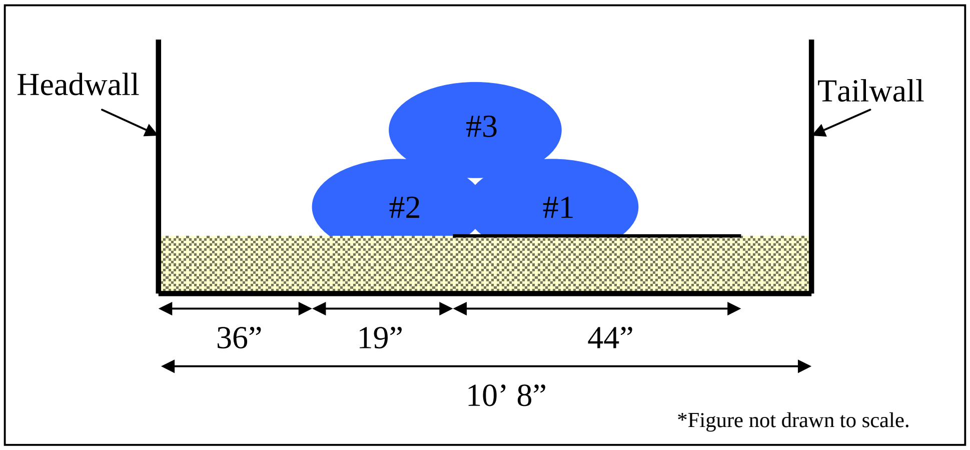

Figure 2-14: Cross Section of Trial 2 Setup

The strapping system for Trial 2 was identical to that used for Trial 1, as depicted in Figure 2-12.

Based on the information gained from Trial 1, it was decided to take measurements at larger increments than those taken for Trial 1. For Trial 2, measurements were taken at headwater elevations of 0 inch, 7½ inches, and 15 inches (see Appendix A for a complete set of figures for this trial). Use of these headwater elevations would hopefully expedite the testing process and accurately gauge the range of movements the tubes would undergo.

The amount of lateral movement that the three-tube configuration underwent from the 0-inch to the 7½-inch headwater elevation was approximately 2 cm. From the 7½-inch increment to the 15-inch increment, the three-tube configuration moved much more. From observations of the plastic sheeting on the sides of the box, the tubes were rolling away from the headwater. An example of the tubes rolling on the sides of the box is shown in Figure 2-15. In order to take measurements at the 15-inch headwater elevation, two hoses were required to provide flow into the headwater side of the box to maintain a constant headwater. A large amount of headwater was then moving beneath or around the tubes and making its way to the tailwater side of the box.

Figure 2-15: Rotation of Tube #2 Against Sidewall of Box at 10-Inch Water Height in Trial 2

After the 15-inch headwater measurements were obtained, the headwater could not be increased any further, despite the two inflow hoses running at maximum flow. Therefore, the maximum headwater achieved for Trial 2 was 15 inches. It was decided, however, to allow the inflow hoses to continue to flow into the headwater side of the box and see if the tubes would continue to move away from the headwater. Two hours after the first 15-inch headwater measurements were taken, more measurements were taken just on tube #2. It was concluded that tube #2 had moved back an additional 7 cm after the first 15-inch headwater measurements were taken. By this point, though, tube #2 had rotated to a position such that the valves installed on the tube were in direct contact with tube #3, causing stress on the valve connections. It was decided to stop testing for fear of shearing off these valve connections.

Based upon the data obtained in this trial, two important problems were identified. At a headwater of 15 inches, the three-tube configuration had moved away from the headwater to a point where the headwater and drainage layer were in very close proximity to one another. There was nearly unimpeded flow from the headwater side of the box to the drainage layer, which is why the headwater could not be raised above the 15-inch increment. Secondly, the movement of the tubes away from the headwater was caused by each individual tube rolling away from the headwater. The strapping system was not restricting the rolling tendency of the tubes, which was unacceptable. Otherwise, as evident with this trial, the tubes would roll until the headwater and the drainage layer were in contact with one another.

For the next trial, it was determined that development of a new strapping system was needed to restrict the rolling movements of the tubes. The strapping system would have to be snug around the tubes and also tighten down on itself when any movement was initiated. That was the goal for the next trial.

Trial 3

For Trial 3, the preliminary setup locations concerning the three-tube configuration and the drainage layer were the same as Trial 2, depicted in Figure 2-14. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 3 for a headwater elevation of 0 inches.

The strapping system used for this trial was different from the previous strapping system used in Trial 1 and Trial 2. This strapping system was designed to tighten down on the tubes with more pressure when movement of the tubes occurred. It was thought that by utilizing a self-tightening strap system the tubes might initially move, but would stop moving after the strapping system had increased the pressure within the straps. Figure 2-16 depicts the strapping system for Trial 3.

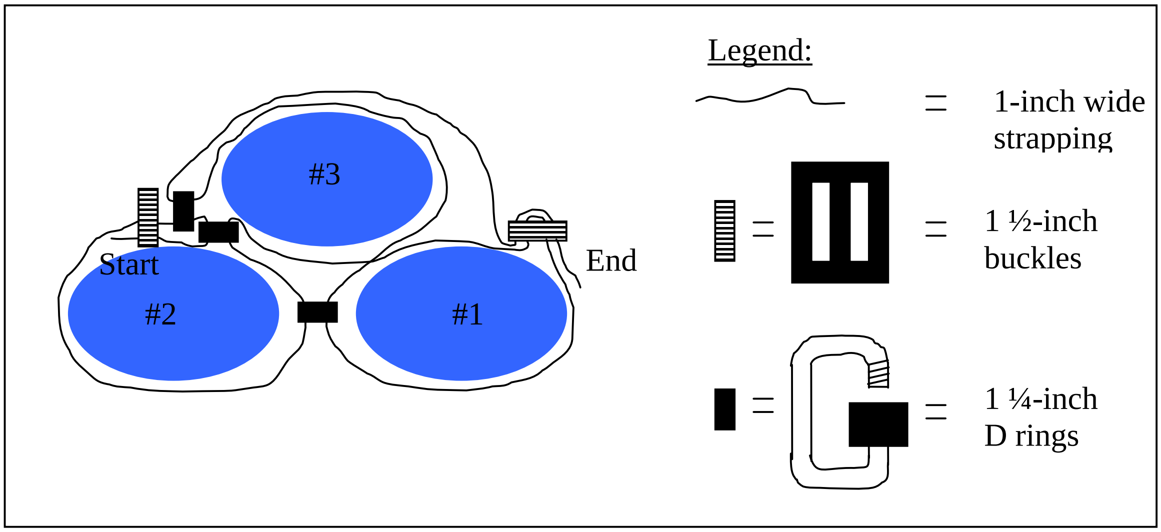

Figure 2-16: Strapping System for Trial 3

The strapping system once again consisted of 1-inch-wide nylon strapping with a maximum tensile force capacity of 500 lbs. Approximately four separate sections of this nylon strapping with lengths of 24 feet were needed for this strapping system. To hold the straps in place around each tube, two types of attachment pieces were utilized. The first was a 1½-inch buckle manufactured from high-density plastic. Eight of these buckles were needed for the entire strapping system. The other attachment piece was 1¼-inch D rings made from a metal alloy. Twelve of these D rings were needed for the entire strapping system.

As a consequence of using this new strapping system, bentonite paste was added to the locations where the strapping system of tubes #2 and #3 encountered one another. This was done in order to prevent leakage of headwater between tube #2 and tube #3. The bentonite paste was liberally applied to the areas where the strapping system tied into tube #2 and then rose vertically over tube #3. Figure 2-17 illustrates the location and amounts of bentonite paste applied to these locations.

