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FRICTION AND LEAKAGE CHARACTERISTICS OF CONFINED, REDUCED-SCALE INFLATABLE STRUCTURES

JOSHUA J. SILL*, KENNETH H. MEANS*, EDUARDO M. SOSA† AND EVER J. BARBERO*

*Department of Mechanical and Aerospace Engineering,
West Virginia University
395 Evansdale Drive, Morgantown, West Virginia 26506-6106, USA
E-mail: drb@cemr.wvu.edu; Web page: http://www.mae.cemr.wvu.edu/

†Department of Civil and Environmental Engineering,
West Virginia University
395 Evansdale Drive, Morgantown, West Virginia 26506-6103, USA
E-mail: eduardo.sosa@mail.wvu.edu; Web page: http://www.cee.statler.wvu.edu/

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Summary: This work is focused on the evaluation of the performance of a small-scale inflatable, or plug, placed in a confined space provided by a circular rigid pipe as a way to contain the propagation of floods. The rigid pipe is a simplified and scaled approximation of an actual tunnel section. The evaluations were conducted using an inflatable plug made of a single layer of coated Vectran® fabric. Friction coefficients of the system were calculated for three different materials lining the pipe so a comparison could be made. These friction coefficients were also compared to laboratory friction machine testing of the same lining materials. This comparison showed that the friction coefficients of the pipe-plug system were lower than the laboratory friction machine tests. Rates of water leakage around the plug were also studied. The leakage rates were recorded for several different plug pressures while varying the tunnel pressure accordingly. It was observed that as pressure differential decreased between the plug and pipe, the leakage rate increased. Results showed also that the plug was able to withstand a pressure differential with manageable water leakage rates.

1 INTRODUCTION

Inflatable technology has become an attractive alternative to several conventional devices used for building temporary or special structures. Inflatable structures offer the benefits of being relatively lightweight and portable, for maintaining the necessary rigidity while in operation, and for having a relatively reduced production cost. These benefits have prompted the use of inflatables in confined spaces, such as pipes and tunnels, to act as barriers with minimal infrastructure modification.[1, 2] Some examples include the large-scale inflatable tunnel plugs that were tested and installed in the London subway system to block smoke spread and limit oxygen supply to tunnel fires[1] and the 23-foot (7 meter) diameter plug, which was filled with water and used in a uranium mine to successfully stop flooding.[2] Currently, West Virginia University (WVU) is conducting research in the area of confined inflatable structures that can be rapidly deployed and pressurized to stop a tunnel flood created by a natural disaster or man-made event where the tunnel is damaged under a waterway.[3-5] With plugs installed at key points, the damaged tunnel section could be contained, limiting the potential losses in a catastrophic event. The work at WVU has progressed in stages from a proof-of-concept, air-inflated structure[3] to full and quarter-scale models pressurized with water and subjected to backpressure for simulations of flooding.[4, 5]

Understanding the behavior of these structures requires studies that can be difficult or expensive to carry out at large scales. Therefore, evaluations at a reduced scale become necessary as an initial step to understand the characteristics of confined inflatable structures. This work is focused on the evaluation of the performance of a small-scale inflatable, or plug, placed in a confined space—provided by a circular rigid pipe—as a way to contain the propagation of floods. The rigid pipe is a simplified and scaled approximation of an actual tunnel section. A reduced-scale test bed was constructed in which a plug could be inflated inside of a pipe with one closed end. This space between the closed pipe end and the plug was pressurized with water, which applied an opposing force on the plug trying to push it out of the pipe. In order to stop the flow of water, the plug had to be capable of being pressurized and had to apply enough pressure on the pipe walls so that it did not move while being acted upon by an opposing force. The reduced-scale tests were conducted with three pipe (called also “tunnel” in this document) inner surface conditions for a variety of water pressures. The goal was to estimate tunnel/plug friction coefficients and water leakage rates that could be used to predict the performance of a full-size inflatable tunnel plug.

2 INFLATABLE PLUG AND TEST SET-UP

The inflatable plug was constructed from a single layer of a high-strength fabric made of Vectran® fibers. The surfaces of the fabric were protected with a urethane coating on both the inside and outside of the plug. This coating was important on the inside to provide watertightness characteristics and important on the outside for protecting the fabric from abrasion. The plug had an outer diameter of 50 inches (127 centimeters [cm]). It was slightly oversized to the tunnel's 48-inch (121.9 cm) diameter in order to ensure maximal contact between the tunnel and plug. The total length from tip to tip of the hemispherical end-caps was 110 inches (279.4 cm). The plug was designed for a maximum inflation pressure of 40 pounds per square inch gauge (psig) (275.79 kilo Pascal [kPa]) at which it had a volume of approximately 800 gallons (3,028 liters). An overview of the plug characteristics is illustrated in Figure 1.

A layout of the reduced-scale flooding simulation system created for conducting the tests of this work is illustrated in Figure 2. The system essentially consists of two closed circuits driven by high-flow and high-pressure water pumps as well as pressure regulators that recirculate and pressurize water, respectively. There is one circuit for pressurization of the plug and one circuit for pressurization of the rigid pipe representative of a tunnel section, as shown in Figure 2. Pressure sensors were installed at the same level in the plug and in the pressurized section behind the plug. A displacement sensor was used to measure plug movement. A collection basin was installed in front of the tunnel exit to measure leakage out of the tunnel. Data was sampled at one-second intervals using a LabView® program.

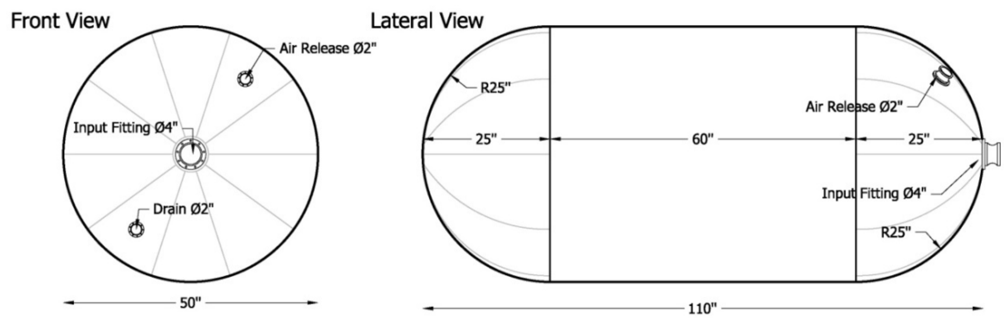


Figure 1: Inflatable plug general dimensions (1 inch = 2.54 cm).

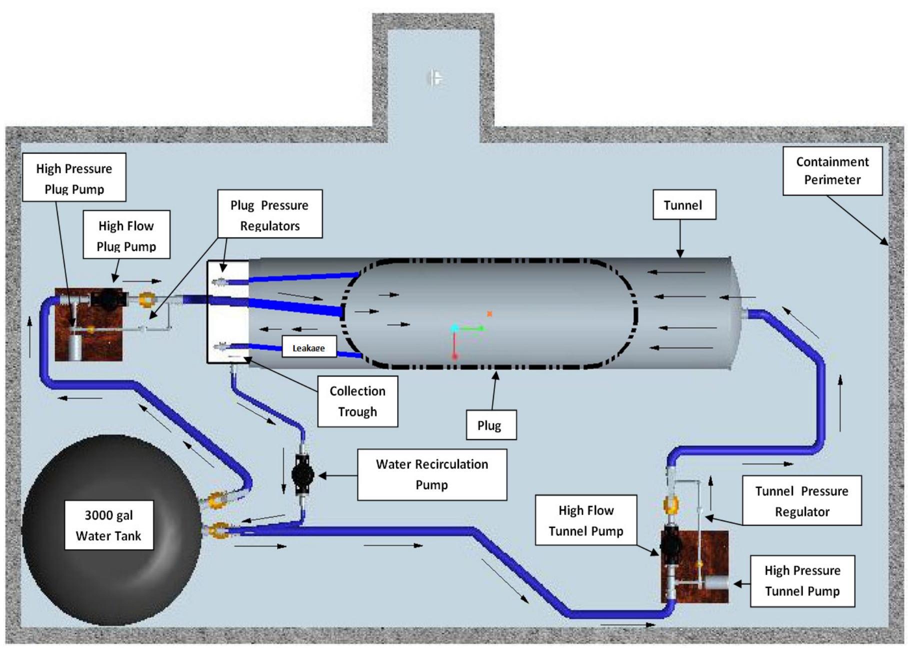
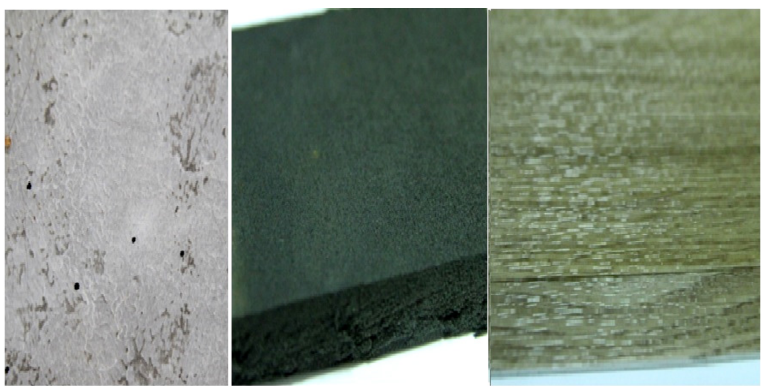