Figure 2-17: Bentonite Paste Applied to Tube #2 and Tube #3 in Trial 3

Based on the information gained from previous trials, it was once again decided to take measurements at larger increments than those taken for Trial 1 and Trial 2. A larger variation between headwater measurements was chosen since very little movement was observed at headwater elevations below 10 inches. For Trial 3, measurements were taken at the 0-inch and 10-inch headwater levels.

The tube deformation measurements from this trial indicate that there was minimal movement of tube #1 and tube #3 as the headwater was raised from 0 inches to 10 inches. Unfortunately, the buckles used in the strapping system still allowed tube #2 to roll within the straps away from the headwater. The 1½-inch buckles were slipping throughout the strapping system and this caused the rolling of tube #2 (see Appendix A for a complete set of figures for this trial). After taking measurements at the 10-inch headwater elevation, the headwater was increased to the 17-inch elevation. At this point, the rolling of tube #2 was so considerable that the valve connections on top of tube #2 were at risk of being sheared off by tube #3, as shown in Figure 2-18. For this reason, Trial 3 was stopped at the 17-inch headwater elevation.

From this trial, it was learned that once again our strapping system was not performing as needed. Our goal was to develop a strapping system that would make the three-tube configuration act as one complete unit rather than three independent tubes. As evidenced from the previous trials, the strapping systems thus far were not restricting the tubes from rolling. For the next trial, a new strapping system was developed in an attempt to restrict this rolling phenomenon.

Figure 2-18: Valve on Tube #2 Nearly Sheared Off by Tube #3 in Trial 3

Trial 4

For Trial 4, the preliminary setup locations concerning the three-tube configuration and the drainage layer were the same as for Trial 2, depicted in Figure 2-14. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 4 for a headwater elevation of 0 inches.

The strapping system used for Trial 4 was designed with new attachment pieces in order to prevent slippage of the buckles as previously encountered in Trial 3. The strapping system incorporated a no-slip buckle that locked tube #2 and tube #3 together. Also, a ratcheting device was used to lock tube #3 to the bottom two tubes. Figure 2-19 illustrates the strapping technique utilized for Trial 4. Figures 2-20 and 2-21 show the no-slip buckle and ratcheting device, respectively. The 1½-inch buckle in this strapping system is an attachment that prevents the ratcheting device from sliding up the 1-inch-wide strapping material. For this strapping system, 4 no-slip buckles, 4 ratcheting devices, 4 buckles, and 20 ft of strapping material were needed.

With this strapping system, it was once again necessary to apply bentonite paste to the contact areas of tube #2 and tube #3 at the strapping system locations. This was needed in order to prevent the headwater from escaping through the indentation provided by the strapping system. Figure 2-22 illustrates the bentonite paste after it has been applied to the areas between tube #2 and tube #3. The process of applying the bentonite paste to the strap locations was continued for each of the subsequent trials.

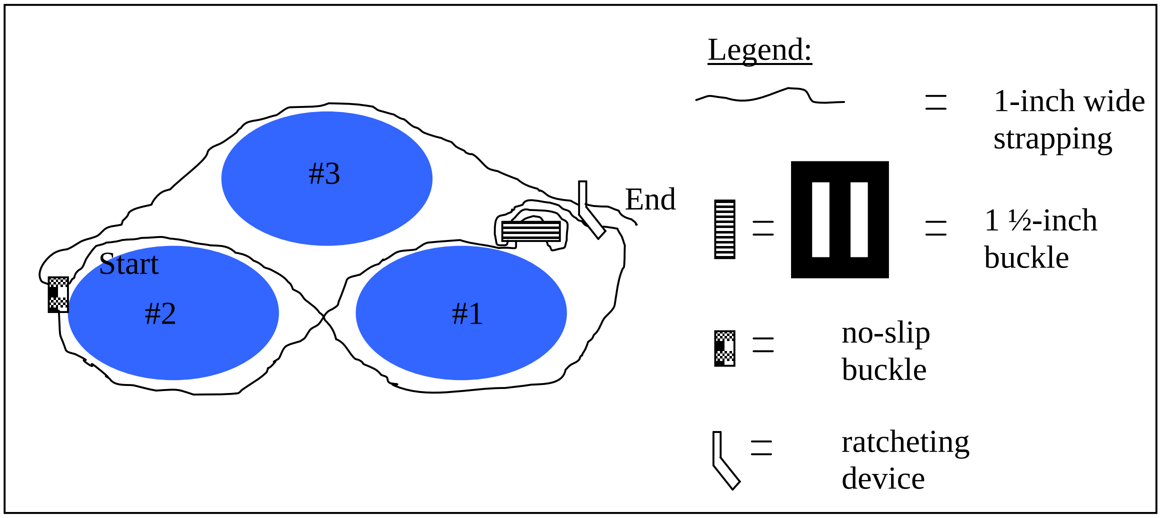

Figure 2-19: Strapping System for Trial 4

Figure 2-20: No-Slip Buckle

Figure 2-21: Ratcheting Device

Figure 2-22: Bentonite Paste Applied to Strap Locations on Tube #2 and Tube #3 in Trial 4

The measurement intervals were once again increased to greater increments than those taken for the previous trials. A larger variation between headwater measurements was chosen since very little movement was observed at headwater elevations below 12½ inches. For Trial 4, measurements were taken at the 0-inch and 12½-inch headwater elevations.

As in previous tests, minimal deflections were observed for both tubes #1 and #3 at a headwater elevation of 12½ inches. Tube #2, on the other hand, experienced some rolling and a horizontal displacement of approximately 1 inch at the same headwater elevation. Appendix A contains a complete set of figures for this trial.

After taking measurements at the 12½-inch headwater level, the headwater was increased in an attempt to achieve a headwater elevation of 17 inches. However, as the headwater elevation increased to 14 inches, it was apparent from the tailwater side that piping of the foundation material beneath the tubes was occurring. Piping began at the location where the strapping system and the underside of tube #2 came in contact with the foundation material. Piping was evident at all four locations where the strapping wrapped under tube #2. As piping progressed, the headwater elevation began to drop rapidly. This piping failure concluded the test.

Upon removing the tubes during the teardown process, it was evident that the piping had created large trenches in the foundation material at the strapping locations. The trenches were approximately 4 inches wide, 2 inches deep, and 16 inches in length. Sand was also found inside the drainage layer, further indicating that a piping failure had occurred.

After reevaluating the strapping scheme, it was determined that the strapping system was to blame for the piping failure. When the tubes are cinched into the strapping system, the straps are tightened down sufficiently such that a ¾-inch depression is formed on the upper surface of the tubes. This depression on the underside of the tubes is not evident, but the effects of the cinched strapping system are still present. Apparently, the amount of normal stress applied to the sand foundation is reduced in these locations as compared to the adjacent areas where the straps are not present. These areas where the stresses are reduced allow piping to initiate and form an erosion tunnel from the headwater to the tailwater side of the box.

Based on this outcome, measures were required to prevent piping at the strapping locations for the upcoming trials. Several methods were reviewed and it was noted that loosening the straps was not an option. The loosening of the strapping scheme would prevent piping but would allow the tubes to roll. It was concluded that pieces of flexible foam material should be placed on the sand foundation at the strapping locations to increase the normal stresses applied to the foundation soil. This would hopefully prevent the piping failure witnessed in this trial.

Trial 5

For Trial 5, the preliminary setup locations concerning the three-tube configuration and the drainage layer were the same as for Trial 2, depicted in Figure 2-14. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 5 for a headwater elevation of 0 inches. The strapping system used in this trial was identical to that for Trial 4. A diagram of the strapping configuration can be found in Figure 2-19.

In order to overcome the piping failure present in Trial 4, foam materiel used in plumbing applications to insulate copper pipes was introduced. The foam material was placed on top of the sand foundation in the areas where the strapping system wrapped under tube #2. The foam extended under the tubes at the strap locations and up onto the drainage layer. Dimensions of the foam were approximately 4 inches wide, ½-inch thick, and 18 inches in length. To ensure a smooth transition from the foundation material to the foam material, the foam was tapered along both sides of its 18-inch length. Somewhat compressible, this foam material was expected to prevent piping. Figure 2-23 depicts the foam material under tube #2 at a strapping location.

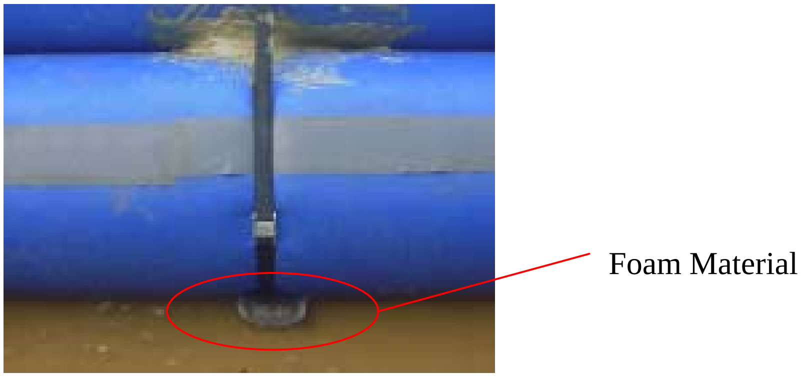

Figure 2-23: Foam Material under Strapping System in Trial 5

Once again, bentonite paste was applied to the contact areas of tube #2 and tube #3 at the strapping system locations. This was needed in order to prevent the headwater from escaping through the indentation provided by the strapping system.

As in all trials, initial measurements were taken at the 0-inch headwater elevation. The headwater elevation was then increased, but only to the 4-inch headwater elevation before failure occurred. Once again, piping was evident at all four strapping locations. At a mere 4 inches of headwater, piping had inflicted a destructive effect on the foundation. The trenches created by the piping left depressions in the soil approximately 2 inches deep, 6 inches wide, and 20 inches in length. Apparently the cushion material was not adequate to keep the sand foundation particles from being piped away. Figure 2-24 depicts the effects of the piping failure on the sand foundation material.

It was determined that there were two issues from Trial 5 to overcome in future tests. First, the foam material must be more compressible. It was believed that the weight of the tube did not compress the material enough to provide a smooth transition from the foam to the soil foundation. However, a more compressible material may not provide adequate pressure on the sand to contain the sand particles and prevent piping. Second, it was conceivable that due to repeated testing and piping failures, the top 2 inches of foundation material had become weak and unstable. Prior to Trial 6, the top 2 inches of the sand foundation would need to be recompacted.

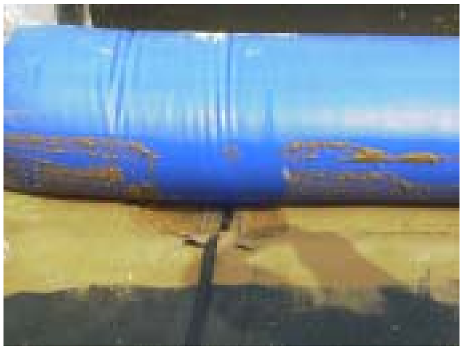

Figure 2-24: Piping Failure at Strap Locations in Trial 5

Trial 6

For Trial 6, the preliminary setup locations concerning the three-tube configuration and the drainage layer were the same as for Trial 2, depicted in Figure 2-14. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 6 for a headwater elevation of 0 inches. The strapping system used in this trial was identical to that for Trial 4. It is diagrammed in Figure 2-19.

Before any additional methods were employed to prevent the piping failure of the previous trials, it was decided to recompact the top 2 inches of the sand foundation material. For this, two compaction methods were implemented. First, a vibratory plate compactor (WACKER^{TM} BPU244A) was used to initially compact the sand with a total of three passes in the longitudinal direction. Next, a flat plate hand compactor compacted the sand along the edges of the box. The square flat plate had side dimensions of 15 inches and a weight of 25 pounds. Figure 2-25 illustrates the flat plate hand compactor in operation.

Figure 2-25: Flat Plate Hand Compactor in Operation

In the previous two trials, the failure of the three-tube configuration was due to piping of the foundation material at the locations of the straps. For Trial 6, it was thought that perhaps a bentonite cutoff trench located beneath each strap location would prevent piping. This would be similar to the treatment of the tube ends along the sides of the box. Therefore, four of these trenches were installed in the box at the locations where the strapping system would encounter the sand foundation material. The trenches had dimensions of 4 inches wide by 1 inch deep by 20 inches long. Figure 2-26 depicts the trenches before tube #2 was placed on top of them. Figure 2-27 depicts one of the trenches after tube #2 was placed on top of it.

Bentonite paste was also applied to the contact areas of tube #2 and tube #3 at the strapping system locations. This was needed in order to prevent the headwater from escaping through the indentation provided by the strapping system.

Initial measurements were taken at the 0-inch headwater elevation. The headwater elevation was then increased to the 12½-inch headwater elevation and measurements were again taken. From these measurements, it was evident that tube #1 had slid back approximately 2 cm. Tube #2 moved in a rolling fashion away from the rising headwater approximately 2 cm. Tube #3 also moved, but it was due to the movement of the bottom two tubes. This movement was in a horizontal direction away from the rising headwater. Figure 2-28 depicts the three-tube configuration at the headwater elevation of 12½ inches. Appendix A contains a complete set of figures for this trial.

Figure 2-26: Bentonite Cutoff Trenches to Prevent Piping under Strap Locations in Trial 6

Figure 2-27: Bentonite Cutoff Trench after Tube #2 Installed

Figure 2-28: Trial 6 at Headwater Elevation of 12 ½-inches

Following these measurements, the headwater elevation was again increased to 15 inches. At this point, another piping failure began to occur at the contact between the strapping system and the foundation material. This piping failure occurred at all four strapping locations. The cause of this piping failure was believed to have been the sand surrounding the bentonite cutoff trenches. Perhaps the trenches were not wide enough to completely cover the influence area of the straps on the underside of the tubes. In that case, there would still not be sufficient normal pressure on the sand foundation material to prevent it from piping. The setup for the next trial would have to be different in order to prevent the same piping problems from occurring.

For the next trial, it was decided to move the drainage layer slightly closer to the headwater beneath tube #2. The reason for this change was a concern over the actual contact area between the drainage layer and the underside of tube #2. If this contact area were too small, then piping could result, as was the case with the previous three trials.

Another change that was made concerned the use of the bentonite cutoff trenches. It was decided to discontinue use of the trenches in favor of a foam material. Since the last foam material did not work adequately, different foam with more compressibility would have to be chosen. Also, the width of this foam would be greater to adequately cover the influence zone of the strapping system on the underside of the tubes.

One more change that would decrease the amount of time needed for testing was also implemented. For the subsequent trials, it was decided to not take measurements until the piping problem could be resolved. This was instituted since the setup and testing time could be shortened to just one day rather than two days. If a suitable method of setup and testing was discovered such that the tubes were overtopped or a sliding failure occurred, then measurements would be taken on the next trial with the identical setup.