Figure 2: Plan view of the reduced-scale flooding simulation system used for testing.

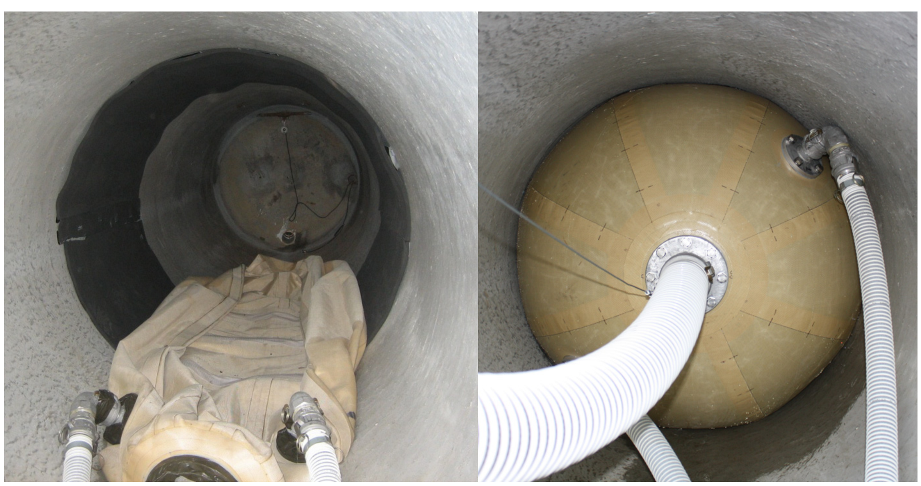
3 TUNNEL LININGS

In order to investigate the surface effects on the friction between the plug and tunnel, three materials were used to line the interior of the tunnel. In addition to the original smooth concrete interior of the tunnel, two more materials were used. These included a 0.25-inch (0.63 cm) thick soft neoprene pad and also a 0.125-inch (0.317 cm) thick vinyl coating. Both materials were bonded to the concrete surface with high-strength adhesive for the execution of the different tests. There were several factors that influenced the selection of these materials, such as roughness, compressibility, ease of application, and potential future application in full-scale prototypes. The materials chosen could be installed easily in a full-scale application if they provide benefits in terms of better friction characteristics and reduced leakage rates. A close look at the surface characteristics of each surface is shown in Figure 3. An example of the application of the neoprene liner is illustrated in Figure 4(a). Figure 4(b) shows the inflatable plug positioned in the pipe for the tests.



(a) (b) (c)

Figure 3: Tunnel linings: (a) Smooth concrete; (b) Neoprene; (c) Vinyl.



(a) (b)

Figure 4: (a) Example of neoprene tunnel lining positioned in the cylindrical portion of the deflated plug; (b) Inflated plug positioned for testing.

4 TESTING PROCEDURE FOR SLIPPAGE EVALUATIONS

The plug was inserted into the tunnel and connected to the inflation system. The plug was then filled with water but not pressurized beyond 5 psig (34.47 kPa). After the plug was filled, the tunnel was then filled with water but not pressurized. Once testing was ready to begin, the tunnel pressure was raised to 2 psig (13.79 kPa) lower than the plug pressure. The data collection system was activated once the pressures were within this 2 psig (13.79 kPa) differential. Data was sampled at one-second intervals, collecting values for plug pressure, tunnel pressure, and plug displacement. The data was recorded for five plug pressures: 5, 10, 15, 20, and 25 psig (34.47, 68.95, 103.42, 137.90, and 172.37 kPa, respectively). Each of these pressures was tested for each of the three tunnel linings.

The goal of the testing was to find the point at which the plug would move due to the force acting on it by the tunnel pressure. Because all pressure regulators and switches were manually operated, two people were required for testing. One person controlled the plug pressure while the other person controlled the tunnel pressure. Changing the tunnel pressure had a residual effect on the plug pressure. That is, when the tunnel pressure was increased or decreased, it produced an increase or decrease of the plug pressure, respectively. This behavior is due to the confining effect of the tunnel and the incompressibility of water. The test was performed by keeping the plug pressure constant and raising the tunnel pressure towards the plug pressure until the plug slipped. A loud thumping noise occurred when slippage took place, indicating the test for that pressure could be stopped. The plug pressure was continuously adjusted to keep it as close as possible to the selected test pressure. If the plug pressure was not adjusted, it would continue to increase as the tunnel pressure was increased, potentially exceeding the maximum pressurization capacity of the plug.

The tests started at the lowest plug pressure and continued to the next highest pressure systematically. When testing for one pressure was completed, the data was recorded and then restarted for the next pressure. When all five plug pressures were recorded for a given tunnel lining, the plug and tunnel were deflated and a new liner was installed. The tests then continued with the same procedure for each additional liner.

5 TESTING PROCEDURE FOR WATER LEAKAGE RATE EVALUATIONS

The plug was inserted into the tunnel and connected to the inflation system. The plug was then filled with water but not pressurized beyond 5 psig (34.47 kPa). After the plug was filled, the tunnel was filled with water but not pressurized. Both pressures were then adjusted to the desired positions, making sure the tunnel pressure always stayed at least 2 psig (13.79 kPa) lower than the plug pressure to avoid the chance of plug slippage. One person controlled the plug pressure regulator and another person controlled the tunnel pressure regulator. By using two people, the pressures could be adjusted simultaneously to reach the desired test point. The pressures had to be carefully observed because the change in one pressure affected the pressure in the other.

Leakage rates were recorded for seven different plug pressures ranging from 5 psig (34.47 kPa) to 35 psig (241.32 kPa) in increments of 5 psig (34.47 kPa). The tunnel pressure was set to percentages of the plug pressure: 20%, 40%, 60%, and 80%. These percentages of the plug pressure were used to keep the data consistent across the various tests. For each plug pressure, three leakage rates were recorded for each of the tunnel pressures. This equaled a total of 12 leakage rates for each plug pressure. An average leakage for each plug and tunnel pressure combination could then be found. A total of 84 leakage tests were performed for each of the three linings, providing a total of 252 measurements.

6 RESULTS

6.1 Slippage tests

Analysis of the results showed that the data displayed unique trends in the plug and tunnel pressures; these trends allowed the slippage point to be easily seen. When the plug slipped, it caused a sudden increase in tunnel volume. This volume increase caused a sudden decrease in the pressure in the tunnel, which also caused a decrease in plug pressure. An example of the changes in the plug and tunnel pressures at the instant of slippage is shown in Figure 5. The slippage itself created very small axial displacements that were detected by the displacement sensor. As seen in Figure 5, the plug remained relatively steady while the pressures were gradually matched until reaching the slippage point in which the plug moved and reached a new equilibrium position. The oscillations in the displacement data were attributed to static interference and a relatively low-resolution sensor used for this set of experiments. A fitting line shows the tendency of the axial displacement in Figure 5. Similar behavior was observed in all combinations of pressures and for the three lining materials.