Trial 7

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-29. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 16 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #2 and tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 36 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2.

The strapping system used in this trial was identical to that for Trial 4. It is diagrammed in Figure 2-19. Measurements were not taken for this trial.

For this trial, foam padding was again utilized on top of the sand foundation in the areas where the strapping system wrapped under the tubes. The foam extended under the tubes at the strap locations and up onto the drainage layer. Dimensions of the foam were approximately 6 inches wide, ½-inch thick, and 36 inches in length. To ensure a smooth transition from the foundation material to the foam material, the foam was tapered along both sides of its 36-inch length. Much more compressible than the foam used in Trial 5, this foam material was expected to prevent piping. Figure 2-30 depicts the foam material under tube #2 at the strapping locations.

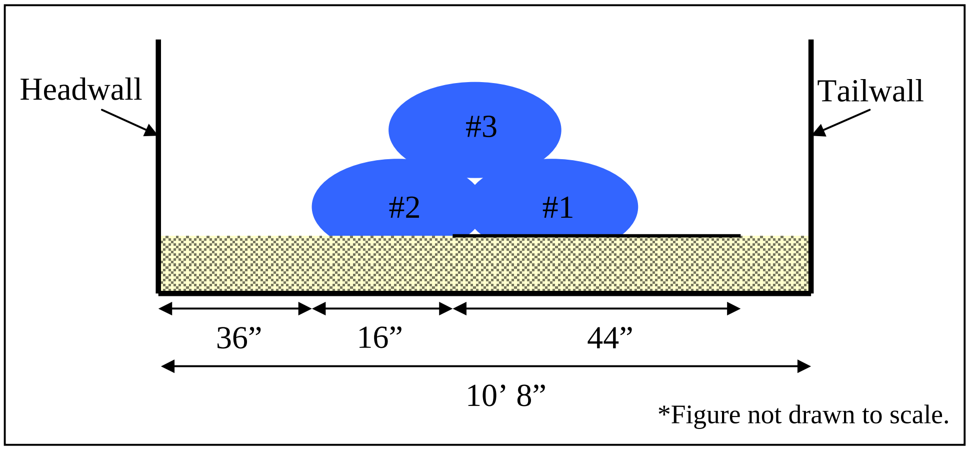

Figure 2-29: Cross Section of Trial 7 Setup

Figure 2-30: Foam Material Placed under Strap Locations for Trial 7

The maximum headwater achieved during this test was 16¾ inches. At this headwater elevation, the test was aborted since tube #2 had rolled back a total of 7½ inches. If the headwater elevation were increased further, the valves on tube #2 would be in jeopardy of being sheared off by tube #3. On a positive note, no evidence of piping existed during this trial. It was concluded that the foam material was adequately preventing a piping failure from occurring at the location where the straps wrapped underneath the tubes.

It was also concluded from this trial that a restraining device would have to be incorporated into the strapping system to prevent the excessive movement experienced by tube #2. This device would have to prevent movement of the strapping system between tube #1 and tube #2. If the device worked properly, then the movement of the tubes would be minimal and the opportunity to overtop or fail the tubes in a sliding failure might be attained.

Trial 8

For Trial 8, the preliminary setup locations concerning the three-tube configuration and the drainage layer are the same as for Trial 7, depicted in Figure 2-29.

The strapping system for this trial was similar to the one used in Trial 4, as diagrammed in Figure 2-19, yet this system had one new modification. At all four locations where the strapping system overlaps itself at the junction of tube #1 and tube #2, a 4-inch c-clamp was installed. The c-clamp was tightened such that the two pieces of strapping material were secured within the footpad of the c-clamp. The c-clamps were screwed down by hand until they could no longer be tightened. Figure 2-31 depicts this new strapping system. For this addition to the strapping system, a total of four c-clamps were needed.

Measurements were not taken for this trial. Maximum headwater achieved for this trial was 18½ inches with failure occurring in a sliding manner. Just before failure, measurements were taken with a tape measure to get an approximation of the horizontal movements of the three-tube configuration. Tube #2 had moved back approximately 5 inches from its initial setup location, while tube #1 had moved back approximately 2 inches. During failure, tube #2 appeared to rise vertically and float for about 1 to 2 seconds before the entire three-tube configuration began to slide backwards. This sliding took place on only one end of the tubes, yet the overall displacement was approximately 10 inches from the beginning of sliding to the end of sliding.

There were groaning noises as the three-tube configuration moved away from the headwater. The entire sliding sequence occurred in a time span of about 5 seconds.

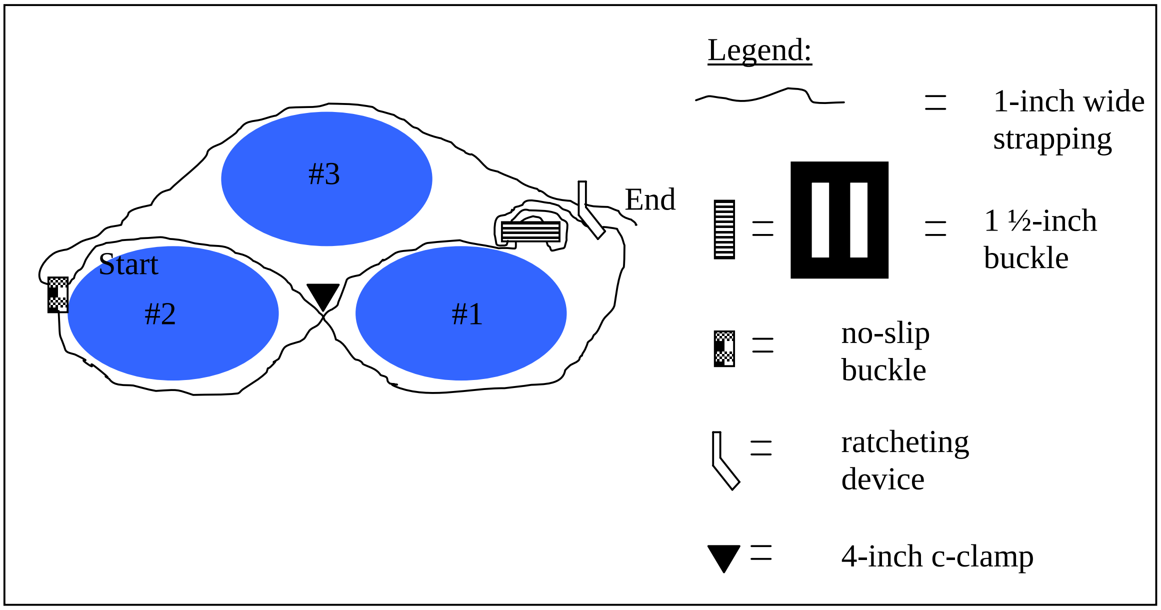

Figure 2-31: Strapping System for Trial 8

After teardown of this configuration, it was observed that there was no movement of the straps within the c-clamp devices used between tube #1 and tube #2. Also, there was no evidence of piping in this trial.

Since this trial setup and configuration produced a successful sliding failure, a decision was made to rerun the identical setup and take measurements for the next trial. In that manner, a more accurate idea of the complexities of the sliding failure could be determined.

Trial 9

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-32. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 16 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #2 and tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 28 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 9 for a headwater elevation of 0 inches.

The preliminary setup locations just described for Trial 9 were similar to the setup locations for Trial 7, with one modification. The entire system, including the three-tube arrangement and the drainage layer, was moved toward the headwall a distance of eight inches. By decreasing the volume required for fill by water, the testing time decreases. No adjustments to the testing procedure needed to be implemented in order to incorporate this modification.

The strapping system for this trial was identical to the strapping system used in Trial 8 and illustrated in Figure 2-31.

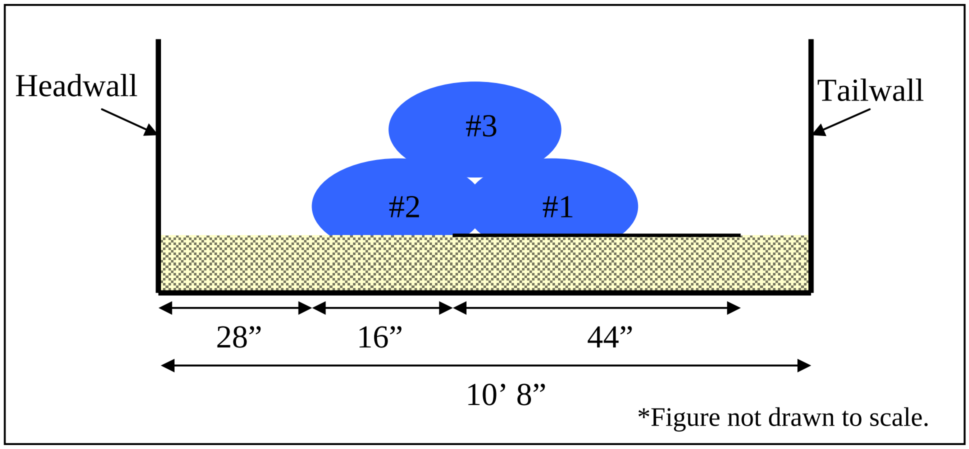

Figure 2-32: Cross Section of Trial 9 Setup

Measurements were taken at the 0-inch, 12½-inch, and 17-inch headwater elevations. The tubes underwent minimal deformation as the headwater increased to the 12½-inch elevation. However, as the headwater increased to the 17-inch headwater elevation, the tubes began to deform. Tube #2 underwent approximately 4 inches of horizontal movement away from the headwater at the location where the bottom of the tube contacts the foundation material. As a whole, the three-tube configuration shifted laterally an average distance of 1¼ inches. Appendix A contains a complete set of figures for this trial.

Since this trial was a duplication of Trial 8, it was expected that a similar sliding failure would occur at a headwater elevation of 18½-inches. However, the tubes did not reach the 18½-inch elevation, but rather failed at the 17½-inch elevation. The failure was due to piping along the entire longitudinal length of the tubes and the trial was aborted at this point.

Upon disassembling of the tubes, it appeared that the strap locations under the tubes were not the cause of the piping failure. Unfortunately, it was discovered that a fairly substantial leak existed in tube #2, thereby decreasing the water pressure within that tube during the test. The effect of the decreased water pressure contributed to the piping failure in this trial. Figure 2-33 depicts the sand piping from under the tubes and onto the top of the drainage layer on the tailwater side of the box.

For the next trial, a decision was made to move the drainage layer location and determine the effect on the stability of the three-tube configuration. In addition, the necessary repairs were made to tube #2 to prevent leaking.

Figure 2-33: Beginning of Piping Failure on Tailwater Side of Tubes in Trial 9

Trial 10

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-34. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 34 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 28 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 10 for a headwater elevation of 0 inches.

The strapping system for this trial was identical to the strapping system used in Trial 8 and illustrated in Figure 2-31.

Once again, bentonite paste was applied to the contact areas of tube #2 and tube #3 at the strapping system locations on the headwater side of the tubes. In addition, bentonite paste was also added to the contact areas of tube #1 and tube #3 at the strapping locations on the tailwater side of the tubes. This was needed in order to prevent the headwater from escaping through the indentation produced by the strapping system on both the headwater side and the tailwater side of the tubes.

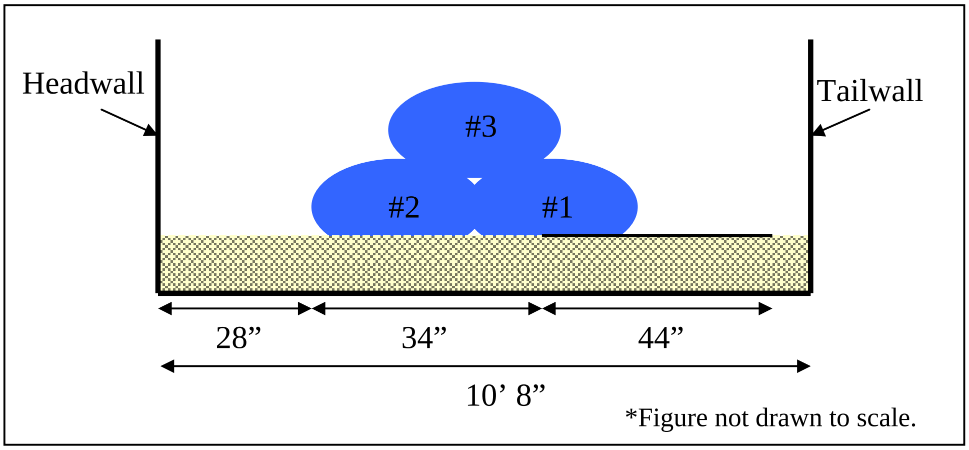

Figure 2-34: Cross Section of Trial 10 Setup

Measurement locations for this trial included the 0-inch and 12 ½-inch headwater elevations. As the headwater was increased to the 12 ½-inch elevation, the tubes experienced minor lateral movement. Overall, the three-tube configuration moved away from the headwater elevation approximately 1¼ inches. Appendix A contains a complete set of figures for this trial.

After the 12½-inch measurements were taken, the headwater elevation was increased to the 16-inch elevation, at which time a sliding failure developed. The test was then terminated due to the three-tube arrangement sliding away from the headwater approximately 3 inches.

For the next trial, it was decided to move the drainage layer to yet another location to determine the effect on the stability of the three-tube configuration.

Trial 11

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-35. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 12 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #2 and tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 28 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 11 for a headwater elevation of 0 inches.

The strapping system for this trial was identical to the strapping system used in Trial 8 and illustrated in Figure 2-31.

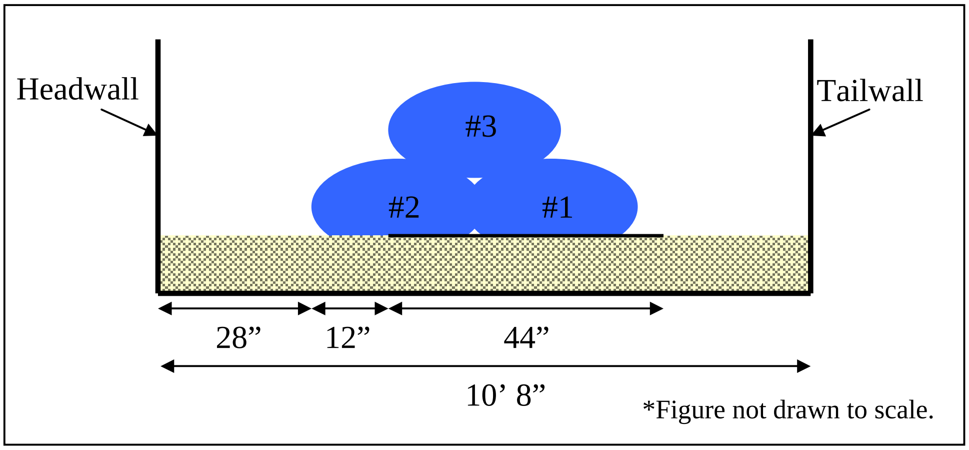

Figure 2-35: Cross Section of Trial 11 Setup

Measurement locations for this trial included the 0-inch, 12½-inch, and 16-inch headwater elevations. Deformations of the tubes were minimal as the headwater was increased from the 0-inch to 12½-inch headwater elevation. Overall, the three-tube configuration moved away from the headwater elevation an average of 1¼ inches. The headwater elevation was then raised to the 16-inch elevation, where deformations increased as well. Tube #2 deformed laterally an additional 1½ inches away from the headwater, while tube #1 and tube #3 deformed an additional 1¼ inches. Figure 2-36 depicts Trial 11 at a headwater elevation of 16 inches. Appendix A contains a complete set of figures for this trial.