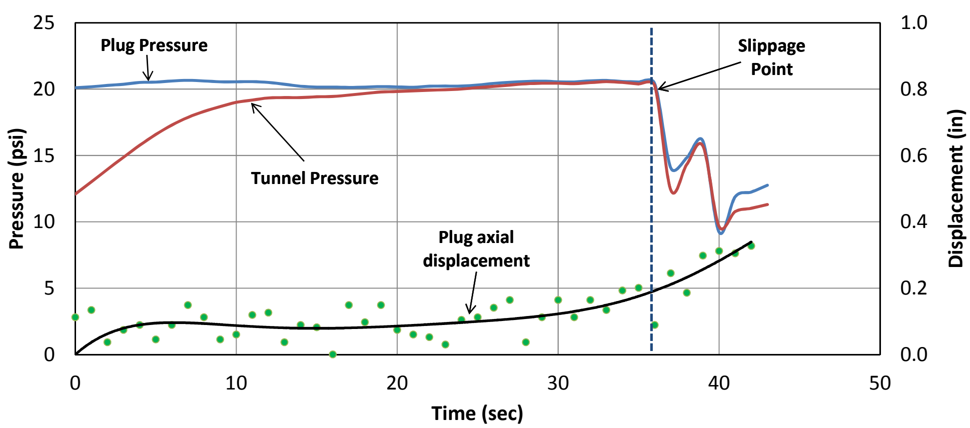


Figure 5: Example of plug and tunnel pressures variation as well as axial displacement up to the point of slippage.

The pressure differential between the plug pressure and tunnel pressure was then used to calculate the friction coefficient for each tunnel lining. A static force balance was used to find the friction coefficient corresponding to the slippage instant in terms of the measured plug and tunnel pressures. The general static friction equation $F_F = f \times N$, where F_F is the resisting tangential force originated by the action of the friction coefficient *f* and the normal force *N,* was used to estimate the friction coefficient of the system at the moment of slippage. Figure 6 shows a free body diagram of the acting forces applied to the tunnel and plug test bed along with their dimensions.

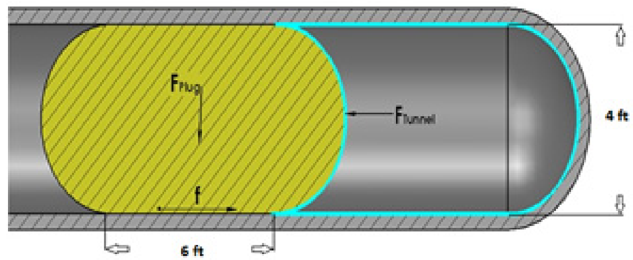


Figure 6: Forces acting on the testing system.

6.2 Evaluation of friction coefficient

The hydrostatic forces and the pressure forces were superimposed and integrated to obtain the normal force used in the general friction equation to obtain the following equation:

$$\frac{F_{TH} + F_{ATP}}{F_{PH} + F_{APP}} = f \tag{1}$$

Where F_{TH} is the hydrostatic tunnel force, F_{ATP} is the force from the applied tunnel pressure, F_{PH} is the hydrostatic plug force, and F_{APP} is the force from the applied plug pressure. The effective contact length (L_C) of the plug was measured and resulted in a value of 72 inches (183 cm) and tunnel diameter of 48 inches (121.9 cm). The forces in terms of measured pressures and geometric properties are:

For the tunnel

$$F_{ATP} = P_{ATP} \times A_T \tag{2}$$

For the plug

$$F_{APP} = P_{APP} \times \pi \times D \times L_C \tag{3}$$

Combining equations (1), (2), and (3), we get:

$$\frac{1568.3 \text{ lbs} + P_{ATP} \times 1808.64 \text{ in}^2}{1709.65 \text{ lbs} + P_{APP} \times 10857.34 \text{ in}^2} = f \tag{4}$$

Where P_{ATP} is the applied tunnel pressure and P_{APP} is the applied plug pressure. The pressure acting on the hemispherical end-cap of the plug was assumed to act on the projected circular area of the plug, which is conservative and gives slightly lower friction coefficients. The resulting tunnel/plug friction coefficients calculated with Equation (4) are summarized in Tables 1 to 3 for concrete, neoprene, and vinyl linings, respectively.

Results summarized in Tables 1 to 3 show that equation (4) predicted the lowest average friction coefficient for neoprene lining with a value of 0.154, while the vinyl lining had the highest value of 0.176. The friction coefficient for a concrete surface was very close to the vinyl with a value of 0.172. These results contradict the assumption that the vinyl covering would have the lowest friction coefficient because of its smoother surface. It is thought that the urethane coating on the plug fabric sticks better to the plastic-like surface of the vinyl lining, therefore creating a higher friction coefficient than in the cases of neoprene or concrete surfaces.