Figure 2-36: Trial 11 at a Headwater Elevation of 16-Inches

At a headwater elevation of 18 inches, a sliding failure occurred. The entire three-tube configuration moved approximately 1 inch in a time span of about 15 seconds. At this point, piping began to occur along the entire longitudinal length of the tubes. This piping was believed to have occurred as a direct result of the sliding failure that was present. Figure 2-37 depicts the three-tube configuration just after the sliding failure. At this point, the trial was terminated.

1 Inch of
Movement Along
Sidewall of Box

Figure 2-37: Trial 11 Just After Sliding Failure

Based upon the sliding failures for some of the previous trials, it was thought that a relationship might exist between the critical headwater elevation and the location of the drainage system beneath the three-tube configuration. For the upcoming trials, an attempt was made to confirm this relationship by moving the drainage system to locations that had not yet been tested. Hopefully, an accurate representation of the effect of the drainage system location on the critical headwater elevation could be determined.

Trial 12

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-38. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 28 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 28 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 12 for a headwater elevation of 0 inches.

The strapping system for this trial was identical to the strapping system used in Trial 8 and illustrated in Figure 2-31.

Measurement locations for this trial included the 0-inch, 12½-inch, and 15-inch headwater elevations. Deformations of the tubes were minimal as the headwater was increased from the 0-inch to 12½-inch headwater elevation. Overall, the three-tube configuration moved away from the headwater elevation an average of 2 cm. The headwater elevation was then raised to the 15-inch elevation, where deformations increased as well. Tube #2 deformed laterally an additional 3 cm away from the headwater, while tube #1 and tube #3 deformed an additional 2 cm. Appendix A contains a complete set of figures for this trial.

At a headwater elevation of 16½ inches, a sliding failure occurred. The entire three-tube configuration moved approximately 2 inches in a time span of about 20 seconds. At this point, the trial was terminated. Figure 2-39 depicts the three-tube configuration just after the sliding failure occurred.

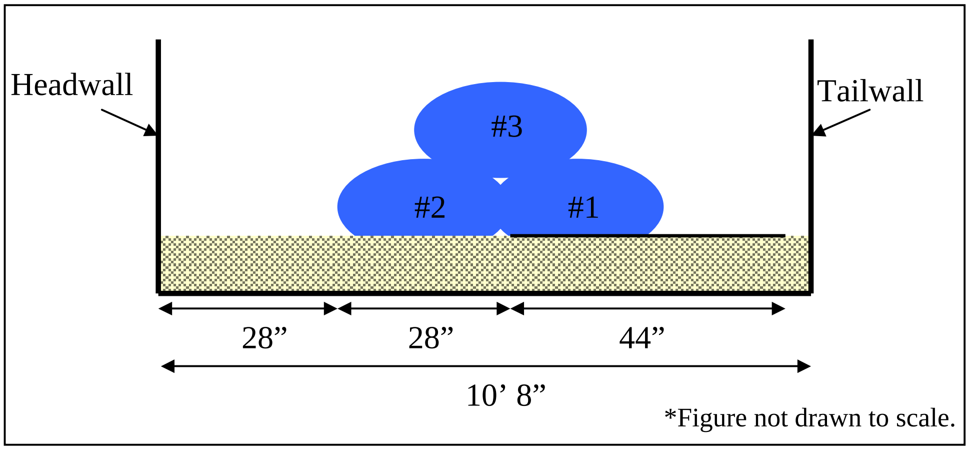

Figure 2-38: Cross Section of Trial 12 Setup

Figure 2-39: Trial 12 Just After Sliding Failure

Trial 13

The preliminary setup locations for this trial concerning the three-tube configuration and the drainage layer are depicted in Figure 2-40. The drainage layer was placed under the bottom two tubes so that the leading edge of the drain was 18 inches from the vertical tangent of tube #2 on the headwater side. The trailing edge of the drainage layer extended 44 inches to the right of this point under tube #1 and into the tailwater side of the box. Tube #2 was placed such that the vertical tangent of the tube on the headwater side was 28 inches to the right of the headwater side of the box. Tube #1 was then placed to the right of this point such that tube #1 and tube #2 were in contact with one another on their vertical tangents. Next, tube #3 was placed in the depression formed by tube #1 and tube #2. The exact dimensions of the tubes relative to one another can be found by referencing Appendix A for Trial 13 for a headwater elevation of 0 inches.

The strapping system for this trial was identical to the strapping system used in Trial 8 and illustrated in Figure 2-31.

Measurement locations for this trial included the 0-inch, 12½-inch, and 15-inch headwater elevations. Deformations of the tubes were minimal as the headwater was increased from the 0-inch to 12½-inch headwater elevation. Overall, the three-tube configuration moved away from the headwater an average of 1 inch. The headwater elevation was then raised to the 15-inch elevation, where deformations increased as well. Tube #2 deformed laterally an additional 1½ inches away from the headwater, while tube #1 and tube #3 deformed an additional 1 inch. Figure 2-41 depicts the three-tube configuration at a headwater elevation of 15-inches. Appendix A contains a complete set of figures for this trial.

At a headwater elevation of 17 inches, a sliding failure occurred. The entire three-tube configuration moved approximately 5 inches in a time span of about 15 seconds. At this point, the trial was terminated.

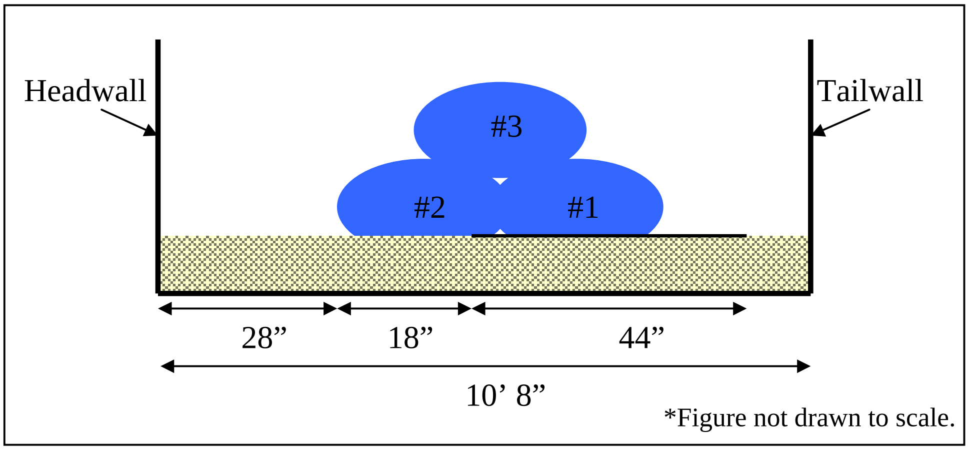

Figure 2-40: Cross Section of Trial 13 Setup

Figure 2-41: Trial 13 at Headwater Elevation of 15-Inches

2.5 Interface Testing

Interface tests were performed between two pieces of reinforced PVC and between reinforced PVC and the strapping material used to hold the three-tube configuration together during testing. The purpose of these tests was to determine the interface friction angles between the respective materials. The measured friction angles are needed for use in numerical modeling of the three-tube configuration. For a complete list of figures pertaining to the interface testing, refer to Appendix A.

Description of the Reinforced PVC Material and the Strapping Material

The reinforced PVC material used in this research was supplied by Detroit Tarp from Romulus, Michigan. The material was an 18-ounce coated vinyl with an approximate thickness of 0.53 mm. Reinforcement within the material was comprised of very thin strands of polyester thread. The reinforcement strands were parallel to one another, interwoven within the PVC material, and had a frequency of nineteen strands of reinforcement per inch of material. The two sides of this material were different in both texture and gloss. The side of the material that comprised the outside of the tubes had a high gloss and was textured due to the reinforcement strands within the material. The side of the material that comprised the inside of the tubes was dull in color and was smoother when compared to the other side. In order to mimic the tube testing conditions, the side of the material that comprised the outside of the tubes was tested for interface strength.

The strapping material used to hold the three-tube configuration together was made of a woven nylon with a width of 25.4 mm and a thickness of 1.6 mm. The strapping material was purchased at a local hardware store. One of the normal uses for the strapping material, as advertised at the hardware store, included securing items to the top of a vehicle.

Procedure for Reinforced PVC Material Against Reinforced PVC Material

The interface tests were performed in general accordance with ASTM D5321. Rather than use the recommended 12-inch-square testing apparatus, though, a 4-inch-square testing apparatus was used. The initial setup was to attach a piece of reinforced PVC to a ¾-inch by 4-inch by 4-inch plywood block that fit snugly within the lower ring of the test apparatus. In order to ensure that the reinforced PVC material was level with the shearing plane between the upper and lower rings, a ¼-inch thick, 3¾-inch square piece of aluminum was utilized as a filler.

The piece of reinforced PVC material attached to the plywood block was cut to dimensions of 4½ inches by 4½ inches. It was placed on the plywood block such that the textured and glossy side of the material was facing up, as was the condition during the three-tube configuration testing. The sides of the reinforced PVC, which extended beyond the wooden block dimensions, were attached to the block using staples. The sequence of attaching the PVC material to the plywood block consisted of first stapling one side of the material to the block, then the opposite side. Relief cuts were made to the corners of the material in order to allow for folding of the remaining sides, and then they too were stapled to the block. The wooden block with the PVC material attached was situated within the lower ring of the apparatus such that the material reinforcement was perpendicular to the shearing direction in order to mimic actual testing conditions. The final outcome was a plywood block that held the PVC material tightly against the top of the block with the reinforcement within the material perpendicular to the shearing plane. For each test, a fresh piece of PVC material was attached to the plywood block.

The next step was to place the top ring on top of the lower ring. A small amount of water was then placed on the PVC material in the lower ring in order to replicate wetted test conditions. Next, a second piece of PVC material with dimensions 4½ inches by 4½ inches was placed face down on the lower ring material. This piece of PVC material was placed such that the reinforcement was perpendicular to the shearing direction. Relief cuts were made on this material as well in order to allow for folding of the material edges within the upper ring. Figure 2-42 depicts the shear box with the upper and lower ring prepared for testing.

In order to distribute a normal stress to the PVC material evenly over its cross section, a sand filler material was used. First, a piece of plastic wrap with approximate dimensions of 12 inches square was placed on top of the upper ring and allowed to drape over the testing rings. The sand filler material was then placed into the upper ring and compacted using a 1-inch steel tamper until the filler material was 1/8-inch below the top of the upper ring. The top platen was then placed on top of the filler material within the upper ring.

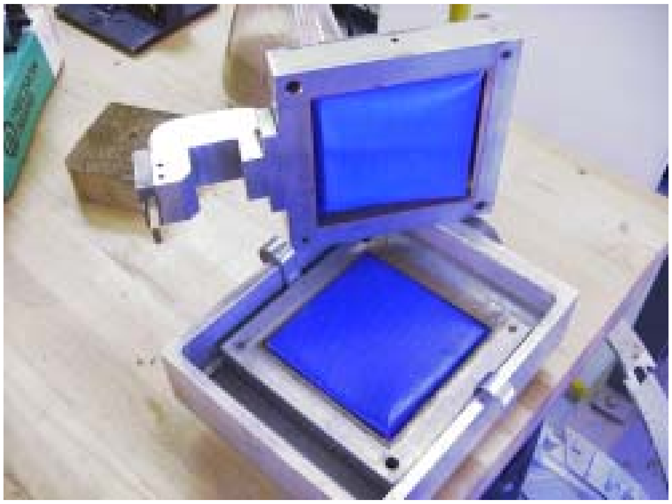

Figure 2-42: Shear Box with Upper and Lower Ring Prepared for Testing

After the top platen was in position, the hanger and appropriate weights were added to the shearing device and the sample was inundated with water. The top ring was raised approximately 1/16-inch with leveling screws, and the upper ring was then locked into the top platen using the set screws. The leveling screws were then removed and the measurement instruments were assembled onto the direct shear apparatus.

The shearing rate for each test was 0.036 inches per minute and the tests were run until approximately 0.45-inch of displacement was observed. For the interface testing of two pieces of reinforced PVC material, the normal weights ranged from 9.6 lb to 59.0 lb in order to apply the normal compressive stresses for each test.

Procedure for Strapping Material Against Reinforced PVC Material

Interface tests were also performed between the strapping material used to hold the three-tube configuration together and the reinforced PVC material. In this series of tests, a somewhat different procedure was utilized in order to set up the shearing apparatus.

The difference in this series of tests concerned the setup of the lower ring in the apparatus. Instead of attaching a piece of reinforced PVC material to the ¾-inch by 4-inch by 4-inch plywood block, strips of the strapping material were attached to it. Four strips of the strapping material, approximately 4½ inches in length and 1 inch wide, were attached to the block. Both sides of the strapping material were identical, so it did not matter which side was placed up on the wooden block. The strapping material was attached to the wooden block using staples. The sequence of attaching the strapping material to the plywood block consisted of first aligning one strip along the side of the block, stapling one end of the strapping to the block, then the opposite end. The strapping material pieces were attached side by side and stapled in a similar manner until the last piece of strapping extended beyond the wooden block sides. This overhanging strip of material was cut off using scissors. The wooden block with the strapping material attached was situated within the lower ring of the apparatus such that the direction of strapping was parallel to the shearing direction in order to mimic actual testing conditions. The final outcome was a plywood block that held the strapping material tightly against the top of the block with the strapping material running parallel to the shear plane. Figure 2-43 depicts the strapping material attached to the wooden block. Considering the strength and resilience of the strapping material, new strips of the material were not attached to the plywood block for each test. Following each test performed on the strapping material, though, a visual observation was made to determine if the surface texture of the strapping material had been altered due to the test. No such alteration or change could be detected.

The rest of the setup process was identical to the previous process used for the reinforced PVC against reinforced PVC. Figure 2-44 depicts the shear box prior to testing of the strapping material against the reinforced PVC material.

Figure 2-43: Strapping Material Attached to the Wooden Block

Figure 2-44: Setup of the Shear Box Prior to Testing

For the interface testing of the strapping material against the reinforced PVC material, the normal compressive stresses were applied using normal weights ranging from 32.5 lb to 58.9 lb. In terms of testing procedure, it should be noted that the first test utilized the 58.9 lb normal weight and then the following tests used progresively smaller values of normal weights.