Table 1: Friction coefficient for concrete lining (1 psig = 6.895 kPa).

Concrete			
Plug Pressure (psig)	Tunnel Pressure (psig)	Pressure Differential (psig)	Friction Coefficient, f Eq. (4)
6.109	5.948	0.161	0.181
10.535	10.461	0.074	0.177
15.271	15.160	0.111	0.173
19.536	18.755	0.781	0.166
24.136	23.020	1.116	0.164
		Average	0.172

Table 2: Friction coefficient for neoprene lining.

Neoprene			
Plug Pressure (psig)	Tunnel Pressure (psig)	Pressure Differential (psig)	Friction Coefficient, f Eq. (4)
4.584	4.473	0.111	0.188
9.518	8.130	1.388	0.155
15.073	12.060	3.013	0.141
19.834	16.251	3.583	0.143
24.706	20.763	3.943	0.145
		Average	0.154

Table 3: Friction coefficient for vinyl lining.

Vinyl			
Plug Pressure (psig)	Tunnel Pressure (psig)	Pressure Differential (psig)	Friction Coefficient, f Eq. (4)
6.667	6.630	0.037	0.183
11.998	11.911	0.087	0.175
15.147	15.023	0.124	0.173
20.416	20.255	0.161	0.171
		Average	0.176

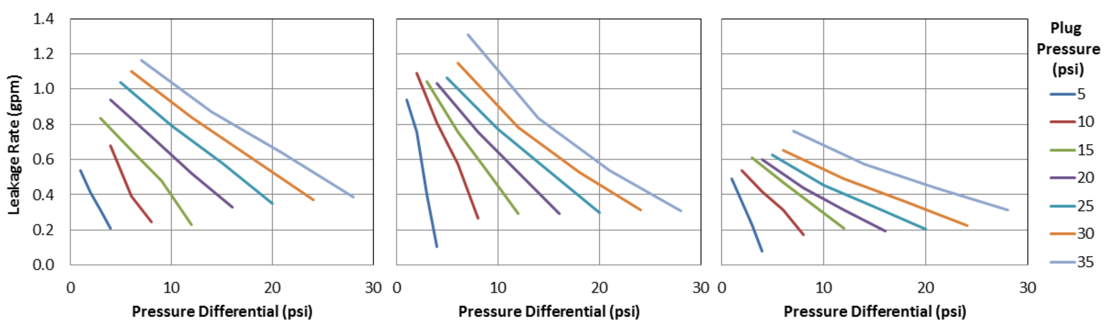
These friction values were also compared to other experimental values obtained from the friction machine testing of the same material.[6, 7] A comparison of these values is shown in Table 4 where it can be clearly seen that the friction values for the plug and tunnel slippage tests are significantly lower than the values predicted from the friction sled tests. This information does not tell us the values are incorrect, but rather that there are other factors influencing the friction characteristics in the tunnel tests that were not present in the sled tests or vice versa. Note also that the sled tests follow the same trend as the plug and tunnel tests in that the neoprene has the lowest friction coefficient and the vinyl has the highest value. It is thought that the leakage pressure or leakage ratio could be influencing the estimation of the friction factor in the tunnel plug system. This relationship between the friction coefficient and leakage rate is summarized in Table 5.

Table 4: Comparison of friction coefficients.

Surface	Average Friction Coefficient	
	Plug Tunnel Test	Friction Machine Test
Concrete	0.172	0.620
Neoprene	0.154	0.610
Vinyl	0.176	0.710

6.3 Evaluation of leakage rates

From the results of the leakage tests it was observed that the leakage rate decreases when the pressure differential between the plug and tunnel increases. That is, a larger pressure differential means that the plug and tunnel pressures are further from each other. When this differential increases, the plug is able to exert more force on the tunnel walls, which seals the contact surface better. Therefore, the water in the tunnel is not able to flow around the plug. This trend is observed across all tunnel linings, as shown in Figure 7.



(a) (b) (c)

Figure 7: Leakage rate for: (a) Concrete; (b) Neoprene; (c) Vinyl.

Pressure differential is not the only factor that influences the leakage rate. Figure 7 shows that for a given pressure differential, the leakage rate increases as the plug pressure increases.