Results

Based upon the data gathered from the interface tests, both peak and residual interface friction angles between the respective materials were determined. Figure 2-45 is a plot displaying the results of the interface tests between the two pieces of reinforced PVC material. Figure 2-46 is a plot displaying the results of the interface tests between the reinforced PVC material and the strapping material.

As can be seen from the respective plots, there is a great deal of scatter associated with the peak strengths of the respective materials, especially for the two pieces of reinforced PVC. In terms of the two pieces of reinforced PVC, possible reasons for the scatter could be attributed to the initial alignment of the materials within the shearing apparatus. In the ideal test setup, the reinforcement orientation within each piece of reinforced PVC was supposed to be parallel to one another. With this type of setup, the ridges caused by the reinforcement within one piece of PVC material could interlock between the ridges caused by the reinforcement of the other piece of PVC. There are various degrees of interlock based on the initial placement of the materials. One interlock position could be that the ridge caused by one reinforcement strand would be down in the valley caused by two other reinforcement strands. Another interlock position could be that the ridge of one reinforcement strand would be situated on top of a ridge caused by another reinforcement strand. Since the reinforcement frequency between the two materials was the same, it could be assumed that if the ridge of one reinforcement strand was in the valley of two other reinforcement strands, then the same was true over the entire two pieces of PVC. It should be noted that there are various interlock positions between the above mentioned cases, but each interlock position could cause a difference in the peak shear stress of the material.

Likewise, if the two reinforced PVC materials were placed in the shearing apparatus such that the reinforcement strands were not quite parallel to one another, this could also cause scatter in the peak stress. The ridges caused by the reinforcement would never have a chance to interlock in the opposite valleys due to this misalignment of the strands. With this type of setup, the interlocking of the reinforcement strands over the surfaces of the two reinforced PVC materials would not be as influential in terms of the peak shear stress.

For the interface tests performed between the strapping material and the reinforced PVC material, the extent of scatter in the peak shear stress was not as severe. This was due to the fact that the frequency of reinforcement within the PVC material did not match the frequency of ridges within the strapping material. The above mentioned reasons for scatter were still valid for these two materials, but the extent of their influence was somewhat minimal compared to the tests performed on two pieces of reinforced PVC.

In order to display the peak shear strength as it relates to normal stress, plots of the Peak Secant Friction Coefficient vs. Normal Stress were developed. The peak secant friction coefficient was defined as the peak shear stress divided by the normal stress at the peak shear stress value. These plots can be found in Appendix A.

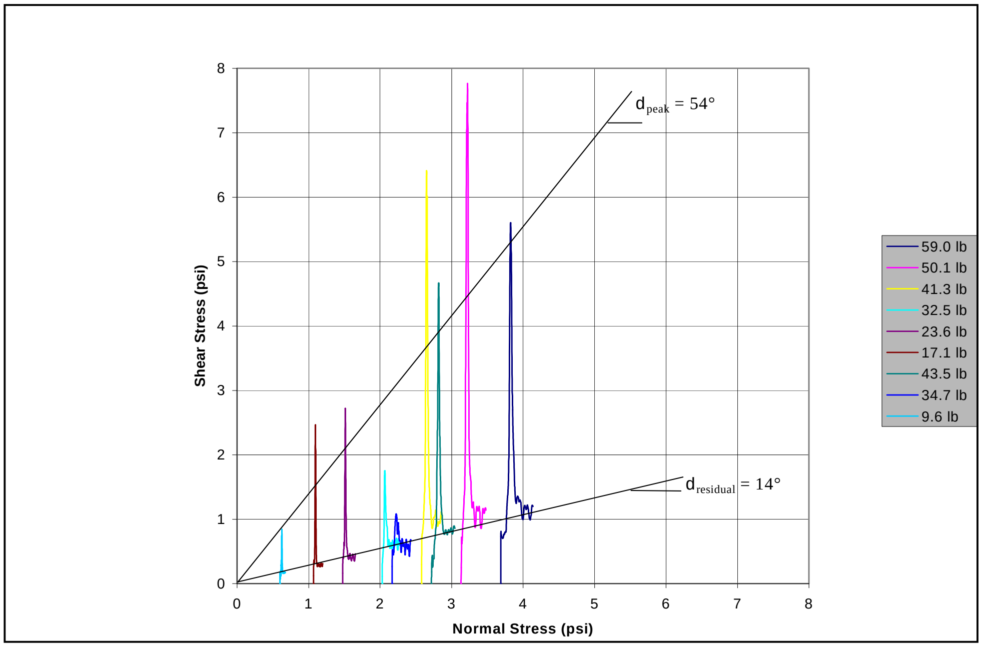

Figure 2-45: Plot of Shear Stress vs. Normal Stress for Reinforced PVC against Reinforced PVC

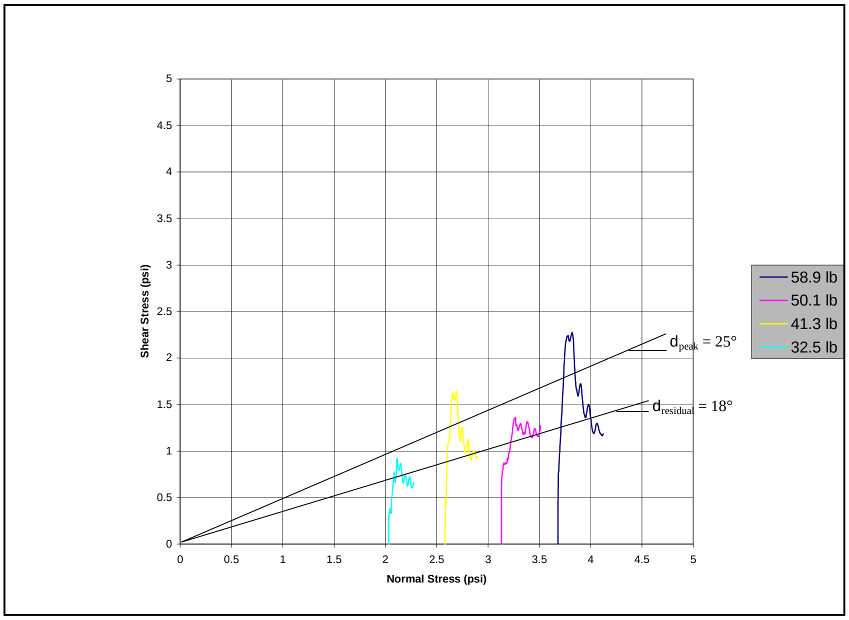

Figure 2-46: Plot of Shear Stress vs. Normal Stress for Reinforced PVC against Strapping Material

In terms of residual friction angles between the respective materials, traditional Mohr envelopes could be determined from the data. The materials reached a residual shear stress value after approximately 0.15-inch of horizontal displacement. It should be noted that the shear stress versus horizontal displacement plots in Appendix A show that a certain amount of horizontal displacement was needed until the peak shear stress was achieved. The reason that the peak shear stress did not occur right away could be explained by the fact that the material on the piece of plywood block was adjusting to the load and getting all of the slack out of the material. The peak shear stress did not occur until the staples restricted the material movement.

Table 2-1 lists the peak and residual friction angles between the respective materials. A complete set of results concerning the interface tests can be found in Appendix A.

Material Type	Peak Friction Angle	Residual Friction Angle
Reinforced PVC Against Reinforced PVC	54°	14°
Strapping Material Against Reinforced PVC	25°	18°

Table 2-1: Values of Peak and Residual Interface Friction Angles between the Respective Materials