This indicates that higher tunnel pressures cause more leakage, despite having the same pressure differentials. A different way of seeing this effect is illustrated in Figure 8 where the leakage rate was plotted in terms of the pressure ratio, defined as the ratio between the tunnel and plug pressures. From Figure 8 it is seen that the higher the pressure ratio (closer to one), the higher the leakage rate.

Because the plug pressure must always be more than the tunnel pressure to avoid unwanted plug slippage, we plotted the pressure ratios with respect to leakage rates; this allowed us to represent how the leakage rate increases with increased pressure ratios. The three linings followed this general trend. However, for the same pressure ratio, the vinyl lining consistently displayed the least leakage rate, followed by the concrete and neoprene liners, as illustrated in the linear trends for each material in Figure 8.

From Figures 7 and 8 it is seen that, depending on the combination of tunnel and plug pressures, the leakage rates varied from a minimum of approximately 0.2 gallons per minute (0.76 liters per minute) to a maximum of approximately 1.2 gallons per minute (4.54 liters per minute). These values are relatively small and were manageable by the draining and pumping system installed in the test set-up.

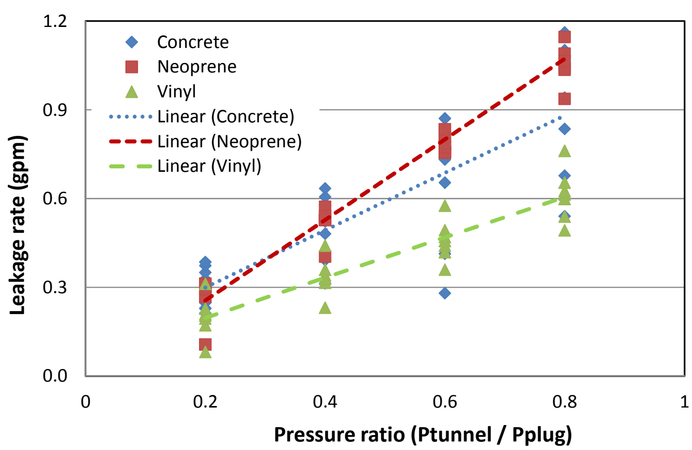


Figure 8: Leakage rate vs. Pressure ratio.

From the analysis of the average friction coefficients and the leakage rates measured at the onset of slippage (that is, that is, the tunnel to plug pressure ratio was close to one) for the different tunnel linings, it was found that there is an inverse relationship between the two quantities. As the leakage rate increases, the friction coefficient decreases, suggesting that the contact between the surfaces of the plug and the liner is reduced, allowing the passage of more water. This behavior is attributed to the surface characteristics of the lining material. The neoprene lining had a smooth surface with a relatively porous texture that possibly allowed more leaks. Concrete and vinyl surfaces have similar surface smoothness, which produced similar friction coefficients. However, vinyl seemed to interact better with the urethane coating of the Vectran fabric, producing a better sealing and therefore, reducing the leakage rate as indicated in the values summarized in Table 5.

Table 5: Relationship between friction coefficient and leakage rate.

Surface	Average Friction Coefficient f	Average Leakage Rate (gpm)	Average Leakage Rate (liter/min)
Neoprene	0.154	1.09	4.13
Concrete	0.172	0.90	3.41
Vinyl	0.176	0.61	2.31

7 CONCLUSIONS

The reduced-scale, confined, inflatable plug, tested under three different friction surfaces, was able to withstand the backpressure applied to the end-cap of the plug and only slip when the tunnel pressure approached the plug pressure—that is, when the tunnel to plug pressure ratio approached one. Thus, monitoring of tunnel and plug pressures is an important operational aspect to ensure adequate blockage of the tunnel in the event of flooding. For the three materials used as liners of the tunnel surface, the leakage rate was relatively small and manageable by the drainage system.

The friction coefficients determined from the different sets of tests presented in this work provided guidelines on the magnitude of friction coefficients that might be useful when designing large-scale confined inflatable plugs. Based on experiments, the friction coefficients estimated at a reduced scale were smaller than those obtained when testing the plug fabric alone in a standard friction test. The leakage rate or leakage pressure may be causing the difference; further testing will be necessary to assess their influence.

ACKNOWLEDGMENTS

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